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Annex 1: Hazard, exposure and vulnerability modelling

1) Hazard, exposure and vulnerability modelling	1.1.1 Heatwaves	**STAR Tool**

Model/ tool type and outputs	The STAR tools have been developed to assess the effectiveness of green infrastructures as a climate change adaption measure. Two tools are available: one is specifically for the evaluation of measures addressing surface temperature increase, the other for addressing surface runoff potential impacts (see Star Tool, heavy precipitation for more information). The former tool output indicates the maximum surface temperature, expressed as an estimate by considering different conceptual designs.
Open access?	Yes
Key data inputs	For the surface temperature tool, required input data includes temperature scenarios, land cover scenarios and soil type. Temperature data should be provided as the daily average air temperature at a height of 2m. The tool's default values are supplied as baseline temperature (1961-1990) and 2050s high temperature scenarios with different probability levels (10%, 50%, 90%). The land cover scenario provides the percentage of different land types within the study area, including buildings, main roads, imperious surfaces, green and blue surfaces and bare soil or gravel surfaces. Finally, in order to account for the different infiltration rates, the hydrologic soil typology needs to be specified.
Key data accessibility/ availability	Default values for all the necessary input parameters (except hydrologic soil type) are automatically provided for the North West of England, where the tool has been developed and tested. For application outside of England, some default input values are automatically provided but they require verification since they have been drawn from assumptions based on the Greater Manchester area. Nevertheless, in this case, users are required to input data values for temperature scenarios, land cover and hydrologic soil type related to the investigated area.
Strengths	The STAR tools are intended to have minimal input requirements, although this will vary depending on the location of application.
Assumptions/ limitations	Due to the Urban Heat Island effect, urban areas are generally warmer than surrounding rural areas. A key limitation is the tools' inability to show the impact of the development on an adjacent neighbourhood, for example, if new development warms adjacent regions through obstructing colder air flows.

Spatial scale and resolution	The STAR tools are suitable for assessments at the neighbourhood scale. Whilst there is no strict limit on the study area size, the use is recommended for areas between 0.04 and 5km² (or 4ha to 500ha). The tool allows users in the North West of England to select their study area(s) from wards, lower layer super output areas and 5km x 5km grid squares, upload their own shapefile boundaries, draw study area boundaries straight onto a map, or list their study areas. Other UK users can also upload their own shapefile boundaries, draw study area boundaries straight onto a map, or list their study areas. Outside of the UK, users will only be able to list their study areas.
Temporal scale and resolution	The maximum surface temperature is provided as a daily value.
Accessibility of outputs	The surface temperature tool provides an easily exportable table with the average maximum surface temperature. This value indicates the hottest surface temperature expected during the day in the study area.
Adaptation policy cycle stages	Step 4) Assessing adaptation options; Step 6) Monitoring and evaluation.
Adaptation policy insights	Outputs of the STAR tools can be used to inform policy, strategy and development. They can be useful for a wide range of professionals and organisations, including planners, developers, master planners, local authorities, urban forestry initiatives, NGOs and academics with an interest in developing understanding regarding the influence of urban greening solution within their local climate.
Relevant application	The tool has been tested in Kuala Lumpur (Malasyia) and in Merseyside and Greater Manchester (North West England). These preliminary applications have provisioned all the default values for all the necessary input parameters required in the current version of the tool for these areas.
Main reference(s)	Gill, S.E. (2006). Climate change and urban greenspace. PhD thesis, University of Manchester. www.ginw.co.uk/resources/Susannah_PhD_Thesis_full_final.pdf; Gill, S.E., Handley, J.F, Ennos, A.R. and Pauleit, S. (2007). Adapting cities for climate change: the role of the green infrastructure. Built Environment. 33, 115-133.
Suitability for rapid assessment	The model results are suitable for rapid assessment.
Websites	https://maps.merseyforest.org.uk/grabs/index.php
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.1 Heatwaves	**Climate projections of the number of heatwave days for European countries (C3S Application)**

Model/ tool type and outputs	The application provides a calculation for the number of heatwave days experienced in Europe for the historical period (1976-2005) and for two projected periods (2031-2060 and 2071-2100) by using different future climate change scenarios. Outputs are provided as maps, which show the number of heatwave days elaborated from the temperature gridded dataset at 0.1°x0.1° spatial resolution. Furthermore, the results are also provided as graphs showing for each country the past and future trends of the number of heatwave days as the mean, maximum and minimum limit.
Open access?	Yes, the application is available on the CDS platform
Key data inputs	The user can select the time period and the Representative Concentration Pathway (RCP) scenario for which the analysis is to be conducted. The application uses two European-wide heatwave definitions: the first definition is provided by the Climatological EURO-CORDEX dataset, and the second definition is proposed in the framework of the Euroheat project. Furthermore, set of nation-specific definitions are available for a limited number of European countries. The user is therefore required to define which of the two heatwave definitions the model refers to.
Key data accessibility/ availability	Temperature statistics for Europe derived from climate projections are available at: https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-temperature-statistics?tab=overview
Strengths	The output of the application can be used as an input for specific impact models.
Assumptions/ limitations	The main limitation of the model is related to the spatial scale resolution, which corresponds to the resolution of the climate models used in the analysis of the temperature data. Furthermore, the tool does not account for indirect factors that can exacerbate the intensity of heatwave events, such as the urban heat island and wind intensity.
Spatial scale and resolution	Application outputs are provided for the 28 member states of the European Union. For Belgium, Italy, Hungary and Lithuania, the results are also available at NUTS1, NUTS2 (for Italy and Belgium) and NUTS2 and NUTS3 level (for Hungary and Lithuania). The nomenclature of territorial units for statistics (Nomenclature des Unités territoriales statistiques – NUTS) is a geographical system, according to which the territory of the European Union is divided into hierarchical levels.

Temporal scale and resolution	The number of heatwave days is provided for three different time periods: historical period (1976-2005); near future (2031-2060); and far future (2071-2100). For the future periods, two different scenarios are available: RCP 4.5 and RCP 8.5.
Accessibility of outputs	The outputs of the analysis can be directly downloaded from the web platform as a .CSV file, which includes information on the model name, the time interval, the mean value and the upper and lower level.
Adaptation policy cycle stages	Step 2) Assessing risks and vulnerability to climate change; Step 3) Identifying adaptation options
Adaptation policy insights	The model outputs can be used for comparing the number of heatwaves over time and under different concentration scenarios. This comparison supports the calculation of expected anomalies and therefore evaluating the impact of climate change on extreme climate variables. This information can support the identification of suitable measures aimed at reducing the impact of extreme weather events.
Relevant application	This tool can support the identification of tailored adaptation strategies in different land-use contexts, such as urban and agricultural areas. In the framework of Copernicus Climate Change Service, the European Health Service provides users with tailor-made climate information for the health domain. This information consists of several climate-health indicators, which include heat and cold stress data. The heatwaves analysis tool also supports research around the occurrence of wildfires, providing information and data that can support locating these events in the context of a changing climate.
Main reference(s)	http://datastore.copernicus-climate.eu/c3s/published-forms/c3sprod/app-health-heat-waves-projections/Web_Application_HEAT-COLD.4A_v1_latest.pdf
Suitability for rapid assessment	The model is useful to ensure a rapid assessment of the potential climate change impacts on extremes. Temperature data required for the analysis are already available on the CDS platform.
Websites	https://cds.climate.copernicus.eu/cdsapp#!/software/app-health-heat-waves-projections?tab=app
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.3 Forest fires	**Fire Weather Index (FWI)**

Model/ tool type and outputs	The Fire Weather Index (FWI) is a prominent and widely applied Fire Danger Rating Systems (FDRS) index. The system is composed of six components which transform input weather/climate data into intermediate quantities, which are subsequently exploited to estimate the final aggregated index. Three of these components represent fuel moisture codes while the other three constitute fire behaviour indices. The FWI expresses conditions favourable for a fire ignition occurrence and its propagation. It has also been applied by several authors to correlate climate change with expected changes in fire severity and damage (for example, Flannigan and Van Wagner, 1991; Xiao-rui *et al.*, 2011; Bedia *et al.*, 2014).
Open access?	Yes
Key data inputs	Four meteorological inputs: daily accumulated precipitation, temperature, relative humidity and instantaneous wind speed, which are generally standardised to measurements at noon, local standard time.
Key data accessibility/ availability	ERA5 or RCM which are available at Copernicus
Strengths	Can be quick to run model simulations and provides support for ignition prevention, fire detection, fire management and adaptation planning.
Assumptions/ limitations	Limitations include a scarcity of appropriate weather/climate data and other fire predisposing factors, such as land use and vegetation, topography and variables affecting human fire initiation and control, are not included in FWI calculations.
Spatial scale and resolution	Spatial scale and resolution are dependent on climate data resolution.
Temporal scale and resolution	Temporal scale and resolution are dependent on climate data resolution.
Accessibility of outputs	Outputs are maps and reports on fire danger to assess climate change impacts on long-term future wildfire hazards, which are easy to understand.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change
Adaptation policy insights	Investigating future high-fire hazard areas could support vulnerability and risk assessments, and thus targeting locations for adaptation options.

Relevant application	Schelhaas *et al.* (2010) applied FWI to evaluate the historical and future fire hazard. Giannakopoulos *et al.* (2014) assessed the vulnerability of Greek Forest to fire risk occurrence through projection of long-term fire related indices (FWI).
Main reference(s)	van Wagner CE (1987) Development and structure of the Canadian forest fire weather index. Forestry technical report 35. Canadian Forestry Service, Ottawa Schelhaas M-J, Hengeveld G, Moriondo M, Reinds GJ, Kundzewicz ZW, Maat H, Bindi M (2010) Assessing risk and adaptation options to fires and windstorms in European forestry. Mitig Adapt Strat Glob Change 15:681–701. doi:10.1007/s11027-010-9243-0 Giannakopoulos C, Karali A, and Roussos A (2014) Tailored stakeholder products help provide a vulnerability and adaptation assessment of Greek forests due to climate change- Geophysical Research Abstracts Vol. 16, EGU2014-6536, 2014
Suitability for rapid assessment	The model can be rapidly used once input data are collected and model calibrated and validated.
Websites	http://www.meteo.unican.es/en/node/73079
Manuals/ training/ videos	https://cran.r-project.org/web/packages/cffdrs/cffdrs.pdf
Wikipedia page	https://en.wikipedia.org/wiki/Forest_fire_weather_index
Other	

1) Hazard, exposure and vulnerability modelling	1.1.3 Forest fires	**FLAMMAP/ FARSITE**

Model/ tool type and outputs	FlamMap is a fire analysis desktop application that describes potential fire behaviour for constant environmental conditions for weather and fuel moisture. Potential fire behaviour calculations include surface fire spread, flame length, crown fire activity type, crown fire initiation and crown fire spread. The application now includes FARSITE outputs (Finney 1998, 2004), which are well-suited for landscape level comparisons of fuel treatment effectiveness given that fuel is the only changeable variable. Outputs and comparisons can be used to identify combinations of hazardous fuel and topography, aiding in the prioritisation of fuel treatments.
Open access?	Yes
Key data inputs	The FlamMap program requires eight spatial data layers: elevation, slope and aspect; fire behaviour fuel models; forest canopy cover; forest canopy height; forest canopy base height; and forest canopy bulk density. Other input data requirements include information regarding dead and live fuel moistures, weather information and wind speed and direction.
Key data accessibility/ availability	Weather/Climate data: ERA5 or RCM which are available at Copernicus Topography: https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem Fuel data: CLC Corine Land Cover 2018 (https://land.copernicus.eu/pan-european/corine-land-cover/clc2018) and literature
Strengths	FlamMap can provide detailed fire assessments suitable for subnational scales. They provide graphical outputs of fire activity metrics which are easy to understand and useful to inform a wide range of decision-making contexts. FlamMap also provides useful information for determining effective fuel treatment locations and are thus able to simulate adaptation options.
Assumptions/ limitations	FlamMap simulates fire behaviour and growth using constant values on fuel moisture and weather. Many do not identify the probability of fire events; Poor or missing representation of the long-term interaction between fire and vegetation.
Spatial scale and resolution	Sub-national, 250 m

Temporal scale and resolution	Temporal scale and resolution are dependent on climate data resolution.
Accessibility of outputs	Maps on fire activity metrics are in ASCII (American Standard Code for Information Interchange) and require manipulation through GIS
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	These models can be applied to define and virtually test fire and fuel management programs and policies, with the aim to develop comprehensive strategies for risk mitigation and climate change adaptation.
Relevant application	Kalabokidis *et al.* (2015), Mitsopoulos *et al.* (2016) and Lozano *et al.* (2017) applied minimum travel time fire simulation algorithm by using the FlamMap and Randig softwares to characterize potential response of fire behaviour under climate change at local and national level, respectively. The findings of the three studies can provide information and support in fire suppression strategy, fire management planning and fire risk mitigation activities.
Main reference(s)	Kalabokidis, K.; Palaiologou, P.; Gerasopoulos, E.; Giannakopoulos, C.; Kostopoulou, E.; Zerefos, C. Effect of Climate Change Projections on Forest Fire Behavior and Values-at-Risk in Southwestern Greece. Forests 2015, 6, 2214-2240. Lozano, O.M., Salis, M., Ager, A.A., Arca, B., Alcasena, F.J., Monteiro, A.T., Finney, M.A., Del Giudice, L., Scoccimarro, E. and Spano, D. (2017), Assessing Climate Change Impacts on Wildfire Exposure in Mediterranean Areas. Risk Analysis, 37: 1898-1916. doi:10.1111/risa.12739 Mitsopoulos, I., Mallinis, G., Karali, A. Giannakopoulos C., Arianoutsou M (2016) Mapping fire behaviour under changing climate in a Mediterranean landscape in Greece. Reg Environ Change 16, 1929–1940 doi:10.1007/s10113-015-0884-0 Salis, M., Del Giudice, L., Arca, B., Ager, A.A., Alcasena-Urdiroz, F., Lozano, O., Bacciu, V., Spano, D., Duce, P. (2018) Modeling the effects of different fuel treatment mosaics on wildfire spread and behavior in a Mediterranean agro-pastoral area. Journal of Environmental Management, 212, pp. 490-505. Alcasena-Urdíroz, F.J., Vega-García, C., Ager, A.A., Salis, M., Nauslar, N.J., Mendizabal, F.J., Castell, R. (2019) Forest fire risk assessment and multifunctional fuel treatment prioritization methods in Mediterranean landscapes. Geographical Research Letters, 45 (2), pp. 571-600.
Suitability for rapid assessment	The model can be rapidly used once trained, calibrated and validated; input data requires medium-term study for accurate data collection
Websites	https://www.firelab.org/project/flammap

Manuals/ training/ videos	An online tutorial is included in the online 'Help' and example data sets are provided with the installation download
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.3 Forest fires	**Standalone Fire Model (SFM)**

Model/ tool type and outputs	Standalone fire model (SFM) is derived from the Community Land Model (CLM-AB) (Migliavacca *et al.*, 2013) and can reproduce burn area extent and the efficiency of fire suppression. It includes both climatic and socio-economic drivers of forest fires, supporting the assessment of adaptation strategies.
Open access?	No
Key data inputs	Key input data includes daily values of temperature, precipitation, wind, specific humidity, and surface pressure; forest biomass of dead wood and litter carbon data; population density.
Key data accessibility/ availability	Weather/Climate data: ERA5 or RCM which are available at Copernicus Global Forest Biomass map (Kindermann *et al.*, 2008) Population density dataset GPW version 3 (CIESIN 2005) Fire suppression from the European Fire Database (EFDB)
Strengths	A new procedure for the calibration of fire suppression efficiency has resolved previous problems of overestimating modelled burned area extent (Migliavacca *et al.*, 2013).
Assumptions/ limitations	Assumptions and limitations include use of static biomass data; exclusion of lightning; simplified representation of fuel, which does not distinguish between species nor explicitly account for shrub and grass fuel components; fire spread is estimated without accounting for landscape fragmentation; inadequate representation of the suppression probability of multiple simultaneous fires.
Spatial scale and resolution	Regional and continental scales, at a spatial resolution of 25×25 km
Temporal scale and resolution	The SFM model uses daily global dataset. The outputs are averaged at 10-years temporal resolution
Accessibility of outputs	Tabular output data (burned area) need to be processed to obtain maps and graphs.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model supports the assessment of adaptation strategies at a pan-European scale.
Relevant application	Khabarov *et al.* (2016) quantitatively assessed two forest fire adaptation options under projected climate change in Europe. The SFM accurately simulated burned area extent in correlation with observed data for selected European test countries. Under future scenarios, the authors estimated an increase in burned areas of approximately 200% by 2090 under a ‘‘no adaptation’’ scenario;

	alternatively, the application of prescribed burnings could potential reduce this increase to below 50%.
Main reference(s)	Khabarov, N., Krasovskii, A., Obersteiner, M., Swart R., Dosio A., san-Miguel-Ayanz J., Durrant T., Camia A., Migliavacca M. (2016). Forest fires and adaptation options in Europe. Reg Environ Change 16, 21–30 (2016) doi:10.1007/s10113-014-0621-0 Migliavacca M, Dosio A, Kloster S, Ward DS, Camia A, Houborg R, Houston Durrant T, Khabarov N, Krasovskii AA, San Miguel–Ayanz J, Cescatti A (2013) Modeling burned area in Europe with the community land model. J Geophys Res Biogeosci. 118(1):265–279. doi:10.1002/jgrg.20026 Krasovskii Andrey, Khabarov Nikolay, Migliavacca Mirco, Kraxner Florian, Obersteiner Michael (2016) Regional aspects of modelling burned areas in Europe. International Journal of Wildland Fire 25, 811-818.
Suitability for rapid assessment	The model requires training, calibration and validation. Input data can be rapidly accessed.
Websites	
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.4 Land desertification	**RUSLE - Revised Universal Soil Loss Equation**

Model/ tool type and outputs	RUSLE is based on equations that describe how features, including plant yield, vegetative canopy and rooting patterns, surface roughness, mechanical soil disturbance and biomass volume of the soil surface and upper layer, affect soil erosion rates caused by rainfall and associated overland flow.
Open access?	Yes
Key data inputs	Input data includes rainfall erosivity, which is related to rainfall volume and intensity; soil erodibility; slope length, steepness, and shape; and land cover, including management (cultural) practices.
Key data accessibility/ availability	ERA5 or RCM daily precipitation data are available at Copernicus; topography data: https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem ; land cover data: CLC Corine Land Cover 2018; WISE Soil Property Databases
Strengths	USLE and the Revised USLE are the most widely applied soil erosion prediction models for a variety of purposes and under multiple different conditions. This approach has a high degree of flexibility and data accessibility with extensive scientific literature, and comparability of results. It is largely supported by GIS tools to derive erosion susceptibility maps. Compared to other approaches, it requires few input data which are easy to acquire or derive.
Assumptions/ limitations	Although widely implemented for estimating rainfall erosivity, several relevant physical processes, such as runoff, infiltration and simulation of soil deposition, are not simulated. This approach identifies erositivity or erosion susceptibility but is incapable of modelling the effect of land use management on sedimentation and does not clarify upstream-downstream hydrological links within watersheds.
Spatial scale and resolution	Regional and continental scale; resolution is dependent on the climate and soil data resolution.
Temporal scale and resolution	Temporal scale and resolution are dependent on the climate data resolution.
Accessibility of outputs	Maps and reports on fire danger to assess climate change impacts on long-term future wildfire hazards.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change
Adaptation policy insights	Outputs provide erosion susceptibility maps under current and future precipitation trends and different land use management practices.
Relevant application	Assessment of soil loss by water erosion in Europe (Panagos *et al.*, 2015) **-** The mean soil loss rate in European Union is estimated at

	2.46 t/ha annually. Policy interventions through CAP reduced overall soil loss by 9.5% during the last decade. 12.7% of European arable lands have soil loss >5 t/ha annually, requiring protection. Among all land uses, arable and sparse vegetation have the highest soil loss rates.
Main reference(s)	Wischmeier, W.H. and D.D. Smith (1978). Predicting Rainfall Erosion Losses: A Guide to Conservation Planning. Agriculture Handbook No. 537. USDA/Science and Education Administration, US. Govt.Printing Office, Washington, DC. 58pp.
Suitability for rapid assessment	This model can be suitable for rapid use as it uses some basic functions to determine soil losses under different management practices. Some parameters are highly specific for different land use/management practices and may be validated against available measurements for the study area, if available.
Websites	https://www.ars.usda.gov/southeast-area/oxford-ms/national-sedimentation-laboratory/watershed-physical-processes-research/research/rusle2/revised-universal-soil-loss-equation-2-overview-of-rusle2/ http://www.ars.usda.gov/Research/docs.htm?docid=5971
Manuals/ training/ videos	USDA website: Revised Universal Soil Loss Equation (RUSLE). http://www.ars.usda.gov/Research/docs.htm?docid=5971
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.4 Land desertification	**SWAT - Soil and Water Assessment Tool**

Model/ tool type and outputs	SWAT (Soil and Water Assessment Tool) is a basin-scale model developed to quantify different eco-hydrological components and interactions in large complex watersheds over extended periods of time. SWAT can be used to predict the environmental impact of land use, land management practices and climate change in large basins, as well as to assess smaller-scale processes such as soil water and erosion, nutrient cycles and non-point source pollution control in watersheds.
Open access?	Yes
Key data inputs	Input data includes climate variables required for water budgets, including precipitation and evapo-transpiration rates; crop/ land management, including planting dates, fertilizer applications and irrigation practices; topography; land cover; and soil data including soil maps.
Key data accessibility/ availability	ERA5 or RCM daily precipitation data are available at Copernicus; topography data: https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem land cover data: CLC Corine Land Cover 2018; WISE Soil Property Databases
Strengths	SWAT allows users to simulate both climatic and human management impacts on the rainfall-runoff process, on surface and sub-surface hydrology, pollutant loading and downstream and agricultural yield impacts. It can also assess best management practices and alternative management policies on soil erosion prevention and control, non-point source pollution control and regional management in watersheds with a strong focus on agricultural practices. Software code is available in public domain and is open source. Free versions have been developed for Mapwindows and QGIS, and SWAT has been extensively used around the world with 700 peer review articles. Training provided from courses through universities. Calibration, uncertainty and sensitivity analysis available through a separate program (SWAT CUP). User manual and technical manuals are available.
Assumptions/ limitations	To reduce the required input detail, SWAT models simplify some hydrological processes such as the identification of sediment sources and sinks using a geographically lumped processes function. Thus, some of erosion processes may be simplified and results may only be reliable if up to 25 input parameters are derived based on calibrations.
Spatial scale and resolution	Sub-national, large (and complex) basin scales.

Temporal scale and resolution	Temporal scale and resolution are dependent on the climate data resolution but can assess both short- and long-term scales.
Accessibility of outputs	Results are available either as text files, which can be easily manipulated by text editors or google/excel sheets, or using alternative GIS Interfaces developed for SWAT which can be used to produce maps and be saved into formats accessible to non-technical user.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	SWAT can provide assessments on best management practices and alternative management policies on soil erosion prevention and control, with a strong focus on agricultural practices.
Relevant application	Adapting SWAT hillslope erosion model to predict sediment concentrations and yields in large Basins (Glavan, 2015) - This application highlights the optimal selection and implementation of agri-environmental measures in river basins to reduce sediment yield and load.
Main reference(s)	Arnold, J. G., Raghavan Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. "Large Area Hydrologic Modeling and Assessment Part I: Model Development." Journal of the American Water Resources Association 34 (1): 73–89. doi:10.1111/j.1752-1688.1998.tb05962.x; Arnold, J. G., D. N. Moriasi, Philip W. Gassman, Karim C. Abbaspour, Michael J. White, Raghavan Srinivasan, C. Santhi, *et al.* 2012. "Swat: Model Use, Calibration, and Validation." American Society of Agricultural and Biological Engineers 55 (4): 1491–1508; Yalew, S., van Griensven, A., Ray, N., Kokoszkiewicz, L., & Betrie, G. D. (2013). Distributed computation of large scale SWAT models on the Grid. Environmental Modelling & Software, 41, 223–230.
Suitability for rapid assessment	No **-** SWAT model presents and uses articulated hydrological functions, which require several input parameters, and validation against measured hydrological data for reliability, particularly under climate change and different land use management options. Experienced use of the model is needed for rapid assessment.
Websites	https://swat.tamu.edu/
Manuals/ training/ videos	https://swat.tamu.edu/workshops/instructional-videos/
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.4 Land desertification	**EPIC - Environmental Policy Integrated Climate Model**

Model/ tool type and outputs	The Environmental Policy Integrated Climate (EPIC) model was developed to estimate soil productivity affected by erosion. It also simulates approximately eighty crops using one crop growth model with unique parameter values for each crop. It can be configured for a wide range of crop rotations and other vegetative and tillage systems and management strategies. EPIC predicts the effects of management decisions on soil, water, nutrient and pesticide movements and their combined impact on soil loss, water quality and crop yields.
Open access?	Yes
Key data inputs	Input data includes climate variables required for water budgets, including precipitation and evapo-transpiration rates; crop management, including planting dates, fertilizer applications and irrigation practices; and soil data.
Key data accessibility/ availability	Weather/ climate data for different variables: ERA5 or RCM are available at Copernicus; crop management: IFPRI IMPACT Webtool (https://www.ifpri.org/publication/ifpri-impact-webtool) and ISI-MIP (Inter-Sectoral Impact Model Intercomparison Project, https://www.isimip.org/) datasets; and soil data from WISE Soil Property Databases.
Strengths	Training provided from courses through universities. Calibration, uncertainty and sensitivity analysis available through a separate program (SWAT CUP). User manual and technical manuals are available.
Assumptions/ limitations	This model requires extensive validation for different soil types and robustness may be limited under extreme environmental conditions, such as during drought or flooding.
Spatial scale and resolution	Sub-national, large (and complex) basin scales.
Temporal scale and resolution	Temporal scale and resolution are dependent on the climate data resolution but can assess both short- and long-term scales.
Accessibility of outputs	Results are available either as text files, which can be easily manipulated by text editors or google/excel sheets, or using alternative GIS Interfaces developed which can be used to produce maps and be saved into formats accessible to a non-technical user.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model can assess different management alternatives to alleviate soil erosion and its effect on crop yield.

Relevant application	Impacts and uncertainties of +2°C of climate change and soil degradation on European crop calorie supply (Balkovic, 2018) - This work implemented over Europe highlights that soil degradation creates a calorie vulnerability, ranging from 0 to 50 Gcal ha−1, due to insufficient compensation for nutrient depletion. This could undermine climate benefits in many regions, if not prevented by adaptation measures, especially in Eastern and North-Eastern Europe.
Main reference(s)	Arnold, J. G., D. N. Moriasi, Philip W. Gassman, Karim C. Abbaspour, Michael J. White, Raghavan Srinivasan, C. Santhi, *et al.* 2012. "Swat: Model Use, Calibration, and Validation." American Society of Agricultural and Biological Engineers 55 (4): 1491–1508; Yalew, S., van Griensven, A., Ray, N., Kokoszkiewicz, L., & Betrie, G. D. (2013). Distributed computation of large scale SWAT models on the Grid. Environmental Modelling & Software, 41, 223–230.
Suitability for rapid assessment	No - EPIC model simulates articulated functions between climate, soil, hydrology and vegetation (and in particular crops) and thus require numerous input variables which may be specific for the study area for reliable simulations. Experienced use of the model is required for rapid assessment.
Websites	https://epicapex.tamu.edu/epic/
Manuals/ training/ videos	https://soil-modeling.org/resources-links/model-portal/epic
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.4 Land desertification	**GIS-RWEQ - GIS-based application of Revised Wind Erosion Equation (RWEQ)**

Model/ tool type and outputs	GIS-RWEQ is a simplified GIS-based application of the model Revised Wind Erosion Equation (RWEQ). The RWEQ is a combination of empirical and process-based modelling, developed to estimate the daily/ weekly/ annual volume of soil eroded and transported by wind: it examines the effects of various cropping systems, wind barriers, soil roughness, hills and residue management schemes.
Open access?	Yes
Key data inputs	Input data includes: Index of Land Susceptibility to Wind Erosion; wind-erodible fraction of the soil; and agriculture field parameters.
Key data accessibility/ availability	Data can be found at the JRC: European Soil Database, EEA Corine and Monitoring Agricultural ResourceS (MARS) climate databases.
Strengths	Requires a limited amount of input data which makes it suitable for upscaling.
Assumptions/ limitations	At large scales of implementation, topographical effects and landscape features may not constitute a significant influence on wind erosion, and therefore use of high-resolution data of approximately 1-5 km may not be required.
Spatial scale and resolution	Regional and continental scale; overall resolution is dependent on the resolution of climate and soil data.
Temporal scale and resolution	Temporal scale and resolution are dependent on the climate data resolution.
Accessibility of outputs	Maps of Index of Land Susceptibility to Wind Erosion, which can be saved into formats accessible to a non-technical user.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options
Adaptation policy insights	The model identifies maps in formats accessible to non-technical users, with different management strategies, such as land use alternatives, to reduce soil erosion.
Relevant application	A New Assessment of Soil Loss Due to Wind Erosion in European Agricultural Soils Using a Quantitative Spatially Distributed Modelling Approach (Borelli 2017).

Main reference(s)	Borrelli, P., Lugato, E., Montanarella, L., & Panagos, P. (2017). A New Assessment of Soil Loss Due to Wind Erosion in European Agricultural Soils Using a Quantitative Spatially Distributed Modelling Approach. Land Degradation & Development, 28: 335-344. Borrelli, P., Panagos, P., Ballabio, C., Lugato, E., Weynants, M. Montanarella, L. 2016. Towards a pan-European assessment of land susceptibility to wind erosion. Land Degradation & Development, 27(4): 1093-1105.
Suitability for rapid assessment	Yes
Websites	https://esdac.jrc.ec.europa.eu/themes/wind-erosion
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.4 Land desertification	**CENTURY**

Model/ tool type and outputs	CENTURY is an ecosystem model of plant-soil nutrient cycling, simulating biogeochemical fluxes of carbon, nitrogen, phosphorus and sulphur, primary production and water balance on a monthly time step. This model primarily provides a tool for ecosystem analysis, enabling the evaluation of management on Soil Organic Matter (SOM) dynamics of different ecosystems and land use types under changing climate.
Open access?	Yes
Key data inputs	Key input data include the climate variables of monthly precipitation and monthly average minimum and maximum temperatures. Soil properties include texture, litter nitrogen, lignin content and tillage disturbance. It is possible for simulations to include the effects of fire, fertilization, irrigation, grazing and various cultivation and harvest methods.
Key data accessibility/ availability	Weather/ climate data: ERA5 or RCM which are available at Copernicus; CORINE LAND COVER; WISE Soil Property Databases
Strengths	CENTURY is a complex model, however this supports the ability to simulate the effect of climate change and adaptation practices on soil carbon stocks. The effect of vegetation growth on different species or functional types can be articulated using CENTURY, and thus determine the effect of vegetation management as an adaptation practice to increase SOC.
Assumptions/ limitations	These models require detailed spatial distribution of vegetation/crop types and descriptions for several soil type- and vegetation layer-specific factors. For example, vertical soil profile and root allocation are frequently required, yet these parameters vary for different vegetation types and under drought conditions. Thus, the parameterization processes could be quite complex, time consuming and contain high degrees of uncertainty.
Spatial scale and resolution	Regional and continental scale; overall resolution is dependent on the resolution of climate and soil data.
Temporal scale and resolution	Temporal scale and resolution are dependent on the climate data resolution.
Accessibility of outputs	Output data needs to be converted into spatial maps, which can be saved into formats accessible to a non-technical user.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model supports the assessment of adaptation strategies at a pan-European scale.
Relevant application	Modelling soil organic carbon in cropland, grassland and forest soils at a global scale (Morais *et al.*, 2019); Soil organic carbon in Italian

	forests and agroecosystems: Estimating current stock and future changes with a spatial modelling approach (Caddeo, 2019) - The results from Caddeo highlight significant differences in Soil Organic Carbon between different land use types and under climate change, suggesting that forest, grassland and permanent crop soils could provide an important contribution to climate change mitigation.
Main reference(s)	Parton, W. J., D. S. Ojima, C. V. Cole, and D. S. Schimel. "A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management." SSSA special publication (USA) (1994); Parton, W. J., D. S. Ojima, and D. S. Schimel. 2005. CENTURY: Modeling Ecosystem Responses to Climate Change, Version 4 (VEMAP 1995). ORNL DAAC, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/820.
Suitability for rapid assessment	No - As for other physically based models, the availability of multiple data-intensive input variables is essential in order to accurately characterize relationships between vegetation-soil-climate and bio-geochemical cycle with acceptable reliability. In order to run simulations with the correct input data, an experienced user of the model is required.
Websites	https://www2.nrel.colostate.edu/projects/irc/public /Documents/Software/Century5/Reference/html/Century/cent5-overview.htm
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.5 Heavy precipitation	**STAR Tool**

Model/ tool type and outputs	STAR tools have been developed to assess the effectiveness of green infrastructures as a climate adaptation measure. Specifically, two tools are available: one is specifically for the evaluation of measures addressing surface temperature increase (see Star Tool, heatwaves for more information), the other for addressing surface runoff from heavy precipitation. Outputs for the surface runoff tool provides the volume and percentage of surface runoff for a study area for rainfall depths of 0-100mm.
Open access?	Yes
Key data inputs	For the surface runoff tool, required input data includes surface cover, precipitation, antecedent moisture conditions and hydrological soil type. The precipitation value is required as daily precipitation depths expressed in mm, and the default precipitation values are provided for North West England are the 99th percentile daily winter precipitation. These values are provided for a baseline (1961-1990) and as 2050s high precipitation scenarios with different probability levels (10%, 50%, 90%). The land cover scenario provides the percentage of different land types within the study area, including buildings, main roads, imperious surfaces, green and blue surfaces and bare soil or gravel surfaces. Finally, in order to account for the different infiltration rates, the hydrologic soil typology needs to be specified. Specifically, seven soil classes with different runoff potential have been proposed.
Key data accessibility/ availability	Default values for all the necessary input parameters (except hydrologic soil type) are automatically provided for the North West of England, where the tool has been developed and tested. For application outside of England, some default input values are automatically provided but they require verification since they have been drawn from assumptions based on the Greater Manchester area. Nevertheless, in this case, users are required to input data values for temperature scenarios, land cover and hydrologic soil type related to the investigated area.
Strengths	The STAR tools are intended to have minimal input requirements, although this will vary depending on the location of application. Specifically, the surface runoff tool supports calculating the percentage of rainfall that subsequently becomes surface runoff and the volume of this surface runoff; assessing the role of different vegetated surfaces which, within urban areas, can constitute an important effect on the runoff volume to be considered.
Assumptions/ limitations	The key limitation of the surface runoff tool is that it does not incorporate several important parameters, including slope and ground water storage depressions, or calculate the speed or rate of runoff. Further, the model has not been validated to date.

Spatial scale and resolution	The STAR tools are suitable for assessments at the neighbourhood scale. Whilst there is no strict limit on the study area size, the use is recommended for areas between 0.04 and 5km² (or 4ha to 500ha). The tool supports users in the North West of England to select their study area(s) from wards, lower layer super output areas and 5km x 5km grid squares, upload their own shapefile boundaries, draw study area boundaries straight onto a map, or list their study areas. Other UK users can also upload their own shapefile boundaries, draw study area boundaries straight onto a map, or list their study areas. Outside of the UK, users will only be able to list their study areas.
Temporal scale and resolution	The temporal resolution of the outputs of the STAR (runoff tool) depends on the precipitation data required as input. Precipitation data can be collected from local observational datasets (generally collected at an hourly or daily frequency) or modelled by means of climate models, which provide data at different temporal resolutions. In the case of using very high-resolution climate models, the daily precipitation can be obtained by averaging hourly data, but more frequently, daily data is the most common output provided by climate models.
Accessibility of outputs	The surface runoff model provides outputs in a table format which can be easily exported and displayed graphically to present surface runoff percentages for different hydrological soil types, land covers and precipitation scenarios within a study area.
Adaptation policy cycle stages	4) Assessing adaptation options; 6) Monitoring & evaluation
Adaptation policy insights	Outputs of the STAR tools can be used to inform policy, strategy and development. They can be useful for a wide range of professionals and organisations, including planners, developers, master planners, local authorities, urban forestry initiatives, NGOs and academics with an interest in developing understanding regarding the influence of urban greening solution within their local climate.
Relevant application	The model has been applied in the Merseyside and Greater Manchester regions. For these areas, default values for all the necessary input parameters are available in the current version of the tool. Preliminary applications have supported characterising the urban environment of the Greater Manchester area.
Main reference(s)	Gill, S.E. (2006). Climate change and urban greenspace. PhD thesis, University of Manchester. www.ginw.co.uk/resources/Susannah_PhD_Thesis_full_final.pdf; Gill, S.E., Handley, J.F, Ennos, A.R. and Pauleit, S. (2007). Adapting cities for climate change: the role of the green infrastructure. Built Environment. 33, 115-133.

Suitability for rapid assessment	The model results are suitable for rapid assessment.
Websites	https://maps.merseyforest.org.uk/grabs/index.php
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.7 Hailstorms	**Hail Detection Algorithm (HAD)**

Model/ tool type and outputs	The main output of hail prediction models are spatial maps that contain information on the physical impacts of hail. By creating a climatology of historical events, the spatial and temporal impacts of hailstorms on society can be investigated and used to inform decision making in the public as well as private domain.
Open access?	Yes
Key data inputs	The HDA utilizes radar-data in combination with meteorological parameters. These parameters are usually derived from numerical weather models, such as HirLAM, that include surface pressure, atmospheric temperature, wind and humidity.
Key data accessibility/ availability	Radar data is often collected by Meteorological Offices, varying in temporal and spatial resolution. For the Netherlands, radar composites are publicly available with a temporal resolution of 5 minutes and a spatial resolution of 1 km².
Strengths	Outputs can provide insights into physical hail hazards on a regional level. Input data or results of hail hazards are presented in the form of spatial maps and are often openly available.
Assumptions/ limitations	There is a lack of hazard simulation models that are linked to societal impact, such as for economic quantification. The effect of climate change on the physical hazard of hail remains to be quantified.
Spatial scale and resolution	The spatial resolution is dictated by the resolution of the input data. To create maps that are climatologically representative, this input data often needs to be resampled and 'smoothed'. This resolution can be around 50 km² or the size of administrative regions (provinces).
Temporal scale and resolution	In general, radar data with the required capacities is available with a temporal resolution of 12 years for the Netherlands.
Accessibility of outputs	Output graphs are publicly accessible for non-technical users.
Adaptation policy cycle stages	2) Assessing physical risks and vulnerability of property to hailstorms.
Adaptation policy insights	The output can be used to identify areas that are prone to hail impacts. With increasing predictability of hailstorm occurrence and severity, several applications in terms of climate adaptation can be taken by different stakeholders. Agricultural diversification by farmers, localized premiums and risk management for the (re)insurance industry and hail protection measures to wind shields, windows or other property, such as solar panels or roofs.

Relevant application	Local hailstorms were used to relate simulated hailstone proxies to solar panel damage and used to assess future potential of solar panels in the Netherlands (Teule, *et al.*, 2020). - Resulting actions may include subsidized insurance.
Main reference(s)	Teule, T., Appeldoorn, M., Bosma, P., D.D., S., Koks, E., & De Moel, H. (2020). The vulnerability of solar panels to hail. Climate-KIC. Witt, A., Eilts, M. D., Stumpf, G. J., Jonhson, J., Dewayne Mitchell, E., & Thomas, K. W. (1998). An Enhanced Hail Detection Algorithm for the WSR-88D. Weather and Forecasting, 286-303. Wouters, L., Boon, M., van Putten, D., van t' Veen, B., Koks, E., & de Moel, H. (2020). A hail climatology of the Netherlands. Amsterdam: Climate-KIC.
Suitability for rapid assessment	Because of these data requirements and the technical expertise to analyse the data, the process of using these models is often time consuming. Graphical hazard maps are generally made available by meteorological offices or researchers and can be combined with local exposure maps. However, detailed vulnerability to hail, communicated as damage functions, are currently not available open source.
Websites	National Meteorological offices. For the Netherlands, a dashboard for historical hail hazards is currently under development at the Royal Netherlands Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut)
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.7 Hailstorms	**AIR Worldwide Severe Thunderstorm**

Model/ tool type and outputs	Hail damage models inform regional and automobile insurers on hail risk. These models are suitable for commercial building insurance, industrial and residential use, private house insurance and agricultural exposure. The model leverages multiple data sources to capture the risk from hail and straight-line wind in a hybrid physical-statistical approach.
Open access?	No
Key data inputs	The model leverages historical weather data from a range of sources, including local storm report databases such as European Severe Weather Database (ESWD), Europe weather radar data and atmospheric reanalysis data. The model's damage functions are based on engineering analyses of construction practices, country-specific building codes and claims data.
Key data accessibility/ availability	Data can be accessed through contacting the company.
Strengths	Models with damage functions can quantify hail risk.
Assumptions/ limitations	No open data and the competitive nature of the insurance industry hampers the transparency of damage models.
Spatial scale and resolution	In the case of damage modelling, the output often includes stochastic event catalogues that are coupled with exposure maps (AIR offers a 1 km² industry exposure database) to simulate projections on an annual or individual storm damage basis. These are generally derived from insurance loss data collected by insurance companies.
Temporal scale and resolution	The AIR model simulates daily hailstorm activity in 1 km² resolution.
Accessibility of outputs	Model and outputs are only accessible to the private companies that own these models.
Adaptation policy cycle stages	2) Assessing physical risks and vulnerability of property to hailstorms.
Adaptation policy insights	The output can be used to identify areas that are prone to hail impacts. With increasing predictability of hailstorm occurrence and severity, several applications in terms of climate adaptation can be adopted by different stakeholders. Agricultural diversification by farmers, localized premiums and risk management for the (re)insurance industry and hail protection measures to wind shields, windows or other property, such as solar panels or roofs.
Relevant application	https://www.air-worldwide.com/models/severe-thunderstorm/

Main reference(s)	Model specifications needs to be verified through contact with the company.
Suitability for rapid assessment	Privately owned damage model, therefore the suitability for rapid assessment is limited.
Websites	https://www.air-worldwide.com/models/severe-thunderstorm/
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.8 Flow and river flow	**ANUGA (Australia National University and Geoscience Australia)**

Model/ tool type and outputs	ANUGA (Australia National University and Geoscience Australia) is a free and open source software tool for hydrodynamic modelling, suitable for predicting the consequences of hydrological disasters such as riverine flooding, storm surges and tsunamis.
Open access?	Yes
Key data inputs	Key data inputs include the Digital Elevation Model, friction, water level and boundary conditions. Different boundary conditions include 1) Reflective boundary: returns same stage as in its neighbour volume, however the momentum vector is reversed 180 degrees (reflected). This is specific to the shallow water equation, as it works with the momentum quantities assumed to be the second and third conserved quantities. A reflective boundary condition models a solid wall. 2) Transmissive boundary: returns the same conserved quantities as those present in its neighbour volume. This is one way of modelling outflow from a domain, but it should be used with caution if flow is not a steady state, as replication of momentum at the boundary may cause numerical instabilities propagating into the domain and eventually causing ANUGA to crash. If this occurs, consider using, for example, a Dirichlet boundary condition with a stage value less than the elevation at the boundary. 3) Dirichlet boundary: Specifies constant values for stage and x- and y-momentum at the boundary. 4) Time boundary: similar to a Dirichlet boundary however the behaviour varies with time.
Key data accessibility/ availability	Data needs to be locally collected based on the application of interest. Some open access databases exist, for example, JRC Data: https://data.jrc.ec.europa.eu/dataset/jrc-liscoast-10009
Strengths	A significant strength of ANUGA is its ability to model the wetting and drying process as water enters and leaves an area. Therefore, it is suitable for simulating water flow onto a beach or dry land and around structures, such as buildings. ANUGA is also capable of modelling hydraulic 'jumps' due to the ability of the finite-volume method to accommodate discontinuities in the solution. A hydraulic jump is a phenomenon in hydraulics which is frequently observed in open channel flow such as rivers and spillways. When liquid at high velocity discharges into a zone of lower velocity, an abrupt rise occurs in the liquid surface.
Assumptions/ limitations	The mathematical model is the 2D shallow water wave equation. As such, it cannot resolve vertical convection and subsequently cannot incorporate breaking waves or 3D turbulence such as vorticity. All spatial coordinates are assumed to be UTM (Universal Transverse Mercator) (meters). Fluid is assumed to have zero viscosity – although kinematic viscosity can be used and modelled using a

	kinematic viscosity operator. The finite volume is a robust and flexible numerical technique, especially when implemented on an irregular triangular mesh, but does not constitute the fastest method. Frictional resistance is assumed to follow Manning's formula, however other techniques exist such as Manning, Chézy, Darcy–Weisbach and Nikuradse.
Spatial scale and resolution	ANUGA is unsuitable for modelling flows in areas larger than one and half UTM zones (9 degrees wide). The resolution is flexible and depends on the setup of the triangular mesh.
Temporal scale and resolution	Precipitation data can be collected from local observational datasets (generally collected at an hourly or daily frequency) or modelled by means of climate models, which provide data at different temporal resolutions.
Accessibility of outputs	All outputs of ANUGA are stored in a NetCDF-like file with extension .SWW - ANUGA is a software/model that contains an inbuilt function to read and convert .sww files. Non-specialists require training in using ANUGA and basic knowledge of NetCDF files.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	ANUGA can be useful for prioritising adaptation practices affecting the flooding process in rivers and coastal areas, such as land use change, some nature-based solutions and grey-infrastructure measures.
Relevant application	ANUGA has been extensively validated against wave tank experiments and field studies where available, and ships with a validation test suite with about 30 analytical solutions, wave tank and field tests. Examples include validation against the wave tank experiment for the Okushiri 1995 tsunami, wave tank runup experiments at University of Queensland, the 2004 Indian Ocean tsunami impact at Patong Beach, and comparison to other models.
Main reference(s)	Rigby, E and Van Drie, Rudy. ANUGA: A New Free and Open Source Hydrodynamic Model [online]. In: Lambert, Martin (Editor); Daniell, TM (Editor); Leonard, Michael (Editor). Proceedings of Water Down Under 2008. Modbury, SA: Engineers Australia ; Causal Productions, 2008: 629-638.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary datasets.
Websites	https://github.com/GeoscienceAustralia/anuga_core
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.8 Flow and river flow	**LISFLOOD**

Model/ tool type and outputs	LISFLOOD (Distributed Water Balance and Flood Simulation Model) is a hydrological rainfall-runoff model that is capable of simulating the hydrological processes that occur within a catchment.
Open access?	Yes
Key data inputs	All model inputs are provided either as maps (grid files in PCRaster format) or tables. Examples include topography, land use, soil, channel geometry and meteorological conditions.
Key data accessibility/ availability	Data needs to be locally collected based on the application of interest. Some open access databases exist, for example, Climate Data Store https://cds.climate.copernicus.eu/#!/home
Strengths	The specific development objective was to produce a tool that can be used in large and trans-national catchments for a variety of applications, including flood forecasting and assessing the effects of river regulation measures, land-use and climate change. A further model, LISVAP, can be used to pre-process evapotranspiration data. LISVAP is a pre-processor for the LISFLOOD water balance and flood simulation model that calculates estimates of potential evaporation and evapotranspiration for three separate reference surfaces, all based on the Penman-Monteith equation.
Assumptions/ limitations	Pixels are always represented as a square: length and width are considered equal with no rectangles. Polders can be simulated on channel pixels where dynamic wave routing is used. For channels where the kinematic wave is used, the routine will not work and may lead to numerical instabilities or even model crashes.
Spatial scale and resolution	LISFLOOD is a fully distributed mode, assessing the watershed as a single unit.
Temporal scale and resolution	When using significantly high-resolution climate models, daily precipitation can be obtained by averaging hourly data, however more frequently, daily data is the most common output provided by climate models.
Accessibility of outputs	LISFLOOD can generate a wide variety of outputs, which are generally either maps or time series in a PCRaster format, which can be visualised with PCRaster's 'aguila' application. Users must be familiar with PCRaster formats, and specific software is required.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	LISFLOOD can be useful for studying the effects of changing climate on the flooding process in large/regional/continental areas.
Relevant application	LISFLOOD has been used to assess the impacts of climate change on flood hazard in Europe. The model is part of EFAS and GLOFAS, and results from EFAS are used by the consortium partners to

	manage flood events across Europe. For further details, see: https://www.efas.eu/sites/default/files/2019-07/Detailed_assessment_report_2018.pdf
Main reference(s)	Van Der Knijff, J. M., Younis, J., & De Roo, a. P. J. (2010). LISFLOOD: a GIS-based distributed model for river basin scale water balance and flood simulation. International Journal of Geographical Information Science, 24(2), 189–212. https://doi.org/10.1080/13658810802549154
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary datasets.
Websites	https://ec-jrc.github.io/lisflood-model/1_introduction_LISFLOOD/
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.8 Flow and river flow	**LISFLOOD-FP (Flood Plain Distributed Water Balance and Flood Simulation Model)**

Model/ tool type and outputs	LISFLOOD-FP is a two-dimensional hydrodynamic model specifically designed to simulate floodplain inundation in a computationally efficient manner over complex topography. It is capable of simulating grids of up to 106 cells for dynamic flood events and can capitalise on new sources of terrain information from remote sensing techniques, such as airborne laser altimetry and satellite interferometric radar.
Open access?	Yes
Key data inputs	The data used for the forcing of LISFLOOD-FP are river and storm surge levels.
Key data accessibility/ availability	Data needs to be locally collected based on the application of interest. Some open access databases exist, for example, Climate Data Store https://cds.climate.copernicus.eu/#!/home
Strengths	The model predicts water depths in each grid cell at each time step, and hence can simulate the dynamic propagation of flood waves over fluvial, coastal and estuarine floodplains. It is a non-commercial, research code developed to improve understanding regarding flood hydraulics, flood inundation predictions and flood risk assessments.
Assumptions/ limitations	Channel flow can be represented using either kinematic or diffusion wave approximations. Generally, the kinematic model has been successfully applied to overland flow while the diffusion model greater describes the subsidence of the flood wave. The model assumes the channel to be wide and shallow, and therefore the wetted perimeter is approximated by the channel width. For plain flooding and out-of-bank flow, it is assumed that flow can be treated using a series of storage cells discretized as a raster grid. Flow between storage cells can be calculated using analytical uniform flow formulae, such as the Manning equation or a weir equation. This yields an approximate solution of a diffusion wave in two dimensions. There is no exchange of momentum between main channel and floodplain flows, only mass. The model assumes flow to be gradually varied. The model uses standard SI units such as for length (metres), time (seconds) and flux (volume per time in m3s-1).
Spatial scale and resolution	LISFLOOD-FP can be applied to regional/continental scales as well as the local scale, however this is generally unsuitable due to higher computational requirements and less accurate results.
Temporal scale and resolution	The temporal resolution is daily/ sub-daily.

Accessibility of outputs	Output of LISFLOOD-FP is in ArcGrid ascii format, and therefore users must be familiar with GIS file formats.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	LISFLOOD_FP can be useful for prioritising adaptation practices affecting the flooding process in rivers and coastal areas, such as land use change, some nature-based solutions and grey-infrastructure measures.
Relevant application	LISFLOOD-FP has been used as a research tool within the pre-operational European Flood Alert System (EFAS), developed by Dr. Ad De Roo at the EU Joint Research Centre. This forms part of the RASP tiered methodology for flood risk assessment, developed on behalf of the Environment Agency of England and Wales and Department for Environment, Food and Rural Affairs (DEFRA), and for research studies at a number of institutions, including Ohio State and the University of Washington in the USA and the University of Messina in Italy.
Main reference(s)	Bates, P., Trigg, M., Neal, J., & Dabrowa, A. (2013). LISFLOOD-FP: User manual. School of Geographical Sciences, Univeristy of Bristol, pp. 1–49. Bristol, UK: University of Bristol.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary datasets.
Websites	http://www.bristol.ac.uk/geography/research/hydrology/models/lisflood/
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.8 Flow and river flow	**HEC-RAS - Hydrologic Engineering Center's River Analysis System**

Model/ tool type and outputs	Hydrologic Engineering Center's (CEIWR-HEC) River Analysis System (HEC-RAS) is designed to perform one and two-dimensional hydraulic calculations for a full network of natural and constructed channels.
Open access?	Yes
Key data inputs	User input data are stored in flat files under separate categories of project, plan, geometry, steady flow, unsteady flow, quasi-steady flow, sediment data and water quality information.
Key data accessibility/ availability	Data needs to be locally collected based on the river basin of interest. Some open access databases exist, for example, Geoportale Italia http://www.pcn.minambiente.it/mattm/
Strengths	HEC-RAS supports users to perform one-dimensional steady flow, one and two-dimensional unsteady flow calculations, sediment transport/mobile bed computations and water temperature/water quality modelling.
Assumptions/ limitations	The availability of information for calibration or parameter estimation depends on the application site. There are also issues regarding the appropriateness of the assumptions inherent in the model given that process such as land management routines, intra-and-inter basin water transfers, reservoir management and irrigation channels are simplified within the models to varying degrees, and it is up to the user to decide if the level of simplification is well-suited or not for their application. User preference and experience: users require knowledge to correctly setup the model and the objectives of the simulation. The complexity of the model is subsequently subjective.
Spatial scale and resolution	River basin scale.
Temporal scale and resolution	The temporal resolution is daily/ sub-daily.
Accessibility of outputs	Output data is predominantly stored in separate binary files (HEC and HDF5). Users must therefore be familiar with HDF5 and HEC file formats, which require specific knowledge.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	HEC-RAS can be useful for prioritising adaptation practices affecting the rainfall-runoff process in a river basin, such as land use change, retention basins and some nature-based solutions.

Relevant application	HEC-RAS has been used for studying landslide dam and subsequent dam-break flood estimation in Northern Pakistan. For further details, see: https://www.researchgate.net/publication/316457946_Dam_Break_Modeling_by_using_HEC-RAS
Main reference(s)	US Army Corps of Engineers. 2016. “HEC-RAS River Analysis System.” User’s Manual - Version 5.0 - CPD-74A. Davis, CA.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset
Websites	https://www.hec.usace.army.mil/software/hec-ras/
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.8 Flow and river flow	**HEC-HMS - Hydrologic Engineering Center - Hydrologic Modeling System**

Model/ tool type and outputs	HEC-HMS (US Army Corps of Engineers - Hydrologic Engineering Center - Hydrologic Modeling System) is a hydrologic model designed to simulate the complete hydrologic processes of dendritic watershed systems.
Open access?	Yes
Key data inputs	Hydro-meteorological data such as temperature, precipitation and streamflow; river basin-specific data including the Digital Elevation Model (DEM), soil map and land-cover; and channel data on stream cross-section and channel geometry.
Key data accessibility/ availability	Data needs to be locally collected based on the river basin of interest. Some open access databases exist, for example, Geoportale Italia http://www.pcn.minambiente.it/mattm/
Strengths	HEC-HMS combines tools simulating the hydrology of natural watersheds with those simulating highly developed urban watersheds, including engineered structures such as reservoirs, pump stations and diversions. The flexibility of the models supports a watershed model to be repurposed with minimal effort. It also provides a simple approach to be coupled with its hydrodynamic counterpart, HEC-RAS.
Assumptions/ limitations	The availability of information for calibration or parameter estimation depends on the application site. There are also issues regarding the appropriateness of the assumptions inherent in the model given that process such as land management routines, intra-and-inter basin water transfers, reservoir management and irrigation channels are simplified within the models to varying degrees, and it is up to the user to decide if the level of simplification is well-suited or not for their application. User preference and experience: users require knowledge to correctly setup the model and the objectives of the simulation. The complexity of a model is subsequently subjective.
Spatial scale and resolution	Lumped/ semi-distributed at the river basin scale.
Temporal scale and resolution	The temporal resolution is daily/ sub-daily.
Accessibility of outputs	All outputs of a HEC-HMS model are stored in a corresponding HEC-DSS file. A limited number of model outputs, including summary tables and graphs, can be accessed and viewed by the user directly from the HEC-HMS interface. Specific knowledge and familiarity with the tool are required.

Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Can be useful for prioritising adaptation practices affecting the rainfall-runoff process in a river basin, such as land use change, retention basins and some nature-based solutions.
Relevant application	HEC-HMS has been used for the assessment of hydrologic impacts of climate change in Tunga–Bhadra river basin, India. For further details, see: https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.9220
Main reference(s)	US Army Corps of Engineers. 2015. "HEC-HMS Hydrologic Modeling System." User's Manual - Version 4.1 - CPD-74A. Davis, CA.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.hec.usace.army.mil/software/hec-hms/
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.8 Flow and river flow	**SWAT - Soil and Water Assessment Tool**

Model/ tool type and outputs	SWAT (Soil and Water Assessment Tool) is a basin-scale model developed to quantify different eco-hydrological components and interactions in large complex watersheds over extended periods of time. SWAT can be used to predict the environmental impact of land use, land management practices and climate change in large basins, as well as to assess smaller-scale processes such as soil water and erosion, nutrient cycles and non-point source pollution control in watersheds.
Open access?	Yes
Key data inputs	Input data includes climate variables required for water budgets, including precipitation and evapo-transpiration rates; crop/ land management, including planting dates, fertilizer applications and irrigation practices; topography; land cover; and soil data including soil maps.
Key data accessibility/ availability	Data needs to be locally collected based on the river basin of interest. Some open access databases exist, for example, Geoportale Italia http://www.pcn.minambiente.it/mattm/ ; ERA5 or RCM daily precipitation data are available at Copernicus; topography data: https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem ; land cover data: CLC Corine Land Cover 2018; WISE Soil Property Databases
Strengths	SWAT allows users to simulate both climatic and human management impacts on rainfall-runoff process, surface and sub-surface hydrology, pollutant loading and downstream and agricultural yield impacts. It can also assess best management practices and alternative management policies on soil erosion prevention and control, non-point source pollution control and regional management in watersheds with a strong focus on agricultural practices. Software code is available in public domain and is open source. Free versions have been developed for Mapwindows and QGIS, and SWAT has been extensively used around the world with 700 peer review articles. Training provided from courses through universities. Calibration, uncertainty and sensitivity analysis available through a separate program (SWAT CUP). User manual and technical manuals are available.
Assumptions/ limitations	Spatial representation of Hydrologic Response Units (HRUs) ignores pollutant routing within a sub-watershed. Model formulas are empirical. Not applicable for 2D or 3D hydraulics applications. Limited snowmelt model. Erosion and sediment transport are limited.

Spatial scale and resolution	The model is semi-distributed at the basin scale. The spatial resolution is sub-basins.
Temporal scale and resolution	The temporal resolution is daily/ sub-daily.
Accessibility of outputs	SWAT provides a series of text files as output results. These results can be read by any text editor and imported into data management softwares. Other SWAT entry states include GIS Interface for maps. Any text editor can open the output files such as notepad. Users need to refer to the manual in order to understand the outputs of the model.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Can be useful for prioritising adaptation practices affecting the rainfall-runoff process in a river basin, such as land use change, retention basins and some nature-based solutions.
Relevant application	SWAT has been used to study complex human-water interactions in river basins for the evaluation of adaptation strategies. For further details, see: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018EF000826
Main reference(s)	Arnold, J. G., Raghavan Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. "Large Area Hydrologic Modeling and Assessment Part I: Model Development." Journal of the American Water Resources Association 34 (1): 73–89. doi:10.1111/j.1752-1688.1998.tb05962.x; Arnold, J. G., D. N. Moriasi, Philip W. Gassman, Karim C. Abbaspour, Michael J. White, Raghavan Srinivasan, C. Santhi, *et al.* 2012. "Swat: Model Use, Calibration, and Validation." American Society of Agricultural and Biological Engineers 55 (4): 1491–1508; Yalew, S., van Griensven, A., Ray, N., Kokoszkiewicz, L., & Betrie, G. D. (2013). Distributed computation of large scale SWAT models on the Grid. Environmental Modelling & Software, 41, 223–230.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://swat.tamu.edu/
Manuals/ training/ videos	https://swat.tamu.edu/workshops/instructional-videos/
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.8 Flow and river flow	**SWIM - Soil and Water Integrated Model**

Model/ tool type and outputs	SWIM (Soil and Water Integrated Model) is designed to investigate climate and land use change impacts at the regional scale.
Open access?	Yes
Key data inputs	Hydro-meteorological data such as temperature, precipitation, streamflow; river basin-specific data including DEM, soil map and land-cover; and land management data.
Key data accessibility/ availability	Data needs to be locally collected based on the river basin of interest. Some open access databases exist, such as Geoportale Italia http://www.pcn.minambiente.it/mattm/
Strengths	SWIM allows users to simulate both climatic and human management impacts on rainfall-runoff process, surface and sub-surface hydrology and agricultural yields.
Assumptions/ limitations	Spatial representation of HRUs ignores pollutant routing within a sub-watershed. Model formulas are empirical. The model is also not applicable for 2D or 3D hydraulics applications/ modelling, such as flood hazard modelling, but should be applied to hydrologic studies such as the water cycle at a basin scale. Limited snowmelt model. Erosion and sediment transport are limited.
Spatial scale and resolution	The model is semi-distributed at the basin scale. The spatial resolution is sub-basins.
Temporal scale and resolution	The temporal resolution is daily/ sub-daily.
Accessibility of outputs	SWIM provides a series of text files as output results. These results can be read by any text editor and imported into data management softwares. Any text editor can open the output files such as notepad. Users need to refer to the manual in order to understand the outputs of the model.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Can be useful for prioritising adaptation practices affecting rainfall-runoff process in a river basin, such as land use change, retention basins and some nature-based solutions.
Relevant application	SWIM has been used for regional impact studies and vulnerability assessments. For further details, see: https://www.tandfonline.com/doi/pdf/ 10.1080/02626667.2014.925560
Main reference(s)	Krysanova, V., Müller-Wohlfeil, D.-I., & Becker, A. (1998). Development and test of a spatially distributed hydrological/water

	quality model for mesoscale watersheds. Ecological Modelling, 106(2), 261–289. Krysanova, V., Hattermann, F., & Wechsung, F. (2005). Development of the ecohydrological model SWIM for regional impact studies and vulnerability assessment. Hydrological Processes, 19(3), 763–783.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://swat.tamu.edu/
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.8 Flow and river flow	**HYPE (HYdrological Predictions for the Environment)**

Model/ tool type and outputs	HYPE (HYdrological Predictions for the Environment) has been developed to support both small-scale and large-scale assessments of water resources and water quality to strengthen international collaboration in hydrological modelling and hydrological data production.
Open access?	Yes
Key data inputs	Hydro-meteorological data such as temperature, precipitation, streamflow; river basin-specific data including DEM, soil map and land-cover; and land management data.
Key data accessibility/ availability	Data needs to be locally collected based on the river basin of interest. Some open access databases exist, for example, Geoportale Italia http://www.pcn.minambiente.it/mattm/
Strengths	HYPE supports the simulation of a variety of hydrologic and land processes, including surface/subsurface hydrology; nutrients (nitrogen and phosphorus); land cover and land/water management.
Assumptions/ limitations	HYPE model uses static land use. Simplification of the processes driving evapotranspiration. Inter-catchment transfer, water abstraction and release and atmospheric deposition of nutrients are static and over-simplified. Static use of daily volumes and concentrations of nutrients from the point sources of pollution, such as waste water treatment and industries.
Spatial scale and resolution	The model is semi-distributed at the basin scale. The spatial resolution is the hydrologic units.
Temporal scale and resolution	The temporal resolution is daily/ sub-daily.
Accessibility of outputs	HYPE provides a series of text files as output results. These results can be read by any text editor and imported into data management softwares. Any text editor can open the output files such as notepad. Users need to refer to the manual in order to understand the outputs of the model.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Can be useful for prioritising adaptation practices affecting rainfall-runoff process in a river basin, such as land use change, retention basins and some nature-based solutions.

Relevant application	HYPE has been used in the Sustainable Urban Development Planner for Climate Change Adaptation (SUDPLAN), an EU FP7 project combining IT and environmental knowledge. For further details, see: http://sudplan.eu/polopoly_fs/ 1.30418!/SUDPLAN_final.pdf
Main reference(s)	Lindström, Göran, Charlotta Pers, Jörgen Rosberg, Johan Strömqvist, and Berit Arheimer. 2010. "Development and Testing of the HYPE (Hydrological Predictions for the Environment) Water Quality Model for Different Spatial Scales." Hydrology Research 41 (3–4): 295319. doi:10.2166/nh.2010.007.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	http://www.smhi.net/hype/wiki/doku.php
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.9 Landslides and avalanches	**LaRiMit - Landslide Risk Mitigation Toolbox**

Model/ tool type and outputs	LaRiMit is a web-based tool that contains a range of innovative and cost-effective structural and non-structural measures for landslide risk mitigation. Approximately 70 mitigation options aimed at reducing both landslide hazard and impacts are included in the tool. Based on the user's inputs and on expert-assigned scores, a hierarchized list of mitigation measures is provided as the output.
Open access?	The tool is freely available on-line, although it is currently under development in the framework of the Klima2050 Project.
Key data inputs	The tool requires users to provide site-specific information related to landslide type of movement; material; depth of movement; rate of movement; and groundwater and surface water conditions.
Key data accessibility/ availability	The required inputs regarding the landslide characteristics and site-specific features are generally either available or easy to collect.
Strengths	This tool may be useful for planning new adaptation measures and can also support recovery actions after a landslide event has occurred.
Assumptions/ limitations	LaRiMiT provides an extensive database of alternatives for reduction measures and represents an expert-assisted tool for the case- and site-specific ranking and best practice selection of landslide risk reduction measures. Nevertheless, it is not a measure design tool and it only suggests a number of suitable measures. Therefore, the operative implementation must be designed by consulting engineering experts. Expert advice for the final choice of solution is recommended in addition to LaRiMit's recommendations in order to confirm that significant assessment factors are not overlooked.
Spatial scale and resolution	Local/ regional.
Temporal scale and resolution	Not applicable.
Accessibility of outputs	A list of recommended and suitable reduction measures is produced. Furthermore, the tool automatically generates an output report for users.
Adaptation policy cycle stages	2) Identifying adaptation options
Adaptation policy insights	The tool is suitable for users working with spatial planning and civil protection as well as civil servants and consulting engineers. It supports decision-making through prioritizing the adaptation and

	mitigation options specifically identified for addressing the user's requirements.
Relevant application	An internal group in the Norwegian Railway Infrastructure Company (Bane Nor) have been asked by the Norwegian Railway Directorate to test LaRiMiT. These tests are currently in progress.
Main reference(s)	http://www.klima2050.no/larimit; Uzielli, M., Choi, J. C., & Kalsnes, B. G. (2017, May). A web-based landslide risk mitigation portal. In Workshop on World Landslide Forum (pp. 431-438). Springer, Cham.
Suitability for rapid assessment	Rapid use of the model.
Websites	https://www.larimit.com/
Manuals/ training/ videos	
Wikipedia page	
Other	The tool will be expanded with new measures and functions. Specifically, future developments are aimed at supporting users to select inputs; producing a larger number of case studies; increasing the integration with geospatial database; and improving the aesthetic of the webpage.

1) Hazard, exposure and vulnerability modelling	1.1.10 Coastal and sea level rise	**Static Inundation Approach/ Bathtub Fill**

Model/ tool type and outputs	The static inundation approach is a simplistic approach for identifying flood hazard areas.
Open access?	This is not a model which may or may not be available, but an approach that can be implemented. This can be conducted using any GIS software, such as ArcGIS (license required) or QGIS (open source).
Key data inputs	This flood hazard approach requires a Digital Elevation Model. The downstream boundary conditions (extreme sea levels) that drive coastal flooding are normally obtained from an extreme value analysis which considers, amongst others, the storm surge height, mean high tide height, mean sea level, wave setup and significant wave height.
Key data accessibility/ availability	Databases for extreme sea levels at a continental and global scale for the current climate and future climate projections can be found, for example, in the Joint Research Centre Data Catalogue (LISCOAST project) and in the GTSR model (Global Tide and Surge Reanalysis - only for current climate). Examples of visualization for extreme water levels at a large scale can be found in tools such as the Coastal Change Hazards Portal developed by the USGS for the entire U.S coastline.
Strengths	The static inundation approach can be conducted with any Geographical Information System Software (for example, QGIS, ArcGIS) and the accuracy will depend both on the quality of the boundary condition, for example, from Extreme Value Analysis, and on the resolution and accuracy of the underlying Digital Elevation Model (DEM).
Assumptions/ limitations	This method assumes that an area will only flood when a specified water level is higher than the elevation of the geographic location if an area is hydraulically connected to the sea. This is a simplistic approach and can be used to determine hotspots of flooding on broad-scale analysis. However, for policy and decision-making purposes, more detailed models are necessary to simulate flooding. Results from this type of approach do not account for the dynamic components of flooding and can lead to underestimation of the hazard in low-lying areas. However, in stable sea-cliff areas, the bathtub approach might be sufficient instead of advanced modelling techniques.

Spatial scale and resolution	This approach can be implemented on different scales. When considering national or local assessments, this method will fall short. Resolution depends on input maps, especially the DEM.
Temporal scale and resolution	This approach can be applied for current climate and future. Resolution depends on input data, especially the DEM.
Accessibility of outputs	The output is a map containing information on the geographical extent and inundation of the potentially identified flood areas.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	This type of model can inform decision makers regarding flooding hotspot zones and indicate regions in which interventions might be necessary. An analysis can be conducted which incorporates existing flood defences to account for some adaptation strategies.
Relevant application	https://coastal.climatecentral.org/map/6/100.8721/13.6553/?theme=sea_level_rise&map_type=coastal_dem_comparison&contiguous=true&elevation_model=best_available&forecast_year=2050&pathway=rcp45&percentile=p50&return_level=return_evel_1&slr_model=kopp_2014
Main reference(s)	Vousdoukas, M., Voukouvalas, E., Mentaschi, L., Dottori, F., Giardino, A., Bouziotas, D., Bianchi, A., Salamon, P. and Feyen, L. (2016). Developments in large-scale coastal flood hazard mapping. Natural Hazards and Earth System Sciences, 16: 1841-1853 Paprotny, D., Morales Napoles, O., Vousdoukas, M. I., Jonkman, B., & Nikulin, G. (2018). Accuracy of panEuropean coastal flood mapping. Journal of Flood Risk Management. https://doi.org/10.1111/jfr3.12459
Suitability for rapid assessment	Yes
Websites	https://sealevel.climatecentral.org/maps/
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.10 Coastal and sea level rise	**Fast Flooding Solvers**

Model/ tool type and outputs	Fast flood solvers are used to rapidly estimate and map flood extent and depth to inform flood hazard. Such fast flooding solvers adopt alternative methods to resolve detailed hydraulics which increase the computational efficiency of the models, making them attractive for quick assessments, probabilistic analysis frameworks and forecasting purposes. Examples of this are: LISFLOOD-FP model, the Flood Modeller -2D Fast Solver and the SFINCS model.
Open access?	LISFLOOD-FP is freely available for research purposes. All other models are not open access and a license is required.
Key data inputs	Predominantly require forcing variables such as discharge or river levels, storm surge levels, precipitation rates and wind information as a function of space and time. Additionally, physical and geographical characteristics are needed such as a Digital Elevation Model (DEM), including combined bathymetry and topography, spatially varying roughness and infiltration rates.
Key data accessibility/ availability	Databases for extreme sea levels at a continental and global scale for the current climate and future climate projections can be found, for example, in the Joint Research Centre Data Catalogue (LISCOAST project) and in the GTSR model (Global Tide and Surge Reanalysis - only for current climate). Examples of visualization for extreme water levels at a large scale can be found in tools such as the Coastal Change Hazards Portal developed by the USGS for the entire U.S coastline. Data for forcing these models can be retrieved from re-analysis data (ERA 5 - https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5) or tidal, precipitation and stage gauges records that belong to the meteorological offices of each country.
Strengths	Quick hazard assessment with increased accuracy. Results can be used for a probabilistic risk assessment and forecasting. Due to the computational efficiency of these models, different adaptation options can be tested in the model, such as the inclusion of flood defences or increase the drainage capacity of open channels. This is predominantly achieved through modification of the DEM or the precipitation input.
Assumptions/ limitations	Running the models require expert input. The model is based on reduced physics, and therefore not all dynamic interactions can be captured by the model.
Spatial scale and resolution	This approach can be implemented on different scales and is suitable for local and regional studies. The resolution depends on

	the input maps, especially the DEM, but also on the model grid size.
Temporal scale and resolution	This approach can be applied for current and future climate. The resolution depends on the input data, especially the DEM.
Accessibility of outputs	The output constitutes either an .nc file or a raster which contains maximum flood depth, maximum flood velocity and coordinates of all cells in the model. In order to translate results to a map, a post processing tool is required, such as ArcGIS or QGIS.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Due to the computational efficiency of these models, different adaptation options can be tested in the model such as the inclusion of flood defences or increase the drainage capacity of open channels. This is predominately achieved through modifying the DEM or the precipitation input. Climate change can be evaluated by increasing the coastal levels according to sea level rise (SLR) climate projections and increasing/decreasing precipitation rates.
Relevant application	Flood Hazard Maps at European and Global Scale. https://data.jrc.ec.europa.eu/collection/id-0054
Main reference(s)	Alfieri, L., Salamon, P., Bianchi, A., Neal, J., Bates, P.D., Feyen, L., 2014. Advances in pan-European flood hazard mapping, Hydrol. Process., 28 (18), 4928-4937, doi:10.1002/hyp.9947; Dottori, F., Salamon, P., Bianchi, A., Alfieri, L., Hirpa, F.A., Feyen, L., 2016a. Development and evaluation of a framework for global flood hazard mapping. Advances in Water Resources 94, 87-102.
Suitability for rapid assessment	Yes
Websites	https://sfincs.readthedocs.io/en/latest/ http://www.bristol.ac.uk/geography/research/ hydrology/models/lisflood/downloads/ https://www.floodmodeller.com/media/36641/2d-fast-solver.pdf
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.10 Coastal and sea level rise	**Coastal Hazard Wheel**

Model/ tool type and outputs	The coastal hazard wheel can be used for multi-hazard assessments at the local, in conjunction with other tools, regional and national levels, as well as for the identification of hazard management options for specific coastlines.
Open access?	Yes, but currently off without ICT support.
Key data inputs	This decision-support tool is based on a comprehensive coastal classification system, which is based on the bio-geophysical parameters determining the character of a coastal environment such as geological layout, wave exposure, tidal range, flora/fauna, sediment balance and storm climate.
Key data accessibility/ availability	The database has a loaded database of coastal hazards: https://www.coastalhazardwheel.org/
Strengths	Dataset ready with 655 hazard evaluations for generic coastal environments. Appropriate for regional and national estimations.
Assumptions/ limitations	Exact level of hazard reduction cannot be obtained for specific management options included in the tool.
Spatial scale and resolution	A single application of the CHW will always be specific to the studied 200-300 meter stretch of coastline. Larger regional and national assessments can consist of, for example, hundreds of individual coastal sections classified with the CHW.
Temporal scale and resolution	The tool can be used to assess gradual inundation due to a changing climate, however it is not particularly applicable for examining future impacts within certain time horizons.
Accessibility of outputs	The output is a wheel classification stating the hazard level and possible options for mitigation. Classification wheel with instruction can be found in: https://coastalhazardwheel.org/media/1217/main-manual-coastal-hazard-wheel.pdf
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The CHW covers the hazards of ecosystem disruption, gradual inundation, saltwater intrusion, erosion and flooding, and contains a total of 655 individual hazard evaluations and a complete hazard profile for each generic coastal environment. The system incorporates climate change effects in the hazard profiles, and is therefore especially relevant for climate change adaptation.
Relevant application	The CHW is designed to support coastal decision-making and information exchange at local, regional and national levels, and

	covers all the main coastal hazards, including ecosystem disruption, gradual inundation, saltwater intrusion, erosion and flooding. It is developed as a universal coastal classification system that contains 131 generic coastal environments and a total of 655 individual hazard evaluations. The initial version of the system was presented in 2012 and based on assessments for the Indian State of Karnataka, the Republic of Djibouti, a significant number of local assessments and feedback from coastal experts. The system has been refined in CHW 3.0 and a standardized application procedure has been developed. An example of the results for a case study in Denmark can be found in https://www.researchgate.net/publication/276913071_The_Coastal_Hazard_Wheel_system_for_coastal_multi-hazard_assessment_management_in_a_changing_climate
Main reference(s)	(Rosendahl Appelquist and Halsnæs 2015; Rosendahl Appelquist and Balstrøm 2015; Rosendahl Appelquist and Balstrøm 2014; Rosendahl Appelquist 2013
Suitability for rapid assessment	Yes
Websites	https://coastalhazardwheel.org/
Manuals/ training/ videos	-
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.10 Coastal and sea level rise	**Physical-Process Based Models: Flood Hazard**

Model/ tool type and outputs	Most advanced modelling technology that can accurately represent flooding mechanisms in coastal areas at the local scale are often full physical-process models. These are used to inform flood hazard. In these models, the different relevant processes, either of the hydrological cycle or of relevant hydrodynamic and transport mechanisms, are specifically represented by the mathematics and physics of each process, and equations are solved for each time step and grid of the model according to the relevant forcing mechanisms. Amongst many advanced models are the Delft3d modelling suite, MIKE Software, ADCIRC, FINEL and SWASH.
Open access?	All models require a license. Some of them have open source code, such as Delft3d.
Key data inputs	These predominantly require forcing variables such as discharge or river levels, storm surge levels, waves, tidal signal, precipitation rates and wind information as a function of space and time. Input can also be derived from extreme event analysis. Additionally, physical and geographical characteristics are needed, such as a Digital Elevation Model (DEM) including combined bathymetry and topography, spatially varying roughness and infiltration rates.
Key data accessibility/ availability	Databases for extreme sea levels at a continental and global scale for the current climate and future climate projections can be found, for example, in the Joint Research Centre Data Catalogue (LISCOAST project) and in the GTSR model (Global Tide and Surge Reanalysis - only for current climate). Examples of visualization for extreme water levels at a large scale can be found in tools such as the Coastal Change Hazards Portal developed by the USGS for the entire U.S coastline. Data for forcing these models can be retrieved from re-analysis data (ERA 5 - https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5) or tidal, precipitation and stage gauges records that belong to the meteorological offices of each country.
Strengths	All main physical mechanisms are included, resulting in high quality data which is especially suitable for small-scale applications. Results can be used for the identification of hotspots for flooding and detailed design of measures.
Assumptions/ limitations	Required modelling time and computational power is high, especially when large-scale areas are under review. Application of the model requires trained staff.

Spatial scale and resolution	The approach can be implemented on a local scale. Resolution depends on the input data, especially the DEM but also on the grid size of the model.
Temporal scale and resolution	The approach can be applied for current and future climate. The resolution depends on the input maps, especially the DEM.
Accessibility of outputs	The output is a map containing information on the geographical extent and inundation of the modelled flooding.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The output of such models can be connected to impact models that can appropriately inform decision-makers. In addition, most of these models can support the testing of coastal interventions in order to study the response of the system to a strategy and compare different strategies.
Relevant application	https://apps.dtic.mil/dtic/tr/fulltext/u2/a631769.pdf https://www.deltares.nl/en/software/delft3d-flexible-mesh-suite/#cases https://www.deltares.nl/en/software/delft3d-4-suite/#cases
Main reference(s)	https://www.deltares.nl/en/software/delft3d-4-suite/#features
Suitability for rapid assessment	No
Websites	https://www.deltares.nl/en/software/delft3d-4-suite/#features
Manuals/ training/ videos	-
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.10 Coastal and sea level rise	**Bruun Rule (Sea Level Rise Retreat)**

Model/ tool type and outputs	For erosion analysis, global shoreline change projections can be used to estimate the associated land loss due to storm events and long-term processes such as sea level rise (SLR) under different climate projections [1]. Recent global estimates of SLR retreat (Athanasiou, *et al.*, 2019) were computed using the Bruun Rule [2] (only for sandy coasts) based on a new dataset of nearshore slopes.
Open access?	Yes - Bruun rule is a method not a model.
Key data inputs	Database made use of beach characteristics and latest erosion trends (see https://data.jrc.ec.europa.eu/dataset/18eb5f19-b916-454f-b2f5-88881931587e/resource/bc7029af-dc3f-4516-a00e-4ebe3dc5164c)
Key data accessibility/ availability	https://data.jrc.ec.europa.eu/dataset/18eb5f19-b916-454f-b2f5-88881931587e
Strengths	Quick beach recession estimates are already provided by the dataset for different time horizons.
Assumptions/ limitations	The Bruun rule has limitations and can only be applicable to sandy beachlines.
Spatial scale and resolution	The spatial scale and resolution depend on the data availability of nearshore slope data, among others.
Temporal scale and resolution	The output can provide a recession estimated in meters. This can potentially be conducted for every segment of sandy coastline, given the information availability.
Accessibility of outputs	CSV file with global projections.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The output of such a basic model can identify potential for coastal recession based on sea level rise. Decision makers can use this information to identify hotspots for erosion and conduct further studies to identify potential measures.
Relevant application	https://www.nature.com/articles/s41558-020-0697-0

Main reference(s)	European Commission, Joint Research Centre (2019): Global shoreline change projections. European Commission, Joint Research Centre (JRC) [Dataset] doi:10.2905/18EB5F19-B916-454F-B2F5-88881931587E PID: http://data.europa.eu/89h/18eb5f19-b916-454f-b2f5-88881931587e
Suitability for rapid assessment	Yes
Websites	https://data.jrc.ec.europa.eu/dataset/18eb5f19-b916-454f-b2f5-88881931587e
Manuals/ training/ videos	-
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.10 Coastal and sea level rise	**Kriebel and Dean (Storm Event Retreat) and Mendoza and Jimenez (2006)**

Model/ tool type and outputs	These are parametric models that can be used to compute coastal erosion estimates at a regional level. Parametric models are defined by a finite set of parameters which are used to predict future data. In this case, this model predicts storm event retreat.
Open access?	Yes - Kriebel and Dean (Storm event retreat) and Mendoza and Jimenez (2006) are methods, not models.
Key data inputs	The (Mendoza and Jimenez, 2006) method is based on storm conditions of significant wave height, peak period and storm duration; and beach characteristics of sediment fall velocity and beach slope. The method from Kriebel and Dean’s convolution model predicts the beach profile response depending on wave breaking and water level variations due to storm surge. All data should to be available either from ERA 5 data of EVA or local/ global databases that depict beach characteristics.
Key data accessibility/ availability	http://www.risckit.eu/np4/file/383/RISC_KIT_D2.3_CRAF_Guidance.pdf
Strengths	Results can provide direct estimates of nourishment quantities which are useful for decision-makers and is a simplistic model.
Assumptions/ limitations	This is an empirical model and therefore has limitations as to where it can be applied.
Spatial scale and resolution	The spatial scale and resolution depend on the resolution of the available input data.
Temporal scale and resolution	The time scale is for a single storm event and the method could potentially be used to assess future storm retreat due to changing climate conditions.
Accessibility of outputs	The output for the Mendoza method constitutes the eroded volume and shoreline retreat and depth. For Kriebel and Dean, only the eroded volume and shoreline retreat are computed.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Results can provide direct estimates of nourishment quantities (useful for decision-makers).

Relevant application	risc Kit results: http://www.risckit.eu/np4/67/ http://www.risckit.eu/np4/9/
Main reference(s)	http://www.risckit.eu/np4/67/ ; [1] Kriebel and Dean, 1993; [2] Mendoza and Jimenez, 2006 - please provide the full references for these papers
Suitability for rapid assessment	Yes
Websites	http://www.risckit.eu/np4/file/383/ RISC_KIT_D2.3_CRAF_Guidance.pdf
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.10 Coastal and sea level rise	**Probabilistic Coastline Recession Model**

Model/ tool type and outputs	This model provides probabilistic estimates of coastal recession based on governing physical processes and can provide greater reliable estimates than the Bruun Rule.
Open access?	PCR model is an approach, not an open source model.
Key data inputs	This model requires input data on long term water levels and wave data, which are commonly available via tide gauges and global wave hindcast models (ERA 5 and wave watch III).
Key data accessibility/ availability	ERA 5 and Wave watch III: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5; https://polar.ncep.noaa.gov/waves/
Strengths	Improved estimates of sea level rise (SLR) retreat without increased computational time.
Assumptions/ limitations	Requires long-term water level data and Monte Carlo simulation which may require trained staff.
Spatial scale and resolution	The spatial scale and resolution depend on input data availability.
Temporal scale and resolution	Can be used to assed the effect of SLR in coastline of sandy beaches. This can be conducted for different time horizons.
Accessibility of outputs	Coastal retreat [m] per stretch of coast analysed.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The PCR model provides probabilistic estimates of SLR driven coastal recession that are required by contemporary risk management style coastal planning frameworks.
Relevant application	https://link.springer.com/article/10.1007/ s10584-011-0107-8
Main reference(s)	Ranasinghe, R., Callaghan, D., & Stive, M. J. (2012). Estimating coastal recession due to sea level rise: beyond the Bruun rule. *Climatic Change*, *110*(3-4), 561-574.
Suitability for rapid assessment	Yes
Websites	

Manuals/ training/ videos	
Wikipedia page	

1) Hazard, exposure and vulnerability modelling	1.1.10 Coastal and sea level rise	**Physical-Process Based Models: Erosion Hazard**

Model/ tool type and outputs	These models provide morphological changes due to sediment transport, but also due to avalanching by dune impact during extreme conditions. They can used to compute coastline position and migration between grid points. Examples are Xbeach, UNIBEST, Delft 3D and Mike software.
Open access?	Xbeach is open source, however most of the physical based models require a license and support.
Key data inputs	Input data often requires a grid and information on bathymetry, wave and flow, morphological, wind, sediment and vegetation, among others depending on the complexity of the study being conducted.
Key data accessibility/ availability	Information can be obtained through local data sources and global datasets for bathymetry and hydrometeorological conditions.
Strengths	Models can be used to observe the effect of adaptation strategies in reducing hazard level. All main processes are included and results can be used for detailed design of measures.
Assumptions/ limitations	The modelling time is high and requires trained staff.
Spatial scale and resolution	The resolution is dependent on the grid, which is designed depending on the availability of data and resolution of the Digital Elevation Model (DEM).
Temporal scale and resolution	Can be used to assess future time horizons by incorporating climate change within the analysis.
Accessibility of outputs	Different types of outputs are normally supported: 1) instantaneous spatial output 2) time-averaged spatial output 3) fixed point output or 4) run-up gauge output, among others.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Such models have been used to perform high-resolution sediment analysis to evaluate shoreline evolution around coastal protection works and inform coastal managers and decision-makers regarding the inclusion of natured-based solutions into coastal protection schemes. Similarly, the output of these detailed models can be used for the evaluation of multiple scenarios as well as a sensitivity analysis of the longshore transport, sediment transport and morphodynamics of coastlines.

Relevant application	EU FAST project, specifically in the MI-SAFE viewer tool.
Main reference(s)	[1] http://www.fast-space-project.eu/
Suitability for rapid assessment	No
Websites	https://publicwiki.deltares.nl/display/OET/MI-SAFE https://xbeach.readthedocs.io/en/ latest/xbeach_manual.html#output-selection
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.10 Coastal and sea level rise	**DIVA Tool**

Model/ tool type and outputs	This tool compiles quantitative information on a range of social, ecological and economic coastal impact indicators in order to overlay this with hazard information to inform flooding and erosion impact.
Open access?	No
Key data inputs	All the relevant data for indicators are included in the dataset of the tool. DIVA comprises of four major components: 1) A detailed global database with biophysical and socio-economic coastal data; 2) Global and regionalised climate and socio-economic scenarios until the year 2500; 3) An integrated model of interacting biophysical and socio-economic coastal processes including adaptation and 4) A graphical user interface for selecting data and scenarios, running model simulations and analysing the results.
Key data accessibility/ availability	https://publicwiki.deltares.nl/display/MESMA/DIVA
Strengths	An integrated model that supports users to produce consistent quantitative information for several indicators, including socio-economic and climate indicators.
Assumptions/ limitations	DIVA does not support analysis for operational coastal management and planning, as this requires an approach that is alternatively scaled.
Spatial scale and resolution	Only applicable for global and regional impact assessments.
Temporal scale and resolution	Estimates of impact can be simulated up until 2500.
Accessibility of outputs	Requires software in order to visualize the outputs.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	This tool supports users to explore the effect of climate change on coastal environments and societies; to explore the cost and benefits of coastal adaptation options; to set priorities for international co-operation with respect to climate change and development; and to use data, scenario and results for scientific research and policy analysis.
Relevant application	PESETA Project: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC87011/reqno_jrc87011_final%20report%20ready_final3.pdf

Main reference(s)	Hinkel, J. and R. J. T. Klein, 2009. The DINAS-COAST project: developing a tool for the dynamic and interactive assessment of coastal vulnerability. Global Environmental Change, 19(3), 384-395. Vafeidis, A. T., R. J. Nicholls, L. McFadden, R. Tol, J. Hinkel, T. Spencer, P. S. Grashoff, G. Boot and R. J. T. Klein, 2008. A new global coastal database for impact and vulnerability analysis to sea-level rise. Journal of Coastal Research, 24(4), 917-924. Hinkel, J., 2005. DIVA: an iterative method for building modular integrated models. Advances in Geosciences 4, 45-50. from: http://www.european-climate-forum.net/ index.php?id=divamodel-publications http://ebmtoolsdatabase.org/tool/ diva-dynamic-interactive-vulnerability-assessment
Suitability for rapid assessment	Yes
Websites	
Manuals/ training/ videos	
Wikipedia page	
Other	The DIVA Tool is currently not available for download due to a lack of resources for maintaining and supporting the software. The DIVA Model, the computational kernel of the DIVA Tool, is being further developed, but without a continuous funding base and without a graphical user interface. The release of new versions of the DIVA Tool with a graphical user interface is contingent on the availability of future funding.

1) Hazard, exposure and vulnerability modelling	1.1.10 Coastal and sea level rise	**FIAT Impact Assessment Tool**

Model/ tool type and outputs	This method can be used for estimating the impact of flooding and for quantifying direct impact. The estimated consequences, or impacts, can be expressed in either monetary values or as the number of affected entities.
Open access?	Yes
Key data inputs	Exposure data can be obtained from detailed local assessments or global data, such as Open Street Map. Vulnerability information based on damage curves at a global scale or detailed for each country/ region. Hazard maps in geotiff format with respective return periods. Exposure and hazard need to be raster based.
Key data accessibility/ availability	https://ec.europa.eu/jrc/en/publication/global-flood-depth-damage-functions-methodology-and-database-guidelines; https://www.openstreetmap.org/#map=7/52.154/5.295
Strengths	The tool enables simple and advanced reproducible calculations of geographic natural hazard impact and risk in a rapid and cost-efficient manner for every region globally.
Assumptions/ limitations	Cannot quantify indirect impacts, the analysis depends on the quality and details of input data. Often requires knowledge on GIS systems.
Spatial scale and resolution	The spatial scale and resolution depend on the input data of hazard maps and exposure dataset, which must be the same.
Temporal scale and resolution	Can be used to estimate future impacts of socio-economic projections are used to modify vulnerability and exposure information.
Accessibility of outputs	Geotiff showing annual damages and damages per return period, as well as a CSv file summarizing the number of people affected and yearly damages.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The monetary assessment is useful for long-term planning strategies as a basis for the choice of measures to improve community resilience to natural hazards (through a cost-benefit analysis). Further, information such as the expected number of people affected is important for emergency response decisions: informing or evacuating communities at risk and preparation and deployment of emergency defences in vulnerable areas.
Relevant application	https://www.sciencedirect.com/science/article/pii/S2212420918314845

Main reference(s)	https://publicwiki.deltares.nl/display/DFIAT/Delft-FIAT+Home
Suitability for rapid assessment	Yes
Websites	https://publicwiki.deltares.nl/display/DFIAT/Delft-FIAT+Home
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.10 Coastal and sea level rise	**INDRA**

Model/ tool type and outputs	INDRA is used for flooding and erosion impact assessments, and includes indicators such as household displacement, financial recovery of households and businesses, business supply chain disruption, ecosystem recovery, risk to life, utility and transport disruption. To compute in addition of economic damages, indirect damages of hazards.
Open access?	Yes
Key data inputs	The model requires detailed information on transportation networks, the maximum extent of the analysis, supply chain and land use in addition to hazard information in the format of shapefiles.
Key data accessibility/ availability	Data can be found in global databases and detailed regional information that will vary per country.
Strengths	The tool accounts for indirect damages of disruptions caused by the hazard.
Assumptions/ limitations	Configuration can be highly detailed. INDRA requires significant training and time for preparation and planning of the input data, however the outputs are subsequently normalized and comparable to measure the regional relative impact. The model can be rerun easily to test various storm conditions along the coast and to work with the stakeholders through an MCA.
Spatial scale and resolution	Only recommended for regional and local geographical scales.
Temporal scale and resolution	N/A
Accessibility of outputs	Results are available in the format of tekst file, plots and maps which can be visualize in the interface of INDRA.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	INDRA allows the comparison of risks at the regional scale to identify key hotspots to improve allocation of resources, improve coastal management and increase the resilience of coastal areas.
Relevant application	http://www.risckit.eu/np4/92/
Main reference(s)	http://www.risckit.eu/np4/9/

Suitability for rapid assessment	No
Websites	https://publicwiki.deltares.nl/display/RISCKIT/WP5
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.1.10 Coastal and sea level rise	**Circle Tool**

Model/ tool type and outputs	The Circle tool creates an interactive participative session in which causal relationships between critical infrastructure (CI) are mapped. It can be used to assess flooding and erosion impact.
Open access?	Yes
Key data inputs	Input data includes the location of critical infrastructure. Participatory sessions can highlight connections between different CI managers in a location and quantify the impacts of disruption in basic units, such as the number of days without communication.
Key data accessibility/ availability	The tool is used as a framework to retrieve data from key stakeholders managing CI.
Strengths	Interactive tool that supports and engages stakeholder participation for the identification of cascading effects.
Assumptions/ limitations	Cannot quantify the costs of cascading effects - indirect impacts.
Spatial scale and resolution	Local and regional scale only.
Temporal scale and resolution	N/A
Accessibility of outputs	The output is an interactive map showing the relationships between cascading effects of critical infrastructure. Results can facilitate interaction and cooperation.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	A Circle workshop helps stakeholders to understand the complex and interdependent relationships between critical infrastructure systems. These relationships, or causal links, can be investigated and visualized even within the context of a relatively data poor environment. Participants are encouraged to examine different adaptation strategies in order to increase resilience to climatic events in light of the information provided by the Circle tool.
Relevant application	https://www.deltares.nl/app/uploads/2015/04/Learning-on-flood-events-on-CIrcle.pdf
Main reference(s)	https://www.deltares.nl/en/software/circle-critical-infrastructures-relations-and-consequences-for-life-and-environment-2/
Suitability for rapid assessment	Yes

Websites	https://www.deltares.nl/en/software/circle-critical-infrastructures-relations-and-consequences-for-life-and-environment-2/
Manuals/ training/ videos	–
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.2.1 ETCCDI extreme climate indices	**ETCCDI Indices**

Model/ tool type and outputs	A set of 27 climate indices that can be computed from daily precipitation and temperature data has been defined by the Expert Team on Climate Change Detection and Indices (ETCCDI). The indices support measurements regarding the intensity, frequency and duration of moderate extremes events. Furthermore, the comparison of the index values estimated for the historical period with the index values obtained from climate projections supports estimations of the potential impact of climate change on future extreme events.
Open access?	Specific software packages, which run under both Microsoft Windows and Unix/Linux, are freely available at: http://etccdi.pacificclimate.org/software.shtml.
Key data inputs	The calculation of ETCCDI indices is based on daily temperature and precipitation data time series. Time series can be derived from directly observed data, which therefore covers a determinate time span period, and/or from simulated data, which can cover both historical and future periods.
Key data accessibility/ availability	Regional Climate Models (RCMs) provide dynamical downscaled high-resolution climate analysis. For the European domains, the C3S Climate Data Store (CDS) provides access to CORDEX regional future projections.
Strengths	Strengths of the ETCCDI indices include changes in weather and climate moderate extreme-event pattern distributions detectable at the local scale and can conduct regional climate reanalysis as well as future projections.
Assumptions/ limitations	Limitations are mainly associated with data availability and climate models' uncertainties, mainly due to different emission scenarios, model parameterization, and dataset reliability.
Spatial scale and resolution	Local/ regional/ national scale. The spatial resolution depends on the climate models used to simulate climate data.
Temporal scale and resolution	Depending on the analysis and the available data, the index values can provide information regarding both historical and future periods. The value for each period/ timeframe is calculated as a yearly average of the daily value, and subsequently these yearly values are averaged for the period.
Accessibility of outputs	The output of the analysis, conducted by applying an index-based approach, is widely understood not only by climate modellers but also largely adopted by other communities, such as impact modellers and the insurance sector, and the results are easily interpretable.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change

Adaptation policy insights	The ETCCDI indices can be used as a support tool in the rapid analysis and assessment of risk since they provide information of changing hazard level as a consequence of the variation in temperature and precipitation patterns. Furthermore, the indices can support the development or revision of national adaptation strategies and plans.
Relevant application	A recent application of these indices can be found in Mysiak *et al.* (2018), where a Climate Risk Index for Italy is proposed to support national authorities in designing adaptation policies and plans.
Main reference(s)	EEA CCIV survey – Responses, accompanying the EEA Report No 1/2018, National climate change vulnerability and risk assessments in Europe, 2018, European Environment Agency; Mysiak, J. *et al.*, (2018). Climate risk index for Italy. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 376(2121), 20170305.
Suitability for rapid assessment	Rapid use of model; rapid access to input data.
Websites	http://etccdi.pacificclimate.org/list_27_indices.shtml
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.2.4 Multi-risk, compound and composite analysis	**ARMONIA/ MURLUMSS**

Model/ tool type and outputs	ARMONIA (Applied multi Risk Mapping of Natural Hazards for Impact Assessment) is a general methodology for multi-risk that can be applied in different case studies and for several hazards, that can be implemented at the local scale. It focuses on the visualisation of different single risks that affect the same location. Hazards are considered as independent events. The project was funded by the EC. It feeds into the decision support system: Multi Risk Land Use Management Support System (MURLUMSS).
Open access?	Yes, although the website appears to be down - www.armoniaproject.net
Key data inputs	The user defines the area and scenario to model: Scenarios require information regarding the types of hazards (from external datasets and models), types of exposure and vulnerability determined using a Multi-Criteria Analysis (MCA). Once these selections have been made, the system subsequently depicts the potential intensities of up to five natural hazards which have been identified in the selected area.
Key data accessibility/ availability	The data is available through the MURLUMSS system. The online guide can be access here: http://www.eurosfaire.prd.fr/7pc/doc/1271840032_ armonia_fp6_multiple_risks.pdf. However, the hardcopy guide comes with a CD that contains the data. The project page has recently been taken down.
Strengths	Quick and easy to use.
Assumptions/ limitations	The multi-risk assessment approach of ARMONIA overlays multiple individual risks. It therefore ignores hazard or impact interactions.
Spatial scale and resolution	Regional (1:50,000 to 1:100,000) and local (municipality) scale (1:500 – 1:50,000)
Temporal scale and resolution	Multi-risk is assessed at a single point of time only.
Accessibility of outputs	The output is presented as risk maps and numerical risk factors.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 4) Assessing adaptation options
Adaptation policy insights	Can be a useful model to identify different multi-hazard risks. Different scenarios can be run, and henceforth the different risk factors per scenario can be compared, thus simulating the implementation of adaptation measures as the user can adjust the "risk "futures".
Relevant application	ARMONIA has been used to map hazards and vulnerability in several case study areas, such as the Arno river basin in Italy.

Main reference(s)	http://www.eurosfaire.prd.fr/7pc/doc/1271840032_armonia_fp6_multiple_risks.pdf and Delmonaco *et al.* (2007).
Suitability for rapid assessment	Rapid use of model. Since the website was recently taken down, the input data cannot easily be accessed anymore.
Websites	www.armoniaproject.net; this website was recently taken down.
Manuals/ training/ videos	http://www.eurosfaire.prd.fr/7pc/doc/1271840032_armonia_fp6_multiple_risks.pdf
Wikipedia page	n/a
Other	

1) Hazard, exposure and vulnerability modelling	1.2.4 Multi-risk, compound and composite analysis	**Event and Fault Trees**

Model/ tool type and outputs	Event and Fault Trees (EFTs) are logic diagrams composed of nodes connected to each other through branches identifying different event scenarios, similar to Bayesian Networks (BNs). Each event is characterised by a defined occurrence probability, making these tools useful in identifying and modelling chains of events leading to risk processes. These methodologies have been widely applied within safety engineering to identify the causes of infrastructure failures and the best methods to reduce them. Fault trees have been used to trace events that can contribute to an accident or failure, while event trees consider the consequences due to an accident, hence the identification of mitigation strategies.
Open access?	No
Key data inputs	These models use quantitative data for probabilistic assessments; however they can also provide solutions in case of limited qualitative data. Fault trees need data on events that can contribute to an accident or failure, while event trees need data of the consequences due to accidents.
Key data accessibility/ availability	Data can be collected through various sources, such as open access population databases, for example, https://data.worldbank.org/ or climate change projections provided by Regional Climate Models (RCMs), historical observations, expert judgment and literature. The greater the complexity of the case, the greater the extensity of the EFT framework required.
Strengths	Flexibility to incorporate qualitative and quantitative data. EFTs can be used to monitor and manage the safety performance of large-scale complex systems. Participatory approaches can be included throughout the model's design and for the identification of potential mitigation strategies.
Assumptions/ limitations	In the case of complex systems, EFTs are limited in their ability to identify non-linear behaviours and represent feedback loops and bi-directional relationships. So far, few applications of EFTs together with spatial analysis are available.
Spatial scale and resolution	EFTs are predominately applied to systems rather than at geographic scales. However, it is possible conduct a spatial representation if the model is integrated with a GIS software.
Temporal scale and resolution	EFTs only review a system at a single time point while dynamic fault trees simulate future scenarios. Scenarios analysis is therefore only if the model implements a "dynamic fault trees" approach.
Accessibility of outputs	Results are easily understandable: stakeholders can readily make changes in their system, evaluate possible effects, design quality

	test and maintain procedures according to their fault tree analysis diagrams. EFTs provide a well-structured, highly visual and comprehensive assessment of the analysed system. They support users or developers to quickly understand the results of the assessment based on logical relationships in order to pinpoint drawbacks and errors in the design process.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options
Adaptation policy insights	Participatory approaches can be included during the model's design and in the identification of potential mitigation strategies. Specifically, stakeholders and experts can be involved through workshops for an inclusive decision-making process on the risk perceived and the assessment of countermeasures.
Relevant application	Lacasse *et al.* (2008) addressed the potential risk arising due to a tsunami triggered by rockslide, scrutinizing different potential early warning systems with the involvement of different stakeholders. Moreover, mutually exclusive logic has been mostly applied in a multi-hazard perspective to evaluate chains of hazards originating from volcanic eruptions (Sandri *et al.*, 2014; Marzocchi *et al.*, 2012; Neri *et al.*, 2008).
Main reference(s)	Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P., Mastellone, M.L., Ruocco, A. Di, 2012. Basic principles of multi-risk assessment: a case study in Italy. Nat. Hazards 62, 551–573. Neri, A., Aspinall, W.P., Cioni, R., Bertagnini, A., Baxter, P.J., Zuccaro, G., Andronico, D., Barsotti, S., Cole, P.D., Esposti Ongaro, T., Hincks, T.K., Macedonio, G., Papale, P., Rosi, M., Santacroce, R., Woo, G., 2008. Developing an Event Tree for probabilistic hazard and risk assessment at Vesuvius. J. Volcanol. Geoth. Res. 178, 397–415. Sandri, L., Thouret, J.C., Constantinescu, R., Biass, S., Tonini, R., 2014. Long-term multi- hazard assessment for El Misti volcano (Peru). Bull. Volcanol. 76, 1–26.
Suitability for rapid assessment	EFTs are suitable for rapid assessment, yet the input data can be readily available or challenging to obtain depending on the case study. In low-complex systems, EFTs are easy to learn and understand, despite accurate application depending on the level of detail of the represented system.
Websites	https://www.edrawsoft.com/difference-faulttree-eventtree.php https://loganfta.com/
Manuals/ training/ videos	https://www.youtube.com/watch?v=GpHOBWncePE https://www.youtube.com/watch?v=QxhMYmpv6n0

Wikipedia page	https://en.wikipedia.org/wiki/Fault_tree_analysis https://en.wikipedia.org/wiki/Event_tree_analysis
Other	

1) Hazard, exposure and vulnerability modelling	1.2.4 Multi-risk, compound and composite analysis	**Artificial Neural Network (ANN)**

Model/ tool type and outputs	ANNs possess a strong capacity to learn from historical data and is a convenient tool able to handle complex non-linear systems and relationships that are difficult to describe using mathematical analytical expressions. Accordingly, they have the potential for the study of global climate change and ecological issues. They are used, for example, for time series of historical events to forecast dryland responses of flood susceptibility.
Open access?	Yes
Key data inputs	The series of input parameters are saved in the input layer, whereas every input variable is expressed by a neuron. Each input is altered by a function weights representing a biological neuron, comparable to synaptic junctions. ANN, as a type of supervised machine learning algorithm, require labelled data as inputs.
Key data accessibility/ availability	Data can be collected through various sources, such as open access population databases, for example https://data.worldbank.org/ or climate change projections provided by Regional Climate Models (RCMs), historical observations, expert judgments and literature.
Strengths	The advantage of ANNs is that they are capable of learning and fitting complex relationships between input data and training targets through a number of learning-recall iterations. The application of neural network models can determine function approximation, forecasting, data clustering, pattern recognition and optimization calculation. Except for the improvement of the algorithm itself, the development of ANNs can also be combined with various other methods to form hybrid models, such as a neural network-decision tree combination used for forecasting and analysis, and an ANN combined with the System Dynamics (SD) and Cellular Automata (CA) models. Moreover, they can be applied across different subjects and disciplines.
Assumptions/ limitations	A limitations is that there is a potential risk for misuse given that ANN model parameters typically require higher overall sensitivity, which are not always available and the selection of the network structure is generally dependent on individual subjective experience (expert-based). ANNs can be more complicated to implement and are more computationally expensive than tree-based machine learning

	methods. Interpretation of ANN outcomes can be difficult since they are often referred to as a "black box" method.
Spatial scale and resolution	Local/ regional/ national depending on the scale/resolution of the input data.
Temporal scale and resolution	Idealized scenarios depending on the scale/resolution of the input data.
Accessibility of outputs	Outputs of ANNs are challenging to interpret, making them inaccessible to end-users.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options; 6) Monitoring & evaluation
Adaptation policy insights	Futures scenarios based on large datasets of 'big data' can provide greater robust alternatives for supporting adaptation policy making.
Relevant application	ANN algorithms have been applied in a coastal dune area of Nebraska Sandhills (USA). The aim of this work was to understand the sensitivity of dryland landscapes to future human and climate disturbances. Specifically, an ANN was used determine the relationship between historic periods of sand deposition in semi-arid grasslands and external climatic conditions, land use pressures and wildfire occurrence.
Main reference(s)	Buckland, C.E., Bailey, R.M. & Thomas, D.S.G. Using artificial neural networks to predict future dryland responses to human and climate disturbances. Sci Rep 9, 3855 (2019). https://doi.org/10.1038/s41598-019-40429-5
Suitability for rapid assessment	The model can be rapidly used once trained, but a long-term study is required for input data collection and model training, calibration and validation.
Websites	https://playground.tensorflow.org/ https://towardsdatascience.com/introduction-to-artificial-neural-networks-ann-1aea15775ef9
Manuals/ training/ videos	https://www.youtube.com/watch?v=AgkfIQ4IGaM&feature=youtu.be
Wikipedia page	https://en.wikipedia.org/wiki/Artificial_neural_network
Other	

1) Hazard, exposure and vulnerability modelling	1.2.4 Multi-risk, compound and composite analysis	**Bayesian (Belief) Networks (BNs)**

Model/ tool type and outputs	Bayesian (Belief) Networks (BNs) are probabilistic graphical models representing a set of random variables and their conditional interdependencies through a Directed Acyclic Graph (DAG) (Pearl, 1988), thus using probability distributions (marginal and conditional) to describe the relationships among system components (Borsuk *et al.*, 2004). Given their graphical representation, BNs provide a valuable tool for the management of complex environmental issues, facilitating the involvement of experts and stakeholders in the evaluation process (Aguilera *et al.*, 2011) and a transparent and effective communication of results to potential end-users (Sperotto *et al.*, 2017). BNs have been applied with a risk assessment perspective to many different environmental issues, including Integrated Water Resource Management, ecology, maritime spatial planning, fishery and agronomy.
Open access?	Yes
Key data inputs	BNs are usually developed using an integrative method, including different and heterogeneous information sources such as experts, data and model results. They require detailed data to define states and extrapolate conditional probabilities, including directly observed data, probabilistic or empirical equations, outputs from model simulations or elicitation from expert knowledge. Using observed data, conditional probabilities are learned directly from the dataset of monitoring or field observations, calculating the probability based on the frequency of observed conditions. In the instance of scarcity of observed data, outputs from models can be used to generate significant quantities of information to encompass numerous cases, as requests through scenario settings. These models are particularly useful when working with climate change modelling and future scenarios for which direct observations are not available. When data learning cannot be applied because data or measures are missing, experts' or stakeholders' elicitation can be employed. Each knowledge source allows for some limitations, which can affect the rigor and credibility of the model. Therefore, the optimal approach would be to integrate different methods with different levels of accuracy and detail.
Key data accessibility/ availability	Data can be collected through various sources of information, such as open access population databases, for example: https://data.worldbank.org/ or climate change projections provided

	by Regional Climate Models (RCMs), historical observations, expert judgments and literature.
Strengths	▪ Ability and flexibility to combine multiple types of data, of both quantitative and qualitative, from heterogeneous data sources and disciplines, such as probabilistic quantities derived from expert knowledge, empirical data from preliminary studies, qualitative experiential understanding and mathematical representations. This may be particularly valuable when data are scarce. ▪ Possibility to update the model with new and greater detailed data as they become available, increasing model utility and reliability for local-scale assessment. ▪ Act as a common platform where different domains of environmental, economic and social can be effectively integrated. ▪ Capability to perform scenario analysis, building on the BN variables estimated using collected data. ▪ As a probabilistic model, BNs are designed to manage uncertainty. This can be useful for adaptive management by supporting decision making using robust quantitative estimates. ▪ Given their graphical representation, BNs provides a simplified visualization of complex relationships in dynamic systems, facilitating a transparent and effective communication of results to stakeholders and potential end-users.
Assumptions/ limitations	▪ Large quantities of data are required for model development. ▪ Limited capacity of BNs for managing continuous variables. ▪ There is potential knowledge bias based on expert elicitation. ▪ The growing complexity of the computational effort for modelling complex systems. ▪ BNs are limited in their representation of spatial and temporal dynamics and feedback loops, which presents a problem for climate change applications as environmental and socio-economic systems involved are characterized by unpredictable dynamics which varying across space and time. ▪ Limits in performing a strong quantitative validation: Generally, the best method for model validation compares models' results with an independent set of observed data. However, this is not always feasible, especially when dealing with complex systems characterized by multiple stressors and variables, where large datasets are commonly lacking or difficult to retrieve. ▪ BNs validation present greater complexity and challenge in the context of predicting future risks, given that it is uncertain whether future trends will emulate historical observations.
Spatial scale and resolution	Local/ regional/ national.
Temporal scale and resolution	‘What if’ scenarios analysis, time scale and resolution of outputs depending on the case study.

Accessibility of outputs	BN outputs are presented as probability distributions of the variables considered within the network, which are easily accessible and understandable to a general audience.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options; 6) Monitoring & evaluation
Adaptation policy insights	BNs are applied to support management and decision-making processes under conditions of environmental variability and uncertainty, providing logical and holistic reasoning in complex systems given that they support the translation of causal assertions between variables into patterns of probabilistic dependence. The aim of the model is to characterise, incorporate and communicate uncertainty, with the potential to provide support to an informed and transparent decision-making process.
Relevant application	Furlan *et al.* (2019) employed a GIS-based Bayesian Network to a Multi-scenario analysis in the Adriatic Sea to support maritime spatial planning. They evaluated the probability and related uncertainty of cumulative impacts under four 'what-if' scenarios representing different marine management options and climate conditions. Additionally, Sperotto *et al.* (2019) used a BNs approach for the assessment of climate change impacts on nutrients loading. The authors used this integrative tool to structure and combine the information available from existing hydrological models, climate change projections, historical observations and expert opinions. Subsequently, alternative risk scenarios were produced to communicate the probability and uncertainty of changes in the concentrations of nutrients NO_3^-, NH_4^+ and PO_4^{3-} delivered from the basin under climate change projections of Representative Concentration Pathways (RCP) 4.5 and 8.5.
Main reference(s)	Pearl, J., 1988. Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference. Morgan Kaufmann.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	Available softwares for Bayesian Network design: ▪ Netica: https://www.norsys.com/netica.html ▪ Hugin: www.hugin.com ▪ GeNIe: www.bayesfusion.com ▪ BN learn (R-package): www.bnlearn.com ▪ Infert.NET: https://dotnet.github.io/infer/ ▪ SamIam: http://reasoning.cs.ucla.edu/samiam/ ▪ JavaBayes: www.cs.cmu.edu/ javabayes/Home/ ▪ Bayesware: www.bayesware.com ▪ R: Blearn library

Manuals/ training/ videos	https://www.youtube.com/watch?v=TuGDMj43ehw
Wikipedia page	https://en.wikipedia.org/wiki/Bayesian_network
Other	

1) Hazard, exposure and vulnerability modelling	1.1.4 Multi-risk, compound and composite analysis	**System Dynamic Models**

Model/ tool type and outputs	System dynamic models (SDMs) include a wide group of approaches which simulate non-linear behaviour of complex systems on a macro-level. SDMs are based on the analysis of the aggregated dynamics of systems components, whose systemic behaviour cannot be explained in terms of the simple sum of single components. They have been widely applied to describe dependencies and interactions among different elements of a complex system, with the main aim of identifying leverage points - sub-sections of systems trigger changes on the wider system. By identifying these leverage points, research can be conducted on possible measures to influence these points.
Open access?	No
Key data inputs	The model can be developed using qualitative information, or significant quantities of quantitative data, for simulating changes of stocks over time. Medium-high complexity of data processing is required depending on the type of input data and the number of feedback loops considered for the simulation.
Key data accessibility/ availability	Data can be collected through various sources of information, such as open access population databases, for example: https://data.worldbank.org/ or climate change projections provided by Regional Climate Models (RCMs), historical observations, expert judgments and literature.
Strengths	SDMs can combine social and behavioural science with the detailed planning and accounting. Although SD modelling is technically demanding, the logic and results of a good SD model are accessible for decision makers to understand. One of the main advantages of using SDMs is their explicit representation of feedback loops demonstrating the reinforcing and balancing effects among the elements of a system. The use of feedbacks loops contributes to improving comprehension regarding nonlinearities and complexity of the considered system. Consequently, applications of SDMs are frequent for macro analysis of social and ecological systems, which are characterised by a high degree of complexity.
Assumptions/ limitations	SDMs require considered design and development of original models, with many interacting variables. Deterministic representations of uncertain behaviours of a system and model validation are among the limitations that require development through external methods, such as Monte Carlo simulations and model testing.

	Although SDMs comprehensively capture temporal dynamics of complex systems, they demonstrate some limitations in representing spatial characteristics, although this can be improved through the combination of SDMs with GIS software.
Spatial scale and resolution	SDMs are predominately applied to systems rather than at geographic scales although it is possible to conduct a spatial representation if the model is integrated with a GIS software.
Temporal scale and resolution	The model describes changes of stocks over time, of which the time scale and resolution depend on the input data.
Accessibility of outputs	Although SDMs are sophisticated, they are also compact enough to run instantly on a laptop computer, permitting a whole series of alternative assumptions and scenarios to be tested quickly and thoroughly in interactive strategy development sessions. The results of SDMs are easy understandable for decision-makers.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options; 6) Monitoring & evaluation
Adaptation policy insights	SDMs are used by organizations which undertake high-risk decisions and require a holistic overview of the major forces that can affect key outcomes either years or decades into the future. They can support stakeholders to better assess the positives and negatives of various options under review.
Relevant application	SDMs have been used to examine socio-ecological systems and the impacts on natural resources, such as for water resource management under climate scenarios (Mereu *et al.*, 2016).
Main reference(s)	Homer JB, Models That Matter: Selected Writings on System Dynamics 1985-2010, Grapeseed Press, 2012. Mereu, S., Sušnik, J., Trabucco, A., Daccache, A., Vamvakeridou-Lyroudia, L., Renoldi, S., Virdis, A., Savić, D., Assimacopoulos, D., 2016. Operational resilience of reservoirs to climate change, agricultural demand, and tourism: a case study from Sardinia. Sci. Total Environ. 543, 1028–1038.
Suitability for rapid assessment	SDMs are rapid to run on a laptop computer on the basis that alternative assumptions and scenarios to be comprehensively and rapidly tested within interactive strategy development sessions.
Websites	https://www.systemdynamics.org/ https://www.anylogic.com/downloads/
Manuals/ training/ videos	https://www.youtube.com/watch?v=IenySRdkRu8 https://www.youtube.com/channel/UCZlM6xlE_al00biBTDdFyzA
Wikipedia page	https://en.wikipedia.org/wiki/System_dynamics
Other	System Dynamics Society https://www.systemdynamics.org/tools

1) Hazard, exposure and vulnerability modelling	1.4.1 Socio-economic vulnerability	**Socio-economic vulnerability modelling**

Model/ tool type and outputs	Vulnerability assessments examine socio-economic, demographic, cultural, environmental, political and institutional constituents of vulnerability. Indicator-based assessments are widely used to assess the relative vulnerability (susceptibility to harm and adaptive capacity dimensions) values of geographic units or population groups by aggregating separate indicators into composite indices and scoreboards.
Open access?	The tool should be constructed with regards to the scope, geographic location and the scale of the analysis. There are several analogous studies can be used as a reference.
Key data inputs	The data for vulnerability indicators can be extracted from multiple sources such as Eurostat, Copernicus and EEA databases.
Key data accessibility/ availability	https://ec.europa.eu/eurostat/data/statistics-a-z/abc https://www.eea.europa.eu/data-and-maps/data#c0=5&c11=&c5=all&b_start=0 https://www.espon.eu/tools-maps/espon-2013-database
Strengths	Allow continuous and rapid monitoring, reporting and evaluation (MRE) which enables policy makers to identify the existing trends and progress made.
Assumptions/ limitations	The key assumptions are i) structural design; ii) choice of analysis scale; iii) indicators used to proxy the vulnerability components; iv) the methodological choices made to combine the indicators into an index. The structural design depends on how consolidated the knowledge is regarding the determinants of vulnerability. The choice of analysis scale plays an important role on the outcomes and the policy implications. Choices among indicators are generally guided by factors such as data availability, desired number of indicators, statistical properties and how representative is the indicator of the underlying vulnerability dimension. A wide spectrum of methodological choices can be employed to construct indices which involves a certain degree of subjectivity.
Spatial scale and resolution	Collective scale (municipal, provincial, regional and national) or community level.
Temporal scale and resolution	Can be constructed annually for at least 20 years.
Accessibility of outputs	The outputs are i) vulnerability maps illustrating relative vulnerability scores for targeted geographical units and/or population groups, ii) internal validation of the method by means of uncertainty/sensitivity analysis performed using various model configurations.

Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 6) Monitoring & Evaluation
Adaptation policy insights	Vulnerability indices measure peoples' needs in terms of adaptation, as well as their ability to cope with climate shocks. They play an important role in designing effective adaptation strategies in which the aim is to reduce adverse effects of climate change.
Relevant application	There have been several attempts to develop indicator-based vulnerability assessments, both at global and European level, such as ND-GAIN from Notre Dame Global Adaptation Initiative, MOVE from EC-CORDIS and ESPON Climate project from EC, Climate-ADAPT by European Environmental Agency and INFORM Global Risk Index from JRC.
Main reference(s)	Marin-Ferrer, M., Vernaccini, L. & Poljansek, K. Index for Risk Management - INFORM. Concept and Methodology. (2017); ESPON. ESPON CLIMATE-Climate Change and Territorial Effects on Regions and Local Economies. (2011); Birkmann, J. *et al.* Framing vulnerability, risk and societal responses: the MOVE framework. Nat. Hazards 67, 193–211 (2013)
Suitability for rapid assessment	Vulnerability indices are designed to enable rapid screening for policy purposes. Quick access to input data depends on the geographic location and scale of the analysis.
Websites	https://gain.nd.edu/our-work/country-index/ https://ec.europa.eu/jrc/en/scientific-tool/index-risk-management-inform http://european-crt.org/index.html
Manuals/ training/ videos	https://gain.nd.edu/our-work/country-index/
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.4.2 Ecosystem vulnerability	**LPJ-GUESS**

Model/ tool type and outputs	LPJ-GUESS (Lund-Potsdam-Jena-GUESS) is a process-based Dynamic Global Vegetation Model (DGVM) designed for regional or global studies. Given data on regional climate conditions and atmospheric carbon dioxide concentrations, it can predict structural, compositional and functional properties of the key ecosystems across the major global climate zones.
Open access?	Yes
Key data inputs	Input data requires information regarding climate, soils and CO_2. Plant Functional Type (PFT) parameters and bioclimatic limits of the species of interest also need to be known. The model can simulate some PFT traits such as rubisco capacity and root:shoot ratio based on external drivers and realised ecosystem state.
Key data accessibility/ availability	It is possible to couple LPJ-GUESS to an RCM. The required climate, soil and CO_2 input data are accessible via public databases.
Strengths	The model uses generic parameterisations that allows it to be applied to any climate zone or biome, including non-forest vegetation such as Arctic tundra or savannah.
Assumptions/ limitations	The model does not include phosphorus, making the model less suitable to simulate phosphorus-limited vegetation growth. The modeller should be familiar with C/C++ programming skills.
Spatial scale and resolution	The model structural unit is at the individual plant level, while the output is at the regional to global scale.
Temporal scale and resolution	Time steps can be set per day, month or year. The model can simulate to a timescale of decades to centuries (both hindcast and forecast).
Accessibility of outputs	Outputs include vegetation composition and cover in terms of major species or plant functional types (PFTs), biomass and soil organic matter carbon pools, leaf area index (LAI), net primary production (NPP), net ecosystem carbon balance, carbon emissions from wildfires, biogenic volatile organic compounds (BVOCs), evapotranspiration, runoff, and nitrogen pools and fluxes. The results can be presented in maps or diagrams. The user needs a basic understanding of carbon and nutrient cycling and vegetation succession to interpret the results.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options

Adaptation policy insights	Can be used to understand bioclimatic drivers of vegetation dynamics, and thereby assessing the response of vegetation to future climate change.
Relevant application	LPJ-GUESS has been used to assess the vulnerability of ecosystems to climate change, for example, in combination with invasion by exotic plant species. Gritty *et al.* (2006) assessed the vulnerability of Mediterranean Basin ecosystems to climate change and invasion by exotic plant species. Their simulations predict that further invasion into Mediterranean island ecosystems is likely to be an increasing problem; in the longer term, almost all ecosystems will be dominated by exotic plants.
Main reference(s)	Smith, B., Prentice, I.C. & Sykes, M.T. 2001. Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. Global Ecology & Biogeography 10: 621-637.
Suitability for rapid assessment	No - the model requires technical knowledge to operate and to ensure that climate, soil and CO_2 data is available as input.
Websites	http://iis4.nateko.lu.se/lpj-guess/index.html
Manuals/ training/ videos	-
Wikipedia page	-
Other	

1) Hazard, exposure and vulnerability modelling	1.4.2 Ecosystem vulnerability	**Regional Vulnerability Assessment (ReVA)**

Model/ tool type and outputs	ReVA was developed as an early warning system to identify ecosystems which are highly vulnerable to being lost or permanently harmed within the next five to 25 years. Further, the method determines which stressors are likely to cause the greatest risk. It was developed as a conceptual framework and can be used assess ecological vulnerability under different scenarios.
Open access?	Yes
Key data inputs	The data requirements include the area or region of concern, existing resources, types of stressors and the questions and concerns regarding the region. A typical question that can be applied to ReVA is: *where* are ecosystems most vulnerable and *what stressor* is likely to cause the most damage? With this information, investments can be targeted to protect valuable ecosystems. The main requirement is that the data used in any analysis must be collected consistently across the region of concern.
Key data accessibility/ availability	The data may be acquired from many sources. Often, the data is available via public/ governmental databases. The model was developed in the USA and data sources for that country are mentioned in the guidelines (Smith *et al.*, 2008). In most cases, however, the type of data will also be available for Europe (for example, in the EU Open Data Portal).
Strengths	ReVA is an integrated approach for spatial vulnerability analysis.
Assumptions/ limitations	ReVA is a conceptual model. To provide quantitative analysis, ReVA requires coupling with mathematical models which are either empirical and/or process models.
Spatial scale and resolution	ReVE can be used for local, regional and national level.
Temporal scale and resolution	The temporal scale depends on the mathematical models used within the conceptual framework of ReVA.
Accessibility of outputs	Outputs are variable, such as maps and graphs, depending on the underlying models that are being used and the target audience.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options

Adaptation policy insights	ReVA methodology establishes a platform that can support environmental decision-makers optimise investment of limited resources and enable proactive decision-making.
Relevant application	ReVA has been developed to support informing environmental decision-makers in the USA through evaluating both current conditions and vulnerability to different scenarios. Using ReVA, environmental decision-makers of the U.S. Environmental Protection Agency (EPA) were able to target the funds for ecosystem protection more effectively.
Main reference(s)	Boughton, D., Smith, E., & O'Neill, R. (1999). Regional vulnerability: a conceptual framework. Ecosyst. Health, 5, 312–322.
Suitability for rapid assessment	Yes
Websites	https://archive.epa.gov/esd/archive-nerl esd1/web/html/products.html
Manuals/ training/ videos	https://archive.epa.gov/esd/archive-nerl esd1/web/pdf/guidelines_reva_20080627.pdf
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.4.2 Ecosystem vulnerability	**GOTILWA+ (Growth Of Trees Is Limited by Water)**

Model/ tool type and outputs	GOTILWA+ is a tree growth process-based model to simulate the sensitivity of forest ecosystems to climate change effects through its influence on tree and stand structure, management techniques and soil properties. Eco-physiological processes such as photosynthesis, transpiration, autotrophic and heterotrophic respiration are simulated in daily time intervals.
Open access?	Yes
Key data inputs	Key input data includes climate data: maximum and minimum temperatures, rainfall, vapour pressure deficit (VPD), wind speed and global radiation; stand characteristics: tree structure, diameter at breast height (DBH) class distribution; tree physiology: photosynthetic and stomatal conductance parameters; site conditions including soil characteristics and hydrological parameters and forest management criteria.
Key data accessibility/ availability	Data needs to be locally collected, such as for site soil conditions and forest management, while some data, such as climate, can be used from open access databases. Tree physiology data can be difficult to obtain for some tree species.
Strengths	GOTILWA+ is a species-specific model, using biophysical processes of tree species to calculate the effect of changing environmental conditions. It provides the possibility to simulate the growth of any one single species forest, either young or mature, plantation or natural forest; the impacts of change in a particular climate on the forest; the impacts of different forest management scenarios; and water stressed situations, which are significant in Mediterranean-type climates.
Assumptions/ limitations	The model requires detailed input data, which is not always available. It can only simulate one single species forest and the nutrient cycle is not included in the model. It also does not distinguish horizontal spatial heterogeneity and tree height, which can be interesting for some applications. Some of the processes included in the model require empirical relationships and it does not include processes such as herbivory or insect attacks. Finally, the model requires a good knowledge of the forest.
Spatial scale and resolution	Local scale of a single forest area.

Temporal scale and resolution	Time resolution of the model is at one-hour time steps for physiological processes, and one day time steps for structural values. Output has three time levels: daily, monthly and yearly.
Accessibility of outputs	Output variables include leaf physiology, tree components above- and below ground, understory and soil components. A basic understanding of tree physiology and forest ecology is needed to interpret the results.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Can be used to assess the effect of different forest management techniques on forest characteristics, for example, carbon stocks, under diverse climate scenarios.
Relevant application	GOTWILA+ has been used to explore the response of different forest types to water availability, especially in the Mediterranean and other (semi-) arid regions. In Sabate *et al.* (2002) climate change effects on the growth of Mediterranean tree species were modelled. In general, the results show that climate change could lead to a higher production due to the increasing atmospheric CO_2 concentration and rainfall in the region.
Main reference(s)	Sabate S, Gracia CA, Sanchez A (2002) Likely effects of climate change on growth of Quercus ilex, Pinus halepensis, Pinus pinaster, Pinus sylvestris and Fagus sylvatica forests in the Mediterranean region. For Ecol Manage 162:23–37
Suitability for rapid assessment	No. The model needs data input of the forest characteristics, which are often not yet known and need to be collected in the field.
Websites	http://www.creaf.uab.es/gotilwa/Index.htm
Manuals/ training/ videos	http://www.creaf.uab.es/gotilwa/Minfo.htm
Wikipedia page	-
Other	

1) Hazard, exposure and vulnerability modelling	1.4.2 Ecosystem vulnerability	**Ecosystem Intactness**

Model/ tool type and outputs	Ecosystem intactness is used as an indicator of an ecosystem's adaptive capacity, measured as the proportion of intact natural vegetation. The proportion of area of native vegetation which has been entirely transformed through agricultural development and urbanization (land-use change) is quantified using a global land cover model.
Open access?	Yes
Key data inputs	A land cover dataset is required for the region of study. Land cover datasets are often open access and are made available by, for example, the Copernicus Institute.
Key data accessibility/ availability	Land cover datasets are often open access, such as the GlobCover Dataset (2004-2009) or the Copernicus Global 100m Land Cover maps (2015).
Strengths	Ecosystem intactness uses open access data and rapid assessment is possible.
Assumptions/ limitations	It assumes that ecosystem intactness is an indicator for ecosystem adaptive capacity. It provides a sufficient assessment, however a greater detailed assessment would be preferable if data availability is not limiting.
Spatial scale and resolution	The spatial scale depends on the input dataset: European Space Agency GlobCover has a 300m resolution; Copernicus Global 100m Land Cover maps 2015 has a 100m resolution.
Temporal scale and resolution	The temporal scale depends on the datasets used for input. The Copernicus Global Land Cover map has an annual time resolution. The ESA GlobCover maps are available for two time periods: December 2004 - June 2006 and January - December 2009.
Accessibility of outputs	Output is a map with land-use change and percentages of the area ecosystems experiencing land-use change using indicator values.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change
Adaptation policy insights	Results provide insights regarding the trends in ecosystem adaptive capacity as result of land-use change.
Relevant application	The model has been applied for a global assessment of ecoregion's adaptive capacity to identify spatial gradients in ecosystem vulnerability to climate change and local stressors.

	The study of Watson *et al.* (2008) shows that the relationship between intactness (adaptive capacity) and stability (exposure) varies widely across ecoregions, with some of the most vulnerable ecosystems located in southern and south-eastern Asia, western and central Europe, eastern South America and southern Australia.
Main reference(s)	Watson, J. E. M., Iwamura, T., & Butt, N. (2013). Mapping vulnerability and conservation adaptation strategies under climate change. Nature Climate Change, 3(11), 989–994.; Arino, O. *et al.* GLOBCOVER. (2008) The most detailed portrait of Earth. ESA Bull. Eur. Space 136, 24–31.
Suitability for rapid assessment	Yes
Websites	http://due.esrin.esa.int/page_globcover.php
Manuals/ training/ videos	-
Wikipedia page	-
Other	

1) Hazard, exposure and vulnerability modelling	1.4.2 Ecosystem vulnerability	**Spatially Explicit Resilience-Vulnerability Model (SERV)**

Model/ tool type and outputs	The SERV model determines vulnerability on a sub-county spatial scale using socio-economic, spatial and place-specific indicators that represent exposure, sensitivity and adaptive capacity. These scores are subsequently aggregated into a vulnerability score.
Open access?	Yes
Key data inputs	The model uses socio-economic, spatial and place-specific indicators that represent exposure, sensitivity and adaptive capacity. In the US, this data is readily available at the national, state and county scale (for example, the US Census Bureau, 2010). In other countries this data is often made available by the national government or, for example, the EU Open Data Portal.
Key data accessibility/ availability	The input data is available for national, state and county scale (in the US). In other countries this data is often made available by the national government or, for example, the EU Open Data Portal.
Strengths	SERV is a model which aggregates a diverse set of vulnerability indicators into one vulnerability score. Furthermore, it accounts for spatially explicit indicators and their effect on the vulnerability score. The SERV model illustrates where within the county certain sensitivity or adaptive capacity indicators are dominant.
Assumptions/ limitations	One limitation of the vulnerability scoring is that some areas exhibit high vulnerability in the lower storm categories, however, subsequently exhibit lower vulnerability in the higher storm categories. The raw sensitivity and adaptive capacity data should be referenced to determine which indicators subject the greatest influence on the overall vulnerability score. Another limitation of the SERV model is that the PCA weighting scheme does not consider how indicator influence could change across the county.
Spatial scale and resolution	Sub-county scale.
Temporal scale and resolution	The output highlights vulnerability under different scenarios, such as three storm scenarios for the year 2050. Typically, it produces an outcome for a single point in time although the researcher might choose to assess scenarios referring to different time periods.

Accessibility of outputs	The output is a holistic vulnerability score at the sub-county level that accounts for spatially explicit indicators. It also identifies hotspots of vulnerability and factors that increase vulnerability.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change
Adaptation policy insights	Holistic vulnerability scores can inform decision makers in targeting mitigation efforts toward areas with the highest vulnerability and at indicators that greatest impact vulnerability.
Relevant application	The SERV model is applied for a vulnerability assessment of Sarasota County, Florida (Frazier *et al.*, 2014). The results indicate that vulnerability varies at the sub-county level and that the inclusion of spatially explicit indicators in vulnerability assessments aids decision-makers in identifying markers of vulnerability in specific areas.
Main reference(s)	Frazier, T. G., Thompson, C. M., & Dezzani, R. J. (2014). A framework for the development of the SERV model : A Spatially Explicit Resilience-Vulnerability model. Applied Geography, 51, 158–172.
Suitability for rapid assessment	No, unless the indicators for exposure, sensitivity and adaptive capacity can be derived from other studies.
Websites	-
Manuals/ training/ videos	-
Wikipedia page	-
Other	

1) Hazard, exposure and vulnerability modelling	1.4.2 Ecosystem vulnerability	**Environmental Vulnerability Index (EVI)**

Model/ tool type and outputs	The environmental vulnerability index (EVI) is a synthesis framework for understanding environmental vulnerability at a country level. EVI reports for countries are organized as a single-page, information-dense report card. These cards present the results for the three aspects of vulnerability, hazards, resistance and damage, and the percentage of indicators relevant to each for which data were available.
Open access?	Yes
Key data inputs	EVI uses 32 indicators of hazards, eight for resistance and 10 which measure damage. A minimum of 80% of the data for these indicators should be available.
Key data accessibility/ availability	The vulnerability indicators can be developed when data availability is scarce. There are still data gaps within the EVI, however a tolerance has been developed into the index which requires a minimum of 80% of data returns over the 50 indicators for a valid EVI evaluation.
Strengths	EVI provides a rapid and standardised method for characterising vulnerability on a national level and identifies environmental, economic and social issues that may need to be addressed.
Assumptions/ limitations	Given EVI is a rapid assessment at a country level, the vulnerability indicators do not incorporate detailed information regarding the areas within a country which are most vulnerable and to which hazards.
Spatial scale and resolution	EVI is designed for use at the national scale but could be evaluated at a range of geographic scales, including regions and provinces.
Temporal scale and resolution	For most indicators, signals are based on average levels observed over the past five years, but may include data for longer time periods for geological events.
Accessibility of outputs	Outputs are accessible and online.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change
Adaptation policy insights	The vulnerability indicators can support environmental managers and policymakers in decision-making for environmental conservation and restoration, taking current and future conditions into account.

Relevant application	EVI has been applied to assess the vulnerability of countries worldwide, including small island development states (SIDS) as part of the Barbados Programme of Action (BPoA). The EVI results for 2004 categorise these countries into five vulnerability groups and include an overall listing of countries and their vulnerability status, as well as country reports that detail the results for a single country.
Main reference(s)	SOPAC. (2005). Building Resilience in SIDS Collaborators: The Environmental Vulnerability Index.
Suitability for rapid assessment	Yes
Websites	http://www.vulnerabilityindex.net/
Manuals/ training/ videos	
Wikipedia page	
Other	

1) Hazard, exposure and vulnerability modelling	1.4.2 Ecosystem vulnerability	**Ecosystem Vulnerability Assessment Approach (EVAA)**

Model/ tool type and outputs	EVAA determines the potential vulnerability of forest ecosystems to climate change over the next one hundred years. The approach combines multiple quantitative models with expert elicitation from scientists and land managers using a seven-step approach. Experts interpret the results of climate projections, habitat suitability models and landscape process models to assess climate change impacts and their interactions and adaptive capacity factors to determine ecological vulnerability and uncertainty.
Open access?	Yes
Key data inputs	EVAA integrates climate change trends and projections, quantitative data from forest impact models, scientific literature and expert knowledge and experience.
Key data accessibility/ availability	Experts with knowledge on local forest ecosystems and their vulnerability to climate change should be involved in the process. In addition, a forest impact model should be used, such as the GOTILWA+ model.
Strengths	EVAA delineates impacts based on ecosystem drivers, stressors and dominant tree species. A key strength in the approach is its collaborative nature. The model incorporates quantitative and qualitative information with local expertise. This approach gives the opportunity to include complex and location-specific information that would not have been part of a numerical model. Also, individual determinations allowed panellists to identify areas of agreement on the perceived risk to a particular community or forest type, generating greater robust results.
Assumptions/ limitations	For instances when quantitative data is not readily available, other sources of information, such as local expertise on species biology or traditional ecological knowledge, would constitute a greater significant component of the analysis. This may reduce the overall confidence in vulnerability determinations for that area given the lack of evidence.
Spatial scale and resolution	Local scale/ forest area.
Temporal scale and resolution	The temporal scale and resolution will depend on input data. Since the model assesses vulnerability to climate change impacts, the time scale is typically decades to a century (such as 2050, 2100).

Accessibility of outputs	Results are presented as technical reports for forest managers.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change
Adaptation policy insights	A key advantage to EVAA is that it can be directly applied to adaptation planning in the forest sector. The outcomes of EVAA studies have been used to select and implement climate adaptation projects in forest management.
Relevant application	The approach is applied to assess the vulnerability of forest ecosystems in eight regions in the Midwestern and Eastern USA. The results were summarized in technical reports for natural resource managers. Across all eight assessment areas, 13 ecosystem or forest types (29%) were rated as having high vulnerability and six (13%) were rated as having low vulnerability. Overall, upland systems dominated by oak species were generally considered to have relatively low vulnerability, while boreal and high-elevation community types were rated as having higher vulnerability.
Main reference(s)	Brandt, L. A., Butler, P. R., Handler, S. D., Janowiak, M. K., Shannon, P. D., & Swanston, C. W. (2017). Integrating Science and Management to Assess Forest Ecosystem Vulnerability to Climate Change. Journal of Forestry, 115(May), 212–221.
Suitability for rapid assessment	No, it takes time to organize an expert session with a broad range of forest (management) experts familiar with the region of interest.
Websites	-
Manuals/ training/ videos	-
Wikipedia page	-
Other	

1) Hazard, exposure and vulnerability modelling	1.4.3 Resilience analysis and assessment	**City Resilience Index**

Model/ tool type and outputs	This is a framework to describes the resilience of a city.
Open access?	This is not a model, but an approach. The guiding documents are freely available.
Key data inputs	A large range of metrics constituting bio-physical, socio-economic and demographic, totalling up to 52 indicators are required.
Key data accessibility/ availability	The data needs to be location specific. This could constitute primary data provided by local authorities or publicly available secondary data, such as from a national census or OECD. Many of the variables can be measured with up to four different metrics and provide the user with a choice, depending on data availability.
Strengths	Comprehensive; globally applicable; validated with international experts and within case studies; and provides both qualitative and quantitative assessment.
Assumptions/ limitations	The CRI assumes that there is a globally uniform understanding of the language to describe the indicators and variables, which is not the case due to differing cultural contexts. It also allows cities some flexibility in the use and weighting of variables, however this does not subsequently support a global comparison of city ranks. The CRI uses 52 indicators, described by 156 variables (questions), which can be measured with 450 metrics - even data-rich cities can often only acquire 60% of the metrics. The number of indicators, variables and metrics is the result of an attempt to balance the complexity and usability of the CRI.
Spatial scale and resolution	City scale - assessment is conducted for the entire city, although sub-city level assessments might be explored in future work.
Temporal scale and resolution	Time scale and resolution are only partially applicable - the CRI includes lagging and leading variables which consider the change in resilience over time, such as measures that have been implemented but will only show an effect in the future. Repetitive assessments can identify resilience development over time, and therefore the time resolution is dependent on the assessment frequency.
Accessibility of outputs	The output is a resilience profile plot, which is easy to understand and communicate. (see example below)
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 4) Assessing adaptation options; 6) Monitoring & evaluation
Adaptation policy insights	The index could support 1) the identification of adaptation options that enhance resilience and 2) to prioritise investments.
Relevant application	It has been applied for members of the 100 Resilient Cities Network to assess member cities' resilience. For example, Liverpool scored highly in a pilot study in leadership and strategy but

	moderately on health and wellbeing. Workshop participants indicated that health budgets were to be cut the following year. In combination with the CRI, this can provide insight into the future development of the resilience in terms of health and wellbeing. It is unclear whether the outcomes of this pilot study influenced policy.
Main reference(s)	CRI. (2016a). Research Report Vol 4 - Measuring City Resilience. *Rockefeller Foundation and ARUP;* CRI. (2016b). Research Report Vol 6 - Measurement Guide. *Rockefeller Foundation and ARUP.*
Suitability for rapid assessment	The model can be readily used based on the documentation of the CRI, input data can be readily accessed if secondary data is used, a more in-depth analysis with local data requires greater time for data collection.
Websites	https://www.cityresilienceindex.org/#/
Manuals/ training/ videos	Available on the website
Wikipedia page	https://en.wikipedia.org/wiki/Urban_resilience#100_Resilient_Cities_and_the_City_Resilience_Index_(CRI)
Other	

1) Hazard, exposure and vulnerability modelling	1.4.3 Resilience analysis and assessment	**CIRCLE**

Model/ tool type and outputs	This is a software-supported stakeholder engagement tool that identifies interdependencies and failure thresholds in a critical infrastructure network.
Open access?	Yes, the tool is online and freely accessible.
Key data inputs	Input from stakeholders is required for information on failure thresholds, costs in case of failure, recovery times and dependence on other services.
Key data accessibility/ availability	Input data is derived from stakeholders.
Strengths	CIRCLE identifies and visualises interdependencies in critical infrastructure networks.
Assumptions/ limitations	There is the assumption that all relevant stakeholders have been identified and invited.
Spatial scale and resolution	Local/ regional scale.
Temporal scale and resolution	N/a.
Accessibility of outputs	Outputs include coloured graphics that visualises the type and strength of critical infrastructure dependencies. (see comprehensive desk review, chapter 1.4.3 and 2.9).
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 4) Assessing adaptation options
Adaptation policy insights	CIRCLE can support the identification of key vulnerabilities and prioritise investment within the critical infrastructure network which require protection.
Relevant application	Resilience to fluvial flooding in Cork: an analysis of the critical infrastructure resiliency to fluvial flooding revealed that the failure of power transformer stations during a 2009 flood event caused cascading effects and led to the disruption of schools, traffic, wastewater treatment, residents, businesses and importantly the hospital. Installing flood protection around the transformer stations increased the resilience of the entire city. Circle has also been applied in multiple cities, including Murcia, Paris, Florida, Istanbul and Amsterdam.
Main reference(s)	de Bruijn, K. M., van der Most, H., Cumiskey, L., Hounjet, M., & Mens, M. (2018). Methods and tools supporting urban resilience

	planning: experiences from Cork, Ireland. Journal of Geoscience and Environment Protection, 6(4), 290–309.
Suitability for rapid assessment	No, stakeholder engagement requires significant time for stakeholder identification and workshop organisation. Data is collected only at the workshop and not readily available.
Websites	https://circle.deltares.org/; https://circle.deltares.org/circle/help.pdf
Manuals/ training/ videos	on the website
Wikipedia page	
Other	

Annex 2: Sectoral models for impact and adaptation assessment

2) Sectoral models for impact and adaptation assessment	2.1 Water supply	**RIBASIM (River Basin Simulation Model)**

Model/ tool type and outputs	RIBASIM solves the water balance equation for a river basin and allocates water to different users according to priorities. The output is flow per location and time and the allocated water.
Open access?	No
Key data inputs	Required data includes hydrological time series, for example, of surface water runoff, rainfall and open water evaporation; aquifers; water users; infrastructure and its operation - dams, weirs, pumps and canals; and water allocation priorities. Depending on the detail of modelling, data required includes crop; cultivation; yield and production costs; number of inhabitants per population type; concentration of various substances in drainage flows; and reservoir sedimentation data.
Key data accessibility/ availability	The hydrological time series usually come from a hydrological model that processes climate scenarios. The river network can be derived from an open map. The infrastructure data must be obtained from the local operator, but often estimates are made. Priorities for water usage are, if specified, the responsibility of local authorities.
Strengths	Represents physical flow processes (water balance) and human interactions with the water system. It can be applied in any location, allows for both surface- and groundwater systems; national or site-specific.
Assumptions/ limitations	The basic principle is the water balance equation. No hydraulics are modelled (flood wave) and reservoir operations are demand driven. Usually monthly time steps are chosen.
Spatial scale and resolution	The spatial scale can be at a river network, national, regional or local level. The resolution is driven by the water use functions and the related infrastructure.
Temporal scale and resolution	Typical time resolutions are in days, 10 days or months. A typical simulation period can cover one or multiple years.
Accessibility of outputs	The primary output is a flow quantity over time. Secondary output is water shortage and allocation as percentage of

	demand. Outputs are accessible for users and the model is usually applied in desktop studies.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Potential impacts of droughts on water supply for different use functions (water shortage) and comparison of different adaptation options.
Relevant application	For the Eastern Nile region, the Eastern Nile Water Simulation Model (ENWSM) has been developed with RIBASIM. The model contains the hydraulic infrastructure and major water usages in the Eastern Nile (EN) with the Bahr el Jebel at Mangalla as the upper and the High Aswan Dam as lower boundary. The potential of the model has been illustrated by a scenario analysis of the EN basin for a number of identified scenarios, measures and strategies on critical EN issues such as water infrastructure development and climate change.
Main reference(s)	Van der Krogt, W. 2010. Technical report: RIBASIM 7.01. Deltares, Delft.
Suitability for rapid assessment	Yes, under the condition that a model is prepared beforehand. The Global RIBASIM initiative aims to have such a model prepared for the whole world.
Websites	https://www.deltares.nl/en/software/ribasim/
Manuals/ training/ videos	https://www.deltares.nl/en/webinars/webinar-session-river-basin-planning-and-modelling-symposium/
Wikipedia page	
Other	http://www.delta-alliance.org/toolboxoverview/RIBASIM

2) Sectoral models for impact and adaptation assessment	2.1 Water supply	**E-Water Source**

Model/ tool type and outputs	E-Water Source solves a water balance for a modelling area, such as a river basin, urban area or catchment, and accounting for different use functions (sectors), water governance/policy and operational rules. It is possible to model hydrological processes and water quality as well.
Open access?	No, but there is a public version that can be used for training purposes.
Key data inputs	Required data includes system inflow, reservoir characteristics and parameters, evaporation from water surfaces and water users and demands.
Key data accessibility/ availability	The hydrological time series usually come from a hydrological model. The river network can be derived from an open map. The infrastructure data must be obtained from the local operator, but often estimates are made. Priorities for water usage are, if specified, the responsibility of local authorities.
Strengths	Represents physical flow processes (water balance) and human interactions with the water system. It can be applied in any location, allows for both surface- and groundwater systems; national or site-specific.
Assumptions/ limitations	The basic principle is the water balance equation. No hydraulics are modelled (flood wave), and reservoir operations are demand driven. Usually monthly time steps are chosen.
Spatial scale and resolution	The spatial scale can be at a river network, national, regional or local level. The resolution is driven by the water use functions and the related infrastructure.
Temporal scale and resolution	Typical time resolution is days, 10 days, months. A typical simulation period can cover one or multiple years.
Accessibility of outputs	The primary output is a flow quantity over time. Secondary output is water shortage and allocation as percentage of demand. Outputs are accessible for users and the model is usually applied in desktop studies.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Potential impacts of droughts on water supply for different use functions (water shortage), comparison of different adaptation options.

Relevant application	A recent water shortage in the Upper Godavari basin increased pressure on the sharing of water between the upstream water users (with reservoirs nearly full) and downstream water users (with reservoirs nearly empty) and this resulted in legal action. E-Water has supported the establishment of long-term modelling capability in Maharashtra using Source (Australia's National Hydrological Modelling Platform) as the river basin modelling tool.
Main reference(s)	N/A
Suitability for rapid assessment	Yes, under the condition that a model is prepared beforehand.
Websites	http://ewater.org.au/products/ewater-source/
Manuals/ training/ videos	https://ewater.org.au/products/ewater-source/best-practice-modelling/
Wikipedia page	
Other	https://ewater.org.au/products/ewater-source/source-overview/

2) Sectoral models for impact and adaptation assessment	2.1 Water supply	**Cropwat**

Model/ tool type and outputs	Cropwat calculates the crop water requirements. The output is water demand over time that can be used for irrigation scheduling.
Open access?	No
Key data inputs	Required data includes crop data on crop coefficient, root depth, allowed depletion and yield coefficient; soil data on hydraulic conductivity saturated/unsaturated, specific yield, porosity and unsaturated flow soil parameters; and climate data on sun hours, rainfall, humidity and temperature.
Key data accessibility/ availability	Local soil data bases, climate stations.
Strengths	Represents bio-physical processes of plant water demand under rainfed or irrigated conditions; features irrigation schemes; can be used for evaluation of measures such as where to irrigate or which plants to grow.
Assumptions/ limitations	Comparatively high data requirements; limited to the agricultural sector.
Spatial scale and resolution	Local scale. Cropwat works with percentage of area, so it is independent of a spatial resolution.
Temporal scale and resolution	Time resolution is month, day, decade. A typical simulation period covers one growth season.
Accessibility of outputs	Primary output is soil water depletion over time. Outputs are accessible for users and the model is usually applied in desktop studies.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Impacts of drought on crop growth and related yield under certain management practices.
Relevant application	Cropwat has been applied for deficit irrigation studies for different regions (China, India, Turkey, Pakistan, United States of America, Australia, among others), various crops (potato, cotton, wheat, peach and pear trees, grapes, groundnuts), and under various ecological conditions. An integrated report can be found here: http://www.fao.org/3/Y3655E/y3655e02.htm#b

Main reference(s)	Smith, M. (1992). CROPWAT: A computer program for irrigation planning and management (No. 46). Food & Agriculture Org.
Suitability for rapid assessment	Yes, under the condition that the model is prepared beforehand.
Websites	http://www.fao.org/land-water/databases-and-software/cropwat/en/
Manuals/ training/ videos	https://books.google.it/books?id=p9tB2ht47NAC&pg=PP1 &source=kp_read_button&redir_esc=y#v=onepage&q&f=false
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.1 Water supply	**Aquacrop**

Model/ tool type and outputs	Aquacrop is a crop growth model that computes the yield response on herbaceous crops to water.
Open access?	Yes
Key data inputs	Required data includes crop characteristics; soil parameters of soil texture, fine soil fraction, water retention, field capacity and wilting point; field management practices; irrigation management practices; and weather conditions such as air temperature, reference evapotranspiration, rainfall and CO_2 concentration.
Key data accessibility/ availability	Crop characteristics are stored in a database. Pedotransfer functions for the soil parameters are available, weather conditions can be obtained from weather services.
Strengths	Represents bio-physical processes of plant growth under rainfed or irrigated conditions; features irrigation schemes; can be used for evaluation of measures such as which plants to grow and where to irrigate.
Assumptions/ limitations	Comparatively high data requirements; limited to the agricultural sector.
Spatial scale and resolution	Local scale. Aquacrop works with percentage of area, so it is independent of a spatial resolution.
Temporal scale and resolution	Time resolution is month, day, decade. A typical simulation period covers one growth season.
Accessibility of outputs	Primary outputs are soil water balance (evapotranspiration, capillary rise, deep percolation, irrigation, rainfall) and biomass over time. Crop biomass is aggregated over the growing season to dry/fresh yield and biomass. Outputs are accessible for users and the model is usually applied in desktop studies.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Impacts of drought on crop growth and related yield under certain management practices.
Relevant application	Modelling Systems for Agricultural Impacts of Climate Change: a system of models and utilities designed to carry out inter-disciplinary climate change impact assessment on agriculture, water resources, forestry and the economy through simulations

	at national level. (http://www.fao.org/documents/card/en/c/edd62158-f16c-4ed1-8914-a3f3d56b6934/)
Main reference(s)	Saxton, K. E., Rawls, W. J. 2006. Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. Soil Sci. Soc. Am. J. 70, 1569–1578. URL web page (for downloading the hydraulic properties calculator): http://hydrolab.arsusda.gov/soilwater/Index.htm
Suitability for rapid assessment	Yes, under the condition that the model is prepared beforehand.
Websites	http://www.fao.org/aquacrop
Manuals/ training/ videos	http://www.fao.org/aquacrop/resources/tutorials/en/
Wikipedia page	
Other	https://www.aquacropos.com/

2) Sectoral models for impact and adaptation assessment	2.1 Water supply	**WEAP (Water evaluation and planning system)**

Model/ tool type and outputs	WEAP calculates water demand, supply, runoff, infiltration, crop requirements, flows, and storage, and pollution generation, treatment, discharge and instream water quality under varying hydrologic and policy scenarios.
Open access?	No
Key data inputs	Demand: domestic water use data (aggregated, per person), water demand of other sectors, groundwater withdrawal, loss rates, reuse rates, rainfall-runoff parameters, plant growth parameters, soil parameters, land use, hydropower demand; climate data: rainfall, evapotranspiration, humidity, wind, irrigation; planting dates, harvesting dates, crop prices, inundation parameters (rice farming); schematization: river network, reservoirs, reservoir parameters (storage capacity, operational parameters).
Key data accessibility/ availability	Demand data: from stakeholder involvement or from local authorities. Climate data: from climate scenarios. The schematization can be derived from open maps.
Strengths	Database with sample data (crop parameters), demand categorized in sectors, financial analysis tools.
Assumptions/ limitations	The basic principle is the water balance equation. No hydraulics are modelled (flood wave) and reservoir operations are demand driven.
Spatial scale and resolution	The spatial scale is at the river network, national, regional or local level. The resolution is driven by the water use functions and the related infrastructure.
Temporal scale and resolution	Time resolution is in days, 10 days or months. A typical simulation period can cover one or multiple years.
Accessibility of outputs	The primary output is flow quantity over time. Outputs are accessible for users and the model is usually applied in desktop studies.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Potential impacts of droughts on water supply for different sectors, comparison of different adaptation options.
Relevant application	ADAPT - Adaptation to Changing Environments: Water, Climate, Food, and Nature: As part of the ADAPT project, WEAP was used

	to develop and evaluate adaptation strategies in the Sacramento Basin (California, USA) and in the Volta Basin (primarily in Burkina Faso and Ghana) to alleviate negative impacts of climate change and variability. A variety of adaptation strategies were analysed with WEAP to address the trade-offs between water allocations that prioritize the environment and food security under changing climate and land-use conditions.
Main reference(s)	William Johnson, Quentin Williams and Paul Kirshen, "WEAP: A Comprehensive and Integrated Model of Supply and Demand," Proceedings of the 1995 Georgia Water Resources Conference, Athens, Georgia, USA, April 11-12, 1995.
Suitability for rapid assessment	Yes, under the condition that the model is prepared beforehand.
Websites	http://www.weap21.org/index.asp?action=200
Manuals/ training/ videos	http://www.weap21.org/index.asp?action=204
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.1 Water supply	**GSFLOW (Groundwater and Surface-water FLOW)**

Model/ tool type and outputs	GSFLOW models couple surface and subsurface water flow.
Open access?	Yes
Key data inputs	Required data includes climate data such as precipitation, maximum and minimum air temperature, and optionally solar radiation and potential evapotranspiration; groundwater stresses (withdrawals); boundary conditions to account for inflows to and outflows from the modelled region, such as streamflow and heads; description of the hydro-geological system including layers and material parameters; network of surface water; and rainfall-runoff parameters.
Key data accessibility/ availability	Geological databases, climate scenarios, local authorities and stakeholders.
Strengths	Physics-based description of the groundwater domain, modelling of surface water and groundwater interaction.
Assumptions/ limitations	No hydraulics are modelled (flood wave) and use functions (from different sectors) must be formulated as withdrawals.
Spatial scale and resolution	Watershed scale, a model area can range from a few up to thousands of square kilometres. The resolution (cell size) is usually chosen based on the data availability, computing time and the desired output resolution.
Temporal scale and resolution	Typical time resolution varies from days to months, but the software also supports shorter time resolutions (hours, minutes, seconds). Typical time scales vary between months over one or multiple years up to infinity (steady state computation).
Accessibility of outputs	The primary output is water level over time, computed for each cell. The secondary output is flow rate and water level or flow that corresponds to the boundary conditions. Outputs are accessible for users and the model is usually applied in desktop studies.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Evaluate the effects of land-use change, climate variability and groundwater withdrawals on surface and subsurface flow.

Relevant application	For the Trout Lake Watershed in north-central Wisconsin (USA), GSFlow was applied to analyse the response of the hydrologic system to climate change. Forecasts of potential climate change showed growing season length increasing by weeks, and both potential and actual evapotranspiration rates increasing appreciably. The hydrologic-system response to climate change was characterized by a reduction in the importance of the snow-melt pulse and an increase in the importance of fall and winter groundwater recharge. The less dynamic hydrologic regime is likely to result in drier soil conditions in rainfed wetlands and uplands, in contrast to less drying in groundwater-fed systems.
Main reference(s)	Markstrom, S.L., Niswonger, R.G., Regan, R.S., Prudic, D.E., and Barlow, P.M., 2008, GSFLOW-Coupled Ground-water and Surface-water FLOW model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005): U.S. Geological Survey Techniques and Methods 6-D1, 240 p.
Suitability for rapid assessment	Yes, under the condition that the model is prepared beforehand.
Websites	https://www.usgs.gov/software/coupled-ground-water-and-surface-water-flow-model-gsflow
Manuals/ training/ videos	https://pubs.usgs.gov/tm/tm6d1/
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.1 Water supply	**Multivariate Standardized Reliability and Resilience Index (MSRRI)**

Model/ tool type and outputs	MSRRI is a drought hazard index for hydrological and socio-economic drought.
Open access?	Not as a tool, but the methodology is published.
Key data inputs	Data requirements include hydrological conditions: inflow to the system; water demand; and reservoir parameters such as storage volume, dead storage, and type of the reservoirs, within-year or over-year.
Key data accessibility/ availability	Hydrological conditions: from a hydrological model prediction, for example, using climate scenarios; observations from gauges. Demand data: from stakeholder involvement or from local authorities. Reservoir parameters can be taken from dam databases such as those published by the International Commission of Large Dams (ICOLD).
Strengths	Indicates the onset of the stress based on the onset of the hydrologic drought and recovery of the system from a socioeconomic perspective. Provides an assessment of the overall stress on the system including the system resilience.
Assumptions/ limitations	The uncertainty in the assessment of demands and water resources values may result in incorrect values of the indicator.
Spatial scale and resolution	The index is computed for a reservoir system, the reservoir system forms the spatial resolution. The spatial scale ranges from one to multiple systems.
Temporal scale and resolution	Time resolution is usually a month, the time scale is one or multiple years.
Accessibility of outputs	Output is the index over time for a reservoir system. Outputs are accessible for users and the method is usually applied in desktop studies but has potential to run on platforms.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; to some extent also 3) Identifying adaptation option (reduce demand, increase storage capacity).
Adaptation policy insights	Impact of water conservation, impact of increase of storage capacity, likelihood to recover from an observed drought (i.e. how likely is it that an inflow pattern occurs that provides recovery?)

Relevant application	The index is mainly applicable for regions with large reservoir capacity. MSRRI was applied for Melbourne, Australia and California, United States of America, where the index components illustrate the differences between meteorological and local reservoir conditions. For example, it is possible that the hydrologic conditions indicate the onset of a drought, but the demand can still be satisfied with the water stored in the reservoirs. In this case, the hydrologic drought does not lead to a socioeconomic drought. On the contrary, the average inflow can be higher than average (no hydrological drought), while storage is still below average, and the demand cannot be satisfied.
Main reference(s)	Mehran, A., O. Mazdiyasni, and A. AghaKouchak (2015): A hybrid framework for assessing socioeconomic drought: Linking climate variability, local resilience, and demand, J. Geophys. Res. Atmos., 120, doi:10.1002/2015JD023147.
Suitability for rapid assessment	Yes
Websites	
Manuals/ training/ videos	
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.1 Water supply	**Water Requirement Satisfaction Index (WRSI) and Geo WRSI**

Model/ tool type and outputs	WRSI is an index for drought impact on the agricultural sector.
Open access?	Yes
Key data inputs	Input data includes crop coefficient, soil water holding capacity, potential evapotranspiration, precipitation, start of the season and end of the season.
Key data accessibility/ availability	Satellite rainfall estimation, crop and soil databases, precipitation databases (https://www.chc.ucsb.edu/data)
Strengths	High resolution and good spatial coverage over all terrains.
Assumptions/ limitations	Stress related to factors other than water availability can affect the results. Satellite-based rainfall estimates have a degree of error that will affect the results of the crop models used and the balance of evapotranspiration.
Spatial scale and resolution	Local to regional scale with a resolution of, for example, 0.1 degrees/ approximately 10 km.
Temporal scale and resolution	The time scale is the growing season. Typical resolutions are decades, months or 1/3 of a month.
Accessibility of outputs	Outputs are accessible for users in the case of desktop studies, but also platforms publish index calculations (current, forecasted, historical) on maps.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change
Adaptation policy insights	Impacts of current drought or drought scenarios on crop yield.
Relevant application	Monitoring (current WRSI) and forecasting (forecast of WRSI by the end of the growing season) for different regions, see for example: https://earlywarning.usgs.gov/fews/search/Africa
Main reference(s)	Verdin, J., Klaver, R. (2002): Grid-cell-based crop water accounting for the famine early warning system. Hydrological Processes, 16(8):1617–1630.
Suitability for rapid assessment	Yes, several platforms produce this index.

Websites	https://www.chc.ucsb.edu/tools/geowrsi
Manuals/ training/ videos	https://www.chc.ucsb.edu/tools
Wikipedia page	
Other	https://lis.gsfc.nasa.gov/projects/fewsnet-east-africa https://lis.gsfc.nasa.gov/projects/fewsnet-southern-africa https://lis.gsfc.nasa.gov/projects/fewsnet-west-africa

2) Sectoral models for impact and adaptation assessment	2.1 Water supply	**Agricultural Stress Index (ASI)**

Model/ tool type and outputs	ASI is an index for drought impact on the agricultural sector.
Open access?	No, but monitoring platforms exist.
Key data inputs	Vegetation Health Index (VHI), start of season (SOS) and end of the grain filling stage (GFS).
Key data accessibility/ availability	Vegetation Health Index (VHI): satellite data; start of season (SOS) and end of grain filling stage (GFS) are crop parameters with spatial variation.
Strengths	Allows to detect agricultural areas with a high likelihood of water stress at global, regional and country levels for early warning systems.
Assumptions/ limitations	The current version of ASI has the following limitations: ▪ The index detects extreme events of drought, which means that agricultural areas affected by moderate drought (referring to temporal intensity at pixel level) would be missed. ▪ It defines two cropping seasons globally. This works accurately for most areas; however, there are regions, such as Central America, where there are four crop seasons in a calendar year. In ASI the first crop season does not necessarily represent the main crop season, but rather the first crop season in a calendar year. ▪ The current version gives equal weight to all phenological phases when calculating the temporal integration without regard to the crop water requirements and their implications on crop yield reduction.
Spatial scale and resolution	Global scale, regional or country scale, resolution 1 km.
Temporal scale and resolution	Updated every 10 days (GIEWS Earth Observation website); for crop season only.
Accessibility of outputs	Various platforms publish current ASI on maps.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change
Adaptation policy insights	ASIS can detect “hotspots” globally where crops may be affected by drought.

Relevant application	The Government of Uganda, a country that faces water shortages, required decision-making support regarding where to accommodate newly arrived refugees in order to prevent/ limit potential water gaps due to increased water demand. The ASI was used to identify relevant drought hazard, exposure and vulnerability for the agricultural sector.
Main reference(s)	Rojas O., Vrieling A., & Rembold F. (2011): Assessing drought probability for agricultural areas in Africa with coarse resolution remote sensing imagery. Remote Sensing of Environment, 115: 343-352. doi:10.1016/j.rse.2010.09.006 Rojas O., Li Y.; Cumani R. (2014): Understanding the drought impact of El Niño on the global agricultural areas: An assessment using FAO's Agricultural Stress Index (ASI). FAO. ISSN 2071-0992. http://www.fao.org/3/a-i4251e.pdf
Suitability for rapid assessment	Yes, currently applied in real-time by multiple platforms.
Websites	http://www.fao.org/giews/earthobservation/asis/index_1.jsp?lang=en
Manuals/ training/ videos	http://www.fao.org/emergencies/resources/videos/video-detail/en/c/1152672/
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.2 Agriculture/ crops	**The Decision Support System for Agrotechnology Transfer (DSSAT)**

Model/ tool type and outputs	DSSAT is a software application program that comprises crop simulation models for over 42 crops (as of Version 4.7) as well as tools to facilitate effective use of the models. The tools include database management programs for soil, weather, crop management and experimental data, utilities and application programs. The crop simulation models simulate growth, development and yield as a function of the soil-plant-atmosphere dynamics. Key outputs are the impact of climate change on crop production, resource use and environmental pollution and management options for adaptation.
Open access?	Yes
Key data inputs	Daily weather data, soil surface and profile information, detailed crop management and crop genetic information. Simulations are conducted at a daily step or in some cases, at an hourly time step depending on the process and the crop model. At the end of each day, the plant and soil water, nitrogen, phosphorus, and carbon balances are updated, as well as the crop's vegetative and reproductive development stage.
Key data accessibility/ availability	WISE database for soil data. Weather/climate data from local weather stations and RCMs and GCMs. Crop observations, such as phenology, yield and management, can be obtained from field experiments and available (local/ regional) databases.
Strengths	DSSAT combines crop, soil, and weather data bases with crop models and application programs to simulate multi-year outcomes of crop management strategies for over 42 crops. DSSAT integrates the effects of soil, crop phenotype, weather and management options, and allows users to ask "what if" questions by conducting virtual simulation experiments on a desktop computer in minutes which would consume a significant part of an agronomist's career if conducted as real experiments.
Assumptions/ limitations	Assumptions and limitations of these models include the availability of input data required for model calibration, evaluation and operation, and the uncertainty related to parameters and simulation processes.
Spatial scale and resolution	Field scale (site specific). Routines for spatial distributed simulations were developed by various researchers.
Temporal scale and resolution	Can project annually for over 100 years at either hourly or daily time steps.
Accessibility of outputs	The model provides output results in text file format. These results can be read by any text editor and converted in other formats.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options

Adaptation policy insights	The models support the assessment of the risks of climate change on agriculture and to evaluate the effects of different management options as adaptation measures to cope with climate change.
Relevant application	DSSAT is widely used by scientists globally and included in the AgMIP project for model intercomparison. Asseng *et al.* (2019) tested and applied a 32-multi-model ensemble to assess climate change impacts on global wheat yield and quality, and to evaluate adaptation strategies as the effect of introducing genotypes adapted to warmer temperatures on crop yield and quality. Their results show that the introduction of combined traits for delayed anthesis and increased grain filling rate could be an effective adaptation strategy for wheat yield, increasing global yield in future climate change conditions. Liu *et al.* (2018) used a multi-crop and multi-climate model ensemble to analyse the impacts on global wheat production with 1.5 and 2.0°C above preindustrial warming. Results show that projected global wheat production will change by −2.3% to 7.0% under the 1.5°C scenario and −2.4% to 10.5% under the 2.0°C scenario, compared to a baseline of 1980–2010.
Main reference(s)	(1) Hoogenboom, G., C.H. Porter, V. Shelia, K.J. Boote, U. Singh, J.W. White, L.A. Hunt, R. Ogoshi, J.I. Lizaso, J. Koo, S. Asseng, A. Singels, L.P. Moreno, and J.W. Jones. 2019. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.7.5 (https://DSSAT.net). DSSAT Foundation, Gainesville, Florida, USA. (2) Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, and J.T. Ritchie. 2003. DSSAT Cropping System Model. European Journal of Agronomy 18:235-265
Suitability for rapid assessment	No - CSMs require detailed input data and proper parameterization and evaluation prior to be applied in assessing risks and adaptation options.
Websites	https://dssat.net/about
Manuals/ training/ videos	Manuals are included in the software.
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.2 Agriculture/ crops	**The Agricultural Production Systems Simulator Model (APSIM)**

Model/ tool type and outputs	APSIM is a platform for modelling and simulation of agricultural systems. APSIM is structured based on plant, soil and management modules. These modules include a diverse range of crops, pastures and trees, soil processes including water balance, nitrogen and phosphorus transformations, soil pH, erosion and a full range of management controls. APSIM is a comprehensive model developed to simulate biophysical processes in agricultural systems, particularly as it relates to the economic and ecological outcomes of management practices under climate risk. It is also being used to explore options and solutions for the food security, climate change adaptation and mitigation and carbon trading problem domains.
Open access?	Yes
Key data inputs	Soil properties, daily climate data, cultivar characteristics, and agronomic management.
Key data accessibility/ availability	The APSIM Initiative (AI; www.apsim.info/AboutUs.aspx) is exploring options for building a linking network that connects users to APSIM data. With a working name of The Stack (http://www.apsim.info/TheStack), this Google Earth-based product allows users to share one or more of their DropBox™ folders with The Stack. The Stack crawler then indexes the files found in the folders and creates a Google Earth KMZ file, allowing Google Earth to show the locations of the files. The Stack already indexes various online databases such as APSoil in Australia (Dalgliesh *et al.*, 2012), the WISE soils database (Romero *et al.*, 2012) and the Watch Forcing Dataset (Weedon *et al.*, 2011). The AI also collects and stores the calibration and validation data that is used to build and test a model's performance. A generic database (REMS) has been developed for storing experimental data (see details in Holzworth *et al.*, 2014).
Strengths	APSIM has evolved from a cropping systems model into an agro-ecosystem model. APSIM integrates models derived in fragmented research efforts, integrating different disciplines. It also facilitates comparison of models or sub-models on a common platform.
Assumptions/ limitations	Assumptions and limitations of these models include the availability of input data required for model calibration, evaluation and operation, the uncertainty related to parameters and simulation processes.
Spatial scale and resolution	Field scale (site specific), but results can be extrapolated to national and regional levels using GIS.

Temporal scale and resolution	The timescale of an APSIM simulation generally ranges from a few days to over a century in duration at a daily resolution.
Accessibility of outputs	The model provides output results in text file format. These results can be read by any text editor and converted in other formats.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The models support the assessment of the risks of climate change on agriculture and to evaluate the effects of different management options as adaptation measures to cope with climate change.
Relevant application	APSIM is widely used by scientists globally and included in the AgMIP project for model intercomparison. Asseng *et al.* (2019) tested and applied a 32-multi-model ensemble to assess climate change impacts on global wheat yield and quality and to evaluate adaptation strategies as the effect of introducing genotypes adapted to warmer temperatures on crop yield and quality. Their results show that the introduction of combined traits for delayed anthesis and increased grain filling rate could be an effective adaptation strategy for wheat yield, increasing global yield in future climate change conditions. Liu *et al.* (2018) used a multi-crop and multi-climate model ensemble to analyse the impacts on global wheat production with 1.5 and 2.0°C above preindustrial warming. Results show that projected global wheat production will change by −2.3% to 7.0% under the 1.5°C scenario and −2.4% to 10.5% under the 2.0°C scenario, compared to a baseline of 1980–2010.
Main reference(s)	(1) Holzworth, Dean P., Neil I. Huth, Peter G. deVoil, Eric J. Zurcher, Neville I. Herrmann, Greg McLean, Karine Chenu, *et al.* "APSIM – Evolution towards a New Generation of Agricultural Systems Simulation." Environmental Modelling & Software 62 (December 2014): 327–350. https://doi.org/10.1016/j.envsoft.2014.07.009. (2) Holzworth, Dean, N. I. Huth, J. Fainges, H. Brown, E. Zurcher, R. Cichota, S. Verrall, N. I. Herrmann, B. Zheng, and V. Snow. "APSIM Next Generation: Overcoming Challenges in Modernising a Farming Systems Model." Environmental Modelling & Software 103 (May 1, 2018): 43–51. https://doi.org/10.1016/j.envsoft.2018.02.002.
Suitability for rapid assessment	No - CSMs require detailed input data and proper parameterization and evaluation prior to be applied in assessing risks and adaptation options. A simplified commercial online tool, Yield Prophet® was developed to suit farmer and consultant needs.
Websites	http://www.apsim.info/
Manuals/ training/ videos	Available on the webpage of the model.
Wikipedia page	

Other	

2) Sectoral models for impact and adaptation assessment	2.2 Agriculture/ crops	**STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard)**

Model/ tool type and outputs	The STICS model can be defined as a dynamic deterministic functional model with a daily time step that describes the thermal, radiative, water, carbon and nitrogen balances at the time scale of the crop cycle and the spatial scale of the pedon, a homogeneous soil unit. In addition, this cropping system model can be used to simulate combinations of cropping and intercropping periods, such as crop sequences and rotations, as well as carbon and nitrogen balances in the medium term. STICS model has been adapted for nearly 20 crop species, including annual, perennial, herbaceous and woody plants.
Open access?	Yes
Key data inputs	Daily weather data, soil, crop and management files.
Key data accessibility/ availability	Weather/climate data from local weather stations and RCMs and GCMs. Crop observations, such as phenology, yield and management, can be obtained from field experiments and available (local/ regional) databases.
Strengths	The strength of STICS approach is to offer a comprehensive crop model adapted to a wide range of crops. It can simulate agriculture areas by accounting for both climate change through precipitation, climatic demand and CO_2 increase, and adaptation in cropping system.
Assumptions/ limitations	Assumptions and limitations of these models include the availability of input data required for model calibration, evaluation and operation, the uncertainty related to parameters and simulation processes.
Spatial scale and resolution	Field scale (site specific).
Temporal scale and resolution	Multi-annual with a daily resolution.
Accessibility of outputs	The model provides output results in text file format. These results can be read by any text editor and converted in other formats.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The models support the assessment of the risks of climate change on agriculture and to evaluate the effects of different management options as adaptation measures to cope with climate change.
Relevant application	STICS is widely used by scientists globally and included in the AgMIP project for model intercomparison. Asseng *et al.* (2019) tested and applied a 32-multi-model ensemble to assess climate change impacts on global wheat yield and quality and to evaluate

	adaptation strategies as the effect of introducing genotypes adapted to warmer temperatures on crop yield and quality. Their results show that the introduction of combined traits for delayed anthesis and increased grain filling rate could be an effective adaptation strategy for wheat yield, increasing global yield in future climate change conditions. Liu *et al.* (2018) used a multi-crop and multi-climate model ensemble to analyse the impacts on global wheat production with 1.5 and 2.0°C above preindustrial warming. Results show that projected global wheat production will change by −2.3% to 7.0% under the 1.5°C scenario and −2.4% to 10.5% under the 2.0°C scenario, compared to a baseline of 1980–2010.
Main reference(s)	(1) Brisson N, Gary C, Justes E, Roche R, Mary B, Ripoche, *et al.*, An overview of the crop model STICS. European Journal of Agronomy 18, no. 3: 309-332 (2003). (2) Brisson N, Mary B, Ripoche D, Jeuffroy MH, Ruget F, Nicoullaud B, *et al.*, STICS: A generic model for the simulation of crops and their water and nitrogen balances. I. Theory and parameterization applied to wheat and corn. Agronomie 18, no. 5-6: 311-346 (1998).
Suitability for rapid assessment	No - CSMs require detailed input data and proper parameterization and evaluation prior to be applied in assessing risks and adaptation options.
Websites	http://www6.paca.inra.fr/stics_eng/
Manuals/ training/ videos	Available on the webpage of the model.
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.2 Agriculture/ crops	**CropSyst (Cropping Systems Simulation Model)**

Model/ tool type and outputs	CropSyst is a multi-year, multi-crop, daily time step simulation model. The model has been developed to serve as an analytic tool to study the effect of cropping systems management on productivity and the environment. The model simulates the soil water budget, soil-plant nitrogen budget, crop phenology, crop canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and pesticide fate. These are affected by weather, soil characteristics, crop characteristics, and cropping system management options including crop rotation, cultivar selection, irrigation, nitrogen fertilization, pesticide applications, soil and irrigation water salinity, tillage operations and residue management.
Open access?	Yes
Key data inputs	Daily weather data, soil, crop and management files.
Key data accessibility/ availability	Weather/climate data from local weather stations and RCMs and GCMs. Crop observations, such as phenology, yield and management, can be obtained from field experiments and available (local/ regional) databases.
Strengths	One key feature of CropSyst is the implementation of a generic crop simulator that enables the simulation of both yearly and multi-year crops and crop rotations via a single set of parameters. Simulations can last a fraction of a year to hundreds of years.
Assumptions/ limitations	Assumptions and limitations of these models include the availability of input data required for model calibration, evaluation and operation, the uncertainty related to parameters and simulation processes.
Spatial scale and resolution	Field scale (site specific), however results can be extrapolated to national and regional levels using GIS.
Temporal scale and resolution	Multi-annual with a daily resolution.
Accessibility of outputs	Tabular data format (.TDF) files, that can be exported to other formats.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The models support the assessment of the risks of climate change on agriculture and to evaluate the effects of different management options as adaptation measures to cope with climate change.
Relevant application	Cropsyst is widely used by scientists globally and included in the AgMIP project for model intercomparison. Donatelli *et al.* (2015)

	that applied CropSyst and BioMA platform to simulate the effects of climate change on wheat, rapeseed and sunflower, and potential adaptation options, such as genotype, planting and irrigation, to offset climate change impacts in Europe. They found that the implementation of simple adaptation measures, such as changing sowing dates and the use of different varieties, may reduce the negative impacts of climate change in most European areas, although different responses according to the analysed crops. Asseng *et al.* (2019) tested and applied a 32-multi-model ensemble to assess climate change impacts on global wheat yield and quality and to evaluate adaptation strategies as the effect of introducing genotypes adapted to warmer temperatures on crop yield and quality. Their results show that the introduction of combined traits for delayed anthesis and increased grain filling rate could be an effective adaptation strategy for wheat yield, increasing global yield in future climate change conditions. Liu *et al.* (2018) used a multi-crop and multi-climate model ensemble to analyze the impacts on global wheat production with 1.5 and 2.0°C above preindustrial warming. Results show that projected global wheat production will change by −2.3% to 7.0% under the 1.5°C scenario and −2.4% to 10.5% under the 2.0°C scenario, compared to a baseline of 1980–2010.
Main reference(s)	(1) Stockle, C. O. and R. L. Nelson. 1994. Cropsyst User's manual (Version 1.0). Biological Systems Engineering Dept., Washington State University, Pullman, WA, USA; (2) Stockle, C. O. and R. L. Nelson. 1996. Cropsyst User's manual (Version 2.0). Biological Systems Engineering Dept., Washington State University, Pullman, WA, USA.
Suitability for rapid assessment	No - CSMs require detailed input data and proper parameterization and evaluation prior to be applied in assessing risks and adaptation options.
Websites	http://sites.bsyse.wsu.edu/cs_suite/cropsyst/index.html
Manuals/ training/ videos	Available on the webpage of the model.
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.2 Agriculture/ crops	**EPIC - Environmental Policy Integrated Climate Model**

Model/ tool type and outputs	EPIC is a cropping systems model that was developed to estimate soil productivity affected by erosion as part of the Soil and Water Resources Conservation Act analysis of 1980, which revealed a significant need at the time for improving technology for evaluating the impacts of soil erosion on soil productivity. EPIC predicts the effects of management decisions on soil, water, nutrient and pesticide movements, and their combined impact on soil loss, water quality, and crop yields for areas with homogeneous soils and management. The processes simulated include leaf interception of solar radiation; conversion to biomass; division of biomass into roots, above ground mass, and economic yield; root growth; water use; and nutrient uptake. It can be configured for a wide range of crop rotations and other vegetative systems, tillage systems, and other management practices, and used as a decision support system to analyze the productivity and sustainability of complex cropping systems. The model can also assess the cost of erosion for determining optimal management strategies.
Open access?	Yes
Key data inputs	Daily weather data, soil, crop and management files.
Key data accessibility/ availability	Weather/climate data from local weather stations and RCMs and GCMs. Crop observations, such as phenology, yield and management, can be obtained from field experiments and available (local/ regional) databases.
Strengths	EPIC can analyze several crop types and their management under different weather, topographical and soil conditions. It investigates the trade-offs between plant growth and yield on the one hand, and environmental impacts and sustainability on the other.
Assumptions/ limitations	Assumptions and limitations of these models include the availability of input data required for model calibration, evaluation and operation, the uncertainty related to parameters and simulation processes.
Spatial scale and resolution	Homogeneous areas up to large fields or small watersheds. GIS Interface developed ad hoc for EPIC (GEPIC) can be used to produce maps.
Temporal scale and resolution	EPIC functions on a daily time step and can simulate hundreds of years - Long term simulations (1 - 4,000 years).

Accessibility of outputs	The model provides output results in text file format. These results can be read by any text editor and converted in other formats.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The models support the assessment of the risks of climate change on agriculture and to evaluate the effects of different management options as adaptation measures to cope with climate change.
Relevant application	EPIC is widely used by scientists globally and included in the AgMIP project for model intercomparison. Liu *et al.* GEPIC – modelling wheat yield and crop water productivity with high resolution on a global scale. Agricultural Systems,94,478-493,2007. Asseng *et al.* (2019) tested and applied a 32-multi-model ensemble to assess climate change impacts on global wheat yield and quality and to evaluate adaptation strategies as the effect of introducing genotypes adapted to warmer temperatures on crop yield and quality. Their results show that the introduction of combined traits for delayed anthesis and increased grain filling rate could be an effective adaptation strategy for wheat yield, increasing global yield in future climate change conditions. Liu *et al.* (2018) used a multi-crop and multi-climate model ensemble to analyze the impacts on global wheat production with 1.5 and 2.0°C above preindustrial warming. Results show that projected global wheat production will change by −2.3% to 7.0% under the 1.5°C scenario and −2.4% to 10.5% under the 2.0°C scenario, compared to a baseline of 1980–2010.
Main reference(s)	(1) Williams JR, Jones CA and Dyke P, Modeling approach to determining the relationship between erosion and soil productivity. Transactions of the American Society of Agricultural Engineers 27, no. 1: 0129-0144 (1984)
Suitability for rapid assessment	No - CSMs require detailed input data and correct parameterization and evaluation prior to be applied in assessing risks and adaptation options.
Websites	http://epicapex.tamu.edu/epic/
Manuals/ training/ videos	Available on the webpage of the model.
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.2 Agriculture/ crops	**SALUS (System Approach to Land Use Sustainability)**

Model/ tool type and outputs	The SALUS program is designed to model continuous crop, soil, water and nutrient conditions under different management strategies for multiple years. These strategies may have various crop rotations, planting dates, plant populations, irrigation and fertilizer applications, and tillage regimes. The program simulates plant growth and soil conditions every day (during growing seasons and fallow periods) for any time period when weather sequences are available. For any simulation run, a number of different management strategies can be run simultaneously. By running the different strategies at the same time, comparisons can be made regarding the effect on crops and soil under the same weather sequences. This also provides a framework whereby the interaction between different areas under different management practices can be easily compared.
Open access?	Available on request from the authors.
Key data inputs	Weather, soil and crop management, soil properties, genetic characteristics of the crops and the site location.
Key data accessibility/ availability	Weather/climate data from local weather stations and RCMs and GCMs. Crop observations, such as phenology, yield and management, can be obtained from field experiments and available (local/ regional) databases.
Strengths	SALUS model simulates rotational cropping systems continuously for multiple years. SALUS has two types of crop models, a simple model and a complex model.
Assumptions/ limitations	Assumptions and limitations of these models include the availability of input data required for model calibration, evaluation and operation, the uncertainty related to parameters and simulation processes.
Spatial scale and resolution	Field scale (site specific), however results can be extrapolated to national and regional levels using GIS.
Temporal scale and resolution	Multi-annual with a daily resolution.
Accessibility of outputs	The model provides output results in text file format. These results can be read by any text editor and converted in other formats.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options

Adaptation policy insights	The models support the assessment of the risks of climate change on agriculture and to evaluate the effects of different management options as adaptation measures to cope with climate change.
Relevant application	Recent publications: (1) Liu, L., & Basso, B. (2020). Impacts of climate variability and adaptation strategies on crop yields and soil organic carbon in the US Midwest. PLOS ONE, 15(1), 1-20. doi: 10.1371/journal.pone.0225433; (2) Liu, L., & Basso, B. (2020). Linking field survey with crop modeling to forecast maize yield in smallholder farmers' fields in Tanzania. Food Security. doi: 10.1007/s12571-020-01020-3; (3) Martinez-Feria, R.A., & Basso, B. (2020). Unstable crop yields reveal opportunities for site-specific adaptations to climate variability. Scientific Reports, 10(2885). doi: 10.1038/s41598-020-59494-2 Link. Liu et al (2018) used a multi-crop and multi-climate model ensemble to analyze the impacts on global wheat production with 1.5 and 2.0°C above preindustrial warming. Results show that projected global wheat production will change by −2.3% to 7.0% under the 1.5°C scenario and −2.4% to 10.5% under the 2.0°C scenario, compared to a baseline of 1980–2010.
Main reference(s)	Basso B, Ritchie JT, Grace PR and Sartori L, Simulation of tillage systems impact on soil biophysical properties using the SALUS model. Italian Journal of Agronomy 1, no. 4: 677-688 (2006).
Suitability for rapid assessment	No - CSMs require detailed input data and correct parameterization and evaluation prior to be applied in assessing risks and adaptation options.
Websites	https://basso.ees.msu.edu/salus/index.html
Manuals/ training/ videos	Basic information available on the webpage of the model.
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.2 Agriculture/ crops	**WOFOST - WOrld FOod Studie**

Model/ tool type and outputs	WOFOST is a simulation model for the quantitative analysis of the growth and production of annual field crops. It is a mechanistic dynamic model that explains daily crop growth on the basis of the underlying processes, such as photosynthesis, respiration and how these processes are influenced by environmental conditions. WOFOST supports the calculation of, for example, attainable crop production, biomass, and water use for a location given knowledge regarding soil, crop, weather and crop management such as sowing date.
Open access?	Yes
Key data inputs	Daily weather data, soil, crop and management files.
Key data accessibility/ availability	Weather/climate data from local weather stations and RCMs and GCMs. Crop observations, such as phenology, yield and management, can be obtained from field experiments and available (local/ regional) databases.
Strengths	WOFOST is one of a suite of models implemented in the EU Crop Growth Monitoring System, which is used operationally to monitor arable crops in Europe and to make crop yield forecasts for the current growing season.
Assumptions/ limitations	Assumptions and limitations of these models include the availability of input data required for model calibration, evaluation and operation, the uncertainty related to parameters and simulation processes.
Spatial scale and resolution	From a spatial perspective, WOFOST is a one-dimensional simulation model, and therefore is without reference to a geographic scale. However, the size of a region to which WOFOST can be applied is limited. This is due to aggregation effects caused by non-linear response of crop models to model inputs. The non-linear behaviour implies that aggregating input data and subsequently running the model provides different results compared to running the model on the original data and subsequently aggregating the model output. In practice, this is resolved by splitting the model spatial domain into small spatial units where the model inputs of weather, crop, soil and management can be assumed constant. Aggregation of simulation results is carried out by aggregating the simulation results for the individual spatial units to larger spatial units. In Europe, WOFOST is typically applied at spatial units of 25x25 km for which scaling errors are negligible.

Temporal scale and resolution	WOFOST typically simulates crop growth with a temporal resolution of one day.
Accessibility of outputs	The model results can be exported into an excel format.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The models support the assessment of the risks of climate change on agriculture and to evaluate the effects of different management options as adaptation measures to cope with climate change.
Relevant application	WOFOST is one of the key components of the European MARS crop yield forecasting system. In the Global Yield Gap Atlas (GYGA), WOFOST is used to estimate the untapped crop production potential on existing farmland based on current climate and available soil and water resources. Ciscar *et al.* (2018) used the BioMA-Wofost platform (de Wit *et al.*, 2018) to estimate the change in yields of six crops (wheat, maize, barley, sunflower, rapeseed, sugar beet) in Europe. Asseng *et al.* (2019) tested and applied a 32-multi-model ensemble to assess climate change impacts on global wheat yield and quality and to evaluate adaptation strategies as the effect of introducing genotypes adapted to warmer temperatures on crop yield and quality. Their results show that the introduction of combined traits for delayed anthesis and increased grain filling rate could be an effective adaptation strategy for wheat yield, increasing global yield in future climate change conditions. Liu *et al.* (2018) used a multi-crop and multi-climate model ensemble to analyze the impacts on global wheat production with 1.5 and 2.0°C above preindustrial warming. Results show that projected global wheat production will change by −2.3% to 7.0% under the 1.5°C scenario and −2.4% to 10.5% under the 2.0°C scenario, compared to a baseline of 1980–2010.
Main reference(s)	Diepen CV, Wolf J, Keulen HV and Rappoldt C, WOFOST: a simulation model of crop production. Soil Use and Management 5, no. 1: 16-24 (1989).
Suitability for rapid assessment	No - CSMs require detailed input data and correct parameterization and evaluation prior to be applied in assessing risks and adaptation options.
Websites	http://www.wageningenur.nl/en/Expertise-Services/Research-Institutes/alterra/Facilities-Products/Software-and-models/WOFOST.htm
Manuals/ training/ videos	Available on the webpage of the model.

Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.2 Agriculture/ crops	**AQUACROP**

Model/ tool type and outputs	AquaCrop is the crop growth model developed by FAO to address food security and assess the effect of the environment and management on crop production. AquaCrop simulates the yield response of herbaceous crops to water and is particularly well suited to conditions in which water is a key limiting factor in crop production.
Open access?	Yes
Key data inputs	Key input data includes weather data, crop and soil characteristics, and management practices that define the environment in which the crop will develop. Weather data includes: daily, 10-daily or monthly maximum and minimum air temperature and mean values of reference evapotranspiration (ETo); daily rainfall data; and mean annual CO_2 concentrations. Soil characteristics are divided into soil profile and groundwater characteristics, and management practices are categorized as field management or irrigation management practices.
Key data accessibility/ availability	Weather/climate data from local weather stations and RCMs and GCMs. Crop observations, such as phenology, yield and management, can be obtained from field experiments and available (local/ regional) databases.
Strengths	To be widely applicable, AquaCrop uses only a relatively small number of explicit parameters and mostly intuitive input-variables requiring simple methods for their determination. On the other hand, the calculation procedures are grounded on basic and often complex biophysical processes to guarantee an accurate simulation of the response of the crop in the plant-soil system.
Assumptions/ limitations	(1) AquaCrop can simulate daily biomass production and final crop yields for herbaceous crops with single growth cycles only; (2) is designed to predict crop yields at the single field scale (point simulations). The field is assumed to be uniform without spatial differences in crop development, transpiration, soil characteristics or management; (3) only vertical incoming (rainfall, irrigation and capillary rise) and outgoing (evaporation, transpiration and deep percolation) water fluxes are considered.
Spatial scale and resolution	AquaCrop is designed to predict crop yields at the field scale (point simulations).
Temporal scale and resolution	Annual scale. Results can be aggregated also at a daily, every 10 days or monthly scale.

Accessibility of outputs	AquaCrop generates outputs files in .xlsx format and graphical outputs of the results using dBase files to be displayed into a GIS environment.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The models support the assessment of the risks of climate change on agriculture and to evaluate the effects of different management options as adaptation measures to cope with climate change.
Relevant application	AquaCrop has been used in many projects implemented by FAO (see: http://www.fao.org/aquacrop/applications/en/) and is included in the AgMIP project for model intercomparison. Asseng *et al.* (2019) tested and applied a 32-multi-model ensemble to assess climate change impacts on global wheat yield and quality and to evaluate adaptation strategies as the effect of introducing genotypes adapted to warmer temperatures on crop yield and quality. Their results show that the introduction of combined traits for delayed anthesis and increased grain filling rate could be an effective adaptation strategy for wheat yield, increasing global yield in future climate change conditions. Liu *et al.* (2018) used a multi-crop and multi-climate model ensemble to analyze the impacts on global wheat production with 1.5 and 2.0°C above preindustrial warming. Results show that projected global wheat production will change by −2.3% to 7.0% under the 1.5°C scenario and −2.4% to 10.5% under the 2.0°C scenario, compared to a baseline of 1980–2010.
Main reference(s)	(1) Raes, D., Steduto, P., Hsiao, T.C., and Fereres, E. 2015. AquaCrop Reference manual. http://www.fao.org/nr/water/aquacrop.html
Suitability for rapid assessment	No - CSMs require detailed input data and correct parameterization and evaluation prior to be applied in assessing risks and adaptation options.
Websites	http://www.fao.org/aquacrop
Manuals/ training/ videos	Available on the webpage of the model.
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.3 Forestry	**3-PG**

Model/ tool type and outputs	The primary output variables from 3-PG include stem, root and foliage biomass, available soil water and stand transpiration, and net primary production. It also provides stand-level outputs familiar to the forest manager and are often used as inputs for management programs.
Open access?	Yes
Key data inputs	The 3-PG model requires as inputs: standard weather data and information regarding soil depth and water-holding characteristics. Initial tree populations are specified and changes in stem populations calculated using a well-established mortality function. The model has relatively few parameters and is simple to use.
Key data accessibility/ availability	Climate data available from several sources for historical and future projections in Copernicus Topography: https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem; Land Cover: CLC Corine Land Cover 2018; WISE Soil Property Databases
Strengths	Relatively simplified model designed for broad applications, unlike other more complex models which can be difficult to calibrate and require many site and species-specific parameters. This can take advantage of simplified parameterization already available for many tree species, while other physical-based models necessitate expensive, multi-year field research programs to support their application.
Assumptions/ limitations	Highly simplified process models usually have lower calibration requirements, but they often cannot adequately address the complexity of forest management under climate change.
Spatial scale and resolution	Stand level, although there is a spatial implementation using an outdated ESRI AML platform.
Temporal scale and resolution	The temporal scale depends on the climate data (at several time scales), while analyses results are usually available at stand level.
Accessibility of outputs	It is written in VBA and provides the user considerable flexibility to use normal spreadsheet operations to transform or display 3-PG outputs.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options

Adaptation policy insights	Supports the evaluation of the effect of forest management and practices to reduce effect of climate change.
Relevant application	Predicting the spatial and temporal dynamics of species interactions in *Fagus sylvatica* and *Pinus sylvestris* forests across Europe (Forrester *et al.*, 2017); Assessing temporal variation of primary and ecosystem production in two Mediterranean forests (Nolè *et al.*, 2013).
Main reference(s)	Landsberg, J. J., & Waring, R. H. (1997). A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest ecology and management, 95(3), 209-228. Landsberg, J.J., R.H. Waring, and N.C. Coops (2003) Performance of the forest productivity model 3-PG applied to a wide range of forest types. Forest Ecology and Management 172, (2/3) 119-214.
Suitability for rapid assessment	Yes - for local conditions, an excel has been developed for easier implementation of the 3-PG model.
Websites	https://3pg.forestry.ubc.ca/
Manuals/ training/ videos	https://3pg.forestry.ubc.ca/3-pg-course/
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.3 Forestry	**FORCLIM - A forest gap model**

Model/ tool type and outputs	FORCLIM is a climate-sensitive forest succession gap model, developed to simulate forest stand dynamics such as tree growth, recruitment and mortality, as well as water and nutrient cycles over a wide range of environmental conditions. The LandClim version incorporates tree growth processes over the landscape, including seed dispersal, disturbances and forest management regimes, based on a simplified version of the forest gap model FORCLIM, in order to maintain computational efficiency at the larger scale. Four disturbance types are implemented: fire, windthrow, bark beetle outbreaks and browsing pressure.
Open access?	Yes
Key data inputs	FORCLIM is currently parameterized for ca. 180 tree species dominant of temperate forests worldwide. As input data FORCLIM requires monthly averages and standard deviations of temperature and precipitation in addition to a few site-specific parameters regarding the soil characteristics.
Key data accessibility/ availability	The essential climate inputs (ERA5 or RCM available in Copernicus) are mean monthly precipitation sums and temperature means at a reference elevation, together with altitudinal lapse rates. It needs a digital elevation model at approx. 25 m resolution (https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem) and a map of soil depths (WISE Soil Property Databases). Wind disturbance is characterized by mean disturbance size and return interval.
Strengths	FORCLIM is currently parameterized for ca. 180 tree species dominant of temperate forests worldwide. The model has been tested comprehensively for the representation of natural forest dynamics of temperate forests of the Northern Hemisphere, with an emphasis on European forests. For example, FORCLIM results match time series data from growth-and-yield plots over 80-100 years remarkably well, and it can also be used under scenarios of anthropogenic climate change. Simulation of a wide range of management scenarios subject to different climatic conditions over multi-decadal to centennial time scales. A particular focus is on large-scale natural disturbances such as fire.
Assumptions/ limitations	The simulations do not aim to provide reliable forecasts or specific transformation knowledge, given the uncertainty regarding key drivers, particularly in areas with a strong direct human influence and in the context of climate change, which will probably combine long-term trends, such as warmer and drier conditions, with

	increased inter-annual variability. Rather, the role of these long-term simulations is to help gain a better understanding of the potentially intricate relationships between landscape structure and dynamics. It does not explicitly account for carbon balances.
Spatial scale and resolution	Designed to study spatially explicit forest dynamics at the landscape scale over long time periods with a fine spatial resolution: spatial extents (>100 ha) at a relatively fine scale (grid cells of 25 × 25 m).
Temporal scale and resolution	Depending on climate data resolution (short and long term).
Accessibility of outputs	TreeViz - A tool to visualize the output of the LandClim model as a 3D landscape.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	It assists in envisaging long-term consequences of alternative management options through rigorously and transparently translating scenarios, formulated in terms of land-use and climate change, to changes of the forest landscape structure.
Relevant application	Yield and tree species composition was tested at a significant number of sites in the European Alps. Simulation of a wide range of management scenarios subject to different climatic conditions across Multiple Biogeographical Regions over multi-decadal to centennial time scales explaining forest composition and biomass (Bugmann and Solomon, 2000). The relative importance of climatic effects, wildfires and management for future forest landscape dynamics in the Swiss Alps (Schumacher and Bugmann, 2006).
Main reference(s)	BUGMANN, H. K. M. (1996). "A Simplified Forest Model to Study Species Composition Along Climate Gradients." Ecology 77(7): 2055-2074. RASCHE, L., L. FAHSE, *ET AL.* (2012). "Enhancing gap model accuracy by modeling dynamic height growth and dynamic maximum tree height" Ecological Modelling 232(0): 133-143.
Suitability for rapid assessment	Yes - when applied to forest ecosystems for which it was designed. The suitability for rapid assessment could be particularly high, given data requirements could be fulfilled with parameterization available for several tree species.
Websites	https://ites-fe.ethz.ch/openaccess/

Manuals/ training/ videos	https://github.com/KIT-IfGG/LandClimTools
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.3 Forestry	**Dynamic global vegetation models (DGVMs): LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator)**

Model/ tool type and outputs	The overall objective of DGVMs is to evaluate the influence of climate on the biogeochemical and hydrological processes regulating vegetation growth dynamics. Although they can be detailed with respect to process simulation, these models are designed to predict general patterns of vegetation development over large spatial and temporal scales and have limited application for evaluating alternative forest adaptation strategies. In general, DGVMs may be best suited to evaluating the impact of changing climate regimes on regional patterns of forest productivity and hydrology.
Open access?	Yes
Key data inputs	Climate data include monthly temperature, precipitation, sunshine with complement of percentage cloud cover, rain day data, atmospheric carbon dioxide (CO_2) and main soil properties. Further needed inputs relate to vegetation mode, disturbance interval such as wildfire, and parameters defining the characteristics of the Plant Functional Traits that will be simulated.
Key data accessibility/ availability	Climate data are available from several sources for historical and future projections in Copernicus; Soil properties can be defined from the WISE Soil Property Databases. Further input from effective vegetation distribution can be derived from CLC Corine Land Cover database, while parameters defining main vegetation functional types are available from the literature.
Strengths	Like other second-generation DGVMs, LPJ-GUESS simulates age-structured dynamics (demography) of woody vegetation as the emergent outcome of growth and competition for light, space and soil resources among individuals and an herbaceous understorey within replicate patches representing “random samples” of a simulated landscape. Unlike gap models, which are usually applied to forest vegetation at the local scale or across a limited region, LPJ-GUESS uses generic parameterisations that allow it to be applied without recalibration to any climate zone or biome.
Assumptions/ limitations	The modelling complexity requires basic programming (C/C++) skills and capabilities to understand and eventually modify source codes. Depending on iterations required (resolution and scale

	extent) simulation can be quite computing demanding relying on computing resources and time for simulations.
Spatial scale and resolution	This spatially distributed model can provide results at different resolutions given the spatial scale of input data.
Temporal scale and resolution	Normally a day or optionally a month for fast processes, and a year for slow processes.
Accessibility of outputs	Results from the model simulation appear in real time in special graph windows. Each shows the development of a model variable through the course of the simulation.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options
Adaptation policy insights	It can effectively describe trends of vegetation dynamics due to climate change and describe the effect of several disturbances as well as management options.
Relevant application	The forest growth across Sweden over the 21st century was simulated by the ecosystem model LPJ-GUESS, comparing four management options, to assess the potential of adaptive forest management to influence the productivity and storm sensitivity of nemoral and boreal forest (Jönsson *et al.*, 2015). Projecting the future distribution of European potential natural vegetation zones with a generalized, tree species-based dynamic vegetation model (Hickler *et al.*, 2012).
Main reference(s)	Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J., Levis, S., Lucht, W., Sykes, M., Thonicke, K. & Venevsky, S. 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ Dynamic Global Vegetation Model. Global Change Biology 9: 161-185.
Suitability for rapid assessment	No - the model requires technical knowledge to operate and to ensure that climate, soil and CO_2 data is available as input.
Websites	http://web.nateko.lu.se/lpj-guess/download.html
Manuals/ training/ videos	http://web.nateko.lu.se/lpj-guess/download.html
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.3 Forestry	**Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3)**

Model/ tool type and outputs	CBM-CFS3 is an aspatial, stand- and landscape-level modelling framework that simulates the dynamics of all forest carbon stocks required under the Kyoto Protocol (above and below ground biomass, litter, dead wood and soil organic carbon) available as output as text files.
Open access?	Yes
Key data inputs	The model uses much the same information as is required for forest management planning: forest inventory, tree species, growth and yield curves, natural and human-induced disturbance information, forest harvest schedule and land-use change information. This is supplemented with information from national ecological parameter databases.
Key data accessibility/ availability	JRC has elaborated a customization of the Archive Index Database for European Union countries. The database behind the CBM-CFS3 stores default ecological information and parameters pertaining to the forest ecosystems for 1034 spatial units resulting from the intersection of 204 European administrative regions and ecological boundaries representing 35 climatic units. It also contains updated parameters for 192 of the main tree species reported by the National Forest Inventories of each EU country.
Strengths	The CBM-CFS3 is a dynamic simulation model that can represent a wide range of forest management activities, land-use changes and natural disturbances, providing annual time step projections of carbon stocks in living biomass, dead organic matter, mineral soil carbon pools, fluxes among the carbon pools to the forest products sector and ecological indicators. An EU Archive Index Database was parameterized to support policy making and research communities interested in applying the CBM-CFS3 with ecological parameters specific to the EU context.
Assumptions/ limitations	Modelling is executed explicitly for specific climatic units, characterized by given precipitation and temperature patterns. It does not reflect climate dynamics changes explicitly within each climate units, but it can provide information across varying climatic units.
Spatial scale and resolution	Ideally implemented for specific Climatic Units as spatial resolution to define climate and ecological conditions.
Temporal scale and resolution	Annual time steps.

Accessibility of outputs	The model contains graphic user interfaces to help users prepare data, define scenarios, perform analyses and examine results.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options
Adaptation policy insights	Evaluate different forest management options and management actions in individual stands, compare results in terms of carbon and select the plan that best meets their objectives.
Relevant application	The model has been adapted and used by the JRC to simulate forest carbon dynamics in 26 EU Member States (Pilli *et al.*, 2016). This included modelling specific characteristics of European forests, including a large variety of management systems, including coppice, coppice with standards and shelterwood.
Main reference(s)	Kurz, W.A, Dymond, C.C, White, T.M.; Stinson, G, Shaw, C.H, Rampley, G.J., Smyth, C.E., Simpson, B.N., Neilson, E.T.;,Trofymow, J.A., Metsaranta, J.M., Apps, M.J (2009) CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecological Modelling 220(4):480-504. Pilli, R., Kull, S.J., Blujdea, V.N.B. *et al.* The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3): customization of the Archive Index Database for European Union countries. Annals of Forest Science 75, 71 (2018).
Suitability for rapid assessment	Yes
Websites	https://www.nrcan.gc.ca/climate-change/impacts-adaptations/climate-change-impacts-forests/carbon-accounting/carbon-budget-model/13107
Manuals/ training/ videos	https://cfs.nrcan.gc.ca/publications?id=39768 The Natural Resources Canada's Canadian Forest Service conducts annual CBM-CFS3 technical training workshops.
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.4 Fish dynamics	**Booster Regression Trees**

Model/ tool type and outputs	This model attempts to assess the potential future suitability of the basins in the former range of species under different climate change scenarios. To achieve this, a three-step procedure was applied: (i) the historical distribution of the European Atlantic sturgeon (*Acipenser sturio*) was assessed prior to its significant decline around 1850; (ii) a robust predictive model was developed using environmental parameters which significantly correlate with the species' historic distribution; (iii) to forecast the distribution in the second half of the century, several sets of future climatic conditions were calculated and entered into the model.
Open access?	All software used was open source (R-package). However, it is not mentioned if the code the authors created to run the model in R is open access. Technically it is possible to reproduce the same results seeing as all their methods are clearly described. Concerning the results, the publication states that data will be accessible soon (published in 2010) however, it is not mentioned where. Recommended to contact authors.
Key data inputs	**Historical predictor** Marine province at the river outlet **Physical predictors** Surface area of the drainage basin Average slope over the basin **Climatic predictors** Average annual temperature at the river outlet Average winter temperature at the river outlet Average summer temperature at the river outlet Average annual precipitation over the basin Average winter precipitation over the basin Average summer precipitation over the basin
Key data accessibility/ availability	There are no references as to whether the database is open access. However, data sources are: The distribution of the European Atlantic sturgeon was established in terms of presence/absence, between 1750 and 1850, using 103 references published during this period, recent synthesis papers, international databases and expert consultations. Bibliographic Historical fish data (from 1750 to 1850) was acquired from the database EuroDiad 3.1 (Cemagref, Cestas, France) on European diadromous fish distribution. Concerning historical weather data: Data were obtained from the CRU TS 2.1 data set (Mitchell and Jones, 2005) comprising of 1200 monthly grids of observed climate for the period 1901–2000 and covering the global land surface at 0.5° resolution. Three different expressions were calculated: annual (TempAnn/PrecAnn), winter

	(mean over December, January and February, TempWin/PrecWin) and summer (mean over June, July and August, TempSum/PrecSum). Data were averaged over 10 years, between 1900 and 1910, to smooth inter-annual variability. Concerning predictions on climatological data: data is derived from the global climate models with four SRES emissions scenarios (Special Report on Emissions Scenarios, IPCC, 2000). In this study, the HADley centre Climate Model version 3 (HadCM3) was used along with the two most pessimistic SRES emissions scenarios (A2 and A1FI). Results from the two emissions scenarios were averaged to provide a mean estimate of changes. Projections were performed for the middle and end of the 21st century.
Strengths	This paper shows the power of boosted regression trees: the ability to analyze and assess large datasets.
Assumptions/ limitations	A major limitation of the model is that it has no assumptions. Boosted regression trees examine how underlying data can best explain the variable of interest, in this case, the presence or absence of the Atlantic sturgeon. This means, any results the model provide as output, have no underlying ecological foundation. Therefore, expert involvement is required in order to provide an ecological narrative.
Spatial scale and resolution	The spatial scale is Europe while the spatial resolution is at the level of a river basin.
Temporal scale and resolution	2050 - 2100. Data was presented as temporal snapshots for year 2050 and 2100. Assumed data is available at resolution of year.
Accessibility of outputs	Output is easily accessible to the laymen. The output is presented in the form of maps. For the year 2050 and 2100 a map is made for the different river basins. Per basin, the chance of occurrence is shown.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options
Adaptation policy insights	The model's specific purpose is to predict suitability for the European Sturgeon in European river basins. The predictions of suitability are based on the IPCC climate change projections for temperature and rainfall. Thus, policy makers could use this model to run other scenarios, based on specific adaptation policies, i.e. adaptation policies that might alter temperature and rainfall predictions in the next 100 years. Alternative scenarios can thus be tested and explore how they affect the suitability of river basins for European Sturgeon.

Relevant application	The model's specific purpose is to predict suitability for the European Sturgeon in European river basins. Future climate data was derived from the HADley centre Climate Model version 3 (HadCM3) using the two most pessimistic SRES emissions scenarios (A2 and A1FI) IPCC (2000). Results from the two emissions scenarios were averaged to provide a mean estimate of changes per river basin. Projections were performed for 2050 and 2100. This model then provided an overview of how suitable each river basin was as habitat for the European Sturgeon.
Main reference(s)	Lassalle, G., P. Crouzet, J. Gessner, and E. Rochard. 2010. Global warming impacts and conservation responses for the critically endangered European Atlantic sturgeon. Biological Conservation 143:2441–2452.
Suitability for rapid assessment	The model can be utilized most effectively by involving experts as soon as possible. However, how quickly the model can be used depends on the complexity of the question and how easily available the data is. Each question requires a specific underlying dataset. The greater a given required dataset deviates from the dataset used by the original author, the longer it will take to have the model up and running.
Websites	https://www.sciencedirect.com/science/article/abs/pii/S0006320710002740?via%3Dihub
Manuals/ training/ videos	N.A. - Although the following article provides a good overview of how to use BRTs in ecology: Elith *et al.*, (2008) *A working guide to boosted regression trees.* Code provided in tutorial.
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.4 Fish dynamics	**Bayesian statistical models**

Model/ tool type and outputs	The main objective of this research was to understand Arctic char (*Salvelinus alpinus*) presence and persistence in Irish lakes with reference to lake morphology metrics, long-term temperature and especially to interactions with other species and mixed fish communities of non-salmonid fish species such as roach, perch, pike, rudd and hybrids. Statistical models of char presence and persistence were developed. A risk analysis was subsequently undertaken to assess the future distribution of this species in Ireland and which Arctic char lakes are vulnerable to potential climate-facilitated by thermally plastic non-salmonid fish species through dispersal and changes in river catchment hydrology.
Open access?	All software used was open source (R-package). However, it is not mentioned if the code the authors created to run the model in R, is open access. Technically, it is possible to reproduce the same results seeing as all their methods are clearly described.
Key data inputs	Inland Fisheries Ireland (IFI) maintains a database that includes records of 26 fish species collected between 1951 and 2016 from 892 lakes across the island of Ireland. Lakes in the IFI database have been surveyed using various standard methodologies, for example, of monofilament multi-mesh survey gillnets, multifilament multi-panel survey gillnets and double fyke nets. In total, 84 lakes in the database had records of Arctic char, with extant populations in 45 lakes.
Key data accessibility/ availability	All data is derived from Irish governmental agencies. There is no reference as to whether the data is open source. The data sources are: Inland Fisheries Ireland (IFI) maintains a database that includes records of 26 fish species collected between 1951 and 2016 from 892 lakes across the island of Ireland (Figure 1). Depth estimates were available for 761 lakes from records held by IFI and the Irish Environmental Protection Agency (EPA).
Strengths	The strength of using a Bayesian model to predict the presence of a fish species is that it supports the incorporation of multiple types of data.
Assumptions/ limitations	The model does not account for any type of ecological relationships. There is no actual empirical data describing the direct effects of temperature increase on Arctic char (*Salvelinus alpinus*). Nor does the model account for how temperature increase might influence lower trophic levels such as phytoplankton and zooplankton communities. Albeit quite accurately, the model produces probability distributions on how likely it is to that the

	Arctic char will occur in a specific lake, given specific abiotic parameters.
Spatial scale and resolution	The spatial scale is Ireland while the spatial resolution is at the level of individual lakes and river basins.
Temporal scale and resolution	N.A. - The model looks at how temperature can be a predictor for the presence of Arctic Char. It does not say in which timeframe temperature increase might occur.
Accessibility of outputs	The output is in the form of probability curves. The curves highlight the probability that a given lake/basin has Arctic Char present, given specific underlying parameters: lake depth and mixed fish community type. The graphs are easy to interpret.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 5) Implementation
Adaptation policy insights	The Bayesian model shows that max-lake-depth and mixed-fish communities are strong predictors for the presence of the Arctic Char. While climate change will not impact the max lake depth over the course of the next century, however, temperature will be affected. As temperatures rise, habitat suitability for many fish species will alter. For some species, habitat ranges will increase. In such instances, mixed fish communities will increase and thus negatively impact the Arctic Char. A potential measure that could be adopted is to decrease the connectivity between basins, therefore reducing the occurrence of mixed-fish communities. Such an analysis could be applied for different fish species and for different underlying (a)biotic parameters.
Relevant application	The main objective of this research was to understand Arctic char (*Salvelinus alpinus*) presence and persistence in Irish lakes with reference to lake morphology metrics, long-term temperature and especially to interactions with other species and mixed fish communities of non-salmonid fish species such as roach, perch, pike, rudd and hybrids. Statistical models of char presence and persistence were developed. A risk analysis was subsequently undertaken to assess the future distribution of this species in Ireland and which Arctic char lakes are vulnerable to potential climate-facilitated by thermally plastic non-salmonid fish species through dispersal and changes in river catchment hydrology.
Main reference(s)	Connor, L., S. Shephard, K. Rocks, and F. L. Kelly. 2019. Potential climate change impacts on Arctic char Salvelinus alpinus L. in Ireland. Fisheries Management and Ecology 26:527–539; INLA

	library, (Rue *et al.*, 2017) Bayesian computing with INLA: A review. Annual Review of Statistics and Its Application
Suitability for rapid assessment	The model can be utilized most effectively by involving experts as soon as possible. However, how quickly the model can be used depends on the complexity of the question and how easily available the data is. Each question requires a specific underlying dataset. The greater a given required dataset deviates from the dataset used by the original author, the longer it will take to have the model up and running.
Websites	https://onlinelibrary.wiley.com/doi/pdf/10.1111/fme.12327
Manuals/ training/ videos	N.A.
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.4 Fish dynamics	**inSTREAM-Gen**

Model/ tool type and outputs	inSTREAM-Gen is an eco-genetic version of the individual-based trout model, inSTREAM (Railsback *et al.*, 2009). InSTREAM-Gen is a mechanistic model that assess the vulnerability of resident Brown trout (*Salmo trutta*) populations within two river types that vary in their sensitivity to warming and hydrological change. A comprehensive mechanistic modelling framework is used that integrates the behavioural and physiological effects of extrinsic environmental drivers with intrinsic dynamics throughout trout life cycle: density dependence, phenotypic plasticity and evolutionary responses.
Open access?	InSTREAM-Gen and its documentation can be freely downloaded (https://github.com/DanielAyllon/inSTREAM-Gen-Fishing-version); Appendix A provides a detailed model description that follows the ODD (Overview, Design concepts, Details) protocol (Grimm *et al.*, 2006, 2010).
Key data inputs	**Fish data:** The model incorporates fish behavioural and physiological effects of extrinsic environmental drivers with intrinsic dynamics – density dependence, phenotypic plasticity and evolutionary responses– across the entire trout life cycle. This is based on research that has resulted in the ecological understanding of these trout species. See the following articles for more information: *Ayllón et al., 2012, 2013, 2016, 2018a; Railsback et al., 1999, 2009; Lynch and Walsh, 1998; Parra et al., 2014.* **Environmental data:** Recorded data was used from the closest stream gauging (Isaba, Navarra Government) and meteorological (Urzainqui, AEMET) stations to generate flow and water temperature time series for the 1993–2011. **Simulation data:** Trout populations were simulated between 1993 and 2100 under five different environmental scenarios. Time series for water temperature and flow were used. Time series over 2012–2100 were projected for each scenario following the methodology fully described in Ayllón *et al.* (2016). These scenarios represent increasing temperature and changes in flow regime due to both climate and land-use change. Water temperature times series were used from RCPs 4.5 and 8.5. Scenarios of hydrological change relied on stream flow projections performed by López-Moreno *et al.* (2014) for the River Aragón basin (River Eska is tributary to River Aragón) for 2021–2050 under the A1B scenario of moderate greenhouse gas emissions.

Key data accessibility/ availability	https://github.com/DanielAyllon/inSTREAM-Gen-Fishing-version
Strengths	Incorporates biological and ecological principles within the model.
Assumptions/ limitations	Albeit based on their extensive ecological understanding, the authors do make assumptions about fish behaviour and ecology. Assumptions such as: fish feeding strategy, fish mortality rates, fish respiration costs, fish maturity size. A key issue is that: "*prediction accuracy of their approach depends highly on the underlying feeding and bioenergetics models, which, as simplifications of complex behavioural and physiological processes, have substantial uncertainties of their own. These uncertainties include the structure and parameterization of the drift-foraging model, especially of the swimming cost and capture success functions (Rosenfeld et al., 2014); parameter uncertainty (Bartell et al., 1986); and the challenges of evaluating parameters at stressfully high temperatures (for example, Myrick and Cech, 2000). Second, it is unclear how variability in temperature, flow or physical habitat influence invertebrate drift production and dynamics (Naman et al., 2016), or whether the energy content of prey will vary due to climate-driven shifts in community composition: future projections of food availability for trout are highly uncertain. Third, we did not account for important indirect effects of climate change, particularly increased interactions (for example, competition, predation, hybridization) with warm-water species, which might decrease population resilience.*"
Spatial scale and resolution	The model is applied to two rivers in Spain - The model explicitly describes one stream reach of variable length and width, which is divided into cells that represent patches of relatively uniform habitat. Cells contain information about their physical habitat (water depth and velocity, availability of cover for feeding and avoiding predators), and their production rate of drift and benthic (search) food. Cells seem to modelled at the level of cm^2.
Temporal scale and resolution	2012-2100 at the resolution of one day.
Accessibility of outputs	Their results are presented as graphs and shows population dynamics in biomass. It is easy to see if a population increases or decreases. However, understanding the underlying principles requires expert knowledge. For example, is a decrease in population caused by age - specific mortality rates? And if so, why are adults greater impacted by increases in temperature than juveniles?
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 4) Assessing adaptation options; 6) Monitoring & evaluation

Adaptation policy insights	The study shows how changes in hydrology and temperature, caused by climate change, effect trout populations. It highlights that the effects of climate change are age-dependent and that the trout's density-dependence, plastic and evolutionary changes in phenology and life-history traits are not sufficient to cope with strong shifts in streamflow regimes. Such information can be used by policy makers to alter river basin properties. For example, measures can be taken to reduce water temperatures. Large canopy is shown to reduce temperatures locally (Dugdale *et al.*, 2018). Parts of the basin could, for example, be reforested.
Relevant application	The model highlights that climate change will most likely impact fish species significantly, but that they are able to cope to certain degree. The model is able to highlight which system changes effect fish the greatest. Adaptive measures can thus be identified.
Main reference(s)	Ayllón, D., S. F. Railsback, B. C. Harvey, I. García Quirós, G. G. Nicola, B. Elvira, and A. Almodóvar. 2019. Mechanistic simulations predict that thermal and hydrological effects of climate change on Mediterranean trout cannot be offset by adaptive behaviour, evolution, and increased food production. Science of the Total Environment 693:133648.
Suitability for rapid assessment	No - Setting up such a model in a different river basin, or using a different species of fish, would require extensive research efforts. Involvement of experts at the onset of a project would help speed up an assessment, as they can provide rough estimations without running a model. But implementing a model of this scale, and quality, cannot be done within a short timeframe.
Websites	https://www.sciencedirect.com/ science/article/pii/S0048969719335740
Manuals/ training/ videos	Yes - https://github.com/DanielAyllon/inSTREAM-Gen-Fishing-version/blob/master/Documentation/InSTREAM-Gen%20%20-%20TRACE%20doc.pdf
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.5 Ecosystems and biodiversity	**Vortex**

Model/ tool type and outputs	Vortex is a Population Viability Analysis (PVA) model which simulate species' extinction risks: Vortex predicts the percentage chance survival rate of a specific population in a defined number of years based on the life history parameters of that population. It can also test subsequent management strategies: assessing the relative increase of the overall population survival rate as a product of various intervention strategies increasing the survival rate at different life stages. Examples include increasing birth rates by protecting nesting sites or increasing dispersal rates through protecting migration corridors.
Open access?	Yes
Key data inputs	Detailed data on life history parameters, such as birth rate, survival rate at different life stages, fecundity, dispersal rate and life expectancy, needs to be collected over multiple generations of a defined population or meta-population. Data regarding the return period and relative impact of management strategies and extrinsic shocks, including weather extreme events, land use change or disease outbreak, on the populations' various life stages are also required in order to incorporate other external influences on the population's long-term survival rate.
Key data accessibility/ availability	Data needs to be locally collected based on individual populations, which makes obtaining this data challenging and time consuming. Some open access population life history databases exist, such as Ecologicaldata: https://ecologicaldata.org/find-data
Strengths	Model simulations can be quick to run and provide information regarding the theoretical effectiveness of intervention strategies prior to implementation.
Assumptions/ limitations	Future population survival predictions are based on current life history parameters, which may vary in response to climate change or other external factors, including the presence/ absence of other species. Therefore, this model only works at the scale of an individual population or one metapopulation of a species and does not consider these external factors.
Spatial scale and resolution	Vortex runs at a local/ regional scale, dependent on the range size of the population under study. The resolution is at a single population or metapopulation only.
Temporal scale and resolution	Vortex can project annually for over 100 years.

Accessibility of outputs	Output constitutes a graph of population size over time, which is easily accessible to interpretation by a general audience.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Vortex can be useful for prioritising individual species' populations for conservation efforts and testing theoretical management strategies before investment and implementation. This can be applied to populations providing important ecosystem services, such as fish stocks or strategies for removing invasive species.
Relevant application	Vortex was applied to the Lord Howe Island Woodhen population, which had become endangered due to human exploitation and predation from wild pigs. The model highlighted the sensitivity of woodhens to pressures and catastrophes through their mortality and fecundity rates. This informed conservation managers that woodhens required the establishment of a remote population in order to avoid extinction (Brook *et al.*, 1997).
Main reference(s)	Lacy, R.C., 1993. VORTEX: a computer simulation model for population viability analysis. *Wildlife research*, *20*(1), pp.45-65; Brook, B.W., Lim, L., Harden, R. and Frankham, R., 1997. How secure is the Lord Howe Island Woodhen? A population viability analysis using VORTEX. Pacific Conservation Biology, 3(2), pp.125-133.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://scti.tools/vortex/
Manuals/ training/ videos	https://scti.tools/downloads/#SoftwareAndManuals
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.5 Ecosystems and biodiversity	**MIGRATE**

Model/ tool type and outputs	MIGRATE is a spatially explicit, grid-based mechanistic species distribution model to simulate range expansion of plant and animal species at the landscape scale. For each grid cell, the carrying capacity is calculated from the proportion of the area of the cell covered by suitable habitat and the mean density of the species within the suitable and occupied habitat.
Open access?	Not known
Key data inputs	MIGRATE uses biological parameters that could be estimated from data in the literature or from field studies. Common parameters include the carrying capacity/ maximum density of mature individuals in optimal conditions; survival rates; reproductive rate; age of first breeding; and dispersal rates.
Key data accessibility/ availability	Input parameters can be estimated from data in literature or field studies. For example, habitat data can be obtained from the Ecosystem Types of Europe dataset (European Environmental Agency) or from national Landcover data sets such as from the UK Centre for Ecology and Hydrology.
Strengths	MIGRATE can be used to simulate the likely response of organisms to both global climate change and the increasing pressures of human land-use on a landscape scale. The model has proven to accurately describe observed rates and patterns of range expansion (in this case for British butterflies), suggesting that the principal constraints acting on the expanding range boundaries of these species have been captured.
Assumptions/ limitations	Historic distributions and species traits need to be available for reliable model outputs.
Spatial scale and resolution	MIGRATE operates on landscape scale, the cells of the grid can have a resolution of, for example, 200m (in Wills *et al.*, 2009).
Temporal scale and resolution	The time step is one year.
Accessibility of outputs	Output are maps with predicted occupied range/ distribution of individual species under different scenarios which are accessible to interpretation by a general audience.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change

Adaptation policy insights	MIGRATE can be used to assess the relative importance of different drivers on the range expansion of species, such as the sensitivity of species to habitat fragmentation.
Relevant application	MIGRATE has been applied to predict changes in northern boundaries of British butterfly species, which are consistent with historical observations of butterfly migration across the British Isles (Willis *et al.*, 2009)
Main reference(s)	Collingham, Yvonne C., Mark O. Hill, and Brian Huntley. "The migration of sessile organisms: a simulation model with measurable parameters." *Journal of Vegetation Science* 7.6 (1996): 831-846.
Suitability for rapid assessment	No - the model requires significant quantities of data which can be time consuming to collect if this is not initially available. Once the data has been collected, the model is quick to run.
Websites	
Manuals/ training/ videos	
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.5 Ecosystems and biodiversity	**MaxEnt**

Model/ tool type and outputs	MaxEnt is a machine-learning species distribution model (SDM) that estimates a species distribution based upon knowledge of the environmental conditions at known occurrence sites.
Open access?	Yes
Key data inputs	MaxEnt is a presence-only model, thus requires data on the location of known occurrences of the species. Furthermore, climatic variables are required as input for the region of study.
Key data accessibility/ availability	Occurrences can be obtained from natural history collections, although those datasets often have a collectors-bias with overrepresentation of rare species. Environmental variables are often available in global or regional open sources datasets.
Strengths	The benefit of a presence-only model is that absence data is not needed, which is often hard to find. MaxEnt has demonstrated to outperform other SDMs in several studies.
Assumptions/ limitations	MaxEnt may underestimate the probability of occurrence within areas of observed presence, while overestimating it in areas beyond the species' known extent of occurrence. Another assumption is that a species occurrence only depends on environmental suitability, while in reality other factors such as dispersal limitations also play a role.
Spatial scale and resolution	The spatial scale and resolution depend on the environmental input data.
Temporal scale and resolution	The time scale depends on the research question and data availability.
Accessibility of outputs	MaxEnt generates geographical maps of a species' environmental suitability, its likelihood of being collected and its local abundance. These maps are easy to interpret by a general audience.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change
Adaptation policy insights	Application of MaxEnt and other SDMs includes support for the selection of conservation areas, predicting the effects of climate change on species ranges and determining the risk of species invasions.
Relevant application	In New Caledonia, MaxEnt was used to predict suitable habitat for threatened and endangered tree species such as *C. Monticola*. This

	information is highly relevant given the potential threats to *C. monticola*'s habitat and to overall biodiversity in New Caledonia due to nickel mining, anthropogenic burning, logging and harmful invasive species. (Kumar *et al.*, 2009)
Main reference(s)	Phillips, S. J., Anderson, R. P. & Schapire, R. E. Maximum entropy modeling of species geographic distributions. Ecol. Modell. 190, 231–259 (2006).
Suitability for rapid assessment	No - the model requires significant quantities of data which can be time consuming to collect if this is not initially available. Once the data has been collected, the model is quick to run.
Websites	
Manuals/ training/ videos	
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.5 Ecosystems and biodiversity	**GLOBIO3**

Model/ tool type and outputs	GLOBIO3 is a species diversity model that uses dose-response relationships to estimate changes in mean species abundance (MSA) as a function of land-use change and other drivers. GLOBIO3 addresses (i) the impacts of environmental drivers on biodiversity and their relative importance; (ii) expected trends under various future scenarios; and (iii) the likely effects of various policy response options. The output (biodiversity) is the remaining mean species abundance (MSA) relative to their abundance in pristine vegetation. MSA is similar to the Biodiversity Integrity Index, the Biodiversity Intactness Index and the Living Planet Index.
Open access?	Yes
Key data inputs	Global environmental drivers of biodiversity change are input for GLOBIO3: land-cover change, land-use intensity, fragmentation, climate change, atmospheric nitrogen deposition and infrastructure development.
Key data accessibility/ availability	Data for the drivers are assessible through IMAGE (Integrated Model to Assess the Global Environment) and GLOBIO2. The Global Land Cover dataset can be added to increase the spatial detail within each IMAGE grid cell. A global map of linear infrastructure can be derived from the Digital chart of the World (DCW) database.
Strengths	GLOBIO3 has proven a valuable model for global and regional biodiversity assessments, especially where scenarios or policy options were compared for their consequences. Although GLOBIO3 is designed for global applications and, as such, can be considered part of the broader IMAGE 2.4 framework, it is possible to use GLOBIO3 to examine the impact of drivers simulated by other models. Furthermore, the GLOBIO3 concept and cause–effect relationships are applicable for countries and regions where extensive data on biodiversity are absent.
Assumptions/ limitations	MSA does not completely cover the complex biodiversity concept, and complementary indicators should be included when used in extensive biodiversity assessments. Also, individual species responses are not modelled in GLOBIO3. Uncertainties in the model relate to the cause–effect relationships, the drivers considered, the models estimating the drivers, the underlying data and the indicators used.

Spatial scale and resolution	The current version of GLOBIO3 is restricted to the terrestrial biomes, excluding Antarctica. The model is designed to compare MSA patterns at the global and regional level.
Temporal scale and resolution	GLOBIO3 can be used to compare MSA in current and future scenarios, for example, how MSA changes between 2000 and 2050. Exact time scale depends on input data and scenarios used.
Accessibility of outputs	Output are values for MSA under different scenarios, which can be presented in graphs and global maps which are accessible for interpretation by a general audience.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options.
Adaptation policy insights	GLOBIO3 can be used to assess impact and effectiveness of adaptation options on biodiversity change at a global scale.
Relevant application	A relevant application is the evaluation of three global-scale policy options on their potential to reduce biodiversity loss: climate change mitigation through expanded use of bio-energy, increase in plantation forestry and increase in protected areas.
Main reference(s)	Alkemade, Rob, *et al.* "GLOBIO3: a framework to investigate options for reducing global terrestrial biodiversity loss." Ecosystems 12.3 (2009): 374-390.
Suitability for rapid assessment	No - the model requires significant quantities of data which can be time consuming to collect if this is not initially available. Once the data has been collected, the model is quick to run.
Websites	https://www.globio.info/home
Manuals/ training/ videos	-
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.5 Ecosystems and biodiversity	**LPJ-GUESS - Lund-Potsdam-Jena GUESS**

Model/ tool type and outputs	LPJ-GUESS is a process-based dynamic vegetation-terrestrial ecosystem model designed for regional or global studies. Models of this kind are commonly known as dynamic global vegetation models (DGVMs). Given data on regional climate conditions and atmospheric carbon dioxide concentrations, it can predict structural, compositional and functional properties of the native ecosystems of major climate zones of the Earth.
Open access?	Yes
Key data inputs	The user needs to provide climate, soils and CO_2 input data. Plant functional type (PFT) parameters and bioclimatic limits of the species of interest need to be known. The model can simulate some PFT trains such as rubisco capacity and root:shoot ratio based on external drivers and realised ecosystem state.
Key data accessibility/ availability	It is possible to couple LPJ-GUESS to a regional climate model. The required climate, soil and CO_2 input data are accessible via public databases.
Strengths	The model uses generic parameterisations that allow it to be applied to any climate zone or biome, including non-forest vegetation such as Arctic tundra or savannah.
Assumptions/ limitations	The model does not include phosphorus. The modeller should be familiar with C/C++ programming skills.
Spatial scale and resolution	The model structural unit is an individual plant. Output is regional to global scale.
Temporal scale and resolution	Time step is day, month or year.
Accessibility of outputs	Outputs include vegetation composition and cover in terms of major species or plant functional types (PFTs), biomass and soil organic matter carbon pools, leaf area index (LAI), net primary production (NPP), net ecosystem carbon balance, carbon emissions from wildfires, biogenic volatile organic compounds (BVOCs), evapotranspiration, runoff, and nitrogen pools and fluxes.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Can be used to understand bioclimatic drivers of vegetation dynamics, and thereby assessing the response of vegetation to future climate change.

Relevant application	LPJ-GUESS has been used to assess the vulnerability of ecosystems to climate change, for example, in combination with invasion by exotic plant species.
Main reference(s)	Smith, B., Prentice, I.C. & Sykes, M.T. 2001. Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. Global Ecology & Biogeography 10: 621-637.
Suitability for rapid assessment	No - the model requires technical knowledge to operate and to ensure that climate, soil and CO_2 data is available as input.
Websites	http://iis4.nateko.lu.se/lpj-guess/index.html
Manuals/ training/ videos	-
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.5 Ecosystems and biodiversity	**Eco-evolutionary biodiversity and extinction model**

Model/ tool type and outputs	This model is a spatially explicit eco-evolutionary model of multi-species responses to climate change. The model shows that both dispersal and evolution differentially mediate extinction risks and biodiversity alterations through time and across climate gradients. High genetic variance and low dispersal minimises extinction risks.
Open access?	Yes
Key data inputs	Environmental variables are temperature and the temperature optimum of communities/ species. Other environmental variables such as precipitation or soil type can also be used as input data.
Key data accessibility/ availability	Input parameters require knowledge regarding the species traits, namely the optimum curve of environmental variables for organismal performance. Environmental data over space and time are often easily retrieved from regional or global open source datasets. Examples of global datasets are the climate datasets of NOAA (US National Oceanic and Atmospheric Administration) or the WorldClim Database.
Strengths	This model accounts for how species interactions and genetic variance influence the response to climate change, while many other models only assess dispersal to model a species' response to climate change. As such, the model shows how greater realistic predictions can be made to assess future extinction risks and biodiversity as result of climate change.
Assumptions/ limitations	The model, as described in the paper, is a conceptual model, and therefore no empirical species data has yet to be incorporated. This raises the question as to whether the model can be readily applied to research questions related to specific species groups.
Spatial scale and resolution	Global spatial scale of climatic regions.
Temporal scale and resolution	The time scale is in centuries.
Accessibility of outputs	Output is in the form of graphs with species richness and extinction level over time and space. These are accessible for a general audience to interpret.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change
Adaptation policy insights	This model highlights the relative importance of dispersal, evolution and interspecific interactions to the biodiversity and extinction rate in different climatic regions. The results suggest that interspecific

	competition mediates the importance of dispersal and adaptation to prevent extinction. Such insights can be used to explore and rank the cost-effectiveness of regional conservation alternatives and demographically oriented management interventions.
Relevant application	An important application is to generate greater realistic predictions regarding how species' range-shifts as a result of climate change affect biodiversity and extinction rates. For example, future species' dispersal could accelerate polar extinctions as warm-adapted species overtake previously cold environments and cold habitats disappear.
Main reference(s)	Norberg, Jon, *et al.* "Eco-evolutionary responses of biodiversity to climate change." Nature Climate Change 2.10 (2012): 747-751.
Suitability for rapid assessment	No - the model requires technical knowledge to operate and interpret the outputs.
Websites	-
Manuals/ training/ videos	-
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.5 Ecosystems and biodiversity	**Generalized Dissimilarity Model (DSM)**

Model/ tool type and outputs	Generalized dissimilarity modelling (GDM) is species diversity model. It uses a statistical technique for analysing and predicting spatial patterns of turnover in community composition (beta diversity) across large regions. GDM can be further adapted to accommodate special types of biological and environmental data including, for example, information regarding phylogenetic relationships between species and barriers to dispersal between geographical locations.
Open access?	Yes
Key data inputs	The model uses environmental input data of climatic variables and locations of species presence, for example, using herbaria data.
Key data accessibility/ availability	The climatic variables data are often open access and species data can be retrieved from herbaria data portals.
Strengths	GDM provides a powerful method to analyse and predict spatial patterns in compositional turnover (beta diversity) across large regions. The approach can support the optimal use of best-available biological and environmental data in a wide range of assessment and planning activities.
Assumptions/ limitations	The model assumes that the relationship between species occurrence and environmental variables is similar across space and time. For short-term effects or high spatial resolutions, factors such as dispersal limitation, stochastic processes and disturbance may make space-for-time substitution in these models less valid.
Spatial scale and resolution	The spatial scale and resolution depend on the input data and model set-up.
Temporal scale and resolution	The time scale and resolution depend on the input data and model set-up.
Accessibility of outputs	Outputs are maps with predicted environmental variables, species occurrence and biodiversity. These are accessible to interpretation by a non-technical audience.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options.
Adaptation policy insights	The approach can be applied to a wide range of assessment activities, including visualization of spatial patterns in community composition, distributional modelling of species or community types, conservation assessment and climate-change impact

	assessment. These applications can subsequently inform decision-making for conservation management and climate adaptation.
Relevant application	Jewitt *et al.* (2016) used DSM to map plant diversity on a landscape scale for South Africa. The results show that (beta) biodiversity was highest in relatively warm, drier summer regions and on dystrophic soils. This information can be used to inform conservation planning.
Main reference(s)	Ferrier, Simon, *et al.* "Using generalized dissimilarity modelling to analyse and predict patterns of beta diversity in regional biodiversity assessment." Diversity and distributions 13.3 (2007): 252-264.
Suitability for rapid assessment	No - DSMs require detailed knowledge regarding the model for the correct interpretation. Collection of input data can also be time consuming.
Websites	-
Manuals/ training/ videos	-
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.6 Energy	**POLES**

Model/ tool type and outputs	The Prospective Outlook for Long-term Energy Systems (POLES) model is a partial equilibrium model with a dynamic year-by-year simulation process, simulating the global energy system from the present day until 2100. It is market-oriented, meaning that market equilibrium prices drive the balance of supply and demand for each type of energy. Separate modules represent the national energy balances and the international markets for the world energy system in 57 countries and regions. In this framework, the EU is represented as 27 Member States. The model was developed to study international energy issues, technology development and global environmental strategies. Population and economic growth scenarios are exogenous variables. The POLES model consists of interconnected modules of final demand, power generation including renewables, fossil fuel supply, international energy markets and prices at the national, regional and global level. This framework has been extended to include climate change impacts on the EU energy system in terms of a) changing energy demand in response to changing HDD and CDD (Heating Degree Days and Cooling Degree Days); changing thermal power plants efficiency due to changing cooling conditions) changed availability in hydro and wind resources; and changed efficiency of solar PV electricity generation.
Open access?	No
Key data inputs	Key input data includes Heating and Cooling Degree Days; air temperature; precipitations; and energy and economic drivers already incorporated into the model.
Key data accessibility/ availability	The model used two main sources of climate data: a) High Resolution Gridded Dataset of the Climate Research Unit at University of East Anglia and from the Tyndall Centre for Climate Change Research, as part of world-energy trends described in two emission scenarios of the IPCC Special Report on Emission Scenarios. Open access datasets are available at: http://www.cru.uea.ac.uk/data; b) Various simulation runs from a suite of climatic models within the ENSAMBLES projects, along four main climatic scenarios. More specifically, a reference case to which the alternate climate runs are compared; a representative average or central climate run based on an A1B baseline energy system scenario; a climate run that shows significant deviations from the average climate run, usually warmer and drier than the average, based on an A1B baseline energy system scenario; a climate run that show significant deviations from the average climate run, usually colder and wetter than the average, based on

	an A1B baseline energy system scenario; a climate run that depicts a representative average or central climate run based on an E1B emissions reduction energy system scenario. This project finished in 2009, with the final report available at: http://ensembles-eu.metoffice.com/docs/Ensembles_final_report_Nov09.pdf
Strengths	Provided a comprehensive assessment of multiple impacts on the energy sector in EU countries, including both demand and supply side impacts.
Assumptions/ limitations	Impacts on heating and cooling demand are modelled, distinguishing between residential and service sector demand; the impact on thermal power plants, wind farms and PV solar are modelled using estimated functions relating plant efficiency and climate variables such as air temperature and wind speed. Impacts on hydropower are based on the LISFLOOD model, an EU-wide GIS-based hydrological rainfall-runoff-routing model, simulating the hydrological processes in a given catchment area. Limitations include the uncertainty of results that are compounded through linking uncertain climatological projections to uncertain economic scenarios; the approximate depiction of some climate-energy links, such as temperature, precipitation and hydropower generation (evaporation from water basins are not accounted for); the unfeasibility of managing short term extreme weather events; and the inclusion of adaptation only through changes in the energy mix, not through testing exogenous adaptation policies or investments.
Spatial scale and resolution	66 world regions and states, of which the 27 EU member states are independently represented. The spatial resolution is this per country/ 'region' constituting macro aggregations of countries.
Temporal scale and resolution	Annual time steps with horizons up to 2100 (typically 2050).
Accessibility of outputs	The outputs of POLES are accessible through the JRC or ClimateCost websites. A background in economics would be useful but the key results are clearly explained.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Increasing efficiency of indoor heating and cooling will decrease the requirement for adaptation. The EU energy system can spontaneously respond climate change through fuel mix adjustments, but this will likely not be sufficient and specific policy actions are required. The extensive economic life of power plants can be an issue for adaptation, and early substantial refurbishment may be required during the lifetime of energy infrastructures.

Relevant application	POLES has been used within the PESETA II project to assess climate change impacts on the EU energy sector. It predicted falls in energy demand throughout Northern Europe and increases in Southern Europe.
Main reference(s)	Dowling P (2013) The impact of climate change on the European energy system. Energy Policy 60:406–417
Suitability for rapid assessment	No rapid use of model; no rapid access to input data. Both require extensive study.
Websites	https://www.enerdata.net/solutions/poles-model.html ; https://ec.europa.eu/jrc/en/poles
Manuals/ training/ videos	Model documentation can be found at: Dowling P (2013) The impact of climate change on the European energy system. Energy Policy 60:406–417
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.6 Energy	**MARKAL/ TIMES**

Model/ tool type and outputs	MARKAL is the predecessor of TIMES and it is no longer maintained but shares the same approach. TIMES is a dynamic linear optimization bottom-up model generator for energy systems which provides a technology-rich basis for estimating energy dynamics over an extended time period. The objective of TIMES is to minimize the net present value (NPV) of the total costs subject to technological, physical and policy constraints in such a way that demand of energy services is satisfied at the minimum total system cost. TIMES can be adapted to any geography but given that it constitutes a set of equations rather than a full model, it requires a detailed database depicting the situation of the energy system under scrutiny in the base year. The model outputs are energy flows, energy commodity prices, GHG emissions, capacities of technologies, energy costs and marginal emissions abatement costs.
Open access?	No: licence required
Key data inputs	Input data includes detailed data on the energy system under scrutiny and relevant climate data, if used for impact assessment/adaptation. The application to the Portuguese hydropower sector required, for instance: i) a comprehensive database on the technical and economic data characterizing existing and future technologies in terms of efficiency, capacity, availability, lifetime, emission factors, investment and operation and maintenance costs; ii) resource potentials and prices for present and future sources of primary energy supply, including imported energy carriers prices; iii) policy constraints; and iv) energy services, materials and mobility end-use demand which are quantified exogenously through the evolution of specific socio-economic indicators, for example, population, GDP, sector production, private consumption and demand elasticities. In an application to Portugal's hydropower sector, climate change is included through changes in runoff under alternate RCPs and the relationship between the % variation in generation and the % variation in runoff is assumed to be linear. In an application to the Norwegian energy system climate data are taken from a suite of climatic models and entail temperatures, HDD and CDD (Heating Degree Days and Cooling Degree Days), solar radiation, wind speed and precipitations.
Key data accessibility/ availability	No open access data available. The modelling framework can be obtained, subject to licence payment, at: https://iea-etsap.org/index.php/etsap-tools/acquiring-etsap-tools

Strengths	A flexible modelling framework with detailed output on the future configuration of the energy sector under scrutiny.
Assumptions/ limitations	The model computes a partial equilibrium for the energy sector between supply and demand; hence, energy suppliers produce the exact quantities that consumers are willing to buy at the equilibrium prices computed by the model. This equilibrium is a result of simultaneous decisions concerning technology investment and operating costs, primary energy supply and trade, assuming perfect market foresight. Typical limitations of TIMES include: approximate modelling of user behaviour; a lack of uncertainty assessment and limited transparency and reproducibility of the model and data; and a lack or sparse representation of future technologies. For the application to hydropower in Portugal, climate change is assumed to significantly impact water resources availability, but not for wind, biofuels, solar irradiance and geothermal resources; there is no variation at the subnational level despite the different hydrological conditions across the country; the load curve is approximated by means of weighted seasonal averages and day, night and peak time period averages. The Norwegian study does not emphasise the role of cooling demand, probably due to the projections available at the time of conducting the study.
Spatial scale and resolution	Fully customizable, from global to local.
Temporal scale and resolution	Fully customizable, both in relation to time horizon and resolution.
Accessibility of outputs	In general, the accessibility of the outputs depends from the project in which the model is applied. Results for Portugal and Norway are published on international peer-reviewed journals.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Hydropower capacity in Portugal is predicted to be significantly impacted, and this could undermine Portugal's ability to meet its carbon reduction targets and will require extra investments. Alternatively, the Norwegian study highlights the beneficial effects of climate change in terms of reduced energy requirements, albeit this study did not acknowledge the significant impact of increasing cooling demand, which undergoes a negligible variation.
Relevant application	Assessment of climate change impacts on hydropower in Portugal and assessment of climate change impacts on the Norwegian electricity sector.
Main reference(s)	TIMES PT: Teotonio C, Rodríguez M (2017) Assessing the impacts of climate change on hydropower generation and the power sector

	in Portugal: a partial equilibrium approach. Renew Sust Energ Rev 74:788–799. MARKAL NORWAY: Seljom P et al (2011) Modelling the effects of climate change on the energy system—a case study of Norway. Energy Policy 39(11):7310–7321
Suitability for rapid assessment	No rapid use of model; no rapid access to input data as both require extensive studies. Model user interfaces for Markal /TIMES exists but still need extensive training and customisation to the study topic.
Websites	https://iea-etsap.org/
Manuals/ training/ videos	https://iea-etsap.org/index.php/documentation
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.6 Energy	**TIAM-WORLD+ GEMINI-E3 + PLASIM-ENTS**

Model/ tool type and outputs	This modelling framework couples an energy module, based on TIMES (TIAM), with a CGE module (GEMINI-E3) and an emulator of a climate module (PLASIM-ENTS). TIAM comprises of several thousand technologies in all sectors of the energy system. It is characterized by several technical and economic parameters and by emission coefficients for the three main GHGs: CO_2, CH_4, and N_2O. It develops TIMES by adding: linearised climate equations; multi-stage stochastic programming; new formulation for the forcing equation (linear approximation of forcing); and the possibility of binding all components of the cost objective function. GEMINI-E3 is a recursive dynamic CGE based on the GTAP framework. PLASIM-ENTS has a 3D dynamic atmosphere, flux-corrected slab ocean and slab sea ice, and dynamic coupled vegetation. The novel features of the modelling framework that connects these three models are the feedback loops between the economic modules, which, among other functions, computes GHG emissions and quantifies the effects of climate changes on the economic system. For informing energy sector adaptation, climate feedback translates temperature changes into changes in HDD and CDD (Heating Degree Days and Cooling Degree Days), which directly impacts on energy demand. The objective of the study is to analyze the impacts of changes in future temperatures on the heating and cooling services of buildings, with the resulting energy and macro-economic effects at global and regional levels. Globally, the climate feedback of increases in temperature due to changes in emissions induced by adaptation of the energy system to heating and cooling, is negligible, partly because heating and cooling-induced changes cancel out and partly because they account for a small share of total final energy consumption. However, significant changes occur at regional levels in relation to the additional power capacity required to satisfy additional cooling services, resulting in increases in electricity prices. In terms of macro-economic impacts, welfare gains and losses are greater associated with changes in energy exports and imports than with changes in energy consumption for heating and cooling.
Open access?	No
Key data inputs	Data requirements include detailed data on the energy systems of the world regions studied (TIAM); the GTAP database of socio-economic variables (GEMINI-E3); and climatic features of the RCPs used for the simulations (PLASIM-ENTS).

Key data accessibility/ availability	This was an output of a FP7 project which ended in 2013 (ERMITAGE FP7/2007-2013, under Grant Agreement no. 265170), and the website is no longer active. Only publications on the projects results can still be found online.
Strengths	This modelling framework is unique in adopting a complete circular systems approach, accounting for emissions, their subsequent impacts on the energy system and subsequent feedback on emissions.
Assumptions/ limitations	The main issue constitutes the framework, which is outdated. The key assumptions and limitations include: "One weakness in the version of PLASIM-ENTS used here is the assumption of fixed sea ice, which leads to the underestimate of emulated high latitude warming. Moreover, its resolution (approximately 5 degree) is relatively coarse. [...] TIAM-WORLD is data-intensive and long-term characteristics of technologies are uncertain and may affect preferred fuels and technologies. Population and economic growth may also deeply affect future energy service demands, amongst them, heating and cooling. Finally, detailed energy statistics for heating and cooling remain spare in some regions. In GEMINI-E3, the key parameters are the elasticities and in particular those related to energy consumption. Like other CGE models they are based on literature review[...] As regards future changes in cooling and heating, their estimation is based on a fixed threshold temperature (18◦C), reflecting the temperature usually used for HDD and CDD computation. The choice of spatially variable threshold temperatures may better reflect real heating and cooling behaviours. Changes in future population density may also affect total HDD and CDD and is not considered in the study."
Spatial scale and resolution	11 world regions: Africa, Australia & New Zealand, Canada, China, Europe, Former Soviet Union, India, Latin America, Middle East, Other Asia, United States of America.
Temporal scale and resolution	Decades, 2010-2100
Accessibility of outputs	Open access version of the results paper is available at: https://core.ac.uk/download/pdf/82977625.pdf
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change
Adaptation policy insights	The substantial irrelevance of heating and cooling at the global level masks important diverging impacts at the regional level. A finer geographical disaggregation is required to capture these varying patterns and to devise appropriate policy responses.
Relevant application	Only within the ERMITAGE project.

Main reference(s)	Labriet, M., Joshi, S. R., Vielle, M., Holden, P. B., Edwards, N. R., Kanudia, A., … Babonneau, F. (2015). Worldwide impacts of climate change on energy for heating and cooling. Mitigation and Adaptation Strategies for Global Change, 20(7), 1111–1136. https://doi.org/10.1007/s11027-013-9522-7
Suitability for rapid assessment	No, each model used would require a significant timeframe to develop familiarity with, and the coupling of models is usually challenging.
Websites	
Manuals/ training/ videos	
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.6 Energy	**ICES -Intertemporal Computable Equilibrium System (Energy Module)**

Model/ tool type and outputs	ICES is a multipurpose tool to assess the impacts of climate change on the economic system, evaluate costs of mitigation and adaptation policies, describe the key role of public sector for mitigation and adaptation policies, and highlight future sustainability scenarios. The model's general equilibrium structure supports the analysis of market flows within a single economy and international flows globally. This implies moving beyond the "simple" quantification of direct costs to offer an economic evaluation of second and higher-order effects within specific scenarios either of climate change, climate policies or different trade and public-policy reforms in the vein of conventional CGE (Computable General Equilibrium) theory. Therefore, ICES can assess multiple impacts and adaptation options. The methods of examining energy sector impacts are reviewed here.
Open access?	No
Key data inputs	The core model is based on the GTAP database. Climate change impacts are captured as exogeneous shocks to economic variables and/or parameters. The model uses demand elasticities to temperature to assess energy sector impacts from De Cian *et al.* (2007), which studies the effect of climate change on households' demand for different energy commodities. Variations in residential energy demand are implemented through exogenous shifts in the households' demand.
Key data accessibility/ availability	De Cian, E., Lanzi, E. and Roson, R., (2007), The Impact of Temperature Change on Energy Demand: A Dynamic Panel Analysis, FEEM Working Paper N.46.2007. (Open access)
Strengths	The model evaluates multiple impacts and the relative magnitude of the costs of inaction for each one. This can inform the relative importance of impacts for policy making.
Assumptions/ limitations	The main assumptions of the general ICES model (detailed under CGE models) are that: the model based on perfectly competitive and frictionless markets may underestimate adjustment costs; technological progress is exogenous; it is ill suited to capture non-market impacts, risk and uncertainty and the dynamics are simplified (recursive). Further, the main issue with the energy module is that only the demand side impacts on the energy sector are included.
Spatial scale and resolution	ICES has a flexible geographical resolution. The study includes impacts on the energy sector (Eboli *et al.*, 2010) in eight world regions; the regionalized version of the model considers 70 sub-

	national regions in the Euro-Mediterranean area: Italy (20 NUTS-2 regions), (NUTS: Nomenclature des Unités Territoriales Statistiques) France (22 NUTS-2 regions), Spain (19 NUTS-2 regions), Portugal (5 NUTS-2 regions) and Greece (4 NUTS-1 regions).
Temporal scale and resolution	5-year intervals up to 2050.
Accessibility of outputs	Yes, on the model webpage: https://www.icesmodel.org/
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	Estimates for residential energy demand indicate a general reduction in natural gas and oil demand (for heating), while impacts on electricity demand are not significantly relevant in Europe.
Relevant application	ICES has been extensively applied to the assessment of climate change impacts and policies. Research projects such as: CALDAM-ENV Link – Calibration of projected climate change damages in ENV-Linkages; HEXE – Opening the economy-climate modelling box to decision-makers. CALDAM-ENV Link resulted in a coordinated calibration of assessment models to support OECD policy analyses (not a part of the project); HEXE, amongst others, resulted in greater integration of the Energy module within the modelling framework. However, both projects are old.
Main reference(s)	Eboli, F., Parrado, R., & Roson, R. (2010). Climate-change feedback on economic growth: Explorations with a dynamic general equilibrium model. Environment and Development Economics, 15(5), 515–533. https://doi.org/10.1017/S1355770X10000252
Suitability for rapid assessment	No rapid use of model and data is possible even though these last are easily accessible upon purchase.
Websites	www.icesmodel.org
Manuals/ training/ videos	
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.6 Energy	**LPJmL+GCAM**

Model/ tool type and outputs	This modelling framework couples a crop model (LPJmL) with an integrated assessment model (GCAM). This is used to evaluate climate change impacts on various crops including energy crops. The objective is to assess whether climate change negatively impacts on energy crops, which could hinder their contribution to decarbonization.
Open access?	Both models are open source and freely available, however the code to couple the models is not.
Key data inputs	Climate data: gridded monthly estimates of temperature and precipitation up to the end of the century from HadGEM2-ES, bias-corrected and downscaled for input to global gridded crop models. Crops yield projections from LPJmL subsequently informed GCAM for economic assessment.
Key data accessibility/ availability	Contacts to request access to HadGEM2 climate projections are available at: https://portal.enes.org/models/earthsystem-models/metoffice-hadley-centre/hadgem2-es
Strengths	This modelling framework supports the assessment of agricultural climate impacts on agricultural and energy systems and how strategies for emissions mitigation may be affected. This could support geographical shifts in crop production toward areas that experience relatively lower climate impacts as a form of adaptation.
Assumptions/ limitations	"This study does not include feedbacks between climate change and non-agricultural vegetation, which could substantially alter land use-related CO_2 emissions and consequently change regional cumulative emissions budgets. Moreover, a global climate change mitigation target is assumed, wherein all regions see the same carbon price, so there is no feedback between shifts in land-use-related emissions in one region and the carbon prices for that particular region. Finally, in this study a global biomass market is assumed, with free trade and equal prices in all regions within any time period. This assumption tends to dampen feedbacks between climate-related changes in regional biomass yields and the costs of emissions mitigation in that particular region." - Kyle, P., Müller, C., Calvin, K., & Thomson, A. (2014). Meeting the radiative forcing targets of the representative concentration pathways in a world with agricultural climate impacts. Earth's Future, 2(2), 83–98. https://doi.org/10.1002/2013ef000199

Spatial scale and resolution	LPJmL simulates yields of 12 different crops, managed grassland and a bioenergy grass crop globally at 0.5◦ × 0.5◦ spatial resolution; GCAM has 14 geopolitical regions, each of which contains up to 18 agro-ecological zones, resulting in 151 land-use regions.
Temporal scale and resolution	The time frame for this coupled model is 2100, with LPjmL output resolution provided annually while GCAMs typically operated in five-year time steps. However, the model contains flexibility to operate at different temporal resolutions through user-defined parameters.
Accessibility of outputs	The main publication can be freely downloaded at: https://agupubs.onlinelibrary.wiley.com/doi/full/ 10.1002/2013EF000199
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options
Adaptation policy insights	The key insights for policy making are: a) Some degree of adaptation will occur spontaneously as migration of crops to the regions that would become more suitable for growing them due to the changed climatic conditions. b) Climate change results overall in more favourable conditions for, and hence higher production of, energy crops. Thus, in principle there would be a positive feedback on mitigation that could dampen the impacts of climate change. c) However, the study also shows that when it comes to land use, the main mitigation lever is not crops but forestry. Hence where mitigation efforts are high, the relevance of this feedback through energy crops is negligible.
Relevant application	Within this study, the focus is the implications for climate-impacted energy crops on mitigation policy. The study is summarised as: "global average climate impacts on yields of bioenergy crops are generally positive, for all emissions pathways (given the suite of models used). In the context of climate change mitigation, bioenergy is the main link between the agricultural and energy systems, and the component of an emissions mitigation portfolio that would be most susceptible to disruption by agricultural climate impacts. Still, the negative climate impacts on some crops—prominently wheat, rice, and soybeans—do lead to a long-term expansion of cropland, as compared with scenarios where agricultural climate impacts are not considered, which does cause additional land-use-change emissions. However, these additional land-use-change emissions are sufficiently small as to not affect

	the strategies of meeting the climate change mitigation targets in the low-climate-forcing scenarios." (Kyle, Müller, Calvin, & Thomson, 2014)
Main reference(s)	Kyle, P., Müller, C., Calvin, K., & Thomson, A. (2014). Meeting the radiative forcing targets of the representative concentration pathways in a world with agricultural climate impacts. Earth's Future, 2(2), 83–98. https://doi.org/10.1002/2013ef000199
Suitability for rapid assessment	No - the use of coupled models requires technical expertise.
Websites	GCAM: http://www.globalchange.umd.edu/gcam/ (overview and access to source code). LPJml: https://www.pik-potsdam.de/research/projects/activities/biosphere-water-modelling/lpjml (overview and access to source code)
Manuals/ training/ videos	Yes, on both websites.
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.6 Energy	**HiREPS (High Resolution Power System)**

Model/ tool type and outputs	HiREPS provides a detailed assessment with a fine geographical resolution of climate change impacts on both the energy supply side for renewable electricity generation in hydro, wind and solar, and demand side of the energy sector in Austria and Germany. This couples a climate model, a runoff model and an energy model, which in its partial equilibrium, cost minimization setting includes a detailed specification of the building sectors and of its energy requirements in relation to heating and cooling.
Open access?	No
Key data inputs	Bias corrected "Climate data from three RCM models; temperature and precipitation were localized to the 1×1 km grid of the hydrological model [...]. The hydrological model provided monthly changes of long-term runoff for 188 river basins as well as key data regarding cooling water availability; [...] The electricity and heating system simulation model HiREPS needed, besides run off values from the hydrological model, additionally, temperature, global irradiation, and wind speed with as high temporal resolution as possible for two domains, Austria and Germany. Temperature and irradiation were used to compute the heating and cooling needs at the hourly level. By identifying the days in which threshold values are likely to be exceeded, heatwaves were included into the model." - Totschnig *et al.*, 2017
Key data accessibility/ availability	The project ended in 2013 and the datasets are no longer available. Equivalent RCM data as those used in this framework can be retrieved from current RCMs.
Strengths	High spatial and temporal resolution. Ability to account for extreme events such as heatwaves.
Assumptions/ limitations	This model is highly detailed for two specific countries, however the uncertain replicability for other countries is a key limitation. The role of the transmission grid and its vulnerabilities are not included. Some features of the Austrian energy system are also assumed to be the same for Germany, such as trends of the building stock.
Spatial scale and resolution	1km x 1km grid resolution across Austria and Germany.
Temporal scale and resolution	Time resolution is hourly for 2051-2080.
Accessibility of outputs	The project deliverables are available at: https://eeg.tuwien.ac.at/research/projects/presence ; The final results were published in **-** Totschnig, G., Hirner, R., Müller, A., Kranzl, L., Hummel, M., Nachtnebel, H. P., … Formayer, H. (2017).

	Climate change impact and resilience in the electricity sector: The example of Austria and Germany. Energy Policy, 103, 238–248. https://doi.org/10.1016/j.enpol.2017.01.019
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options
Adaptation policy insights	"In the scenarios analysed, changes in the natural gas price have larger impact on the electricity generation cost than weather variability between different years or climate change[...] Analysis of the required secured capacity shows, that in the last quarter of the 21st century the annual maximum residual loads are growing and are dominated by strong cooling demand peaks. Promoting passive cooling options, efficient building designs and options for a controlled down regulation of cooling devices seems to be advisable to avoid installing large thermal power plant backup capacities. The evaluated climate model simulations show only small changes in photovoltaic, wind and hydropower generation for 2051−2080 in Austria and Germany." - (Totschnig *et al.*, 2017)
Relevant application	PRESENCE project: "The hydrological modelling shows that seasonal changes are very similar in all considered climate change scenarios: summer runoff decreasing, winter runoff increasing. [...] Regarding the impact on heating and cooling, a major finding is that the impact of climate change is much lower than the leverage of energy policy framework conditions. Although space cooling might not be a more issue from an annual energy balance point-of-view, it may have a major impact on electricity peaks and the design-factor of electricity grids, if no adoption measures are undertaken. The results of the energy system modelling clearly shows that energy efficiency and a higher share of renewable energy can significantly contribute to increasing the energy systems resilience[...]. The analysis of extreme periods [...] reveals, that for most climate scenarios periods with high residual loads in winter will remain in a very similar range as for historic periods. However, in all climate scenarios such periods during summer will significantly increase until 2050-2080 if not significant efforts are taken to reduce cooling loads."
Main reference(s)	Totschnig, G., Hirner, R., Müller, A., Kranzl, L., Hummel, M., Nachtnebel, H. P., … Formayer, H. (2017). Climate change impact and resilience in the electricity sector: The example of Austria and Germany. Energy Policy, 103, 238–248. https://doi.org/10.1016/j.enpol.2017.01.019
Suitability for rapid assessment	Rapid assessment is not possible due to the complexity of the model and dataset.

Websites	Brief summary and key deliverables are available at: https://eeg.tuwien.ac.at/research/projects/presence
Manuals/ training/ videos	n.a.
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.6 Energy	**LEAP+ WEAP - Long-range Energy Alternatives Planning System + Water Evaluation And Planning**

Model/ tool type and outputs	LEAP is a widely used and user-friendly energy model, mainly used for mitigation policy assessment. Coupled with the water catchment model, WEAP, it has been applied to climate change impact assessment on hydropower on the Zambezi river in Africa. Given the flexibility of the LEAP tool, this approach can, in principle, be replicated across the EU.
Open access?	WEAP and LEAP require a licence, which is free for developing countries, but contains a fee for developed countries.
Key data inputs	Key input data requirements include electricity demand projections, technical characteristics of existing and planned power plants, climate data of temperature and precipitations and water catchment characteristics.
Key data accessibility/ availability	For the Zambezi study, data are available as supplementary material from the publisher for this journal article, although this is not open access: https://www.sciencedirect.com/science/ article/pii/S0301421516306656#ec0005
Strengths	LEAP+WEAP is a flexible, popular and user-friendly framework. Both WEAP and LEAP were developed by the same institution (SEI) with the same approach. The African example described and in the main publication should be replicable with relative ease for other locations.
Assumptions/ limitations	The main limitations relate to challenges regarding finding relevant data for African catchments with incomplete information for a number of energy (hydropower) plants. Moreover, the analysis relies on overly stylized scenarios (i.e. extremely simplified scenarios).
Spatial scale and resolution	Power plant/ river catchment level.
Temporal scale and resolution	Time resolution is annual, 2011- 2070.
Accessibility of outputs	Outputs for this study are only available through the publication.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options

Adaptation policy insights	Besides recommendations with a local focus, the Zambezi study makes the following general points: climate change impacts should be an essential consideration within infrastructure planning for the hydropower sector and overall national and regional energy planning, accounting for conflicting water resource use priorities. This has implications for EU countries, particularly southern nations.
Relevant application	The Zambezi case study could be applied to EU river catchments. LEAP has been widely applied in policy making globally and, for instance, has been used to develop multiple countries' INDCs under the UNFCCC.
Main reference(s)	Spalding-Fecher, R., Joyce, B., & Winkler, H. (2017). Climate change and hydropower in the Southern African Power Pool and Zambezi River Basin: System-wide impacts and policy implications. Energy Policy. https://doi.org/10.1016/j.enpol.2016.12.009
Suitability for rapid assessment	No - training is needed and database needs to be populated before application to other geographies. However, LEAP appears to be simpler to use than other models considered within this section, according to its webpage: https://www.energycommunity.org/default.asp?action=introduction
Websites	LEAP: https://www.energycommunity.org/default.asp?action=introduction; https://www.weap21.org/index.asp. Both models are open access only for developing countries.
Manuals/ training/ videos	Yes, on both websites.
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.6 Energy	**MAED (Model for Analysis of Energy Demand) + LEAP + MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact)**

Model/ tool type and outputs	This framework couples two energy demand modules (MAED and residential demand module from LEAP) with a linear programming energy supply optimization model (MESSAGE), which provides the least cost energy and electricity supply mix scenario. This framework is used to assess internal adaptation in relation to changes in the energy mix with alternate climate scenarios for the Brazilian electricity sectors. Impacts on hydropower, biomass and thermal efficiency of natural gas power plants are reviewed.
Open access?	No, MAED is licenced by IAEA and MESSAGE from IIASA (International Institute for Applied Systems Analysis, Austria). LEAP requires a licence, which is free for developing countries but contains a fee for developed countries. However, the code to couple the models is not freely available.
Key data inputs	For the demand modules, MEAD and LEAP, data on demography, economy, lifestyle and energy use technologies are required. For the energy supply module MESSAGE, input data includes resource endowments, infrastructures, conversion technologies, energy trade, innovation, pollution, emissions, energy costs and prices. Climate scenario projections for temperature and precipitations under alternate SRES (Special Report on Emissions Scenarios) from HadCM3 GCM are also required.
Key data accessibility/ availability	Only climate data are open access, available from the IPCC at: https://www.ipcc-data.org/sim/gcm_clim/SRES_TAR/hadcm3_download.html
Strengths	This framework provides a comprehensive assessment of multiple impacts on the energy sector in Brazil; including both demand and supply side impacts.
Assumptions/ limitations	The model is old and computes a partial equilibrium between supply and demand for the energy sector, however this study the framework is applied in is specific to Brazil. Adaptation is assumed to be only reflected through adjustments in the fuel mix. The study finds that "technical and socioeconomic premises used in the MAED–MESSAGE simulation [...] are likely to evolve and change in the future. The A2 and B2 emission scenarios represent qualitative storylines which have a wide range of local specific trajectories for

	future energy development. Changes in energy prices, technology costs and technological advances can lead to another set of optimal adaptation options. Different socioeconomic premises and changes in consumer behaviour – induced by demand side management [...] also influence the modelling results". Further, "the adaptation modelling is subjected to a cascade of uncertainties regarding the emission scenarios, the translation of those into changes in global climate (GCM results), the downscaling into regional climate and, finally, the modelling of the impacts on energy production and consumption". (de Lucena, Schaeffer & Szklo, 2010). It is also noted that the modelling framework cannot incorporate extreme events.
Spatial scale and resolution	This framework operates at the national scale while the assumptions and results for hydropower are at the river basin level.
Temporal scale and resolution	The temporal resolution is at 5-year time periods from 2005-2035.
Accessibility of outputs	The results are of this study is specific to Brazil and can found detailed in the main publication under 'Main Reference(s)'. It could be relevant for other tropical countries with a similar agricultural sector.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options
Adaptation policy insights	No particularly relevant recommendations beyond the local policy dimension, which pointed to the opportunity to increase installed capacity based on natural gas and sugarcane bagasse, wind power and coal/nuclear plants. The authors warn that these results are "based on the techno-economic premises used in the simulation, which may vary in the long-term. " (de Lucena, Schaeffer & Szklo, 2010) As these results are specific to Brazil' energy system, wider policy implications cannot be derived.
Relevant application	Only Brazil, however the MESSAGE model is a widely used one for assessing energy and mitigation policies.
Main reference(s)	de Lucena, A. F. P., Schaeffer, R., & Szklo, A. S. (2010). Least-cost adaptation options for global climate change impacts on the Brazilian electric power system. Global Environmental Change, 20(2), 342–350. https://doi.org/10.1016/j.gloenvcha.2010.01.004
Suitability for rapid assessment	Rapid assessment is not possible due to the complexity of the model coupling methodology. However, see LEAP entry.
Websites	

Manuals/ training/ videos	no
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.6 Energy	**ToPDAd (Tool-supported policy development for regional adaptation): GINFORS (Global INterindustry FORecasting System) + GRACE (Global INterindustry FORecasting System)+ENDIP (extended title unavailable)+ Balmorel +VTT-TIMES (TIMES model (The Integrated MARKAL-EFOM System - used at VTT -Technical Research Centre of Finland)**

Model/ tool type and outputs	The ToPDAd project analyses several climate change impacts and vulnerabilities for the EU, together with a number of adaptation options. It couples GINFORS, a simulation model for medium-long term projections up to 2050 (the year within which the project assumes climate change impacts to be moderate), with GRACE, a multi-country dynamic Computable General Equilibrium model for long-term projections up to 2090 when adaptation is expected to be necessary given the predicted high climate impacts. The analysis is supported by the ENDIP model in order to addresses challenges related to decision making under uncertainty in the energy sector. VTT-TIMES is a global energy sector model and is used to portray the impacts of global drivers, such as global emission limits based on the selected RCP or the global economic development in the selected SSP, to the electricity sector in Northern Europe. The partial equilibrium energy model, Balmorel, is used to capture the impacts of temperature changes on Northern Europe's energy demand and climatic-induced changes on electricity generation. This study investigates several sectors as well as energy. Moreover, ToPDAd provides a simulation tool which, for the energy sector, supports the evaluation of alternative adaptation options for electricity generation in Northern Europe and nuclear generation in France.
Open access?	No
Key data inputs	The modelling framework draws on the IPCC RPCs 2.6 and 4.5, and SSPs 1 and 4, which are combined into four alternative scenarios. Population forecasts are taken directly from SSP1. Fossil fuel prices use the 2012 IEA's Energy Technology Perspectives. Current and

	planned climate policies have been incorporated into the scenarios and extra policies modulated according to the sustainability features of the scenarios.
Key data accessibility/ availability	Input data are not available as the project website does not provide them; output results can be visualised through the ToPDAd tool at: http://topdad.services.geodesk.nl/interactive-tool
Strengths	Includes adaptation options, accounts for multiple impacts and provides a tool for rapid visualisation of the results.
Assumptions/ limitations	The main limit of this project is linked to the case-study approach: only Northern Europe (Scandinavia, Baltic countries, Germany and Poland) incorporate the complete electricity sector, while the France case study only examines nuclear generation. The exercise is also limited by the choice of the scenarios and adaptation options, which entails "a stepwise adaptation decomposition approach" to "tests to what extent the technical coping range, together with automatic adaptation in power investment planning, accommodates changes in availability of renewable energy resources, given emission reduction targets. The steps distinguished are a baseline without climate change, climate change without adaptation in power capacity investments, and climate change plus adaptation in power capacity investments." (Perrels *et al.*, 2015).
Spatial scale and resolution	Scandinavia, Baltic countries, Germany, Poland and France.
Temporal scale and resolution	The two main time periods are 2015-2050 and 2051-2090 at the subnational resolution (NUTS3 Regions).
Accessibility of outputs	Outputs can be found on the project webpage: www.topdad.eu, and through the simulation tool at: http://topdad.services.geodesk.nl/interactive-tool
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options
Adaptation policy insights	The project's results highlight that although "the EU energy system can largely accommodate gradual climate change, it is particularly vulnerable extreme weather events". Although investments in energy infrastructure do take into account climate uncertainty, they would benefit by increased scientific knowledge on future climate patterns." In the case of nuclear generation in France, " the results show that losses could vary between tens and several hundred billion euros per decade as of 2100, if the current infrastructure and policies remain in place. Adaptation strategies like building a smart grid and changing the coolant regulations for

	nuclear plants could reduce economic losses by a third or more." (Perrels *et al.*, 2015). The project thus makes a case for policies supporting investments in adaptation in the energy sector.
Relevant application	The project has made the outputs available for the selected case studies; the approach is, in principle, replicable across the EU, however, it would require restarting the project as these tools are not all readily available, nor is the approach to couple the various tools.
Main reference(s)	www. topdad.eu; topdad.services.geodesk.nl/project-results; Perrels, A., Heyndrickx, C., Prettenthaler, F., Kortschak, D., Ciari, F., Bösch, P., … Thompson, A. (2015). Sectoral and cross-cutting multi-sector adaptation strategies for energy, transport and tourism. 308620(308620). Retrieved from www.topdad.eu/upl/files/116701 Damm, A., Köberl, J., Prettenthaler, F., Rogler, N., & Töglhofer, C. (2017). Impacts of +2 °C global warming on electricity demand in Europe. Climate Services, 7, 12–30. https://doi.org/10.1016/j.cliser.2016.07.001
Suitability for rapid assessment	No, only an output exploration tool is available. The coupling exercise here is highly complex, involving the integration of five modelling frameworks.
Websites	No, only the Balmorel model is open access: http://www.balmorel.com/
Manuals/ training/ videos	
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.7 Tourism	**ToPDAd (GINFORS +GRACE+ENDIP+WEDDA): Tool-supported policy development for regional adaptation (ToPDAd): GINFORS (Global INterindustry FORecasting System) +GRACE (Global INterindustry FORecasting System) +ENDIP (extended title unavailable) +WEDDA (WEather Driven Demand Analysis)**

Model/ tool type and outputs	The ToPDAd project analyses several climate change impacts and vulnerabilities for the EU, together with a number of adaptation options. It couples GINFORS, a simulation model for medium-long term projections up to 2050 (the year within which the project assumes climate change impacts to be moderate), with GRACE, a multi-country dynamic CGE (Computable General Equilibrium) model for long-term projections up to 2090 when adaptation is expected to be necessary given the predicted high climate impacts. The analysis is supported by the ENDIP model in order to addresses challenges related to decision making under uncertainty in the energy sector. Using the WEDDA framework to derive overnight stays, ToPDad then analyses mountain and beach tourism at a high spatial resolution. Moreover, ToPDAd provides a simulation tool to evaluate alternative adaptation options for beach and mountain tourism.
Open access?	No
Key data inputs	The project uses monthly counts of overnight stays from national statistic agencies. Beach tourism relies on "weather data from E-OBS gridded dataset and ERA-INTERIM reanalysis data using data from two different climate models: CNRM-CM5 and HadGEM2ES. Two combinations of Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) are considered: RCP4.5/SSP4 and RCP8.5/SSP5". For mountain tourism, the project uses "historical and future climate data, including snow depth [...] from the FP7-Project IMPACT2C. [...] Three combinations of Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) are considered: RCP2.6/SSP1, RCP4.5/SSP4 and RCP8.5/SSP5." (from ToPDAd project's website: http://topdad.services.geodesk.nl/web/guest/beach-tourism)

Key data accessibility/ availability	Input data for mountain tourism are available in map form: https://www.atlas.impact2c.eu/en/tourism/wintertourism/?parent_id=336; beach tourism data is not available. Output results can be visualised through the ToPDAd tool: http://topdad.services.geodesk.nl/interactive-tool
Strengths	Includes explicitly defined adaptation options; accounts for multiple impacts; wide geographical coverage; supports the assessment of different tourism activities at the same destination, which could constitute a potential adaptation strategy; provides a simulation tool to extract tourism flow projections at the location of interest.
Assumptions/ limitations	The exercise is limited by the choice of the scenarios and of the minimal number of adaptation options under review. Adaptation is only considered based on its influence on tourism demand and can only include the strategies: maintaining holiday type while shifting holidays to a more favourable time period and /or moving to an alternative destination, or changing type of holidays but maintaining the same destination. Supply side adaptation options, for example, investing in artificial snowmaking or developing touristic appeal with new activities and attractions, are not considered.
Spatial scale and resolution	For EU mountain tourism, this project investigates mountain destinations in the Alps, Pyrenees and Scandinavia, as well as several selected sites in Eastern Europe, at the NUTS3 level. For beach tourism, this project investigates all EU coastal provinces at the NUTS3 level except for central and northern Britain, Ireland and northern Scandinavia.
Temporal scale and resolution	Climate change impacts are assessed for the periods 2015-2045 and 2035-2065 at the subnational resolution (NUTS3 Regions).
Accessibility of outputs	Results of this study can be obtained through the project webpage: www.topdad.eu and through the simulation tool: http://topdad.services.geodesk.nl/interactive-tool
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options
Adaptation policy insights	For mountain tourism, the results highlight the requirement to enhance attractiveness outside the winter season. For beach tourism, the results point to a need of increasing flexibility in providing tourist services outside the traditional summer season for Mediterranean Europe, and to be prepared to face increased competition from northern Europe destinations whose attractiveness will increase under climate change.
Relevant application	The results of this study are only applicable for the specific cases. For mountain tourism, results highlight that "for many European

	skiing destinations, the potential for climate-induced increases of summer overnights stays might not be big enough to counterbalance the expected losses of winter overnight stays. Hence, without further improvements in the relative attractiveness of these regions, they are in danger of facing a climate-induced loss in overnight stays and tourism revenues. The magnitude of the loss reflects a region's exposure to climate change impacts and thus informs affected stakeholders about the need and pressure for adequate adaptation strategies." For beach tourism "climatic conditions will improve across Europe during current shoulder seasons (spring and autumn), thus prolonging the beach season. At the same time, competition during shoulder seasons will increase. Mediterranean resorts, hoping to compensate for the expected loss of tourists during midsummer by a prolonged season, will have to compete with other European regions in the shoulder seasons. As a result, they might not be able to fully compensate for the expected loss of overnight stays during midsummer. For northern Europe, small to significant improvements in the climatic conditions for beach holidays are expected, depending on the climate model considered [...]. As long as improvements are only small, the better climate will however not suffice to attract additional overnight stays". (from http://topdad.services.geodesk.nl/web/guest/beach-tourism)
Main reference(s)	www. topdad.eu; topdad.services.geodesk.nl/project-results; Prettenthaler, F., & Dominik, K. (2015). The effects of climate change on alpine skiing tourism a European approach. In The Economics of Weather and Climate Risks Working Paper Series.
Suitability for rapid assessment	No, only an output exploration tool is available. The coupling exercise here is highly complex, involving the integration of five modelling frameworks.
Websites	
Manuals/ training/ videos	
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.7 Tourism	**ICES -Intertemporal Computable Equilibrium System (Tourism Module)**

Model/ tool type and outputs	ICES is a multipurpose tool to assess the impacts of climate change on the economic system, evaluate costs of mitigation and adaptation policies, describe the key role of public sector for mitigation and adaptation policies, and to predict likely future sustainability scenarios. The model's general equilibrium structure supports the analysis of market flows within a single economy and global international flows. This implies moving beyond the "simple" quantification of direct costs, to offer an economic evaluation of second and higher-order effects within specific scenarios, either of climate change, climate policies or different trade and public-policy reforms in the vein of conventional CGE theory. Therefore, ICES can assess multiple impacts and adaptation options.
Open access?	No
Key data inputs	The core model is based on the GTAP database. Climate change impacts are captured as exogeneous shocks to economic variables and/or parameters. The model assesses exogeneous shocks due to changes in tourism flows and expenditures under climate change from the HTM model (The Hamburg Tourism Model, which simulates future tourism flows and international and domestic tourism expenditure based on econometrically estimated equations of departures and arrivals. See related entry) in relation to market service demands and on disposable income in destination countries. One study (Bigano, Bosello, Roson, & Tol, 2008) couples these shocks with sea level rise to capture the combined effect of demand shift and physical impacts.
Key data accessibility/ availability	Bigano, A., Hamilton, J. M., & Tol, R. S. J. (2006). The impact of climate on holiday destination choice. Climatic Change, 76(3–4). https://doi.org/10.1007/s10584-005-9015-0; (Summary of the results of the HTM model used in ICES - full dataset not available)
Strengths	The model evaluates multiple impacts and the relative magnitude of the costs of inaction for each one. This can inform the relative importance of impacts for policy making. To date, it is the only modelling framework to include both push and pull impacts on tourism in a CGE framework.
Assumptions/ limitations	The main assumptions of the general ICES model (detailed under CGE models) are that: the model based on perfectly competitive and frictionless markets may underestimate adjustment costs; technological progress is exogenous; it is ill suited to capture non-market impacts, risk and uncertainty and the dynamics are

	simplified (recursive). Further, the same issues mentioned for the HTM model apply here, which include: climate is only derived from temperature values; there is no distinction made between different types of holidays and tourist activities; and databases are now outdated. Moreover, in ICES, the tourism sector is present solely as a component of the market services sector, and hence the sectoral resolution is coarse and no distinction can be made across the effects for the various kinds of tourism, such as beach versus mountain tourism. Ad-hoc assumptions were necessary to rescale tourism input data to the market service sector, which implies that macroeconomic impacts are actually described in terms of a broader economic entity, and hence tourism-specific dynamics could be coarsely captured.
Spatial scale and resolution	ICES has a flexible geographical resolution. The study includes impacts on the energy sector (Eboli *et al.*, 2010) in eight world regions; the regionalized version of the model considers 70 sub-national regions in the Euro-Mediterranean area: Italy (20 NUTS-2 regions), (NUTS - Nomenclature des Unités Territoriales Statistiques) France (22 NUTS-2 regions), Spain (19 NUTS-2 regions), Portugal (5 NUTS-2 regions) and Greece (4 NUTS-1 regions).
Temporal scale and resolution	5-year intervals up to 2050.
Accessibility of outputs	Yes, on the model webpage: https://www.icesmodel.org/
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The magnitude and trend of either positive (increase in the underlying variable) or negative (decrease in the underlying variable) variations in tourism flows could directly affect regional economies. At a global scale, climate change could result in reductions in welfare, creating regional inequality.
Relevant application	Research projects such as: CALDAM-ENV Link – Calibration of projected climate change damages in ENV-Linkages; COACCH (CO-designing the Assessment of Climate CHange costs) CALDAM-ENV Link resulted in a coordinated calibration of assessment models to support OECD policy analyses (not a part of the project); COACCH is work in progress and has generated an assessment of climate change costs of inaction for various sectors of the economy including tourism, to be discussed and elaborated with stakeholders in the further stages of the project.
Main reference(s)	Berrittella, M., Bigano, A., Roson, R., & Tol, R. S. J. (2006). A general equilibrium analysis of climate change impacts on tourism. Tourism Management, 27(5).

	https://doi.org/10.1016/j.tourman.2005.05.002; Bigano, A., Bosello, F., Roson, R., & Tol, R. S. J. (2008). Economy-wide impacts of climate change: A joint analysis for sea level rise and tourism. Mitigation and Adaptation Strategies for Global Change, 13(8), 765–791. https://doi.org/10.1007/s11027-007-9139-9 (Joint tourism and sea level rise study)
Suitability for rapid assessment	No rapid use of the model or obtaining the data, however it is possible to purchase some data.
Websites	www.icesmodel.org
Manuals/ training/ videos	
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.7 Tourism	**Snow Reliability Indexes**

Model/ tool type and outputs	Snow reliability indices are a broad group of physical indicators that capture the technical suitability of mountain destinations for skiing. The future reliability of mountain destinations can be assessed by correlating snow reliability conditions to snow line projections and its expected persistence at any given altitude, computable using climate models and orographic data. Indices differ in terms of the quantity of snow which is considered reliable, with 5cm constituting 'reliable' in earlier studies while more recent and robust studies use 30cm. Indicators also differ in their temporal dimension in relation to the persistence of snow cover for a minimum number of days or during peak periods of the year, such as Christmas. More recent studies account for the role of snowmaking, which to a certain extent, can effectively compensate for unfavourable natural snow cover conditions.
Open access?	No
Key data inputs	Data on altitude, orography/ orientation of ski slopes, snow precipitation, snowline location, temperature and presence of snowmaking infrastructures are required.
Key data accessibility/ availability	GIS data for orography information, climate models for climate data, local business associations for snowmaking facilities. When used to inform the general public, the information captured by these indexes is usually translated into accessible forms such as using a 1 to 5 scale.
Strengths	These indicators can be calculated with a high geographic resolution, and hence can provide precise information to inform the development of business strategies and investment decisions of tourist operators in a given area.
Assumptions/ limitations	There is a wide array of possible indicators in the literature, constituting a challenge for users to select the appropriate indicator. Different locations may require greater conservative indicators than others due to mountain slope geographical features (steep slopes facing south may experience the quality of the snow cover deteriorate faster than mild slopes facing north; altitude is also an important factor here); the significant length and timing of the ski season can also vary, making some indicators of limited use at certain locations, because the minimal duration and /or the exact timing of the period in which certain conditions must be met in order to have a specific indicator -originally designed for other locations - yield a positive indication of snow reliability may be hardly met at certain locations where nonetheless, winter sports

	are usually feasible during the season. Further, adequate consideration of snowmaking is still limited in the literature.
Spatial scale and resolution	Local, given that the indicators must adequately portray the situation at each destination in order to be useful. The resolution can be high, specifying the varying snow quality of different slopes within the same ski area.
Temporal scale and resolution	The time scale can vary however, time intervals must be at least seasonal, preferably monthly.
Accessibility of outputs	Outputs can be found in various peer reviewed publications and are easily accessible to a non-technical user.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options; 5) Implementation; 6) Monitoring & evaluation
Adaptation policy insights	Steiger *et al.* (2017) note that there is "growing interest from increasing range of decision-makers, including institutional investors, ski area owners, grooming and snowmaking equipment companies, insurance companies, and real estate developers, for climate risk information and expert advice on climate change implications for individual ski areas and the wider ski industry. This demand is likely to increase given the predicted rise in frequency of warm and snow-poor ski seasons, subsequently impacting on ski tourism operations and destination reputations, with climate risk disclosure requirements becoming increasingly formalized within the financial community. Therefore, facilitation of accelerating climate change impacts and their implications could support the adoption of adaptation measures that could develop a greater climate-resilient and sustainable tourism sector across mountain regions globally.”
Relevant application	The snow reliability indexes are included in the C3S tourism: https://climate.copernicus.eu/european-tourism . Here, users are able to find the relevant information for their destination of choice.
Main reference(s)	Steiger, R., Scott, D., Abegg, B., Pons, M., & Aall, C. (2019). A critical review of climate change risk for ski tourism. Current Issues in Tourism, 22(11), 1343–1379.
Suitability for rapid assessment	Computing the indexes can be simple (in most instances, this amounts to summing the number of days a certain condition is met). However, navigating the geographic and meteorological databases searching for the right data to compute the indexes can be challenging.
Websites	

Manuals/ training/ videos	
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.7 Tourism	**Tourism Climate Index (TCI)/ Holiday Climate Index (HCI)**

Model/ tool type and outputs	These are a group of indicators that capture the climatic suitability of destinations for tourism-related activities. They are weighted sums of sub-indices, each one capturing a key aspect of climate suitability for tourist activities. They have been refined to accommodate threshold values for certain climatic variables, such as wind and precipitation; adjust the original index formulae which allocated excessive weighting to the effect of temperature, providing the opportunity for acceptable scores for windy and high precipitation days; include cloud cover to account for tourism aesthetics; and to differentiated according to holiday types. This yielded, for instance, the Holiday Comfort Index for sun and sand tourism and the Urban Comfort Index for urban destinations. A slightly different approach has been adopted by the Physiologically Equivalent Temperature index, which attempts to capture the perception of climate rather than climate itself. All of these indices represent mathematical aggregations of climate variables and can be projected using future values of the climate variables derived from climate models.
Open access?	The indices are simple formulas, published in the literature, that can be readily re-computed using climate data.
Key data inputs	The original formulation required the following data: maximum daily temperature and minimum daily relative humidity (%), which combined yield the daytime comfort index; mean daily temperature and mean daily relative humidity (%) which combined yield the daily comfort index; precipitation (mm); sunshine (hrs) and wind (km/h). Other formulae, such as the Holiday Comfort Index (Scott *et al.*, 2016) include other climate variables such as cloud cover.
Key data accessibility/ availability	Any open access climate model can provide the input data required. Issues may arise though in relation to the geographical resolution for local applications.
Strengths	These indices provide a quick and easy outlook on the links between climate conditions and attractiveness of destinations. They can be adapted to different market sectors, computed at almost any geographical and temporal level of disaggregation, and are able to capture seasonal variations in the suitability of destinations resulting from climate change.
Assumptions/ limitations	Using these indices for future tourism scenarios under climate change assumes a direct relationship between climate conditions and tourists' preferences and assigns climate as the primary determinant in tourism destination choice. While there is some

	empirical evidence correlating TCI and tourists' destination choices (de Freitas, Scott *et al.*, 2008), this evidence is not comprehensive nor exhaustive for all market segments. Moreover, the determination of the weights can be arbitrary if based on expert judgment, as such in early studies, or of significance limited to the area of interest if they have been estimated based on surveys of the tourists at the destination under scrutiny. However, it could also be argued that the weightings could retain validity between similar destinations catering for the same kind of tourists: for instance, it could be expected that people usually going to Costa Brava for their holidays are relatively indifferent between destinations in that area, and hence the weightings can be transferrable/ similar given to climate characteristics of all Costa Brava destinations. However, the same weights might be less appropriate for, for example, Sardinia and less so for Brighton. Finally, these indices are not able to directly provide a quantification of climate changes on tourism in relation to economics and need to be incorporated as drivers in a demand or CGE model.
Spatial scale and resolution	These indexes can be applied from regional to local level, dependent on the geographical resolution of the climate models providing the input data. Highly aggregate indices at the country level, however, provide minimal useful information because they amalgamate diverse climatic conditions of different destinations, and therefore do not provide a clear representation of tourism attractiveness.
Temporal scale and resolution	The temporal resolution is dependent on the available climate data resolution for the projections at the location(s) under investigation.
Accessibility of outputs	The index outputs are accessible: there are numerous publications available in the literature, of which some are open access. Indices can also be rapidly computed from climate modelling data.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options; 6) Monitoring & evaluation
Adaptation policy insights	They can provide useful indications regarding changing patterns in tourism seasons, and hence support the adjustment of business plans and policies accordingly.
Relevant application	TCI and HCI are included in the C3S tourism: https://climate.copernicus.eu/european-tourism . Here, users are able to find the relevant information for their destination of choice.
Main reference(s)	Mieczkowski Z (1985) The Canadian Geographer/Le Géographe Canadien, 29(3), 220–233. https://doi.org/10.1111/j.1541-0064.1985.tb00365.x;

	Dubois, G., Ceron, J. P., Dubois, C., Frias, M. D., & Herrera, S. (2016). Reliability and usability of tourism climate indices. Earth Perspectives, 3(1), 2. https://doi.org/10.1186/s40322-016-0034-y; de Freitas, C. R., Scott, D., & McBoyle, G. (2008). A second generation climate index for tourism (CIT): specification and verification. International Journal of Biometeorology, 52(5), 399–407. https://doi.org/10.1007/s00484-007-0134-3; Scott, D., Rutty, M., Amelung, B., & Tang, M. (2016). An inter-comparison of the Holiday Climate Index (HCI) and the Tourism Climate Index (TCI) in Europe. Atmosphere, 7(6). https://doi.org/10.3390/atmos7060080
Suitability for rapid assessment	Computing the indexes can be straight forward (formulas are simple weighted sums). However, navigating the geographic and meteorological databases searching for the right data to compute the indexes can be challenging.
Websites	
Manuals/ training/ videos	
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.7 Tourism	**Hamburg Tourism Model (HTM)**

Model/ tool type and outputs	The Hamburg Tourism Model (HTM) simulates future tourism flows and international and domestic tourism expenditure on the basis of econometrically estimated equations of departures and arrivals. Temperature is included as a quadratic term along with other explanatory variables, such as destination's GDP and coast length. By computing bilateral flows between all countries globally and the internal flows of domestic tourism, the HTM is able to account for both push and pull factors**.** The quadratic specification supports the identification of optimal temperatures for tourism, and to correlate tourism demand with alternative future climate scenarios to derive tourist flows and expenditure projections.
Open access?	No
Key data inputs	Input data includes temperature; tourist arrivals and departures, domestic and international, and their expenditures in the base year; country GDP and population in the base year; projections of relevant climate scenarios; and coast length and surface area for each country.
Key data accessibility/ availability	Base year values and projections for population and GDP, geographical features and temperature data are freely available from multiple sources. However, there are no consistent open access datasets for tourist flows, which need to be purchased from the World Tourism Organization or national trade associations or chambers of commerce.
Strengths	HTM accounts for both push and pull drivers; provides global coverage and includes domestic tourism.
Assumptions/ limitations	HTM limitations include: climate is only derived from temperature values; there is no distinction made between different types of holidays and tourist activities; and databases are now outdated.
Spatial scale and resolution	National level, however downscaling has been performed for selected countries (UK, Ireland, Germany, Italy) at the regional level (NUTS2 and NUTS3).
Temporal scale and resolution	The time scale outputs are annual and up to 2050.
Accessibility of outputs	The outputs are only available through main publications and are easy for a non-technical user to understand.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change

Adaptation policy insights	The model predicts that current hotspots for tourism, such as Mediterranean Europe, will likely experience a reduction in the number of tourists while northern destinations will likely experience an increase. Domestic tourism will tend to increase across the EU. However, in absolute terms, tourism numbers will generally increase globally due to population and income dynamics.
Relevant application	A downscaled version of this model was used for the Italian Climate Change Adaptation Strategy: https://www.minambiente.it/notizie/strategia-nazionale-di-adattamento-ai-cambiamenti-climatici-0 . Climate change will have a significant impact on coastal destination and provinces containing historical cities because these are traditionally sought by international tourists, who will tend to switch to destinations to those with a milder climate; less internationally popular destination will be less affected due to the increasing trend of domestic tourism; tourism flows projections were used to model climate change impacts on the tourism sector within the ICES model - please refer to the ICES -Tourism Module entry.
Main reference(s)	Hamilton J, Maddison D, Tol R. Climate change and international tourism: a simulation study. Glob Environ Change 2005, 15:253–266; Bigano, A., Hamilton, J. M., & Tol, R. S. J. (2006). The impact of climate on holiday destination choice. Climatic Change, 76(3–4). https://doi.org/10.1007/s10584-005-9015-0; Hamilton, J. M., & Tol, R. S. J. (2007). The impact of climate change on tourism in Germany, the UK and Ireland: A simulation study. Regional Environmental Change, 7(3), 161–172. https://doi.org/10.1007/s10113-007-0036-2
Suitability for rapid assessment	No - The model is complex, the code is no longer freely available, and the dataset needs to be updated.
Websites	
Manuals/ training/ videos	
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.8 Cities and urban areas	**SLEUTH - Slope, Land use, Exclusion, Urban, Transportation and Hill shade**

Model/ tool type and outputs	SLEUTH is a cellular automaton model that simulates urban expansion and the changing surrounding land uses. It can be used as one of a suite of models to contribute to the simulation of the Urban Heat Island (UHI) effect, as well as to anticipate and forecast future changes or trends of development, to describe and assess impacts of future development and to explore the potential impacts of different policies. SLEUTH was developed with predefined growth rules applied spatially to gridded maps of cities in a set of nested loops and was designed to be both scalable and universally applicable. There are four growth rules: spontaneous growth; new spreading centre growth; edge growth; and road-influence growth.
Open access?	Yes - http://www.ncgia.ucsb.edu/projects/gig/Dnload/download.htm
Key data inputs	The model uses two land use maps with a consistent classification scheme, along with at least four urban maps to represent the unique historical pattern of growth required for the model's calibration and application (Gazulis and Clarke, 2006). An exclusion layer is used to control urban growth in areas where urbanisation is restricted according to local land use policies, such as protected areas or water bodies. Outputs from digital elevation models are used to create the slope and hill shade layers for the area of simulation. Finally, it requires multiple weighted road maps from different time periods that determine the probability of urban development according to the accessibility of the location. Further information about input data requirements can be found at: http://www.ncgia.ucsb.edu/projects/gig/About/dtInput.htm
Key data accessibility/ availability	An open data repository for the SLEUTH project can be found at: http://www.ncgia.ucsb.edu/projects/gig/ Repository/SLEUTHapplications.html
Strengths	SLEUTH is a popular land change model that has been applied globally because it is open access, availability of source code and ease of use (Clarke, 2005). It can also be coupled to other social and physical models for a range of applications, including an urban runoff model to study the effect of urbanisation on local microclimate and surface hydrology.
Assumptions/ limitations	SLEUTH biases edge growth, which restricts the suitable level of dispersed growth in fine resolution data. It also has inefficient memory use, inappropriate fit statistics and is unable to identify

	areas where growth is more likely to occur (Jantz *et al.*, 2010). To address these, SLEUTH-3r was devised.
Spatial scale and resolution	The spatial scale is typically for a single urban environment (city-level), with the resolution dependent on the scale of the initial input maps used.
Temporal scale and resolution	Due to the slow nature of urban processes, time intervals are typically 10 years, with no information for development within these time periods. Forecasts can be made for 2100.
Accessibility of outputs	SLEUTH uses GIS software to produce maps of urban development. Therefore, users need to be familiar with using GIS software to apply SLEUTH, but the results are easy to interpret by a non-technical user.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change (if coupled with other models); 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	SLEUTH informs policymakers through anticipating and forecasting future changes or trends of development, by describing and assessing the impacts of future development, and to explore the potential impacts of different policies. Coupled with other models, it can be used to investigate the influence of urban development on the microclimate for effects such as UHI, surface run off for flood risk and sustainable land use.
Relevant application	SLEUTH was coupled with a Town-Energy Balance – Building Energy Model (TEB-BEM) urban climate, NEDUM socio-economic and urban architecture models to assess the impact of long-term urban growth on UHI. Multiple urban land use, social, technological and global trends were tested to develop seven alternative scenarios for socio-economic futures and their relative impact on UHI. These results can be used to inform future land use policies.
Main reference(s)	Chaudhuri, G., & Clarke, K. (2013). The SLEUTH land use change model: A review. Environmental Resources Research, 1(1), 88-105.; Dietzel, C., & Clarke, K. C. (2007). Toward optimal calibration of the SLEUTH land use change model. Transactions in GIS, 11(1), 29-45.; KantaKumar, N. L., Sawant, N. G., & Kumar, S. (2011). Forecasting urban growth based on GIS, RS and SLEUTH model in Pune metropolitan area. International journal of geomatics and geosciences, 2(2), 568-579. ; Liu, X., & Andersson, C. (2004). Assessing the impact of temporal dynamics on land-use change modeling. Computers, Environment and Urban Systems, 28(1-2), 107-124. ; Houet, T., Marchadier, C., Bretagne, G., Moine, M. P., Aguejdad, R., Viguie, V., ... & Masson, V. (2016). Combining narratives and modelling approaches to simulate fine

	scale and long-term urban growth scenarios for climate adaptation. Environmental Modelling & Software, 86, 1-13.
Suitability for rapid assessment	No - SLEUTH can be computationally inefficient and requires calibration for each new study area.
Websites	http://www.ncgia.ucsb.edu/projects/gig/index.html
Manuals/ training/ videos	http://webspace.ship.edu/cajant/documents/ sleuth_training_manual.pdf#page=12&zoom=100,92,96
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.8 Cities and urban areas	**Town Energy Balance/ Building Energy Model**

Model/ tool type and outputs	Town-Energy Balance (TEB) and Building Energy Model (BEM) simulate the energy exchanges between the local atmosphere and buildings: buildings release heat and contribute to the Urban Heat Island (UHI) effect, while buildings' heating and cooling energy requirements also depend on localised meteorological conditions. The TEB model parameterises both the urban surface layer and the roughness sublayer.
Open access?	Yes - TEB: https://github.com/teb-model/teb ; BEM: https://github.com/emoncms/openbem
Key data inputs	TEB uses energy budgets for roofs, walls, windows and roads; outputs from BEM; atmospheric data and surface cover information. BEM use energy budgets for floors, internal mass and indoor air; heating and cooling energy demands; waste fluxes of sensible and latent heat; and air exchange rate due to ventilation. Human behaviour can be incorporated into these models to include energy demand variations during peak activity times.
Key data accessibility/ availability	Surface cover information comes from the Corine Land Cover database with a horizontal resolution of 250m. Atmospheric data can be obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF), which are updated every six hours. Other data needs to be locally obtained. For example, in France, the French Geographical Institute provides information on building morphology, and the French Institute on Economics and Statistics (INSEE) provides population census data, density and practices relating to building energy consumption.
Strengths	TEB and BEM are readily coupled with other models to examine a wide range of urban dynamics, such as the coupling with the Interaction Soil Biosphere Atmosphere (ISBA) model to investigate the impact of green spaces on UHI.
Assumptions/ limitations	TEB uses a canyon approach where the urban geometry is simplified and represented by a road boarded by buildings (Masson, 2000). Within a grid, all urban canyons are identical, with the same building height and road width, and all canyon orientations exist with the same likelihood. Vegetation is considered as an open area that is not subject to shadow effects of buildings and to radiation trapping within the canyon. The turbulent fluxes, especially for vegetation, are calculated using inadequate conditions since they are based on meteorological forcing provided above buildings instead of within the street (Lemonsu *et al.*, 2012). There is also a lack of information available regarding residential air conditioning

	and ventilation which are important particularly in areas where heating plays little to no role (Schoetter *et al.*, 2017).
Spatial scale and resolution	TEB can operate at a 250m^2 resolution. BEM works at around 100m^2 (fine-scale mesoscale modelling) to around 100km^2 (for representation of urbanised areas in global climate models).
Temporal scale and resolution	The time resolution can be hourly to capture diurnal fluctuations in energy use and span multiple days or be averaged out over months.
Accessibility of outputs	TEB models produce graphs of surface flux (W/m^2) over time, which are accessible for a non-technical user to interpret.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options; 6) Monitoring & evaluation
Adaptation policy insights	TEB and BEM models can be used to simulate the diurnal fluctuations in UHI across an urban area. This can subsequently be used to identify potential adaptation measures for modifying building energy use to support the reduction in the UHI effect. This has further implications for health of the urban population and energy demands under climate change.
Relevant application	TEB was used to simulate UHI over Rotterdam, which correlated closely with observed warming across urban areas in The Netherlands, highlighting the effectiveness of TEB to capture diurnal fluctuations in UHI. This study will subsequently be used to inform strategies related to the UHI effect, human comfort and urban air quality (Jansson *et al.*, n.d).
Main reference(s)	Masson, V. (2000). A physically-based scheme for the urban energy budget in atmospheric models. *Boundary-layer meteorology*, *94*(3), 357-397. Schoetter, R., Masson, V., Bourgeois, A., Pellegrino, M., & Lévy, J. P. (2017). Parametrisation of the variety of human behaviour related to building energy consumption in the Town Energy Balance (SURFEX-TEB v. 8.2). Geoscientific Model Development, 10(7), 2801. Lemonsu, A., Masson, V., Shashua-Bar, L., Erell, E., & Pearlmutter, D. (2012). Inclusion of vegetation in the Town Energy Balance model for modelling urban green areas. Piringer, M., Grimmond, C. S. B., Joffre, S. M., Mestayer, P., Middleton, D. R., Rotach, M. W., ... & Karppinen, A. (2002). Investigating the surface energy balance in urban areas–recent advances and future needs. Water, Air and Soil Pollution: Focus, 2(5-6), 1-16.

	Jansson, C., Samuelsson, P., and Lindstedt, D. (no date) Using the Town Energy Balance model (TEB) in regional climate simulations over the Netherlands. Rossby Centre internal document
Suitability for rapid assessment	No - significant quantities of data are required for use of these models.
Websites	https://github.com/teb-model/teb
Manuals/ training/ videos	-
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.8 Cities and urban areas	**NEDUM**

Model/ tool type and outputs	NEDUM is a dynamical Land-Use-Transport-Interaction model which dynamically describes how transport network influences land-use across a city. There are four main variables: rents, population density, dwelling size and housing density based on the floor-area ratio. NEDUM aims to explain urban spatial distribution based on two mechanisms, which translates into "if the price of transportation increases, households will have less incentive to live in the suburbs and the city density will increase close to the centre" (Viguié and Hallegate, 2010).
Open access?	No
Key data inputs	Demographic data includes municipality population sizes and the average household size; mean disposable household income; total surface area, percentage of surface urbanised and surface dedicated to housing; rent prices, real estate price evolution; accommodation size; transportation costs for private vehicles and public transport and trip duration.
Key data accessibility/ availability	Data needs to be obtained locally. For example, in France, the majority of demographic data can be obtained from the French Institute on Economics and Statistics (INSEE).
Strengths	NEDUM, once fully calibrated, can accurately simulate historical urban evolution dynamics. It can also be coupled to other models, such as Town Energy Balance models, to simulate the Urban Heat Island (UHI) effect.
Assumptions/ limitations	The city structure and characteristics are assumed to be determined by the presence of jobs, which are all assumed to be located in the city centre. Additionally, city characteristics are assumed to depend only on the distance to the centres, ie. the city is axis symmetrical.
Spatial scale and resolution	NEDUM can simulate for a single urban area, with size dependent on the scale and resolution of the input data.
Temporal scale and resolution	NEDUM could simulate socio-economic dynamics for a hundred years at an annual resolution.
Accessibility of outputs	Outputs include graphs of varying socio-economic variables such as the median income per tax household in a year against distance from the city centre or over time. These graphs are accessible to interpretation by a non-technical audience.

Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	NEDUM simulates future socio-economic dynamics, which determine urban morphology. This has implications for climate and flood vulnerability and can be coupled with other models such as SLEUTH and Town Energy Balance models to investigate UHI. Subsequent adaptation options can be tested using the outputs of NEDUM to determine urban population vulnerability.
Relevant application	NEDUM was coupled with TEB-BEM urban climate, SLEUTH geographic expansion and urban architecture models to assess the impact of long-term urban growth on UHI. Multiple urban land use, social, technological and global trends were tested to develop seven alternative scenarios for socio-economic futures and their relative impact on UHI. These results can be used to inform future land use policies.
Main reference(s)	Viguié, V., & Hallegatte, S. Technical report on NEDUM model development.; Houet, T., Marchadier, C., Bretagne, G., Moine, M. P., Aguejdad, R., Viguie, V., ... & Masson, V. (2016). Combining narratives and modelling approaches to simulate fine scale and long-term urban growth scenarios for climate adaptation. *Environmental Modelling & Software*, *86*, 1-13.
Suitability for rapid assessment	No - the model requires significant quantities of data and calibration for each case study.
Websites	-
Manuals/ training/ videos	-
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.8 Cities and urban areas	**UrbClim (Urban Climate Modelling)**

Model/ tool type and outputs	UrbClim allows users to perform operational urban heat island/heat stress assessments (global applicability, developed at VITO). The model solves a set of simplified prognostic flow equations for the atmospheric boundary layer and contains detailed urban surface physics. The model has undergone extensive validation for several European (Antwerp, Almada, Athens, Barcelona, Berlin, Bilbao, Brussels, Ghent, London, Paris, Skopje) and global cities (New Delhi, Colombo). From this, it has consistently emerged that the model has an accuracy at least as good as that of more complex models. For more detailed information about the UrbClim model: De Ridder, K., D. Lauwaet, and B. Maiheu, 2015. UrbClim – a fast urban boundary layer climate model. Urban Climate, 12, 21-48.
Open access?	No
Key data inputs	Besides model configuration data as land use and vegetation data (mostly provided using remote sensing data), UrbClim requires: - 3-hourly surface data: downwelling short-wave radiation, downwelling long-wave radiation, surface air pressure and precipitation; - monthly sea surface temperature (in case of a city located near the coast); - 3-hourly vertical profile (lowest 3km of atmosphere) data of air temperature, specific humidity, U and V wind components
Key data accessibility/ availability	ERA5 or RCM which are available at Copernicus. The model can also be driven with model output from global or regional climate projections. Future urban growth impact analysis can be done using the VITO Geodynamix model. Geodynamix is a toolbox for spatially dynamic land use modelling at high spatial resolutions. The toolbox allows to simulate land use scenarios at high spatial and time-resolution, i.e. 1ha spatial scale and in time-steps of 1 year. Results allow to evaluate and adjust considered spatial planning strategies, in order to anticipate on the social-economic and climatic drivers affecting territorial change and optimise the balance between environment, social well-being and economic development.
Strengths	The UrbClim model is unique in its capability of simulating long time periods at a high spatial resolution (~100 m) while not compromising on accuracy. Compared to traditional 'urbanized' mesoscale atmospheric models, UrbClim is faster by more than two orders of magnitude. As a result, it is one of the only models worldwide that is capable of conducting simulations of sufficient

	length (tens of years) and number (nested within an ensemble of large-scale climate models) to be of relevance for the generation of proper local climate statistics, including an uncertainty range.
Assumptions/ limitations	The model is a physical boundary layer downscaling model. Not included are cloud physics and precipitation (taken from forcing data).
Spatial scale and resolution	Spatial resolution of output fields ranges from 100m to 1km.
Temporal scale and resolution	Hourly output fields are generated.
Accessibility of outputs	Raw output fields are in NetCDF-format. Post-processing tools are available to generate maps in user friendly formats. Raw hourly output fields of basic meteorological quantities (temperature, humidity, wind speed components), are generally further combined or aggregated to yield, for example, the number of heat wave days or cooling degree days.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 4) Assessing adaptation options
Adaptation policy insights	The UrbClim model downscales large-scale climate information to the urban level providing accurate information about the heat stress present in its city taking into account the urban heat island effect. The model output resolution of 100m allows users to perform hot and cool spot analysis which is needed to set up heat mitigation strategies and action plans.
Relevant application	The model has been applied for many cities worldwide. A case study for the city of Antwerp is documented inside the EEA Climate-ADAPT service: https://climate-adapt.eea.europa.eu/metadata/case-studies/adapting-to-heat-stress-in-antwerp-belgium-based-on-detailed-thermal-mapping As part of the Copernicus Climate Change Service (C3S) European Health contract, VITO provided urban climate data for 100 European cities: https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-urban-climate-cities?tab=overview
Main reference(s)	URBCLIM: De Ridder, K., et al. UrbClim – a fast urban boundary layer climate model. Urban Climate, 2015 (12), 21-48. García-Díez, M., et al. Advantages of using a fast urban boundary layer model as compared to a full mesoscale model to simulate the urban heat island of Barcelona. Geoscientific Model

	Development, 2016 (9), 4439–4450. Hooyberghs, H., et al. Influence of climate change on summer cooling costs and heat stress in urban office buildings. Climatic Change, 2017 (144), 721-735. Maheng, D., et al. The Sensitivity of Urban Heat Island to Urban Green Space—A Model-Based Study of City of Colombo, Sri Lanka. Atmosphere 2019 (10), 151. Lauwaet, D., et al. Detailed urban heat island projections for cities worldwide: dynamical downscaling CMIP5 global climate models. Climate, 2015 (3), 391-415, doi:10.3390/cli3020391. Sanchez-Martinez, G., et al. Projected heat related mortality under climate change in the metropolitan area of Skopje. BMC Public Health, 2016(16), 407. Sharma, R., et al. Urban Heat Island and Future Climate Change—Implications for Delhi's Heat. J Urban Health (2019) 96, 235. GEODYNAMIX: White, R., Engelen, G., & Uljee, I. (2015). Modeling cities and regions as complex systems. From theory to planning applications. Cambridge, MA, USA, & London, UK: The MIT Press. Crols, T. (2017), Integrating network distances into an activity based cellular automata land-use model. Semi-automated calibration and application to Flanders, Belgium. PhD dissertation, VUB-VITO, Brussels.
Suitability for rapid assessment	The model can be applied rapidly using Copernicus data (C3S, CLMS).
Websites	https://vito.be/en/product/urbclim-urban-climate-modelling
Manuals/ training/ videos	Available upon request
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.9 Critical infrastructure	**Critical Infrastructures: Relations and Consequences for Life and Environment (CIrcle)**

Model/ tool type and outputs	CIrcle is a tool to support the analysis of (inter)dependencies between critical infrastructures. Failure of critical infrastructures may lead to cascading effects exceeding the area directly affected by a hazard, such as large-scale power outages. By creating an interactive participative session in which causal relationships between critical infrastructure are mapped, insight can be gained regarding how failure of one asset can affect another asset.
Open access?	Yes
Key data inputs	Information on (inter)dependencies between critical infrastructures identified with stakeholders, including network operators and emergency services.
Key data accessibility/ availability	CIrcle uses open data and models supported by Deltares in combination with information on critical infrastructure (inter)dependencies that is gathered during workshops with stakeholders.
Strengths	Interactive qualitative tool that allows and enhances stakeholder participation for the identification of cascading effects. Moreover, the CIrcle tool can also help to understand the risk perception of the different participants/stakeholders.
Assumptions/ limitations	Cannot be used for the quantification of damages to physical assets and losses due to disrupted services.
Spatial scale and resolution	CIrcle is a qualitative tool that can be used on multiple spatial scales depending on stakeholder input.
Temporal scale and resolution	CIrcle is a qualitative tool that can be used on multiple timescales depending on stakeholder input.
Accessibility of outputs	Directly accessible from the CIrcle tool.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	This tool helps to bring together stakeholders and experts to assess the interdependencies between critical infrastructures, and hotspots for intervention can be identified to prevent unwanted cascading effects in the future.
Relevant application	Extreme weather conditions, such as flash floods, heavily affected roads in Murcia, Spain. CIrcle helped to bring together stakeholders

	and experts to assess the (inter)dependencies between critical infrastructures and identify the vulnerability and resilience of critical infrastructures in the Murcia area. See https://circle.deltares.org/index.php?p=success-stories for more relevant applications of the CIrcle tool.
Main reference(s)	See websites
Suitability for rapid assessment	Yes
Websites	https://circle.deltares.org/ https://www.deltares.nl/en/software/circle-critical-infrastructures-relations-and-consequences-for-life-and-environment-2/
Manuals/ training/ videos	See main website
Wikipedia page	N/A
Other	

2) Sectoral models for impact and adaptation assessment	2.9 Critical infrastructure	**Multiregional Impact Assessment Model (MRIA)**

Model/ tool type and outputs	The failure of critical infrastructures can cause disruptions with widespread economic impacts. These macroeconomic impacts can be quantified using the MRIA. This a multiregional supply-use model that estimates a new economic equilibrium in the short-term disaster aftermath. The MRIA allows for a supply shock, i.e. constraints due to disrupted services, and spatial substitution effects (Koks *et al.*, 2019a). By including geospatial information on critical infrastructures, the wider economic impacts of business disruption due to failure of these critical infrastructures can be quantified.
Open access?	No
Key data inputs	Exposure data on critical infrastructures, such as detailed information on roads; hazard data including flood maps with a return period of 50 years; as well as information on the dependencies between business activities and infrastructural assets.
Key data accessibility/ availability	Infrastructure hazard data can be accessed from Open Street Map (open access). Local hazard data is not always available. A fall-back option is to use coarser-resolution global hazard datasets.
Strengths	The traditional input-output (IO) model is suitable to explore demand-side disruptions, however, reaches its limitations when considering supply-side disruptions while natural disasters primarily affect this side of the economy. The MRIA improves on this by accounting for a supply shock and spatial substitution effects.
Assumptions/ limitations	Requires a large amount of input data to run and a thorough understanding of the (inter)dependencies of critical infrastructures. This could be problematic when applying the model to a new area with limited input data available.
Spatial scale and resolution	Depends on input data.
Temporal scale and resolution	Depending on input data.
Accessibility of outputs	Directly accessible from the model.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	This model can assess the potential benefits of adaptation policies in terms of the avoided damages because of this policy. Only

	adaptation policies that have a direct impact on critical infrastructures can be assessed.
Relevant application	The first application of the integration of critical infrastructures at detailed level in the MRIA has been carried out by Koks *et al.* (2019b). The study uses geospatial information on the location of electricity substations and business areas exposed to flooding in the United Kingdom (UK).
Main reference(s)	Koks, E.E. Pant, R., Husby, T., Többen, J. & Oosterhaven, J. (2019a). Multiregional Disaster Impact Models: Recent Advances and Comparison of Outcomes. In Okuyama, Y, & Rose, A. (Eds.), Advances in Spatial and Economic Modelling of Disaster Impacts (pp. 191-218). Switzerland: Springer. Koks, E.E., Pant, R., Thacker, S. & Hall, J.W. (2019b). Understanding Business Disruption and Economic Losses due to Electricity Failures and Flooding. International Journal of Disaster Risk Science, 10, 421-438.
Suitability for rapid assessment	No - it requires a lot of input data and calibration.
Websites	N/A
Manuals/ training/ videos	N/A
Wikipedia page	N/A
Other	

2) Sectoral models for impact and adaptation assessment	2.9 Critical infrastructure	**Rapid Natech Risk Assessment Tool (RAPID-N)**

Model/ tool type and outputs	Natural hazard affecting critical chemical infrastructure can trigger accidents involving the releases of toxic substances, fires and explosions. These impacts could eventually result in health effects, environmental pollution and economic losses. Natural hazard triggered technological accidents are so-called NaTech events. The Rapid Natech Risk Assessment Tool (RAPID-N) provides an online, integrated NaTech risk assessment and mapping framework. The tool supports different types of plant units and natural hazards and allows assessments with minimum data input.
Open access?	Yes
Key data inputs	The RAPID-N tool is driven by an extensive dataset containing information on different parameters and a basic set of fragility curves. Missing data are estimated from available data by using scientific equations and estimation methods. Custom damage classifications and fragility curves can be created.
Key data accessibility/ availability	RAPID-N database is based on a limited number of studies on NaTech related damage states and fragility curves.
Strengths	Web-based software application allowing for easy and user-friendly data entry, complementary data estimation and rapid risk assessment.
Assumptions/ limitations	Extensive dataset based on limited studies on NaTech risks.
Spatial scale and resolution	RAPID-N allows assessments at local and regional levels.
Temporal scale and resolution	This is dependent on the input data and whether it is used to examine future climate adaptation strategies. Time scale depends on the time scale of the hazard or exposure data that are available.
Accessibility of outputs	Directly accessible from the tool. Results are presented as summary risk reports and NaTech risk maps.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options; 6) Monitoring & evaluation
Adaptation policy insights	RAPID-N can be used at different stages of the NaTech risk management process. In the prevention and preparedness phase, it can be used to assess and map the potential consequences of NaTech events for land-use and emergency-planning purposes.

	After a NaTech event, the RAPID-N allows for rapidly estimating the damage and consequences.
Relevant application	The tool has been used to assess the impact of earthquakes on oil transport pipelines in Europe. RAPID-N can be used by various stakeholders, such as industry and authorities, to support the identification of weaknesses in the network and allows the assessment of the potential consequences. This information can be used to reduce risks to a desired level.
Main reference(s)	Girgin, S. (2012). RAPID-N Rapid Natech Risk Assessment Tool. User Manual Version 1.0. Girgin, S. & Krausmann, E. (2013). RAPID-N: Rapid natech risk assessment and mapping framework. Journal of Loss Prevention in the Process Industries, 26(6), 949-960. https://doi.org/10.1016/j.jlp.2013.10.004 Girgin, S & Krausmann, E. (2016). Pipeline NaTec Risk Assessment with RAPID-N.
Suitability for rapid assessment	Yes
Websites	https://rapidn.jrc.ec.europa.eu/
Manuals/ training/ videos	See main website
Wikipedia page	N/A
Other	

2) Sectoral models for impact and adaptation assessment	2.9 Critical infrastructure	**Critical Infrastructure Elements Resilience Assessment (CIERA)**

Model/ tool type and outputs	CIERA allows for an assessment of the level of resilience of critical infrastructure elements, thereby evaluating the robustness, ability to recover functionality after the occurrence of a disruptive event and the capacity to adapt to previous disruptive events. Both the assessment of technical and organizational resilience is included in the research. The tool can be used to identify weak points in order to strengthen resilience.
Open access?	No
Key data inputs	Knowledge on functioning of critical infrastructural asset. This includes information on the level of crisis preparedness, redundancy, detection capability, responsiveness, physical resistance as well as material, financial and human resources or processes required for element recovery following a disruptive event.
Key data accessibility/ availability	Knowledge from stakeholders.
Strengths	CIERA assesses the level of resilience of individual critical infrastructure assets. Moreover, not only can CIERA be used to assess the resilience of critical infrastructure to natural disasters, but also for threats from technogenic, such as process-technological, and anthropogenic, such as cyber-attack, origins.
Assumptions/ limitations	The assessment is limited to individual assets of critical infrastructure. In addition, the approach is static and must always be aimed at a particular disruptive event.
Spatial scale and resolution	Infrastructural asset level.
Temporal scale and resolution	This is dependent on the input data and whether it is used to examine future climate adaptation strategies.
Accessibility of outputs	Directly accessible from the assessment.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	CIERA provides insights in various predefined components of resilience. The score per variable can be used to pinpoint weaknesses in the infrastructural asset on a technical and organizational level.

Relevant application	A control room of an electricity distribution operator is used as a case study (Rehak *et al.*, 2019). Scores on robustness, recoverability and adaptability were assigned using various variables taking into account the functional, structural and performance parameters. Weak points can be identified, which is useful to develop appropriate measures to strengthen infrastructural resilience.
Main reference(s)	Rehak, D., Senovsky, P., Hromada, M., & Lovecek, T. (2019). Complex approach to assessing resilience of critical infrastructure elements. International Journal of Critical Infrastructure Protection, 25, 125-138. https://doi.org/10.1016/j.ijcip.2019.03.003
Suitability for rapid assessment	Yes
Websites	N/A
Manuals/ training/ videos	N/A
Wikipedia page	N/A
Other	

2) Sectoral models for impact and adaptation assessment	2.9 Critical infrastructure	**DamageScanner**

Model/ tool type and outputs	A python package that is (loosely) based on the original DamageScanner, which calculated potential flood damages based on inundation depth and land use using depth-damage curves in the Netherlands. The DamageScanner was originally developed for the 'Netherlands Later' project (Klijn *et al.*, 2007). The original land-use classes were based on the Land-Use Scanner in order to evaluate the effect of future land-use change on flood damages. This package aims to make this method widely available and for everyone to use. Next to a (generalized) function for estimating damages based on raster data, it also includes a damage assessment function using vector land-use data. The latter functionality is useful for assessing critical infrastructures at a detailed level. Even though the method is initially developed for flood damage assessments, it can calculate damages for any hazard using a required fragility curve (i.e. a one-dimensional relation).
Open access?	Yes
Key data inputs	Damage or fragility curves, which provide the relationship between the intensity of the hazard and the potential damage to the critical infrastructure assets; maximum damages for each critical infrastructure type to be assessed; and data on critical infrastructure exposure.
Key data accessibility/ availability	Exposure data of critical infrastructures can be accessed from Open Street Map (open access). Damage curves and maximum damages are found to be in the literature online, however, are highly case specific. Local hazard data are not always available. A fall-back option is to use coarser-resolution global hazard datasets.
Strengths	Open access and widely applicable as long as there are hazard and exposure data available.
Assumptions/ limitations	Choice of damage curves and maximum damages; exposure data or hazard data may not be available in the area of choice; useful for estimating direct damages to critical infrastructure assets rather than indirect effects.
Spatial scale and resolution	Depends on exposure input data.
Temporal scale and resolution	This is dependent on the input data and whether it is used to examine future climate adaptation strategies. Time scale depends on the time scale of the hazard or exposure data that are available.

Accessibility of outputs	Directly accessible from the model. Outputs include damage estimates per critical infrastructure type.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	This model can assess the potential benefits of adaptation policies in terms of the avoided damages because of this policy. Only adaptation policies that have a direct impact on buildings can be assessed.
Relevant application	The DamageScanner has been used widely to assess the benefits of adaptation policies for fluvial and pluvial flooding to residential buildings. For example, the DamageScanner was applied for the assessment of current and future flood impacts in the Netherlands, showing that the potential flood damage is projected to increase over the 21st century (De Moel *et al.*, 2011).
Main reference(s)	Koks. E.E. (2019). DamageScanner: Python tool for disaster damage assessments. Zenodo. http://doi.org/10.5281/zenodo.2551015 De Moel, H., Aerts, J. & Koomen, E. (2011). Development of flood exposure in the Netherlands during the 20th and 21st century. Global Environmental Change, 21(2), 620-627.
Suitability for rapid assessment	Yes - if building footprint and flood hazard data are available.
Websites	https://github.com/ElcoK/DamageScanner
Manuals/ training/ videos	See main website
Wikipedia page	N/A
Other	

2) Sectoral models for impact and adaptation assessment	2.10 Buildings	**Hazard United States Multi-Hazard (HAZUS-MH) Flood Model**

Model/ tool type and outputs	The HAZUS MH Flood Model, which includes a library of more than 900 damage curves for use in estimating damage to various types of buildings and infrastructure. Based on estimated property damage, the model estimates shelter requirements and direct and indirect economic losses arising from floods.
Open access?	No
Key data inputs	Two inputs to the damage module are required to estimate building damage: (1) the building occupancy type and first floor elevation, which typically include design levels; and (2) the depth of flooding at the building or area weighted throughout the census block where the building is located. The model building type may not be known for each building, however it can be estimated from the default inventory using a relationship between the building type and occupancy.
Key data accessibility/ availability	Building footprint data can be accessed from Open Street Map (open access) or open-access region/country-level databases. Local hazard data are not always available. A fall-back option is to use coarser-resolution global hazard datasets.
Strengths	Well-validated model for the United States.
Assumptions/ limitations	This model is specifically built for the United States, so it may be difficult to apply in a European context.
Spatial scale and resolution	Building footprint level.
Temporal scale and resolution	This is dependent on the input data and whether it is used to examine future climate adaptation strategies. Time scale depends on the time scale of the hazard or exposure data that are available.
Accessibility of outputs	The outputs of the damage module are area-weighted estimates of damage as a percent of replacement cost, at the census block or for a given building. These are used as inputs to the induced physical damage and direct economic and social loss modules.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	This model can assess the potential benefits of adaptation policies in terms of the avoided damages because of this policy. Only adaptation policies that have a direct impact on buildings can be assessed.

Relevant application	This model has been applied in various academic exercises to assess the benefits of adaptation policies. For instance, Banks *et al.* (2013) showed that Hazus-MH is a promising tool to be used for adaptation planning. https://link.springer.com/article/10.1007/s11069-013-0876-7
Main reference(s)	Scawthorn, C., Flores, P., Blais, N., Seligson, H., Tate, E., Chang, S., ... & Lawrence, M. (2006). HAZUS-MH flood loss estimation methodology. II. Damage and loss assessment. Natural Hazards Review, 7(2), 72-81.
Suitability for rapid assessment	Yes – possible to conduct "Quick Look" assessments, which supports the user to quickly evaluate potential flooding from specific flood depths at specific locations.
Websites	https://www.fema.gov/hazus-mh-flood-model
Manuals/ training/ videos	N/A
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.10 Buildings	**Multi-Coloured Manual**

Model/ tool type and outputs	The handbook is intended to be a stand-alone "Step-by-Step" guide to assessing the benefits of flood and coastal erosion risk management. When combined with the knowledge of the costs of the plans and schemes required, the user can assess the relationships between the benefits and costs of investment decisions. This comparison should enable the users to identify those risk management plans and schemes which maximise the economic return to England and Wales and, therefore, represent "best value for money" through economic efficiency.
Open access?	No
Key data inputs	Exposure data on individual building footprints, either raster or vector based.
Key data accessibility/ availability	Building footprint data can be accessed from Open Street Map (open access) or open-access region/country-level databases. Local hazard data are not always available. A fall-back option is to use coarser-resolution global hazard datasets.
Strengths	Large building dataset; in depth analysis of vulnerability; possibility of analysing damage on individual components. Considers building fabric and systems; building inventory; external areas such as fences, gardens and sheds; and clean-up costs.
Assumptions/ limitations	Not well validated. Specifically built for the United Kingdom, so it may be difficult to apply elsewhere.
Spatial scale and resolution	Building footprint level.
Temporal scale and resolution	This is dependent on the input data and whether it is used to examine future climate adaptation strategies. Time scale depends on the time scale of the hazard or exposure data that are available.
Accessibility of outputs	Directly accessible from the model. Outputs include damage estimates per building or land-use class type.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	This model can assess the potential benefits of adaptation policies in terms of the avoided damages because of this policy. Only adaptation policies that have a direct impact on buildings can be assessed.
Relevant application	The Multi-Coloured Manual has been applied widely in the UK to assess the potential benefits of adaptation for river and coastal risk

	management. Babovic *et al.* (2019) have used the MCM to create adaptation pathways. The MCM was applied to estimate economic damages in their case study.
Main reference(s)	Penning-Rowsell, E., Priest, S., Parker, D., Morris, J., Tunstall, S., Viavattene, C., ... & Owen, D. (2014). Flood and coastal erosion risk management: a manual for economic appraisal. Routledge.
Suitability for rapid assessment	Yes - if building footprint and flood hazard data are available.
Websites	https://www.mcm-online.co.uk
Manuals/ training/ videos	See main website
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.10 Buildings	**DamageScanner**

Model/ tool type and outputs	A python package that is (loosely) based on the original DamageScanner, which calculated potential flood damages based on inundation depth and land use using depth-damage curves in the Netherlands. The DamageScanner was originally developed for the 'Netherlands Later' project (Klijn *et al.*, 2007). The original land-use classes were based on the Land-Use Scanner in order to evaluate the effect of future land-use change on flood damages. This package aims to make this method widely available and for everyone to use. Next to a (generalized) function for estimating damages based on raster data, it also includes a damage assessment function using vector land-use data. Even though the method is initially developed for flood damage assessments, it can calculate damages for any hazard using a required fragility curve (i.e. a one-dimensional relation).
Open access?	Yes
Key data inputs	Damage or fragility curves, which provide the relationship between the intensity of the hazard and the potential damage to the building; maximum damages for each building type to be assessed; and data on building footprints (either raster or vector-based).
Key data accessibility/ availability	Building footprint data can be accessed from Open Street Map (open access). Damage curves and maximum damages are found to be in the literature online, however, are highly case specific. Local hazard data are not always available. A fall-back option is to use coarser-resolution global hazard datasets.
Strengths	Open access and widely applicable as long as there are flood and exposure data available, such as building footprints.
Assumptions/ limitations	Choice of damage curves and maximum damages; assumptions are required regarding the building type of each building as this is often not widely available; exposure or hazard data may also not be available in the area of choice.
Spatial scale and resolution	Building footprint level. When adopting a raster-based approach, it depends on the input data which could vary from 1x1m to 1x1km.
Temporal scale and resolution	This is dependent on the input data and whether it is used to examine future climate adaptation strategies. Time scale depends on the time scale of the hazard or exposure data that are available.
Accessibility of outputs	Directly accessible from the model. Outputs include damage estimates per building or land-use class type.

Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	This model can assess the potential benefits of adaptation policies in terms of the avoided damages because of this policy. Only adaptation policies that have a direct impact on buildings can be assessed.
Relevant application	The DamageScanner has been used widely to assess the benefits of adaptation policies for fluvial and pluvial flooding to residential buildings. Du *et al.* (2019) presented an integrated modelling framework to simulate the flood risk in Shanghai to analyze the costs and benefits of adaptation strategies used to reduce that risk. See for instance https://www.sciencedirect.com/science/ article/pii/S0959378019307113 or https://link.springer.com/article/10.1007/s10113-013-0514-7.
Main reference(s)	Koks. E.E. (2019). DamageScanner: Python tool for disaster damage assessments. Zenodo. http://doi.org/10.5281/zenodo.2551015
Suitability for rapid assessment	Yes - if building footprint and flood hazard data are available.
Websites	https://github.com/ElcoK/DamageScanner
Manuals/ training/ videos	See main website
Wikipedia page	N/A
Other	

2) Sectoral models for impact and adaptation assessment	2.10 Buildings	**Delft-FIAT**

Model/ tool type and outputs	The Flood Impact Assessment Tool (FIAT) is a flexible open source tool set for building and running flood impact models that are based on the unit-loss method. The modeler can build and run impact models compatible with all major hydro-dynamic and GIS-software. To run the Flood Impact Model, the calculation core can be run using as an executable, a python interpreter, as a service through a website and in an operational flood early warning system (FEWS – see https://publicwiki.deltares.nl/display/FEWSDOC/FIAT+adapter). The calculation core is professionally programmed without a graphical user interface in order to make custom-made application as easy as possible.
Open access?	Yes
Key data inputs	Exposure maps, impact functions and maximum damages, all related through a model configuration file. The exposure maps should be formatted following an open data standard or defacto standard such as Tiff, asc, and need to fulfil some basic requirements. The other inputs are managed through an excel worksheet.
Key data accessibility/ availability	Building footprint data can be accessed from Open Street Map (open access). Damage curves and maximum damages are found to be in the literature online, however, are highly case specific. Local hazard data are not always available. A fall-back option is to use coarser-resolution global hazard datasets.
Strengths	The main advantage of this open-source tool is that it is flexible, as it can accommodate multiple different types of impact categories and these can be easily adjusted by the user. Moreover, it is efficient because the calculation engine can manage large and high-resolution input maps due to block division techniques in the input/output raster and vector files.
Assumptions/ limitations	Choice of damage curves and maximum damages; assumptions are required regarding the building type of each building as this is often not widely available; exposure or hazard data may also not be available in the area of choice.
Spatial scale and resolution	Building footprint level. When adopting a raster-based approach, it depends on the input data which could vary from 1x1m to 1x1km.

Temporal scale and resolution	This is dependent on the input data and whether it is used to examine future climate adaptation strategies. Time scale depends on the time scale of the hazard or exposure data that are available.
Accessibility of outputs	Directly accessible from the model. Outputs include damage estimates per building or land-use class type.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	This model can assess the potential benefits of adaptation policies in terms of the avoided damages because of this policy. Only adaptation policies that have a direct impact on buildings can be assessed.
Relevant application	Delft-FIAT is, for instance, used in the Dynamic Adaptive Policy Pathways (DAPP) approach (section 5.6). This approach aims to support the development of an adaptive plan that can manage conditions of deep uncertainty.
Main reference(s)	Burzel, A., Bouwer, L., De Bruijn, K., Sala Calero, J. (2017). Delft-FIAT: An open-source flood impact analysis tool. 10.5281/zenodo.1400183.
Suitability for rapid assessment	Yes - if building footprint and flood hazard data are available.
Websites	https://publicwiki.deltares.nl/display/DFIAT/Delft-FIAT+Home
Manuals/ training/ videos	See main website
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.10 Buildings	**In-depth Synthetic Model for Flood Damage Estimation (INSYDE)**

Model/ tool type and outputs	INSYDE adopts a synthetic approach consisting of the simulated, step-by-step inundation of residential buildings and in the evaluation of the corresponding damage based on building and hazard features. Such a methodology can also be referred to as a what-if analysis. Damages are first modelled on a component-by-component basis using physically based mathematical functions and are subsequently converted into monetary terms using full replacement costs derived from a reference price list. The damage functions are designed using an expert-based approach with the support of existing scientific and technical literature, loss adjustment studies and damage surveys conducted for past flood events in Italy. The model structure is designed to be transparent and flexible, and therefore it can be applied in different geographical contexts and adapted to the actual knowledge of hazard and vulnerability variables. The model has been tested in a recent flood event in northern Italy. Validation results provided good estimates of post-event damages, with similar or superior performances when compared with other damage models available in the literature. In addition, a local sensitivity analysis was performed in order to identify the hazard variables that have greater influence on damage assessment results.
Open access?	Yes
Key data inputs	Inundation maps (water depth), flow velocity, duration of the hazard and detailed building characteristics.
Key data accessibility/ availability	Building footprint data can be accessed from Open Street Map (open access) or open-access country level databases. Damage curves and maximum damages are found to be in the literature online, however, are highly case specific. Detailed building characteristics are harder to find and often require local data and knowledge. Local hazard data are not always available. A fall-back option is to use coarser-resolution global hazard datasets.
Strengths	The model was validated against loss data collected for a recent flood event in northern Italy and compared with the results provided by several damage models in the literature. INSYDE presents two main strengths. First, damage functions are derived component by component, which supports an in-depth analysis and description of damage mechanisms. Second, not only losses to the building fabric and functions/ systems are modelled, but also costs related to cleaning the building, removing water and waste, and

	drying, which can represent an important share of the total economic damage in some cases.
Assumptions/ limitations	Requires a large amount of input data to run. This could be problematic when applying the model to a new area with limited input data available. In particular, information on flood duration is often not available.
Spatial scale and resolution	Building footprint level.
Temporal scale and resolution	This is dependent on the input data and whether it is used to examine future climate adaptation strategies. Time scale depends on the time scale of the hazard or exposure data that are available.
Accessibility of outputs	Directly accessible from the model. Outputs include damage estimates per building or land-use class type.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	This model can assess the potential benefits of adaptation policies in terms of the avoided damages because of this policy. Only adaptation policies that have a direct impact on buildings can be assessed.
Relevant application	INSYDE can be applied to assess the benefits of adaptation policies for fluvial and pluvial flooding to residential buildings.
Main reference(s)	Dottori, F., Figueiredo, R., Martina, M. L., Molinari, D., & Scorzini, A. (2016). INSYDE: a synthetic, probabilistic flood damage model based on explicit cost analysis.
Suitability for rapid assessment	Yes - if building footprint and flood hazard data are available.
Websites	https://ec.europa.eu/jrc/en/publication/insyde-synthetic-probabilistic-flood-damage-model-based-explicit-cost-analysis, https://github.com/ruipcfig/insyde/
Manuals/ training/ videos	See main website
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.10 Buildings	**Bayesian Network Flood Damage Estimation MOdel for the private sector (BN-FLEMOps)**

Model/ tool type and outputs	The BN-FLEMOps has been developed for flood loss estimation at the level of individual residential buildings, that is, microscale applications, and was first presented by Wagenaar *et al.* (2018). It estimates relative building loss of residential buildings, that is, the relation between the absolute building loss and the replacement value of the building. Building loss includes all costs, such as costs of wages and material, that are associated with repairing the damage to the building structure caused by flooding. In Ludtke *et al.* (2019), the structure of the microscale BN-FLEMOps model is preserved, and European-wide proxy data are acquired and tested for the mesoscale application of the model.
Open access?	No
Key data inputs	Information on hazard return periods, duration of the hazard, inundation maps (water depth), building area (exposure footprint data) and information on flood experience.
Key data accessibility/ availability	Building footprint data can be accessed from Open Street Map (open access) or open-access region/country-level databases. Damage curves and maximum damages are found to be in the literature online, however, are highly case specific. Detailed building characteristics are harder to find and often require local data and knowledge. Local hazard data are not always available. A fall-back option is to use coarser-resolution global hazard datasets.
Strengths	The European approach developed in Ludtke *et al.* (2019) is validated using official loss figures of past flood events in three case study areas of varying spatial scale in Germany, Italy, and Austria. It delivers consistent flood loss estimates and inherently provides uncertainty information.
Assumptions/ limitations	Requires a large amount of input data to run. This could be problematic when applying the model to a new area with limited input data available. In particular, information on flood duration is often not available.
Spatial scale and resolution	Building footprint level. When adopting a raster-based approach, it depends on the input data which could vary from 1x1m to 1x1km.
Temporal scale and resolution	This is dependent on the input data and whether it is used to examine future climate adaptation strategies. Time scale depends on the time scale of the hazard or exposure data that are available.

Accessibility of outputs	Directly accessible from the model. Outputs include damage estimates per building or land-use class type.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	This model can assess the potential benefits of adaptation policies in terms of the avoided damages because of this policy. Only adaptation policies that have a direct impact on buildings can be assessed.
Relevant application	BN-FLEMOps can be applied to assess the benefits of adaptation policies for fluvial and pluvial flooding to buildings.
Main reference(s)	Wagenaar, D., Lüdtke, S., Schröter, K., Bouwer, L. M., & Kreibich, H. (2018). Regional and temporal transferability of multivariable flood damage models. Water Resources Research, 54(5), 3688-3703. Lüdtke, S., Schröter, K., Steinhausen, M., Weise, L., Figueiredo, R., & Kreibich, H. (2019). A consistent approach for probabilistic residential flood loss modeling in Europe. Water Resources Research.
Suitability for rapid assessment	No - it requires a lot of input data and calibration.
Websites	https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019WR026213
Manuals/ training/ videos	See main website
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.11 Transport	**Railway Infrastructure Loss (RAIL)**

Model/ tool type and outputs	Flood damage to the European railway network can be assessed using the RAIL model developed by Kellermann *et al.* (2015). RAIL can estimate the expected structural flood damage to the standard cross-section of a railway track and the resulting repair (replacement) costs.
Open access?	No
Key data inputs	Comprehensive flood hazard information, i.e. area-wide data on water depths at affected track sections, are required to apply the RAIL model at the catchment scale. Spatial data on the railway system.
Key data accessibility/ availability	Local hazard data are not always available. A fall-back option is to use the coarser-resolution global hazard datasets.
Strengths	Model specifically developed to assess the flood damage to railway infrastructure. The resulting RAIL model can estimate the expected structural damage for the standard cross-section of railway track sections and resulting repair costs.
Assumptions/ limitations	The two key assumptions within the model design are (1) the construction height of the railway substructure and (2) the cost calibration factor for the estimation of economic losses linked to damage classes.
Spatial scale and resolution	Railway segment level.
Temporal scale and resolution	This is dependent on the input data and whether it is used to examine future climate adaptation strategies. Time scale depends on the time scale of the hazard or exposure data that are available.
Accessibility of outputs	Directly accessible from the model. Outputs include damage estimates per railway segment.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	This model can assess the potential benefits of adaptation policies in terms of the avoided damages because of this policy. Only adaptation policies that have a direct impact on railway infrastructure can be assessed.
Relevant application	Bubeck *et al.* (2019) applied the model to assess climate risks to the European railway infrastructure. They show that to cover the risk increase due to climate change, European member states

	would need to increase expenditure in transport by €1.22 billion annually under a 3°C warming scenario without further adaptation. Limiting global warming to the 1.5°C goal of the Paris Agreement would result in avoided losses of €317 million annually.
Main reference(s)	Kellermann, P., Schönberger, C., & Thieken, A. H. (2019). Large-scale application of the flood damage model RAilway Infrastructure Loss (RAIL).
Suitability for rapid assessment	Yes - when inundation maps are available
Websites	https://www.nat-hazards-earth-syst-sci.net/16/2357/2016/
Manuals/ training/ videos	
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.11 Transport	**Global Multihazard Transport Risk Analysis (GMTRA)**

Model/ tool type and outputs	A global transport asset risk analysis for earthquakes, floods and cyclones. Provides exposure, damage and risk estimates for road and railway infrastructure using open-access data.
Open access?	Yes
Key data inputs	Detailed spatial information on the transport system, including infrastructure type, width and value and hazard information.
Key data accessibility/ availability	Local hazard data are not always available. A fall-back option is to use the coarser-resolution global hazard datasets.
Strengths	Fully open-access model able to assess the damage to all transport infrastructure assets available within Open Street Map.
Assumptions/ limitations	Due to limited empirical information and existing research on this topic at a global scale, many assumptions had to be made to conduct this study. For transparency and ease of interpretation, assumptions are clearly set out in both the “Methods” section and in Supplementary Table 1 in the Supplementary Materials of Koks *et al.* (2019).
Spatial scale and resolution	Infrastructure segment level.
Temporal scale and resolution	This is dependent on the input data and whether it is used to examine future climate adaptation strategies. Time scale depends on the time scale of the hazard or exposure data that are available.
Accessibility of outputs	Directly accessible from the model. Outputs include damage estimates per infrastructure segment.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	This model can assess the potential benefits of adaptation policies in terms of the avoided damages because of this policy. Only adaptation policies that have a direct impact on transport infrastructure can be assessed.
Relevant application	GMTRA can be used to assess the benefits of adaptation measures. Koks *et al.* (2019) showed through a cost-benefit analysis using the model output that increasing flood protection would have positive returns on ~60% of roads exposed to a 1/100 year flood event.
Main reference(s)	Koks, E. E., Rozenberg, J., Zorn, C., Tariverdi, M., Vousdoukas, M., Fraser, S. A., ... & Hallegatte, S. (2019). A global multi-hazard risk

	analysis of road and railway infrastructure assets. Nature communications, 10(1), 1-11.
Suitability for rapid assessment	Yes - when inundation maps are available.
Websites	https://github.com/ElcoK/gmtra
Manuals/ training/ videos	See main website
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.13 Health and other climate adaptation models	**Air Pollution Model (with potential to consider climate change)**

Model/ tool type and outputs	Climate change will change the concentrations of ozone and particulate matter, affecting health impacts from air pollution. There are an existing suite of air quality and health models used extensively across Europe, and at national level. The most used in European policy is the IIASA GAINS modelling framework, but there are numerous health-based air pollution modelling frameworks that are used at national and local scale as well. These models can be extended to consider climate change effects, for example, by taking climate model projections and using to look at future air pollution changes. An example is the study by the IMPACT2C project, 2015, which looked at impacts of climate change on the concentrations of ozone and particular matter. Many of the air pollution and health models, such as GAINS, also assess options to reduce air pollution, and thus by implication, climate change induced changes, and include cost-benefit analysis. These are centred on air pollution control options, rather than targeted climate adaptation options.
Open access?	Data for relationships and population freely available. Requirement for baseline air pollutant emissions. Some models are open access.
Key data inputs	Inputs include a range of models. Some use emission inputs and estimate air quality concentrations. It is also possible to use climate change models and derive projections (gridded) that are input to air quality models.
Key data accessibility/ availability	Data available from open access sources (Copernicus, Eurocordex, Eurostat).
Strengths	Quantification of future health impacts of climate change on health-based air pollution. Some integrated models, such as GAINS, also support analysis of policy options and costs for reducing air pollution.
Assumptions/ limitations	The main assumptions with these approaches are the degree to which correlations and functional relationships derived fully capture complex linkages between climate and health outcomes, and the transferability between locations and to future climate change.
Spatial scale and resolution	European and national and local.

Temporal scale and resolution	Depends on model inputs used, but typically run for future time intervals through to 2101.
Accessibility of outputs	Data usually produced as fatalities and major and minor cases of morbidity, and thus outputs easily accessible. Easily accessible to interpretation by a general audience.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) identifying adaptation options; 4) assessing adaptation options
Adaptation policy insights	Can be useful for identifying risks and justifying the benefits (and cost-benefit analysis) for adaptation options, from existing modelling frameworks of costs, cost effectiveness and cost benefit analysis of air pollution options.
Relevant application	The impacts of climate change on air pollution for Europe were assessed in the IMPACT2C project (2015). For ozone, models predict an average increase across Southern and Central Europe due to climate change though the level of increase and the economic costs are low. For particulate matter, changes due to climate change are uncertain, as the models did not agree on sign, but impacts/benefits could potentially be several billion Euro a year. It is noted that decreases in air pollution from air pollution and mitigation policy strongly reduce current impacts in the future, thus marginal changes of climate change on future air pollution levels are low – certainly compared to the co-benefits of air quality and mitigation policy. Several studies have examined the potential benefits of heatwave alert systems under climate change (Hunt *et al.*, 2016; Bouwer *et al.*, 2018; Chiabai *et al.*, 2018). These report these schemes have large benefits in reducing future mortality. For example, the estimated benefits on setup of a warning system, real-time surveillance of health data, and emergency plans for vulnerable people with visits and care offer, are typically assessed to have 40 to 80% effectiveness and have high benefit to cost ratios. Hunt *et al.* (2016), analysing London, found that the marginal benefit to cost ratio, i.e. the additional benefits versus the increase in additional resource costs, led to a high benefit to cost ratio when the full value (the VPF) was used, ranging from 10:1 to 30:1 for the 2040s depending on the level of climate change. There are some studies that have extended to other urban heat adaptation options. Kingsborough *et al.* (2017) estimated the impact of green infrastructure on reducing the risk of heat-related deaths in London, although their findings indicate large increases in green spaces are needed to significantly reduce down heat related fatalities.

Main reference(s)	IMPACT2C (2015). Deliverable D8.1 Design and production of an ensemble of air quality simulations and evaluation of health impacts. Deliverable of the IMPACT2C project.
Suitability for rapid assessment	a. Quick access to input data/ previous studies It is possible to access previous data quickly and interpret. There is also lots of existing results on air pollution mitigation that can be used to consider options for addressing climate change related impacts. It is also possible to use previous impact data for rapid adaptation analysis. However, to fully assess benefits requires detailed analysis (air quality modelling). b. Rapid use of models and methods There are rapid models that these simplified approaches - though these are normally based on emission changes - thus difficult to adapt to climate context. There are lots of models for looking at options for air quality improvements, including rapid models.
Websites	https://www.iiasa.ac.at/web/home/research/researchPrograms/air/GAINS.html
Manuals/ training/ videos	
Wikipedia page	
Other	

2) Sectoral models for impact and adaptation assessment	2.13 Health and other climate adaptation models	**Valuation Tool**

Model/ tool type and outputs	The World Health Organisation tool to estimate health and adaptation costs consists of a document describing the methods and a manual with an Excel spreadsheet, providing a visual aid for calculating costs for a number of health endpoints.
Open access?	The report is freely available. As a visual aid for application of the tool, a simple Excel file is available upon request to the WHO Regional Office for Europe (climatechange@ecehbonn.euro.who.int), which consists of three spreadsheets for data input and two spreadsheets for outputs.
Key data inputs	The tool requires data inputs on health impacts. This input required for application is beyond the scope of the tool. Thus, the analytical team should ascertain the components of health damage due to climate change before applying the economic tool. These data can be obtained either from existing national (or subnational) assessments of vulnerability, impact and adaptation or from studies on specific health outcomes. If these are not available, a health impact assessment must be conducted before estimating the costs.
Key data accessibility/ availability	This will depend on the country or region, see key data inputs.
Strengths	Quantification of future health impacts of climate change on health-based air pollution. Some integrated models, such as GAINS, also support analysis of policy options and costs for reducing air pollution, but with the additional strength that economic values are produced.
Assumptions/ limitations	Focused on economic valuation only, and thus requires existing health impact inputs. This leads to assumptions and limitations in, for example, the degree to which correlations and functional relationships derived fully capture complex linkages between climate and health outcomes, and the transferability between locations and to future climate change.
Spatial scale and resolution	National, though could also be used for local (city), regional (sub national).
Temporal scale and resolution	The time scale depends on model inputs used, however a typical simulation for future time intervals through to 2100.
Accessibility of outputs	Data usually produced as fatalities and economic costs.

Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The economic toolkit in this document is aimed to assist decision-makers in making evaluations of health impacts of climate change by providing explicit economic costs of the health impacts of climate change and the planned costs of adaptation.
Relevant application	It is expected to be applied in Member States mainly by line ministries responsible for climate change adaptation but could also be used by researchers and others.
Main reference(s)	World Health Organization. Regional Office for Europe. (2013). Climate change and health: a tool to estimate health and adaptation costs. World Health Organization. Regional Office for Europe. https://apps.who.int/iris/handle/10665/329517
Suitability for rapid assessment	The tool itself is a fairly rapid model but it requires input data that is not rapid assessment. IT provides a rapid way to estimate economic costs for previously estimated health impacts.
Websites	http://www.euro.who.int/__data/assets/pdf_file/0018/190404/WHO_Content_Climate_change_health_DruckII.pdf
Manuals/ training/ videos	-
Wikipedia page	-
Other	-

Annex 3: Economic models

3) Economic models	3.1 Integrated assessment models (IAMs)	**WITCH - World Induced Technical Change Hybrid**

Model/ tool type and outputs	WITCH is a multi-region, dynamic optimization, hard linked integrated assessment model (IAM) featuring a detailed description of the energy sector, game theoretical set up and adaptation modules. Determines macro-regional optimal/ cost minimizing allocation of investment across different options and climate change policy costs under different assumptions related, for example, to the availability of abatement technology, the degree and timing of international participation to the abatement efforts, risk and uncertainty of climate change damages. It also quantifies the social cost of carbon under different assumptions.
Open access?	Not yet, however a policy simulator is available at: https://www.witchmodel.org/simulator/
Key data inputs	Macroeconomic data characterizing the initial model year in relation to macro-regional GDP, population, capital stock, emissions, energy use; and parameters for the substitutability of inputs in the aggregated production function. Parameters describing the reduced form climate change damage function and carbon cycle module. Data regarding emission reduction costs and cost and effectiveness of adaptation per type, in different regions for the calibration of the adaptation modules are also required. All these data can be derived from literature surveys, expert judgments, fully fledged climate models and econometric estimations.
Key data accessibility/ availability	The majority of data are accessible from the literature or from model documentation.
Strengths	The WITCH model can study complex dynamic interactions across countries and policies investigating the trade-off between mitigation and adaptation, can introduce risk and uncertainty, and couples a top-down structure with bottom-up description of the energy sector.
Assumptions/ limitations	WITCH is based upon the theory of the Ramsey growth model. It is an aggregated, top-down, macro-regional model and therefore, especially in the case of adaptation policies, it cannot simulate at a local or measure-specific resolution. It epitomises common criticisms of IAMs regarding the lack of empirical foundation of its climate-change damage reduced form function, and therefore its degree of realism. The same criticism extends also to the calibration of the adaptation module.

Spatial scale and resolution	Different model version exists. The basic version considers the world divided into 17 macro-geo-political blocks and 20 different energy generation technologies.
Temporal scale and resolution	WITCH simulates until the end of the century in 10-year time intervals.
Accessibility of outputs	Outputs are accessible through scientific publications and reports. A user-friendly policy simulator is freely available however adaptation policies are not included.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model identifies the optimal/ cost minimizing allocation of investments across different climate policy actions for mitigation and adaptation, other investments in physical capital and research and development, and regions. The main results are that adaptation costs are significantly greater in developing than in developed regions: 80% vs 20% of a total of $ 1 trillion in 2100 in a 2.5°C climate scenario. Adaptation costs will be high, but manageable only in moderate climate change scenarios (2.5°C); the joint use of mitigation and adaptation reduces total climate change policy costs. Under catastrophic uncertainty, mitigation policies are required to a greater degree than adaptation.
Relevant application	The WITCH model has been extensively applied to policy optimization and policy evaluation exercises, to the study of strategic behaviour of countries to participate to international environmental agreements and to investigate the optimal mix between mitigation and several forms of adaptation (anticipatory, reactive and adaptive capacity building).
Main reference(s)	Bosetti, V., C. Carraro, M. Galeotti, E. Massetti and M. Tavoni (2006), 'WITCH: A World Induced Technical Change Hybrid Model', The Energy Journal, 27(Special Issue 2), 13-38; Bosello, F., C. Carraro and E. De Cian (2010), 'Climate policy and the optimal balance between mitigation, adaptation and unavoided damage', Climate Change Economics, 1(2), 71-92
Suitability for rapid assessment	A user-friendly policy simulator is freely available however adaptation policies are not included.
Websites	https://www.witchmodel.org/; https://www.witchmodel.org/simulator/
Manuals/ training/ videos	All available on the model website.

Wikipedia page	NA
Other	

3) Economic models	3.1 Integrated assessment models (IAMs)	**DICE - Dynamic Integrated Climate-Economy**

Model/ tool type and outputs	DICE is a global, dynamic optimization, hard linked integrated assessment model. It determines the global optimal/ cost minimizing allocation of investment across different options and climate change policy costs under different assumptions related, for example, to the availability of abatement technology, the degree and timing of international participation to the abatement efforts, and risk and uncertainty of climate change damages. It also quantifies the social cost of carbon under different assumptions.
Open access?	The model requires GAMS software. The model is available at: http://www.econ.yale.edu/~nordhaus/homepage/homepage/ DICE2016R-091916ap.gms
Key data inputs	Macro-economic data characterizing the initial model year in relation to macro-regional GDP, population, capital stock, emissions and energy use; and parameters for the substitutability of inputs in the aggregated production function. Parameters describing the reduced form climate change damage function and carbon cycle module. The information can be retrieved from literature surveys, expert opinion and fully fledged climate models and econometric estimations.
Key data accessibility/ availability	Data are available in the model documentation and on the model website.
Strengths	The DICE model can investigate optimal climate change policies while introducing several complexities, such as risk and uncertainty on climate change damages, different discounting processes and different forms of uncertainty.
Assumptions/ limitations	The DICE model is based upon the Ramsey growth model theory. It is a one country model and therefore, especially in the case of adaptation policies (see AD-DICE), it cannot simulate at a local or measure-specific resolution. It epitomises common criticisms of IAMs regarding the lack of empirical foundation of its climate-change damage reduced form function and, therefore, its degree of realism.
Spatial scale and resolution	Global model with the world represented by one aggregated economic system.

Temporal scale and resolution	Intertemporal model simulating to the end of the century in 10-year time intervals, although the simulation time horizon can be extended.
Accessibility of outputs	Outputs are accessible through scientific publications and reports.
Adaptation policy cycle stages	The original DICE model has not been applied to the study of adaptation; however, some authors have developed the model in this direction (see AD-DICE).
Adaptation policy insights	Not applicable, however can assess optimal climate change mitigation policies and assessment of the social cost of carbon.
Relevant application	Not applicable
Main reference(s)	Nordhaus, W. and P. Sztorc (2013), "DICE 2013R: Introduction and User's Manual", available at: http://www.econ.yale.edu/~nordhaus/homepage/homepage/documents/DICE_Manual_100413r1.pdf
Suitability for rapid assessment	No - The model is complex and requires appropriate training to be used.
Websites	https://sites.google.com/site/williamdnordhaus/dice-rice
Manuals/ training/ videos	All available at the model website
Wikipedia page	https://en.wikipedia.org/wiki/DICE_model
Other	

3) Economic models	3.1 Integrated assessment models (IAMs)	**AD-DICE - Dynamic Integrated Climate-Economy with Adaptation**

Model/ tool type and outputs	AD-DICE is a global one-region, dynamic optimization, hard-linked IAM. It is an evolution of the basic DICE model that introduces an adaptation expenditure module. It therefore enriches the analysis of optimal climate change policies of DICE with adaptation determining the optimal quantity of resources to allocate to adaptation globally and the timing of their application (see also DICE).
Open access?	No
Key data inputs	Macroeconomic data characterizing the initial model year in relation to macro-regional GDP, population, capital stock, emissions and energy use; parameters for the substitutability of inputs in the aggregated production function; parameters describing the reduced form climate change damage function and carbon cycle module; data regarding emission reduction costs and cost and effectiveness of adaptation per type, and for the calibration of the adaptation module. The information can be retrieved from literature surveys, expert opinion and fully fledged climate models and econometric estimations.
Key data accessibility/ availability	The AD DICE "core" is the same as the DICE model. Data are thus available in DICE documentation. Assumptions used for the calibration of the adaptation function are well documented in the paper presenting the model and results.
Strengths	The AD-DICE model can study complex dynamic interactions across countries and policies investigating the trade-off between mitigation and adaptation, can introduce risk and uncertainty and the role of discounting.
Assumptions/ limitations	AD-DICE is based upon the theory of the Ramsey growth model. It is an aggregated, top-down, macro-regional model and therefore, especially in the case of adaptation policies, it cannot simulate at a local or measure-specific resolution. It epitomises common criticisms of IAMs regarding the lack of empirical foundation of its climate-change damage reduced form function, its adaptation function and, therefore, its lack of realism.
Spatial scale and resolution	The model represents the world economy through an aggregated global economic system.

Temporal scale and resolution	Intertemporal model simulating to the end of the century in 10-year time intervals, although the simulation time horizon can be extended.
Accessibility of outputs	Outputs are accessible through scientific publications and reports.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	In the short term, the key damage reduction policy strategy is using adaptation, while in the long-term mitigation is preferable. Mitigation and adaptation are, to a certain degree, substitutable; the effect of adaptation on mitigation is greater than that of mitigation on adaptation. Note that the model produces aggregated results: adaptation is discussed per "macro-typology" and not examining the specific adaptation measure.
Relevant application	The AD-DICE model has been applied to study the optimal combination and trade-off between mitigation and adaptation strategies.
Main reference(s)	de Bruin, K.C., Dellink, R., and R.S. J. Tol (2009) ," AD-DICE: an implementation of adaptation in the DICE model", Climatic Change, Volume 95, Issue 1–2, pp 63–81
Suitability for rapid assessment	No - The model is complex and requires appropriate training to be used.
Websites	
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.1 Integrated assessment models (IAMs)	**RICE - Regional-Integrated Climate-Economy**

Model/ tool type and outputs	RICE is a multi-region, dynamic optimization, hard linked integrated assessment model (IAM) featuring game theoretical set up. It determines macro-regional optimal/ cost minimizing allocation of investments across different options and climate change policy costs under different assumptions related, for example, to the availability of abatement technology, the degree and timing of international participation to the abatement efforts, and risk and uncertainty of climate change damages. It also quantifies the social cost of carbon under different assumptions.
Open access?	The model requires GAMS software despite a version of RICE currently being available in Excel. The full model code is provided in the model documentation freely available at: https://eml.berkeley.edu/~saez/course131/Warm-World00.pdf
Key data inputs	Macro-economic data characterizing the initial model year in relation to macro-regional GDP, population, capital stock, emissions and energy use; and parameters for the substitutability of inputs in the aggregated production function. Parameters describing the reduced form climate change damage function and carbon cycle module. The calibration of these parameters is complex and involves development of specific studies, literature survey and expert elicitation and econometric estimations.
Key data accessibility/ availability	Data are available in the model documentation.
Strengths	The RICE model can investigate optimal climate change policies while introducing several complexities, such as risk and uncertainty on climate change damages, different discounting processes and simulation of strategic behaviour in international climate negotiations.
Assumptions/ limitations	RICE is an aggregated, top-down, macro-regional model and therefore, especially in the case of adaptation policies, it cannot simulate at a local or measure-specific resolution. It epitomises common criticisms of IAMs regarding the lack of empirical foundation of its climate-change damage reduced form function and, therefore, its degree of realism.
Spatial scale and resolution	RICE is a global model with the world divided into 10 different macro-regions.

Temporal scale and resolution	Intertemporal model simulating to the end of the century in 10-year time intervals, although the simulation time horizon can be extended.
Accessibility of outputs	Outputs are accessible through scientific publications and reports.
Adaptation policy cycle stages	The original RICE model has not been applied to the study of adaptation; however, some authors developed the model in this direction (see AD-RICE).
Adaptation policy insights	Not applicable, however can assess optimal climate change mitigation policies and assessment of the social cost of carbon.
Relevant application	Not applicable
Main reference(s)	Nordhaus, W.D: and . Yang (1996), "A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies", The American Economic Review Vol. 86, No. 4, pp. 741-765; Nordhaus W.D. and Boyer J. (1999), "Warming the world, economic modelsof global warming", MIT press, available at: https://eml.berkeley.edu/~saez/course131/Warm-World00.pdf
Suitability for rapid assessment	No - The model is complex and requires appropriate training to be used.
Websites	https://sites.google.com/site/williamdnordhaus/dice-rice
Manuals/ training/ videos	All available at the model website.
Wikipedia page	
Other	

3) Economic models	3.1 Integrated assessment models (IAMs)	**AD-RICE - Regional-Integrated Climate-Economy with Adaptation**

Model/ tool type and outputs	AD-RICE is a multi-region, dynamic optimization, hard linked integrated assessment model (IAM) featuring game theoretical set up. It is an evolution of the basic RICE model that introduces an adaptation expenditure module. It therefore enriches the analysis of optimal climate change policies of RICE with adaptation determining the optimal quantity of resources to devote in each of the macro-regions modelled, to adaptation and their timing. All other analyses are similar to the output capacity of the RICE model (see also RICE).
Open access?	No
Key data inputs	Macroeconomic data characterizing the initial model year in relation to macro-regional GDP, population, capital stock, emissions and energy use; parameters for the substitutability of inputs in the aggregated production function; parameters describing the reduced form climate change damage function and carbon cycle module; data regarding emission reduction costs and cost and effectiveness of adaptation per type, and in different regions for the calibration of the adaptation modules. The information can be retrieved from literature surveys, expert opinion and fully fledged climate models and econometric estimations.
Key data accessibility/ availability	AD RICE "core" is the same as the RICE model. Data are thus available in RICE documentation. Assumptions used for the calibration of the adaptation function are well documented in the paper presenting the model and results.
Strengths	The AD-RICE model can study complex dynamic interactions across countries and policies investigating the trade-off between mitigation and adaptation, can introduce risk and uncertainty, and simulate strategic behaviour in international climate negotiations.
Assumptions/ limitations	AD-RICE is based upon the theory of the Ramsey growth model. It is an aggregated, top-down, macro-regional model and therefore, especially in the case of adaptation policies, it cannot simulate at a local or measure-specific resolution. It epitomises common criticisms of IAMs regarding the lack of empirical foundation of its climate-change damage reduced form function, its adaptation function and, therefore, its lack of realism.
Spatial scale and resolution	Global economy model with the world divided into 13 macro geo-political blocks.

Temporal scale and resolution	Intertemporal model simulating to the end of the century in 10-year time intervals, although the simulation time horizon can be extended.
Accessibility of outputs	Outputs are accessible through scientific publications and reports.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options; All this however "in aggregated". For example, adaptation is discussed per "typology" (proactive, reactive) and not per single measure and macro-regionally, and not per site.
Adaptation policy insights	AD-RICE confirms the results of AD DICE, highlighting the greater adaptation needs of developing countries.
Relevant application	The AD-RICE model has been applied to study the optimal combination and trade-off between mitigation and adaptation strategies.
Main reference(s)	Agrawala, S., Bosello, F., Carraro, C, de Bruin, K., De Cian, E., Dellink, R., and E. Lanzi (2011), “Plan or React? Analysis of adaptation costs and benefits using integrated assessment models”, Climate Change Economics, Vol. 2, No. 3 (2011) 175–208
Suitability for rapid assessment	No - The model is complex and requires appropriate training to be used.
Websites	
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.1 Integrated assessment models (IAMs)	**FUND - Climate Framework for Uncertainty, Negotiation and Distribution**

Model/ tool type and outputs	FUND is a multi-region, dynamic optimization, hard linked integrated assessment model (IAM). Different from the majority of IAMs, although still using reduced form climate change damage functions, it specifies a damage function per main impact category: agriculture, forestry, water resources, energy consumption, sea level rise, ecosystem, human health in relation to multiple diseases, extreme weather derived from a number of climate hazards, mortality and morbidity. FUND highlights the optimal climate change mitigation policy at the regional level and the social cost of carbon.
Open access?	Yes at: https://github.com/fund-model/MimiFUND.jl - The model software needed is named Julia.
Key data inputs	In the FUND model, population and per capita income follow exogenous scenarios. The FUND scenario is based on the EMF14 Standardised Scenario, (Leggett *et al.*, 1992). Other scenarios considered follow the SRES A1B, A2, B1 and B2 scenarios (Nakicenovic and Swart, 2001), as implemented in the IMAGE model (IMAGE Team, 2001). The model includes parameterization for the damage functions and for the abatement cost functions. The parameters are derived from the literature, expert judgments, econometric and statistic techniques.
Key data accessibility/ availability	All the data required to run the model are available at the model website.
Strengths	The FUND model can investigate complex dynamic interaction across countries and policies, and can introduce risk, uncertainty and discounting.
Assumptions/ limitations	FUND is based upon the theory of the Solow growth model, it is an aggregated, top-down, multi-region model and therefore, especially in the case of adaptation policies, it cannot simulate at a local or measure-specific resolution. It epitomises common criticisms of IAMs regarding the lack of empirical foundation of its climate-change damage reduced form function and, therefore, its degree of realism.
Spatial scale and resolution	Global economy model with the world divided into 16 macro geo-political blocks.

Temporal scale and resolution	Time scale is 1950-2300 with annual intervals.
Accessibility of outputs	Outputs are accessible through scientific publications and reports.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 4) Assessing adaptation options. However, the FUND model has not been extensively applied to adaptation.
Adaptation policy insights	Applied to the analysis of sea-level rise impacts, the FUND model demonstrates that adaptation through coastal protection has a greater impact and provides a greater rapid response than mitigation through emission reduction. Furthermore, the benefits of coastal protection through avoided damages are almost consistently greater than the costs (Tol. 2007. The double trade-off between adaptation and mitigation for sea level rise: An application of FUND. Mitigation and Adaptation Strategies for Global Change, 12(5), 741–753.)
Relevant application	FUND was originally established to investigate the role of international capital transfers in climate policy. However, this rapidly evolved to study the impacts of climate change in a dynamic context, and it is now frequently used to perform cost-benefit and cost-effectiveness analyses of greenhouse gas emission reduction policies, to study equity of climate change and climate policy, and to support game-theoretic investigations for international environmental agreements. In some applications, it has been used to examine the cost effectiveness of coastal protection. It has been used in several FP6,7 projects, and is one of a suite of models used by the US Environmental Protection Agency and other federal agencies to quantify carbon costs.
Main reference(s)	All model documentation available at: http://www.fund-model.org/documentation/ ; All model publications available at: http://www.fund-model.org/publications/
Suitability for rapid assessment	No - The model is complex and requires appropriate training to be used.
Websites	http://www.fund-model.org/ ; https://github.com/fund-model/MimiFUND.jl
Manuals/ training/ videos	All available at the model website.
Wikipedia page	
Other	

3) Economic models	3.1 Integrated assessment models (IAMs)	**PAGE - Policy Analysis of the Greenhouse Effect**

Model/ tool type and outputs	PAGE is a hard linked intertemporal IAM that uses income, population and emissions policies to simulates the impacts of global and regional temperature changes and sea-level rise on market and non-market sectors. It also includes a stochastic discontinuity: a single tipping point resulting in a large loss of GDP. PAGE also models an exogenously determined adaptation policy that reduces impacts for a price. Finally, the costs of reducing emissions below their business-as-usual path are also calculated. A key feature of PAGE is the inclusion of uncertainty distributions, consisting of triangular distributions in the default version of the model, for over 100 key scientific and economic parameters. This supports PAGE to simulate probabilities, through a Monte Carlo procedure, of outcome distributions.
Open access?	No, although an open source application of PAGE is available at: https://www.nature.com/articles/sdata2018187#Sec8. The model was developed in Excel.
Key data inputs	The PAGE damage function predominately relies on estimates prepared by the IPCC Working Group II for the Third Assessment Report (TAR) (IPCC. 2001. Climate change 2001: Impacts, adaptation, and vulnerability, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change). An important source of this data is chapter 19, Vulnerability to Climate Change and Reasons for Concern: A Synthesis.
Key data accessibility/ availability	The PAGE damage function predominately relies on estimates prepared by the IPCC Working Group II for the Third Assessment Report (TAR) (IPCC. 2001. Climate change 2001: Impacts, adaptation, and vulnerability, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change). An important source of this data is chapter 19, Vulnerability to Climate Change and Reasons for Concern: A Synthesis.
Strengths	PAGE supports the application of cost effectiveness analysis of adaptation and mitigation under different benefit and cost assumptions. It includes a stochastic discontinuity and the inclusion of uncertainty distributions for over 100 key scientific and economic parameters. This supports PAGE to simulate probabilities, through a Monte Carlo procedure, of outcome distributions.
Assumptions/ limitations	It epitomises common criticisms of IAMs regarding the lack of empirical foundation of its climate-change damage reduced form function and, therefore, its degree of realism. This criticism also

	extends to the calibration of the cost effectiveness element of the adaptation module. Finally, adaptation can be represented as an aggregate only.
Spatial scale and resolution	Global economy model with the world divided into eight macro geo-political blocks.
Temporal scale and resolution	The time intervals in PAGE can be variable, starting in the default model at 2008 and ending in 2200.
Accessibility of outputs	Outputs are accessible through scientific publications and reports.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 4) Assessing adaptation options
Adaptation policy insights	The model highlights that adaptation benefits are generally greater than costs, and it has been used in the Stern review (2006) to compute a marginal cost of carbon of $ 314/tC.
Relevant application	PAGE has been applied to investigate the optimal combination of mitigation and adaptation policies under uncertainty: PAGE was applied in the 2006 Stern Review to derive insights regarding the cost of climate change. It has also been applied in FP6,7 projects such as CLIMATECOST, and is one of a suite of models used by the US Environmental Protection Agency and other federal agencies to evaluate carbon costs.
Main reference(s)	Hope, Chris. The PAGE09 integrated assessment model: A technical description. Cambridge Judge Business School Working Paper, 2011, 4(11); Hope, Chris. The marginal impact of CO2 from PAGE2002: An integrated assessment model incorporating the IPCC's five reasons for concern. Integrated Assessment, 2006, 6(1): 19-56.
Suitability for rapid assessment	No - The model is complex and requires appropriate training to be used.
Websites	
Manuals/ training/ videos	See main references
Wikipedia page	
Other	

3) Economic models	3.1 Integrated assessment models (IAMs)	**FAIR - Framework to Assess International Regimes**

Model/ tool type and outputs	The FAIR 2.0 model integrates three sub-models: 1) a climate model for evaluating the climate impacts of global emission profiles and calculating the regional contributions to climate change; 2) an emissions allocation model to explore and evaluate the emission allowances for different climate regimes; 3) a mitigation-cost and emission-trading model to distribute the emission reduction objective over the different regions, gases and sectors following a least-cost approach.
Open access?	No
Key data inputs	Historical emission datasets for the greenhouse gases, CO_2, CH_4, N_2O and the halocarbons covered by the Kyoto Protocol for the period from 1760 to 1995 are required for the FAIR climate module. Subsequently, in order to develop different future reference scenario projections (1995-2100), required data includes: population, Gross Domestic Product (GDP) in US$ or Purchasing Power Parity (PPP)$, and baseline emissions of GHGs without climate policies. The FAIR model includes marginal abatement cost curves (MACCs). In order to modify the model default settings, data on MACCs are required.
Key data accessibility/ availability	All data are available from official statistical sources and RCP/SSPs databases. See, for example, World Bank and FAO, and https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=welcome
Strengths	The FAIR model can investigate optimal climate change policies while introducing several complexities, such as risk and uncertainty on climate change damages and different discounting processes.
Assumptions/ limitations	The FAIR model is an example of a "reduced form" model. Different simplified climate models can be used to originate emission profiles in different socio-economic scenarios. The emission reduction module is based upon marginal abatement cost curves that link abatement levels to carbon prices. The adaptation module is based upon the methodology developed for the AD-RICE model. The model is a typical top-down model and, therefore, its results present a "low level" of either geographical or technological detail. This is particularly relevant for the description of adaptation policies that can be represented just as aggregated expenditure items.
Spatial scale and resolution	Global model with the world divided into 17 macro geo-political blocks.

Temporal scale and resolution	1995-2100 in 10-year time intervals.
Accessibility of outputs	Outputs are accessible through scientific publications and reports.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 4) Assessing adaptation options with the addition of an adaptation module.
Adaptation policy insights	One main finding from FAIR application is that the adaptation cost in developing countries can be so high in the long term that the final total cost of climate change, including residual damages and mitigation costs while accounting for the revenues raised within hypothetical carbon markets where they can sell carbon credits, will be higher regardless in these regions. Additional support to climate change policies in developing countries should therefore be instigated (Hof, den Eltzen and van Vuuren, 2009).
Relevant application	The main application of the FAIR model is to support policy makers in assessing the environmental and economic implications of international climate regimes for differentiation of future mitigation commitments, compatible with the stabilisation of atmospheric concentrations of greenhouse gases. A version of the model includes an adaptation module enabling the investigation of the impact of adaptation costs on the climate change cost distribution across world regions.
Main reference(s)	den Elzen, M.G.J. & Lucas, P.L. (2005), "The FAIR model: A tool to analyse environmental and costs implications of regimes of future commitments", Environmental Modeling and Assessment 10: 115. https://doi.org/10.1007/s10666-005-4647-z; Hof, A., Den Elzen, M.G., van Vuuren, D. (2010), "Including adaptation costs and climate change damages in evaluating post-2012 burden-sharing regimes", Mitigation and Adaptation Strategies to Global Change 15:19–40
Suitability for rapid assessment	No - The model requires appropriate training to be used.
Websites	
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.1 Integrated assessment models (IAMs)	**REMIND - Regional Model of Investments and Development**

Model/ tool type and outputs	REMIND is a hard linked, globally multi-regional IAM incorporating the economy, the climate system and a detailed representation of the energy sector. It solves for an inter-temporal Pareto optimum in economic and energy investments in the model regions, fully accounting for interregional trade in goods, energy carriers and emissions allowances. REMIND supports the analysis of technology options and policy proposals for climate mitigation.
Open access?	No, but the code is available at: https://www.pik-potsdam.de/acl_users/credentials_cookie_auth/require_login?came_from=https%3A//www.pik-/research/transformation-pathways/models/remind/remind-source-code
Key data inputs	Macro-economic data characterizing the initial model year in relation to macro-regional GDP, population, capital stock, emissions and energy use; and parameters for the substitutability of inputs in the aggregated production function. Parameters describing the reduced form climate change damage function and carbon cycle module. Data regarding emission reduction costs are also required. The information can be retrieved from literature surveys, expert opinion and fully fledged climate models and econometric estimations.
Key data accessibility/ availability	Data are available from the literature and partially from the model documentation.
Strengths	The REMIND model can investigate complex dynamic interactions across countries and policies, introduce risk and uncertainty, and couples a top-down structure with a bottom-up description of the energy sector.
Assumptions/ limitations	REMIND is based upon the theory of the Ramsey growth model. It is an aggregated, top-down, macro-regional model and therefore, especially in the case of adaptation policies, it cannot simulate at a local or measure-specific resolution. It epitomises common criticisms of IAMs regarding the lack of empirical foundation of its climate-change damage reduced form function and, therefore, its degree of realism.
Spatial scale and resolution	Global model with the world divided into 11 macro geo-political blocks and 50 energy generation technologies.
Temporal scale and resolution	2005-2100 with 5-year intervals until 2060 and 10-year step until 2100.

Accessibility of outputs	Outputs are accessible through scientific publications and reports.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change
Adaptation policy insights	The REMIND model has not yet been applied to the study of adaptation and does not feature an adaptation module.
Relevant application	Optimal climate change (mitigation) policy, assessment of the social cost of carbon.
Main reference(s)	https://www.pik-potsdam.de/research/transformation-pathways/models/remind/remindequations.pdf
Suitability for rapid assessment	No - The model is complex and requires appropriate training to be used.
Websites	https://www.pik-potsdam.de/research/transformation-pathways/models/remind https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_REMIND
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.1 Integrated assessment models (IAMs)	**IMAGE - Integrated Model to Assess the Global Environment**

Model/ tool type and outputs	IMAGE is a soft linked integrated assessment modelling framework. It represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change, biodiversity and human well-being.
Open access?	The model is not open source; however, it has a user-friendly visualization tool is available at: https://models.pbl.nl/image/index.php/Download
Key data inputs	Given IMAGE is an integrated modelling framework, the initial input data for model drivers are extensive. The resulting parameter values are used as inputs for different components of IMAGE 3.0. The most important data requirements for the model are population, economic development, trade regimes, environmental and other policies, technical changes in the energy and agricultural systems, lifestyle parameters and energy and land resources.
Key data accessibility/ availability	The initial values are estimated from the literature and data, while future changes in values are inferred from narratives and scenario drivers.
Strengths	The modularity of the framework supports an in-depth study of a range of systems affected by climate change and policies.
Assumptions/ limitations	The complexity of the framework requires proficiency in use and a significant quantity of data.
Spatial scale and resolution	Global model considering 26 macro regions. Land use, land cover, and associated biophysical processes are simulated at 5 x 5 arcminutes to 30 x 30 arcminutes resolution in order to capture local dynamics.
Temporal scale and resolution	1990-2100 with 10-year time intervals.
Accessibility of outputs	Outputs are accessible through scientific publications and reports. Furthermore, a visualisation tool is available at: https://models.pbl.nl/image/index.php/Download
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change
Adaptation policy insights	IMAGE includes damage and cost-benefit analysis modules that calculate the consumption loss resulting from climate change damage and compares these with the consumption losses of adaptation and mitigation costs. Estimates of adaptation costs and residual damage are based on the AD-RICE model, which are

	based on total damage projections made by the RICE model. Calibration of the regional adaptation cost functions is based on an assessment of each impact category described in the RICE model using relevant studies and with expert judgement, where necessary.
Relevant application	IMAGE is used for scenario analysis, including IPCC SreS and SSPs, indicating how future conditions could develop assuming no deliberate or drastic changes in prevailing economic, technology and policy developments occur, commonly referred to as a baseline/ business-as-usual/ no-new-policy assessment. Further, IMAGE can investigate how policies and measures prevent unwanted impacts on the global environment and human development and has been applied to estimate regional adaptation costs including analyses of irrigation options (Hof, den Elzen and van Vuuren. 2010. Including adaptation costs and climate change damages in evaluating post-2012 burden-sharing regimes. Mitigation and Adaptation Strategies for Global Change, 15(1), pp.19-40).
Main reference(s)	Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., Müller, C., Prins, A. (2014), Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications, The Hague: PBL Netherlands Environmental Assessment Agency.
Suitability for rapid assessment	Yes if limited to the output provided by the model's user friendly interface.
Websites	https://models.pbl.nl/image/index.php/ Welcome_to_IMAGE_3.0_Documentation
Manuals/ training/ videos	All available at the model website
Wikipedia page	NA
Other	

3) Economic models	3.1 Integrated assessment models (IAMs)	**AIM - Asia-Pacific Integrated Model**

Model/ tool type and outputs	AIM is a soft linked integrated assessment modelling framework. It represents interactions between greenhouse gas emissions and mitigation policy options; and atmospheric CO_2 concentrations and global mean temperature increase, climate change impacts on the natural environment and the socio-economy of the Asian-Pacific region.
Open access?	The model is not open source; however, some data and codes are available at: http://www-iam.nies.go.jp/aim/data_tools/index.html#rcp
Key data inputs	Given AIM is an integrated modelling framework, the initial input data for model drivers are extensive. The economic module requires global social accounting matrices and the energy module requires technological parameters specification.
Key data accessibility/ availability	The model is not open source; however, some data and codes are available at: http://www-iam.nies.go.jp/aim/data_tools/index.html#rcp
Strengths	The modularity of the framework supports an in-depth study of a range of systems affected by climate change and policies.
Assumptions/ limitations	The complexity of the framework requires proficiency in use and a significant quantity of data.
Spatial scale and resolution	15 Asian Regions - Rest of Asia, Bangladesh, Bhutan, India, Indonesia, Jordan, Laos, Marshall Islands, Myanmar, Nepal, Pakistan, Papua New Guinea, Sri Lanka, Thailand and The Philippines.
Temporal scale and resolution	1990-2100 with 5-year time intervals.
Accessibility of outputs	Outputs are accessible through scientific publications and reports.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change
Adaptation policy insights	The AIM model has been predominately applied to the analysis of climate change impacts and mitigation policies.
Relevant application	The AIM model has been applied for scenario building exercise (including IPCC SRES) and for mitigation policy assessment. It could, in principle, be applied to assess the macro-economic implication of adaptation expenditure.
Main reference(s)	Kainuma, M., Matsuoka, Y., and Morita, T. (2003). (Eds.) Climate Policy Assessment Asia-Pacific Integrated Modeling, Springer-

	Verlag; S. Fujimori, T. Masui, Y. Matsuoka, 2012, AIM/CGE [basic] manual. Discussion paper series, 2012-01, Center for Social and Environmental Systems Research, National Institute Environmental Studies: http://www.nies.go.jp/social/dp/pdf/2012-01.pdf
Suitability for rapid assessment	No - The model is complex and requires appropriate training to be used.
Websites	http://www-iam.nies.go.jp/aim/index.html
Manuals/ training/ videos	All available at the model website.
Wikipedia page	NA
Other	

3) Economic models	3.2 Computer general equilibrium (CGE) models	**ICES - Intertemporal Computable Equilibrium System**

Model/ tool type and outputs	ICES is a multi-country, multi-sector, recursive-dynamic computable general equilibrium (CGE) model developed by the Euro-Mediterranean Center on Climate Change that is currently used to study macro-economic impacts of climate change, mitigation policies and some types of autonomous and planned adaptation such as changes in energy demand patterns, crop switching and coastal protection.
Open access?	No
Key data inputs	The core model database is provided by social accounting matrices of domestic and international economic exchanges, detailed at the sectoral level. Data for climate change impact and policy assessments need to be provided by external sources, such as other (hazard) modelling exercises or studies.
Key data accessibility/ availability	Input data are publicly available but not open access given that the database is a commercial product: the Global Trade Analysis Project (GTAP) dataset is periodically updated and released by Purdue University (https://www.gtap.agecon.purdue.edu/)
Strengths	Capacity to represent market adjustments; explicit representation of international trade; and the sub national characterisation of the EU enables a better representation of climate change and adaptation regional effects.
Assumptions/ limitations	Model based on perfectly competitive and frictionless markets may underestimate adjustment costs. Technological progress is exogenous. Ill-suited to capture non-market impacts, risk and uncertainty. The dynamics are simplified (recursive).
Spatial scale and resolution	The model can, in principle, feature 57 sectors and 140 countries/macro regions. The extension of GTAP database, however, usually considers a narrower set of regions and sectors. A version of the ICES model has been developed representing the EU in 119 sub-national regions.
Temporal scale and resolution	The model solves in yearly or 5-year time intervals until 2070.
Accessibility of outputs	Outputs are typically reported in peer review journals and reports.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 4) Assessing adaptation options

Adaptation policy insights	Enables the assessment of macro-economic consequences of climate change, including price and quantity effects on market exchanges; can be used to assess the indirect economic implication of specific adaptation strategies once their cost and effectiveness have been defined.
Relevant application	Extensively applied to the assessment of climate change impacts and policies. Currently part of the H2020 COACCH project model suite.
Main reference(s)	Bosello, F., Standardi G. (2015), "A Sub-national CGE model for the European Mediterranean Countries", Research Paper CMCC, RP0274; Eboli F., Parrado R., Roson R. (2010), "Climate Change Feedback on Economic Growth: Explorations with a Dynamic General Equilibrium Model", Environment and Development Economics, Volume 15 (5), pp 515 -533.
Suitability for rapid assessment	No rapid use of model and data are possible even though data can be easily accessible upon purchase.
Websites	https://www.icesmodel.org/
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.2 Computer general equilibrium (CGE) models	**GRACE - Global Responses to Anthropogenic Changes in the Environment**

Model/ tool type and outputs	GRACE is a multi-country, multi-sector, recursive-dynamic computable general equilibrium (CGE) model developed at CICERO (Center for International Climate Research), Norway, which is currently used to study the macro-economic impacts of climate change and mitigation policies.
Open access?	No
Key data inputs	The core model database is provided by social accounting matrices of domestic and international economic exchanges, detailed at the sectoral level. Data for climate change impact and policy assessments need to be provided by external sources, such as other hazard modelling exercises or studies.
Key data accessibility/ availability	Input data are publicly available but not open access given that the database is a commercial product. However, the Global Trade Analysis Project (GTAP) dataset is periodically updated and released by Purdue University: https://www.gtap.agecon.purdue.edu/
Strengths	Strengths of GRACE include the capacity to represent market adjustments, explicit representation of international trade and the sub national characterisation of the EU enables a greater representation of climate change and adaptation regional effects.
Assumptions/ limitations	The model is based on perfect competitive and frictionless markets, which may underestimate the adjustment costs. Technological progress is exogenous, and the model is unable to capture non-market impact, risk and uncertainty. The dynamics are also simplified/ recursive.
Spatial scale and resolution	The model can in principle feature 57 sectors and 140 countries/macro regions (the extension of GTAP database), however GRACE usually represents fewer world macro regions and a narrower number of sectors.
Temporal scale and resolution	2010-2100 in one-year time intervals.
Accessibility of outputs	Outputs are accessible through scientific publications and reports.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 4) Assessing adaptation options
Adaptation policy insights	GRACE supports the assessment of macro-economic consequences of climate change, including price and quantity effects on market

	exchanges, and can be used to assess the indirect economic implication of specific adaptation strategies once their cost and effectiveness have been defined.
Relevant application	Extensively applied to the assessment of climate change impacts and mitigation policies. It could, in principle, be applied to assess the macro-economic implications of adaptation expenditure.
Main reference(s)	Aaheim, H. A. and N. Rive (2005). A Model for Global Responses to Anthropogenic Changes in the Environment (GRACE). Report. Oslo, Norway, CICERO. 5. Rive, N. and T. K. Mideksa (2009). Disaggregating the Electricity Sector in the GRACE Model. Report. Oslo, Norway, CICERO. 2009:02: 18. Aaheim, H.A., A. Orlov, T. Wei, and S. Glomsrød (2018). GRACE model and applications. Report. Oslo, Norway, CICERO. 2018:01: 47.
Suitability for rapid assessment	No rapid use of model and data are possible.
Websites	https://cicero.oslo.no/en/the-grace-model
Manuals/ training/ videos	
Wikipedia page	NA
Other	

3) Economic models	3.2 Computer general equilibrium (CGE) models	**RHOMOLO**

Model/ tool type and outputs	RHOMOLO is a spatial computable general equilibrium (CGE) model of the European Commission focusing on EU regions. It has been developed and maintained by the Regional Economic Modelling team at JRC in Seville in cooperation with DG REGIO. It is used for policy impact assessment and provides sector-, region- and time-specific simulations to support the EU policy on investments as well as reforms.
Open access?	A simplified version of the model can be used through a user-friendly interface with registration for an ECAS account.
Key data inputs	EU inter-regional SAM (social accounting matrix) derived from: Thissen M., Husby, T., Ivanova, O. and Mandras G. (2018). European NUTS 2 regions: construction of inter-regional trade-linked Supply and Use tables with consistent transport flows. JRC Working Papers series.
Key data accessibility/ availability	Eurostat National SUTs (supply and use tables), Eurostat national accounts, annual data on national accounts and sectoral splits, BACI international reconciled bilateral commodity trade dataset, STAN (STructural ANalysis on industry performance) database, national IO tables, and UN trade in services database.
Strengths	Strengths include the capacity to represent market adjustments, explicit representation of international trade and the sub national characterisation of the EU that can, in principle, support a greater representation of climate change and adaptation regional effects, and the possibility to switch from perfect to imperfect competitive markets.
Assumptions/ limitations	The assumed frictionless markets within the model may underestimate the adjustment costs. Technological progress is exogenous, and the model is unable to capture non-market impact, risk and uncertainty. The dynamics are also simplified/ recursive.
Spatial scale and resolution	10 sectors and NUTS 2 level for the whole EU (267 regions).
Temporal scale and resolution	Recursive-dynamic one-year time intervals until 2045.
Accessibility of outputs	In addition to the open source, simplified version of the model performing a limited set of experiments, outputs are accessible through reports and peer reviewed publications of which a recent version is available at: https://ideas.repec.org/s/ipt/termod.html

Adaptation policy cycle stages	The RHOMOLO model has not been applied to the study of climate change impacts and adaptation yet, however its spatial detail can provide potential new developments in this field.
Adaptation policy insights	The RHOMOLO model has not been applied to the study of climate change impacts and adaptation yet, however its spatial detail can provide potential new developments in this field.
Relevant application	RHOMOLO is extensively applied to support impact assessments of the EU Structural and Investment Funds and by the European Investment Bank (EIB) for the evaluation of the macro-economic impact of the EIB group.
Main reference(s)	Lecca P., Barbero J., Christensen M.A., Conte A., Di Comite F., Diaz-Lanchas J., Diukanova O., Mandras G., Persyn D., Sakkas S. (2018), "RHOMOLO V3: A Spatial Modelling Framework" JRCTechnical report. Available at: https://ec.europa.eu/jrc/en/publication/rhomolo-v3-spatial-modelling-framework
Suitability for rapid assessment	No rapid use of model and data for adaptation analysis are possible, although a simplified version is available online.
Websites	https://ec.europa.eu/jrc/en/rhomolo
Manuals/ training/ videos	Access to the simplified version of the model: https://rhomolo.jrc.ec.europa.eu/
Wikipedia page	NA
Other	

3) Economic models	3.2 Computer general equilibrium (CGE) models	**EPPA - Economic Projection and Policy Analysis**

Model/ tool type and outputs	EPPA is a multi-country, multi-sector, recursive-dynamic computable general equilibrium (CGE) model developed at MIT that is currently used to study macro-economic impacts of climate change and mitigation policies.
Open access?	No
Key data inputs	The core model database is provided by social accounting matrices of domestic and international economic exchanges, detailed at the sectoral level. Data for climate change impact and policy assessments need to be provided by external sources, such as other hazard modelling exercises or studies.
Key data accessibility/ availability	Input data are publicly available but not open access given that the database is a commercial product. However, the Global Trade Analysis Project (GTAP) dataset is periodically updated and released by Purdue University: https://www.gtap.agecon.purdue.edu/
Strengths	Strengths of EPPA include the capacity to represent market adjustments, explicit representation of international trade and the sub national characterisation of the EU enables a greater representation of climate change and adaptation regional effects.
Assumptions/ limitations	The model is based on perfect competitive and frictionless markets, which may underestimate the adjustment costs. Technological progress is exogenous, and the model is unable to capture non-market impact, risk and uncertainty. The dynamics are also simplified/ recursive.
Spatial scale and resolution	The model can in principle feature 57 sectors and 140 countries/macro regions, the extension of GTAP database, however EPPA usually only considers a reduced set of regions and sectors.
Temporal scale and resolution	10-year time intervals until 2100.
Accessibility of outputs	Outputs are typically reported in peer review journals and reports.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 4) Assessing adaptation options
Adaptation policy insights	EPPA supports the assessment of macro-economic consequences of climate change, including price and quantity effects on market exchanges, and can be used to assess the indirect economic implication of specific adaptation strategies once their cost and effectiveness have been defined.

Relevant application	Extensively applied to the assessment of climate change impacts and mitigation policies. It could, in principle, be applied to assess the macro-economic implication of adaptation expenditure.
Main reference(s)	Paltsev, S., Reilly, J.M., Jacoby, H.D., Eckaus, R.S., McFarland, J., Sarofim, M., Asadoorian M. and M. Babiker (2005), "The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4" MIT Report No. 125
Suitability for rapid assessment	No rapid use of model and data for adaptation analysis are possible.
Websites	
Manuals/ training/ videos	
Wikipedia page	https://en.wikipedia.org/wiki/Integrated_Global_System_Model#cite_note-2
Other	

3) Economic models	3.2 Computer general equilibrium (CGE) models	**ENVISAGE - Environmental Impact and Sustainability Applied General Equilibrium Model**

Model/ tool type and outputs	ENVISAGE is a multi-country, multi-sector, recursive-dynamic computable general equilibrium (CGE) model developed at the World Bank that is currently used to study macro-economic impacts of climate change and of mitigation policies.
Open access?	No
Key data inputs	The core model database is provided by social accounting matrices of domestic and international economic exchanges, detailed at the sectoral level. Data for climate change impact and policy assessments need to be provided by external sources, such as other hazard modelling exercises or studies.
Key data accessibility/ availability	Input data are publicly available but not open access given that the database is a commercial product. However, the Global Trade Analysis Project (GTAP) dataset is periodically updated and released by Purdue University: https://www.gtap.agecon.purdue.edu/
Strengths	Strengths of ENVISAGE include the capacity to represent market adjustments, explicit representation of international trade and the sub national characterisation of the EU enables a greater representation of climate change and adaptation regional effects.
Assumptions/ limitations	The model is based on perfect competitive and frictionless markets, which may underestimate the adjustment costs. Technological progress is exogenous, and the model is unable to capture non-market impact, risk and uncertainty. The dynamics are also simplified/ recursive.
Spatial scale and resolution	The model can in principle feature 57 sectors and 140 countries/macro regions, the extension of GTAP database, however, ENVISAGE usually only considers a reduced set of regions and sectors.
Temporal scale and resolution	10-year time intervals until 2100.
Accessibility of outputs	Outputs are typically reported in peer review journals and reports.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 4) Assessing adaptation options
Adaptation policy insights	ENVISAGE supports the assessment of macro-economic consequences of climate change, including price and quantity

	effects on market exchanges, and can be used to assess the indirect economic implication of specific adaptation strategies once their cost and effectiveness have been defined.
Relevant application	Extensively applied to the assessment of climate change impacts and mitigation policies. It could, in principle, be applied to assess the macro-economic implication of adaptation expenditure.
Main reference(s)	Dominique van der Mensbrugghe (2010) "THE ENVIRONMENTAL IMPACT AND SUSTAINABILITY APPLIED GENERAL EQUILIBRIUM (ENVISAGE) MODEL Version 7.1" The World Bank December, 2010
Suitability for rapid assessment	No rapid use of model and data for adaptation analysis are possible.
Websites	
Manuals/ training/ videos	
Wikipedia page	NA
Other	

3) Economic models	3.3 Macro-econometric models	**E3ME - Energy, Environment, Economics Macro Economic**

Model/ tool type and outputs	E3ME is a global, macro-econometric model designed to address major economic, social and environmental challenges. Outputs are macro-economic effects of perturbations including unemployment levels and distributional effects across income groups.
Open access?	No, however the model can be shared through an agreement with the developers.
Key data inputs	The model has a purpose-developed database. Inputs are subsequently the economic perturbations under investigation.
Key data accessibility/ availability	The model is not open source, although it can occasionally be obtained under licence.
Strengths	Strengths of E3ME are the high level of disaggregation, econometric specification that provides a strong empirical basis for analysis, and integrated assessment of the global economies, energy systems, emissions and material demand.
Assumptions/ limitations	Post Keynesian economic theory with non-optimising agents which imply the potential existence of market failures and sticky prices. The assumption that historic behaviour can be extrapolated into the future is questionable and the degree of uncertainty around model results increases when long-term scenarios with structural change are assessed.
Spatial scale and resolution	61 global regions, including all G20 and EU Member States plus a set of regions to meet global totals, 43 economic sectors in each region, with more sectors in Europe.
Temporal scale and resolution	2010-2050 in one-year time intervals.
Accessibility of outputs	Available from scientific publications and reports.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change
Adaptation policy insights	Not applicable, however can assess the macro-economic assessment of mitigation and energy policy and of different types of economic shocks.
Relevant application	Not applicable
Main reference(s)	https://www.e3me.com/how/papers/

Suitability for rapid assessment	No - The model is complex and requires appropriate training to be used.
Websites	https://www.e3me.com/what/
Manuals/ training/ videos	https://www.e3me.com/what/e3me/
Wikipedia page	NA
Other	

3) Economic models	3.4 Behavioural economics	**Economic experiment of willingness-to-pay for flood insurance by Robinson and Botzen (2019) (no model name)**

Model/ tool type and outputs	This study examines the relevant psychological factors which can account for the probability neglect of flood risk and willingness-to-pay for flood insurance. Probability neglect implies the rounding of very low probabilities to zero and a willingness-to-pay of zero for flood insurance. It is relevant to the probability weighting function, which is a component of risk attitude under Prospect Theory, Rank Dependent Utility Theory and Dual Theory. The study focusses on the psychological variables anticipatory and anticipated emotions, as well as the threshold of concern heuristic which predicts that disaster probabilities reducing below a threshold level of concern are neglected. Results are also compared under real and hypothetical incentives. Real incentives imply that respondents are paid in the experiment based on their choices.
Open access?	N/a - this constitutes an individual study and no model or tool is applied here.
Key data inputs	Input data is panel data obtained through experiments, given that the respondents were required to make multiple flood insurance decisions over time. The probability of flooding varied across decisions, and respondents were asked to state the maximum value they would be willing to pay to cover the cost of flood damage to their home. Data for the psychological factors was elicited using Likert scale response formats, which are typically used to assess respondents' degree of agreement with provided statements. Real incentives were given in accordance with the Becker-DeGroot-Marschak mechanism combined with the Random Problem Selection Method.
Key data accessibility/ availability	Data can be accessed from http://journal.sjdm.org/vol13.3.html -- The paper "The impact of regret and worry on the threshold level of concern for flood insurance demand: Evidence from Dutch homeowners" uses the same data.
Strengths	The study uses a large sample of homeowners as opposed to students, who are often used as a convenient sample in economic experiments. The study uncovers various correlations between individual psychology and flood insurance demand, which is useful for designing policies aimed at promoting disaster preparedness and demand for insurance.

Assumptions/ limitations	Some learning may have occurred across flood insurance decisions, and therefore data may not be entirely independent. The study is artificial given that respondents are endowed a hypothetical home and bank balance from which they pay for insurance. The endowment effect also implies that individuals are more risk seeking when endowed with a prior monetary gain.
Spatial scale and resolution	Can be conducted online with an unlimited number and spatial extent of respondents.
Temporal scale and resolution	Can be conducted at one point in time or at multiple points over time.
Accessibility of outputs	The outputs highlight the influence of psychological variables on demand for flood insurance. Experiment results are easy to interpret for individuals with basic statistics skills.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options
Adaptation policy insights	The study finds that a proportion of respondents will not insure regardless of the flood probability. Policies aimed at improving risk comprehension and communication, such as risk ladders, may be beneficial in these circumstances. A significant proportion of respondents indicated the personal flood probability they are likely to experience is below their threshold level of concern. Framing the flood probability over a greater time horizon than one year, for example, the likelihood of at least one flood occurring over 40 years has a one-in-three chance, may overcome these threshold levels of concern. Moreover, combining disaster risk into an insurance policy containing multiple risks may create a combined probability of loss from all insurable events that exceeds individual thresholds of concern. Some respondents indicated that they would regret paying for insurance if a flood did not occur. These individuals may benefit from risk awareness campaigns and multi-year insurance with penalty costs applied to early policy cancellation to prevent short-sighted behaviour.
Relevant application	This method was applied to the Netherlands.
Main reference(s)	Robinson, P. J., & Botzen, W. J. W. (2019). Determinants of probability neglect and risk attitudes for disaster risk: An online experimental study of flood insurance demand among homeowners. Risk Analysis, 39(11), 2514-2527.
Suitability for rapid assessment	Pretesting of the experiment design and data collection can be time consuming.
Websites	https://onlinelibrary.wiley.com/doi/full/10.1111/risa.13361

Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.4 Behavioural economics	**Economic experiment of willingness-to-purchase hurricane insurance by Kunreuther and Michel-Kerjan (2015) (no model name)**

Model/ tool type and outputs	This study examines whether individuals prefer fixed-price multi-year insurance or annual contracts which may fluctuate in price. In a repeated decision, experiment respondents were provided the chance to purchase either a one- or two-period contracts or no insurance against the risk of hurricane damage to their property. The loading factor which determines the insurance price was also altered between actuarially fair insurance and 5% or 10% premium loading.
Open access?	N/a - this constitutes an individual study and no model or tool is applied here.
Key data inputs	Input data is panel data obtained through experiments, given that the respondents were required to make multiple hurricane insurance decisions over time. However, the data are treated as cross-sectional in the analysis. The loading factor for the two-period contract and whether a hurricane occurred between the two periods, which impacted the loading factor in period two, varied across decisions. Respondents were asked whether they would be either willing to purchase a one- or two-period contract or no insurance to cover the cost of hurricane damage to their home. Risk preferences were elicited according to the Holt-Laury procedure.
Key data accessibility/ availability	The data should be collected using an experiment and are not open access.
Strengths	The study is incentivized, greater aligning insurance decisions to actual demand than hypothetical decisions. The study uses a large sample of the United States general population as opposed to students, who are often used as a convenient sample in economic experiments. The experimental nature of the study avoids problems of confounding, which may occur when comparing two countries offering different disaster risk insurance contracts of, for example, one-period and multi-year. When assessing insurance up-take rates in reality, it could be challenging to ascertain whether differences in demand are due to multi-year insurance or other confounding factors.
Assumptions/ limitations	Given that the experimenters pre-decided the loss rounds, some deception occurred and therefore the probability did not reflect the true likelihood of loss. Some learning may also have occurred

	across hurricane insurance decisions, and therefore data may not be completely independent. The study is artificial given that respondents are endowed a hypothetical home and bank balance from which they pay for insurance. The endowment effect also implies that individuals could adopt greater risk seeking behaviour when endowed with a prior monetary gain. The Holt-Laury task, which was used to elicit risk preferences, has been criticized given that it is difficult to understand, and it conflates several components of risk preference.
Spatial scale and resolution	Can be conducted online with an unlimited number and spatial extent of respondents.
Temporal scale and resolution	Can be conducted at one point in time or at multiple points over time.
Accessibility of outputs	The outputs highlight the influence of availability of multi-year insurance on demand for hurricane insurance. Experiment results are easy to interpret for individuals with basic statistics skills.
Adaptation policy cycle stages	3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The study finds that under actuarially fair insurance, greater than five times as many individuals prefer the two-period to the one-period contract. Moreover, there is high demand for the two-period contract under modest increases in the loading factor, implying that individuals value price stability over time. Risk averse individuals are more likely to purchase the two-period than one-period contract. A significant proportion of respondents did not purchase any insurance. These individuals may benefit from policies aimed at increasing the risk probability above their individual concern threshold.
Relevant application	This method was applied to the USA.
Main reference(s)	Kunreuther, H., & Michel-Kerjan, E. (2015). Demand for fixed-price multi-year contracts: Experimental evidence from insurance decisions. Journal of Risk and Uncertainty, 51(2), 171-194.
Suitability for rapid assessment	Pretesting of the experiment design and data collection can be time consuming.
Websites	https://link.springer.com/article/10.1007/s11166-015-9225-4
Manuals/ training/ videos	
Wikipedia page	

Other	

3) Economic models	3.4 Behavioural economics	**Economic survey of willingness-to-pay for flood insurance by Botzen and van den Bergh (2012) (no model name)**

Model/ tool type and outputs	This study examines whether the communication of baseline probabilities, and changes in flood probabilities using risk ladders, facilitates risk comprehension by respondents and has an effect on the level of willingness-to-pay for flood insurance and its sensitivity to probability changes. The study also compares flood insurance demand under an ex-post public flood damage compensation scheme to that of no compensation. Moreover, correlations between risk perceptions, risk aversion, geographical characteristics and flood insurance demand are provided.
Open access?	N/a - this constitutes an individual study and no model or tool is applied here.
Key data inputs	Input data is panel data obtained through experiments, given that the respondents were required to make multiple flood insurance decisions over time. Flood insurance demand was elicited under scenarios where a risk ladder was used to communicate the flood probability and where the risk ladder was omitted. Similarly, demand was elicited for scenario where government compensation was either available or not. The flood probability also varied from current likelihoods of 1 in 1250, to scenarios with two higher probabilities due to climate change of 1 in 600 and 1 in 400. Risk perceptions and risk aversion were elicited using subjective response formats. Geographic characteristics were recovered from GIS maps.
Key data accessibility/ availability	The data should be collected using a survey and are not open access.
Strengths	The study uses a large sample of homeowners as opposed to students, who are often used as a convenient sample in economic experiments. The study investigates correlations between individual psychology and flood insurance demand, which is useful for designing policies aimed at promoting disaster preparedness and demand for insurance. The experimental nature of the study circumnavigates problems of confounding, which may occur when comparing two countries which offer different flood damage compensation schemes, for example, government compensation versus no compensation. However, it could be challenging to ascertain whether differences in demand are due to government

	compensation or other confounding factors when assessing actual insurance up-take rates. The same applies when comparing countries/areas using different risk comprehension tools.
Assumptions/ limitations	Some learning may have occurred across flood insurance decisions, and therefore data may not be entirely independent. The risk aversion elicitation is not based on revealed preferences. The study is also not incentivised, and therefore participants' insurance decisions in the experiment may not reflect actual demand in comparison to incentivised decision-making.
Spatial scale and resolution	Can be conducted online with an unlimited number and spatial extent of respondents.
Temporal scale and resolution	Can be conducted at one point in time or at multiple points over time.
Accessibility of outputs	Outputs include the influence of risk communication, government compensation, risk perceptions, risk aversion and geographical factors on demand for flood insurance. Survey results are easy to interpret for individuals with basic statistics skills.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The study finds that communication of baseline probabilities, and changes in flood probabilities using risk ladders, facilitated risk comprehension and impacted on the level of willingness-to-pay for flood insurance, resulting in greater sensitivity to probability changes. Government compensation reduced flood insurance demand, and therefore this type of ex post relief may have a detrimental effect on disaster preparation efforts. A significant proportion of respondents did not purchase insurance. These individuals may benefit from policies aimed at increasing the risk probability above their threshold level of concern. Framing the flood probability over a greater time horizon than one year, for example, the likelihood of at least one flood occurring over 40 years has a one-in-three chance, may overcome these threshold levels of concern. Risk perceptions constitute a significantly greater predictor of flood insurance demand than indicators of objective flood risk derived from geographical characteristics. Therefore, policies aimed at influencing individuals' risk perceptions may aid in adaptation.
Relevant application	This method was applied to the Netherlands.
Main reference(s)	Botzen, W. J. W., & van den Bergh, J. C. (2012). Risk attitudes to low-probability climate change risks: WTP for flood

	insurance. Journal of Economic Behavior & Organization, 82(1), 151-166.
Suitability for rapid assessment	Pretesting of the survey design and data collection can be time consuming.
Websites	https://www.sciencedirect.com/science/article/pii/S0167268112000145
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.4 Behavioural economics	**Economic survey of willingness-to-pay for flood insurance by Bradt (2019) (no model name)**

Model/ tool type and outputs	This study examines the impact of two behaviourally informed policies – nudges and boosts – on flood insurance demand. The study implements two nudges, an 'informational' and an 'affective' nudge, and a statistical numeracy boost. Risk beliefs are also elicited.
Open access?	N/a - this constitutes an individual study and no model or tool is applied here.
Key data inputs	Input data is cross-sectional given that the respondents were required to make a single flood insurance decision at one point in time. Flood insurance demand was elicited under a scenario where respondents are provided the probability of flooding in a single year and a scenario where the risk was communicated over a 30-year time horizon. Demand was also elicited under scenarios where respondents were either previously provided statistical training regarding the interpretation of probabilities, or where this training was absent. Finally, demand was elicited under a scenario where information on coastal flooding in the United States and a set of images of flooding in coastal areas were provided, and a scenario where they were not. Risk beliefs were elicited using subjective response formats.
Key data accessibility/ availability	The data should be collected using a survey and are not open access.
Strengths	The data are cross-sectional, which limits learning effects and greater ensures independent flood insurance demand observations. The experimental nature of the study limits potential confounding factors which may occur when comparing two countries which offer different policies for increasing flood insurance demand. It could be challenging to ascertain whether differences in demand are due to these policies or other confounding factors when assessing actual insurance up-take rates.
Assumptions/ limitations	The sample size is relatively small in comparison with other similar studies, and therefore the statistical power of the results could be questioned. The study is also not incentivised, and therefore participants' insurance decisions in the experiment may not reflect actual demand in comparison to incentivised decision-making. The study is also artificial in the sense that respondents are endowed a hypothetical home. The endowment effect also implies that

	individuals are greater risk seekers when endowed with a prior monetary gain.
Spatial scale and resolution	Can be conducted online with an unlimited number and spatial extent of respondents.
Temporal scale and resolution	Can be conducted at one point in time or at multiple points over time.
Accessibility of outputs	Outputs include the influence of boosts and nudges on demand for flood insurance. Survey results are easy to interpret for individuals with basic statistics skills.
Adaptation policy cycle stages	4) Assessing adaptation options
Adaptation policy insights	The study finds that the statistical numeracy boost reduces respondents' willingness-to-pay for flood insurance, perhaps because the boost greater highlighted that the risk is lower than threshold levels of concern. The nudges demonstrated greater effectiveness at increasing willingness-to-pay for flood insurance than the boost. The affective nudge was more influential than presenting the flood probability over a longer time horizon.
Relevant application	This method was applied to the USA.
Main reference(s)	Bradt, J. (2019). Comparing the effects of behaviorally informed interventions on flood insurance demand: an experimental analysis of 'boosts' and 'nudges'. Behavioural Public Policy (In press).
Suitability for rapid assessment	Pretesting of the survey design and data collection can take time.
Websites	https://www.cambridge.org/core/journals/behavioural-public-policy/article/comparing-the-effects-of-behaviorally-informed-interventions-on-flood-insurance-demand-an-experimental-analysis-of-boosts-and-nudges/47B35632F9BE3F60D20CA7BF31B4A13A#fndtn-information
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.4 Behavioural economics	**Economic experiment of willingness-to-purchase flood insurance by Chaudhry *et al.* (2018) (no model name)**

Model/ tool type and outputs	This study examines the impact of extending the time horizon over which the risk of flood loss is communicated, i.e., presenting the cumulative probability of loss across time, on flood insurance demand. The effect of this framing on individual risk perceptions was also investigated.
Open access?	N/a - this constitutes an individual study and no model or tool is applied here.
Key data inputs	Input data are panel data given that the respondents were required to make multiple flood insurance decisions over time. Flood insurance demand was elicited under a scenario where the flood probability was communicated as a 1% likelihood of loss in a single play/year and a scenario which communicated a 26% likelihood of at least one loss occurring over thirty plays/years. Other scenarios altered the sequence of loss (none, early and late), and whether the risk was framed in a neutral context with no reference to flooding, or in the flood risk context. Risk perceptions were elicited using subjective response formats.
Key data accessibility/ availability	The data should be collected using an experiment and are not open access.
Strengths	The study includes multiple robustness checks to verify whether the key results are consistent under different scenarios. The study is incentivized, which greater aligns insurance decisions to actual demand than hypothetical decisions. The study uses a large sample of the United States general population as opposed to students, who are often used as a convenience sample in economic experiments. The experimental nature of the study limits potential confounding factors which may occur when comparing two countries which offer different policies for increasing flood insurance demand. It could be challenging to ascertain whether differences in demand are due to these policies or other confounding factors when assessing actual insurance up-take rates.
Assumptions/ limitations	Some deception occurred given that the experimenters chose the loss rounds beforehand, and therefore the probability did not reflect the actual likelihood of loss. Some learning may have occurred across flood insurance decisions, and therefore data may not be entirely independent. The study is also artificial given that respondents are endowed a hypothetical home and bank balance

	from which they pay for insurance. The endowment effect also implies that individuals are greater risk seekers when endowed with a prior monetary gain.
Spatial scale and resolution	Can be conducted online with an unlimited number and spatial extent of respondents.
Temporal scale and resolution	Can be conducted at one point in time or at multiple points over time.
Accessibility of outputs	Outputs include the influence of extending the time horizon over which the risk of flood loss is communicated on demand for flood insurance. Experiment results are easy to interpret for individuals with basic statistics skills.
Adaptation policy cycle stages	4) Assessing adaptation options
Adaptation policy insights	Extending the time horizon resulted in elevated risk perceptions and increased the likelihood of flood insurance purchase. This result was robust to time and experiencing a loss.
Relevant application	This method was applied to the USA.
Main reference(s)	Chaudhry, S. J., Hand, M., & Kunreuther, H. (2018). Extending the time horizon: Elevating concern for rare events by communicating losses over a longer period of time. Working Paper University of Pennsylvania.
Suitability for rapid assessment	Pretesting of the experiment design and data collection can take time.
Websites	https://riskcenter.wharton.upenn.edu/wp-content/uploads/2018/08/WP201805_Extending-Time-Horizon_Chaudhry-etal.pdf
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.4 Behavioural economics	**Economic experiment of willingness-to-purchase flood damage reduction measures by Mol *et al.* (2020) (no model name)**

Model/ tool type and outputs	This study examines the effects of different financial incentives, such as insurance premium discounts and mitigation loans, probability levels, and deductibles on risk reduction investments in a natural disaster insurance market with compulsory coverage.
Open access?	Survey questions and experimental instructions can be found in paper (publishers' website with restricted access): https://www.sciencedirect.com/science/article/pii /S2214804318304658?via%3Dihub Preprint open access at website of the first author: https://www.jantsje.nl/publication/mol-2019-b/ postprint-mol-2019-b.pdf
Key data inputs	Input data are panel data given that the respondents were required to make multiple investment in flood damage-reduction decisions over time. Flood damage-reduction investments were elicited under scenarios: without insurance, with insurance, with insurance and premium discounts available, with insurance and mitigation loans available, and with insurance and premium discounts as well as mitigation loans available. Other scenarios altered the flood probability deductible. Risk and time preferences were elicited using multiple price lists.
Key data accessibility/ availability	The data should be collected using an experiment and are not open access.
Strengths	The study is conducted in a laboratory environment with an experimenter present, ensuring high subject motivation. A real effort task is included which avoids the endowment effect. The effort task asked subjects to manually open a set number of boxes containing fictional money. The idea of the task is to increase subjects' sense of ownership of the money. The risk preference elicitation task is preferred over the traditional Holt-Laury procedure, which scores lower on out-of-sample prediction and consistency. The study is incentivized: the stake sizes and chances of earning money are much greater than in other experiments in the domain of choices under low-probability/high-impact risk. This incentivization greater aligns insurance decisions to actual demand than hypothetical decisions. The experimental nature of the study limits potential confounding factors which may occur when

	comparing two countries which offer different policies for increasing flood protection demand. It could be challenging to ascertain whether differences in demand are due to these policies or other confounding factors when assessing actual protection up-take rates.
Assumptions/ limitations	The risk operationalization is not fully transparent. The experiment was conducted with students, who are not the population of interest. Some learning may have occurred across flood damage-reduction decisions, and therefore data may not be entirely independent. The study is artificial given that respondents are endowed a hypothetical home and bank balance from which they pay for damage-reduction investments.
Spatial scale and resolution	Can be conducted with a limited number of respondents due to high monetary incentives offered to respondents.
Temporal scale and resolution	Can be conducted at one point in time or at multiple points over time.
Accessibility of outputs	Outputs include the influence of financial incentives, probability levels and deductibles on demand for flood risk reduction. Experiment results are easy to interpret for individuals with basic statistics skills.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 4) Assessing adaptation options
Adaptation policy insights	The study finds that protective investments increases with risk aversion, higher deductibles and loss probabilities in line with rationality. A premium discount also increases investment, while the availability of a mitigation loan does not. Moral hazard is present in the high-probability scenarios, but not in the low-probability scenarios. Therefore, moral hazard does not pose as significant an issue in typical disaster insurance markets.
Relevant application	This method was applied to the Netherlands.
Main reference(s)	Mol, J. M., Botzen, W. J. W., & Blasch, J. E. (2020). Risk reduction in compulsory disaster insurance: Experimental evidence on moral hazard and financial incentives. Journal of Behavioral and Experimental Economics, 84.
Suitability for rapid assessment	Pretesting of the experiment design and data collection can take time.
Websites	https://www.sciencedirect.com/science/article/pii/S2214804318304658

Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.4 Behavioural economics	**Economic experiment of willingness-to-purchase coinsurance by Papon (2008) (no model name)**

Model/ tool type and outputs	This study examines the impact of the length of the commitment period of insurance policies, i.e., the length of time an individual commit to maintaining the same insurance decision, on insurance demand.
Open access?	N/a - this constitutes an individual study and no model or tool is applied here.
Key data inputs	Input data are panel data given that respondents were required to make multiple coinsurance decisions over time. Insurance demand was elicited under a scenario where subjects commit to an insurance choice for one period only, and under a scenario where subjects commit to an insurance choice for four periods in a row (see multi-year insurance).
Key data accessibility/ availability	The data should be collected using an experiment and are not open access.
Strengths	The risk operationalization is transparent and involves the random drawing of letters from a vessel (A to Y) to determine whether subjects experience the risk in a given decision. Therefore, there is a reduced likelihood of subjects questioning the risk. The study is conducted in a laboratory environment with an experimenter present, ensuring high subject motivation. The study is also incentivized, which greater aligns insurance decisions to actual demand than hypothetical decisions. The experimental nature of the study limits potential confounding factors which may occur when comparing two countries which offer different policies for increasing flood protection demand. It could be challenging to ascertain whether differences in demand are due to these policies or other confounding factors when assessing actual protection up-take rates.
Assumptions/ limitations	The experiment was conducted with students, who are not the population of interest. Some learning may have occurred across insurance decisions, and therefore data may not be entirely independent. The study is artificial given that respondents are endowed a hypothetical bank balance from which they pay for insurance. The endowment effect also implies that individuals are greater risk seekers when endowed with a prior monetary gain.
Spatial scale and resolution	Can be conducted with a limited number of respondents due to high monetary incentives offered to respondents.

Temporal scale and resolution	Can be conducted at one point in time or at multiple points over time.
Accessibility of outputs	Outputs include the influence of availability of multi-year insurance on demand for insurance. Experiment results are easy to interpret for individuals with basic statistics skills.
Adaptation policy cycle stages	4) Assessing adaptation options
Adaptation policy insights	The level of coverage demanded by respondents increased with the commitment period. Full and zero insurance were the most commonly selected choices. Full insurance was more commonly chosen under the longer commitment period, and zero insurance under the shorter one.
Relevant application	This method was applied in France.
Main reference(s)	Papon, T. (2008). The effect of pre-commitment and past-experience on insurance choices: An experimental study. The Geneva Risk and Insurance Review, 33(1), 47-73.
Suitability for rapid assessment	Pretesting of the experiment design and data collection can take time.
Websites	https://link.springer.com/article/10.1057/grir.2008.8
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.4 Behavioural economics	**Economic survey of flood risk perception by Botzen *et al.* (2009) (no model name)**

Model/ tool type and outputs	This study examines the factors which determine flood risk perceptions, providing insights for policy makers and insurance companies. Increasing knowledge of citizens regarding the causes of flooding may increase flood risk awareness, which has greatest significance to individuals who live in areas unprotected by dikes given that they tend to underestimate their risk of flooding.
Open access?	Subset of survey questions can be found in appendix of paper (open source): https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2009WR007743
Key data inputs	Input data are cross-sectional given that the respondents were surveyed at one point in time. The respondents were asked to assess the flood probability through three different question formats. (1) The respondents were asked to rate, on a scale from 0 to 10, the probability that their household would suffer financial damage as a result of various risks, including flooding. (2) The respondents were asked for a quantitative estimate of the return period of flooding. (3) The respondents were asked to provide a qualitative estimate of the probability of a flood occurring in their residential area.
Key data accessibility/ availability	The data should be collected using a survey and are not open access.
Strengths	This study used a large sample of homeowners who live in the Dutch river delta: relevant decision-makers who should consider the adoption of adaptation measures given that they are at a high level of flood risk. The study used three different measures for flood risk perception, controlling for several biases including the ranking of other risks. Furthermore, the statistical methods of this study provide greater accurate estimates of several variables on risk perception in comparison to conventional simple correlation analyses.
Assumptions/ limitations	The focus of this study was on the Netherlands, where the last severe flood was in 1953: only 3% of respondents had any flood risk experience. This is a limitation given that the study aims to investigate the impact of flood risk experience on flood risk perception. The use of subjective response formats is also a limitation as it is prone to memory errors and social desirability bias. Further, the respondents were asked a similar question

	multiple times, which may result in a learning effect or a preference for consistency.
Spatial scale and resolution	Can be conducted online with an unlimited number and spatial extent of respondents.
Temporal scale and resolution	Can be conducted at one point in time or at multiple points over time.
Accessibility of outputs	Outputs include the influence of several factors on risk perception. Survey results are easy to interpret for individuals with basic statistics skills.
Adaptation policy cycle stages	4) Assessing adaptation options
Adaptation policy insights	Increasing the knowledge of citizens regarding the causes of flooding may increase flood risk awareness, which subsequently may increase flood risk preparedness. Informing citizens is especially important in areas with the lowest protection standards, such as without dike infrastructure, as homeowners in these areas tend to be unaware of the high risk.
Relevant application	This method was applied to the Netherlands.
Main reference(s)	Botzen, W. J. W., Aerts, J. C. J. H., & van den Bergh, J. C. J. M. (2009). Dependence of flood risk perceptions on socioeconomic and objective risk factors. *Water Resources Research*, *45*(10), 1–15.
Suitability for rapid assessment	Pretesting of the survey design and data collection can take time.
Websites	http://doi.wiley.com/10.1029/2009WR007743
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.4 Behavioural economics	**Economic survey of flood risk perception by Botzen *et al.* (2015) (no model name)**

Model/ tool type and outputs	This study used New York City as a case study to analyse individual perceptions of flood risks through examining both anticipated probability and anticipated damage. These individual risk perceptions are related to objective risk indicators. On average, the probability of tail risks is overestimated, while potential damage is underestimated.
Open access?	Survey questions are available at appendix of (open access) paper: http://journal.sjdm.org/15/15415/jdm15415.pdf
Key data inputs	Input data are cross-sectional given that the respondents completed a single survey. Two distinct aspects of flood risk perception were estimated: anticipated probability and anticipated damage. In addition, variables characterized by intuitive thinking were examined: past flood experience, high worry and perception of the probability falling above a threshold level of concern.
Key data accessibility/ availability	The data should be collected using a survey and are not open access.
Strengths	This study examined the deviation between objective and subjective flood risks estimates with respect to both probability and damage. The extensive questionnaire supported the authors to correlate the results to several intuitive thinking variables, including worry and threshold level of concern. The study used a large sample of NYC homeowners with recent flood experience.
Assumptions/ limitations	The study relied on the respondents' numerical estimates of anticipated flood risks; however it did not control for the numeracy skills of these respondents.
Spatial scale and resolution	Can be conducted over the telephone or online with an unlimited number and spatial extent of respondents.
Temporal scale and resolution	Can be conducted at one point in time or at multiple points over time.
Accessibility of outputs	Outputs include the influence of several psychological variables on flood risk perception of both damage and probability. Survey results are easy to interpret for individuals with basic statistics skills.
Adaptation policy cycle stages	4) Assessing adaptation options

Adaptation policy insights	It is crucial to provide individuals with adequate information regarding both their objective flood probability and damage. The authors recommend enforcing and strengthening mandatory flood insurance purchase requirements and setting minimum building code standards.
Relevant application	This method was applied to the USA.
Main reference(s)	Botzen, W. J. W., Kunreuther, H. C., & Michel-Kerjan, E. O. (2015). Divergence between individual perceptions and objective indicators of tail risks: Evidence from floodplain residents in New York City. *Judgment and Decision Making*, *10*(4), 365–385.
Suitability for rapid assessment	Pretesting of the survey design and data collection can take time.
Websites	http://journal.sjdm.org/15/15415/jdm15415.pdf
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.4 Behavioural economics	**Face-to-face interviews of flood risk perception and perceived distance by O'Neill *et al.* (2016) (no model name)**

Model/ tool type and outputs	This study examined the distance to a perceived flood zone using cognitive mapping methodology. This distance is a crucial factor in determining the cognitive and affective (emotional) components of flood risk perception. Risk perception is found to be greater aligned with the degree of worry than with objective (spatial) flood risk estimates.
Open access?	N/a - this constitutes an individual study and no model or tool is applied here.
Key data inputs	Input data are 30-minute face-to-face interviews including a cognitive mapping exercise. The level of detail obtained through these interviews is extensive, which is traded-off against sample size.
Key data accessibility/ availability	The data should be collected using a survey and are not open access.
Strengths	This study captures respondents' perceived distance to a perceived flood zone using cognitive mapping methodology. The article demonstrates a deviation between risk perception and reality, which is related to the degree of worry.
Assumptions/ limitations	One potential bias within the cognitive mapping exercise is framing of the base map: respondents may assume that the base map is centred on the flood area and act accordingly. Due to the cross-sectional nature of the data, the causal direction of the effects could be questioned.
Spatial scale and resolution	The study was conducted with a limited number of respondents due to the labour-intensive and extensive time of one-on-one interviews.
Temporal scale and resolution	Can be conducted at one point in time or at multiple points over time.
Accessibility of outputs	Outputs include the impact of perceived flood exposure on flood risk perception. Interview results and cognitive maps are easy to interpret.
Adaptation policy cycle stages	4) Assessing adaptation options

Adaptation policy insights	Individuals who live within flood zones yet do not perceive this are of greatest interest for flood-risk management. Some respondents may underestimate the time required for an emergency evacuation, which could be subsequently incorporated into the design of flood risk awareness campaigns.
Relevant application	This method was applied to Ireland.
Main reference(s)	O'Neill, E., Brereton, F., Shahumyan, H., & Clinch, J. P. (2016). The impact of perceived flood exposure on flood-risk perception: The role of distance. *Risk Analysis*, *36*(11), 2158–2186.
Suitability for rapid assessment	Pretesting of the survey design and data collection can take time.
Websites	http://doi.wiley.com/10.1111/risa.12597
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.4 Behavioural economics	**Expected utility theory extended with information search under low probabilities**

Model/ tool type and outputs	The model examined the effect of information regarding the loss probability on three alternative insurance strategies: ignore insurance, buy insurance immediately and seek information.
Open access?	Yes
Key data inputs	The main input data are flood probabilities derived from hydrological models and flood damage from a catastrophe (flood damage) model. Information regarding premiums and their loading factors are used as inputs for the insurance module.
Key data accessibility/ availability	The required data are typically not open access.
Strengths	The model highlights a justification for commonly observed instances when individuals do not purchase insurance against low-probability high-loss events, even when favourable premiums are offered. Possible remedies are offered, including better information regarding probabilities as well as about the level of insurer profits.
Assumptions/ limitations	The model assumes that individuals have prior beliefs regarding loss probabilities and make rational decisions based on expected utility maximization. An alternative explanation could be that individuals are unable to distinguish between probabilities when these are low.
Spatial scale and resolution	Local/ regional/ national.
Temporal scale and resolution	No time component is part of the model: this theoretical model can be applied to unlimited time scale.
Accessibility of outputs	This study used a simple economic model analysing the influence of search costs on insurance uptake. It can be used by individuals with basic economics/ mathematics skills.
Adaptation policy cycle stages	4) Assessing adaptation options; 5) Implementation
Adaptation policy insights	The study highlighted that individuals require conviction that the probability of damage is greater than their personal threshold level before they will want to research greater accurate information regarding its value: the potential size of mitigated damages. This could be resolved through better information regarding loss probabilities and loading factors. Alternatively, insurers may bundle policies of several low-probability high-impact risks, such as fire,

	flood and burgling risks. Bundling policies leads to higher overall probabilities of damage, which may reach personal thresholds of concern.
Relevant application	This method was applied to the USA.
Main reference(s)	Kunreuther, H. C., & Pauly, M. V. (2004). Neglecting disaster: Why don't people insure against large losses? *Journal of Risk and Uncertainty*, *28*(1), 5–21.
Suitability for rapid assessment	Simple model, suitable for rapid assessment. Collecting input data would be time consuming.
Websites	https://link.springer.com/article/10.1023/B:RISK.0000009433.25126.87
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.4 Behavioural economics	**Psychological survey of flood risk perception by Bosschaart *et al.* (2013) (no model name)**

Model/ tool type and outputs	This study explored students' flood-risk perception within flood-prone areas of the Netherlands and the role of knowledge in the formation of flood-risk perception. The study used a sample of 483 15-year-old geography students from different flood prone areas in the Netherlands.
Open access?	Survey questions are available at appendix of (open access) paper: https://link.springer.com/article/10.1007%2Fs11069-013-0774-z
Key data inputs	Input data are cross-section given that the respondents completed a single survey. Knowledge was assessed using two scales of 12 close-ended questions. Risk perception was assessed at the personal level and at the general level using statements on a 5-point scale.
Key data accessibility/ availability	The data should be collected using a survey and are not open access.
Strengths	This was the first study to examine flood risk awareness and flood risk perception in the age groups when risk perception may be established, as opposed to in adults when individuals are less likely to be influenced by information regarding risk awareness. This study used a significant sample size of 15-year-old students in the Netherlands, including a reference group from higher-elevation areas.
Assumptions/ limitations	Knowledge was tested using two scales of twelve close-ended questions: the type of knowledge could be further explored, for example, by classifying the answers into different knowledge fields or by including open ended questions. Further, the sample was limited to the highest educational levels, in which at least three years of geography study were required.
Spatial scale and resolution	Can be conducted over the telephone or online with an unlimited number and spatial extent of respondents.
Temporal scale and resolution	Can be conducted at one point in time or at multiple points over time.
Accessibility of outputs	Outputs include the influence of several factors on local and general knowledge regarding flood risk. Survey results are easy to interpret for individuals with basic statistics skills.

Adaptation policy cycle stages	5) Implementation; 6) Monitoring & evaluation
Adaptation policy insights	The study highlighted that students' general knowledge regarding flood risk were greater than the knowledge of local adults. Yet it appeared that local knowledge solely effected individuals' risk perceptions. Therefore, these results justify the adoption and communication of a cohesive strategy by educational authorities regarding how and why increasing flood-risk perception are important, in particular with respect to geography education.
Relevant application	This method was applied to the Netherlands.
Main reference(s)	Bosschaart, A., Kuiper, W., van der Schee, J., & Schoonenboom, J. (2013). The role of knowledge in students' flood-risk perception. *Natural Hazards*, *69*(3), 1661–1680.
Suitability for rapid assessment	Pretesting of the survey design and data collection can take time.
Websites	http://link.springer.com/10.1007/s11069-013-0774-z
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.4 Behavioural economics	**Literature review on flood risk perception by Lechowska (2018) (no model name)**

Model/ tool type and outputs	This review attempted to answer: What determines flood risk perception? The results were developed based on critical analysis of the empirical research. The organization of the research results on the flood risk assessment conducted herein aims to improve the understanding of the human perception of flood risk.
Open access?	N/a - this constitutes an individual study and no model or tool is applied here.
Key data inputs	50 empirical studies were overviewed which discussed one of the following keywords: flood risk perception, risk perception, flood, factors, awareness, worry and preparedness, trust, fear, emotion, denial, risk underestimation, action, attitude, disasters, vulnerability, resilience.
Key data accessibility/ availability	The data was collected using a literature search and are not open access. Papers were collected through a search on Google Scholar, Web of Science/Knowledge and Scopus.
Strengths	The results were developed based on critical analysis of the empirical research. Three levels of influence were identified in the literature: primary, which clearly influence risk perception; secondary, where the influence is not clear and requires further research; and intervening, often describing the context.
Assumptions/ limitations	The review demonstrated that the relationships between particular characteristics in determining flood risk perception are not clear, and many authors highlight diverse conclusions from similar research. This may be due to the lack of a theoretical framework and the use of multiple measuring scales.
Spatial scale and resolution	The review did not assess geographical location of the conducted studies. Insights can be applied globally.
Temporal scale and resolution	The review included studies from 1998 to 2018. Insights can be applied to new surveys (either one point in time or multiple points over time).
Accessibility of outputs	Review results are accessible.
Adaptation policy cycle stages	6) Monitoring & evaluation

Adaptation policy insights	The flood risk perception factors identified in this review could be adopted into communication strategies to improve public flood risk perception.
Relevant application	This was a holistic literature review on risk perception.
Main reference(s)	Lechowska, E. (2018). What determines flood risk perception? A review of factors of flood risk perception and relations between its basic elements. *Natural Hazards*, *94*(3), 1341–1366.
Suitability for rapid assessment	n.a.
Websites	http://link.springer.com/10.1007/s11069-018-3480-z
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.4 Behavioural economics	**Economic survey of flood risk perception by Mol *et al.* (2020) (no model name)**

Model/ tool type and outputs	This study assessed the possible flood risk misperceptions of floodplain residents in the Netherlands and offered insights into factors that influence under- or overestimation of perceived flood risk. Results highlighted that many Dutch floodplain inhabitants significantly overestimate the probability but underestimate the maximum expected flood water level.
Open access?	Survey questions can be found at companion paper (publishers' website, restricted access): https://www.sciencedirect.com/science/article/pii/S0167268118303378. Preprint open access at website of the first author: https://www.jantsje.nl/publication/mol-2018/postprint-mol-2018.pdf
Key data inputs	Input data are cross-sectional given that the respondents were surveyed at a single point in time. The respondents were asked to assess the flood probability and expected damage and water levels. Two questions were used to elicit perceived flood probability: on a qualitative scale from 'zero' to 'very high' and a quantitative estimation of the return period.
Key data accessibility/ availability	The data should be collected using a survey and are not open access.
Strengths	This study used a large sample of homeowners who reside within the Dutch river delta: relevant decision-makers who should consider the adoption of adaptation measures given that they are at a high level of flood risk. This information was combined with detailed objective risk data through GIS methods. This study examined factors related to flood risk perceptions and extended the analysis to incorporate flood risk misperceptions.
Assumptions/ limitations	The majority of damage estimates by the respondents appeared to be correct when the authors compared perceived damages with expected damage calculations by experts, which may be because the maximum flood damage is correlated to the property value. The water level question asked for the 'expected water level in your home in case of a flood', which is not identical to the maximum water level, and was used as an objective indicator of flood risk. Therefore, the results may be perceived as a lower bound.

Spatial scale and resolution	Can be conducted over the telephone or online with an unlimited number and spatial extent of respondents.
Temporal scale and resolution	Can be conducted at one point in time or at multiple points over time.
Accessibility of outputs	Outputs include the influence of several variables on flood risk perception: expected water levels, damage and probability. Survey results are easy to interpret for individuals with basic statistics skills.
Adaptation policy cycle stages	4) Assessing adaptation options
Adaptation policy insights	The results highlighted that it could be beneficial to promote information campaigns targeted towards homeowners within the river delta, specifically in the low-lying areas. A potential approach could be to focus on communicating consequential risk factors, such as damage estimates and the maximum water level, as they are salient and relatable, as opposed to probabilities or return periods which can be challenging to translate into tangible terms.
Relevant application	This method was applied to the Netherlands.
Main reference(s)	Mol, J.M., Botzen, W.J.W, Blasch, J.E., de Moel, H. (2020) Insights into flood risk misperceptions of homeowners in the Dutch river delta. *Manuscript submitted for publication.*
Suitability for rapid assessment	Pretesting of the survey design and data collection can take time.
Websites	Manuscript in review, survey questions can be found in companion (published) article: https://www.sciencedirect.com/science/article/pii/S0167268118303378
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.4 Behavioural economics	**Survey of implemented flood damage mitigation measures by Poussin *et al.* (no model name)**

Model/ tool type and outputs	This study assessed the implemented flood damage mitigation measures by households in France and estimated statistical models which could highlight which factors influenced the adoption of these measures, such as individual risk perceptions and coping appraisals.
Open access?	No
Key data inputs	Input data are cross-sectional data given that the respondents completed a single survey. The main input data are information regarding implemented flood damage mitigation measures, and variables that influence flood preparedness decisions, such as risk perceptions, coping appraisals and socio-demographic characteristics.
Key data accessibility/ availability	The data should be collected using a survey and is not open access.
Strengths	The study collected data from a large sample of households from three flood-prone areas in France, providing insights regarding a variety of variables which influence the adoption of flood damage mitigation measures.
Assumptions/ limitations	The survey data was collected through postal mail, which resulted in a low response rate.
Spatial scale and resolution	Can be conducted over the telephone or online with an unlimited number and spatial extent of respondents.
Temporal scale and resolution	Can be conducted at one point in time or at multiple points over time.
Accessibility of outputs	Model outputs include the effects of a variety of variables on the implementation of flood damage mitigation measures, including risk perceptions, coping appraisals, flood experience, risk attitudes, flood risk management policies and incentives, social network and norms, and socio-economic characteristics.
Adaptation policy cycle stages	4) Assessing adaptation options; 5) Implementation
Adaptation policy insights	The estimated statistical models provided insights regarding the influential factors on the implementation of flood risk mitigation measures. The overall findings demonstrated that risk perceptions had a limited effect on risk mitigation behaviour, while coping

	appraisals had a greater significant influence. Several variables that have been added to the Protection Motivation Theory framework appear to be influential in households' flood preparedness decisions, such as flood experience, local flood risk management policies and incentives and the social network. Policy recommendations based on these results included the requirement to improve communication campaigns on flood damage mitigation measures and to provide additional financial incentives for risk reduction.
Relevant application	This method was applied in France.
Main reference(s)	Poussin, J., Botzen, W.J.W., Aerts, J.C.J.H. (2014). Factors of influence on flood damage mitigation behaviour by households - Literature review and results from a French survey. *Environmental Science and Policy*, 40: 69-77.
Suitability for rapid assessment	Pretesting of the survey design and data collection can take time.
Websites	https://www.sciencedirect.com/science/article/abs/pii/S1462901114000264
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.4 Behavioural economics	**Survey of implemented flood damage mitigation measures by Bubeck *et al.* (no model name)**

Model/ tool type and outputs	This study assessed the implemented flood damage mitigation measures and flood insurance purchases by households in Germany and estimated statistical models that could highlight which factors influenced the adoption of these measures, such as individual risk perceptions and coping appraisals.
Open access?	No
Key data inputs	Input data are cross-sectional given that the respondents completed a single survey. The main input data are information on implemented flood damage mitigation measures and flood insurance purchases, and variables that influence flood preparedness decisions, such as risk perceptions, coping appraisals and socio-demographic characteristics.
Key data accessibility/ availability	The data should be collected using a survey and are not open access.
Strengths	The study collected data from a large sample of households from Germany and provided insights regarding a variety of variables which influenced the adoption of different types of flood damage mitigation measures and the purchase of flood insurance.
Assumptions/ limitations	The survey was implemented in different areas along the Rhine river, a relevant study area given that it is a densely populated river basin of major economic importance. Further research could examine whether the results may be transferred to other flood-prone areas in Germany.
Spatial scale and resolution	Can be conducted over the telephone or online with an unlimited number and spatial extent of respondents.
Temporal scale and resolution	Can be conducted at one point in time or at multiple points over time.
Accessibility of outputs	Model outputs include the effects of a variety of variables on the implementation of flood damage mitigation measures and the purchase of flood insurance, including risk perceptions, coping appraisals, flood experience, risk attitudes, non-protective responses, social network and norms, and socio-economic characteristics.
Adaptation policy cycle stages	4) Assessing adaptation options; 5) Implementation

Adaptation policy insights	The estimated statistical models provided insights regarding the influential factors on the implementation of flood risk mitigation measures and flood insurance purchases. The overall findings demonstrated that coping appraisals, and in particular response efficacy and self-efficacy, constituted an important influence on flood preparedness decisions. Policy recommendations based on these results included that risk communication should greater focus on the potential of flood-mitigation measures to effectively reduce damage and to provide information regarding how to implement these measures.
Relevant application	This method was applied in Germany.
Main reference(s)	Bubeck, P., Botzen, W.J.W., Kreibich, H. and Aerts, J.C.J.H. (2013). Detailed insights into the influence of flood-coping appraisals on mitigation behaviour. Global Environmental Change, 23(5): 1327-1338.
Suitability for rapid assessment	Pretesting of the survey design and data collection can take time.
Websites	https://www.sciencedirect.com/science/article/abs/pii/S0959378013000836
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.4 Behavioural economics	**Survey of implemented flood damage mitigation measures by Botzen *et al.* (no model name)**

Model/ tool type and outputs	This study assessed the implemented flood damage mitigation measures by households in New York City, and estimated statistical models that could highlight which factors influenced the adoption of these measures, such as individual risk perceptions, coping appraisals and a variety of other behavioural characteristics which influenced individuals' decisions to flood-proof homes.
Open access?	No
Key data inputs	Input data are cross-sectional given that respondents completed a single survey. The main input data are information regarding implemented flood damage mitigation measures and variables that influence flood preparedness decisions, such as risk perceptions, coping appraisals, socio-demographic characteristics and behavioural characteristics including risk aversion.
Key data accessibility/ availability	The data should be collected using a survey and are not open access.
Strengths	The study collected data from a large sample of households in New York City and provided insights regarding a variety of behavioural variables which influenced the adoption of different types of flood damage mitigation measures.
Assumptions/ limitations	The survey was implemented shortly post-Hurricane Sandy when New York City was flooded, meaning that the results may not be transferable to areas where a recent flood disaster has not occurred.
Spatial scale and resolution	Can be conducted over the telephone or online with an unlimited number and spatial extent of respondents.
Temporal scale and resolution	Can be conducted at one point in time or at multiple points over time.
Accessibility of outputs	Model outputs include the effects of a variety of variables on the implementation of flood damage mitigation measures, including risk perceptions, coping appraisals, risk attitudes, time preferences, social and private norms, and socio-economic characteristics.
Adaptation policy cycle stages	4) Assessing adaptation options; 5) Implementation

Adaptation policy insights	The estimated statistical models provided insights regarding the influential factors on the implementation of flood risk mitigation measures. The overall findings highlighted that coping appraisals, and in particular response efficacy and self-efficacy, constituted an important influence on flood preparedness decisions. Other behavioural characteristics influenced individual decisions to flood-proof homes, such as risk attitudes, time preferences, and feelings of being well prepared for flooding. Private property-owners' decision to elevate their property were predominantly influenced by building code regulations and were negatively correlated with expectations of receiving federal disaster relief. Policy recommendations based on these results include that risk communication should greater focus on the potential of flood-mitigation measures to effectively reduce damage and to provide information regarding how to implement these measures.
Relevant application	This method was applied in the USA.
Main reference(s)	Botzen, W.J.W., Kunreuther, H.C., Czajkowski, J., de Moel, H. (2019). Adoption of individual flood damage mitigation measures in New York City: An extension of Protection Motivation Theory. Risk Analysis, 39(10): 2143-2159.
Suitability for rapid assessment	Pretesting of the survey design and data collection can take time.
Websites	https://onlinelibrary.wiley.com/doi/full/10.1111/risa.13318
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.5 Insurance	**Dynamic Integrated Flood and Insurance (DIFI) model**

Model/ tool type and outputs	DIFI is a partial equilibrium model of flood insurance markets in the EU. Flood risk is estimated following a catastrophe model approach, which is input for an insurer supply module that estimates flood insurance premiums, and a consumer module that estimates unaffordability of flood insurance, demand for coverage and household investments in adaptation measures that limit flood risk. Future flood risk is estimated under scenarios of climate change and socio-economic development. Flood insurance systems in countries are modelled according to stylized market structures, including solidary public structures, semi-voluntary private markets, voluntary private markets and public-private partnership markets. The model simulates premiums, affordability of premiums, the market penetration and risk reduction that is incentivized through insurance by offering premium discounts for flood-proofing buildings. Based on a multi-criteria analysis that encompasses criteria of equity and efficiency, the model evaluates whether it is desirable to reform flood insurance markets to cope with changing risks.
Open access?	No
Key data inputs	Input data are flood probabilities as derived from hydrological models, and flood damage in terms of property damage from a catastrophe (flood damage) model. Information on premium loading factors in different types of insurance market structures provides input for the insurance supply module. Moreover, information on individual perceptions of flood risk is input for the consumer behaviour module. Other input data include the lifespan and costs and benefits of flood-proofing measures; data on household income; and population growth.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access.
Strengths	DIFI is a comprehensive framework of insurance demand, supply and flood risk to evaluate the performance of existing flood insurance market structures in EU member states, desirability of reforms in insurance markets, and the effectiveness of stimulating the undertaking of adaptation measures through insurance incentives.
Assumptions/ limitations	The current model version is focused on river flood risk only. The model is highly data intensive and the empirical basis for the

	household decision rule that determines flood insurance demand and investments in flood-proofing measures is limited.
Spatial scale and resolution	The spatial resolution is the NUTS2 level, an EU statistical region, for all EU member states.
Temporal scale and resolution	Years 2015, 2035 and 2055.
Accessibility of outputs	Model outputs include maps of risk reduction that are incentivized by insurance, unaffordability of premiums, insurance market penetration rates and desirable reforms of flood insurance markets.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model provides insights into whether it is desirable to reform flood insurance market structures in an EU member state under scenarios of climate change. Moreover, it highlights the effectiveness of different flood insurance arrangements in stimulating policyholders to adopt adaptation measures that limit flood risk to their home and home contents. Results demonstrate that the average flood insurance premiums may double in the EU up to the year 2050 unless additional risk reduction measures are taken. This risk increase can be partly limited if insurance provides greater incentives to policyholders to adopt measures that reduce flood risk. Moreover, the affordability of insurance can be improved to introduce reforms in most EU member states that involve moving toward public-private flood insurance systems.
Relevant application	The model has been applied to evaluate flood insurance market structures in all EU member states. The results highlight that the expected risk increase from climate change can be partially limited if insurance provides greater incentives to policyholders to adopt measures that reduce flood risk. Moreover, the affordability of insurance can be improved to introduce reforms in most EU member states that involve moving toward public-private flood insurance systems.
Main reference(s)	Hudson, P., Botzen, W.J.W., Aerts, J.C.J.H. (2019). Flood insurance arrangements in the European Union for future flood risk under climate and socio-economic change. *Global Environmental Change*, 58:101966.
Suitability for rapid assessment	Use of model is not rapid; long-term study required for necessary dataset.
Websites	https://www.sciencedirect.com/science/article/abs/pii/S0959378018306022?via%3Dihub

Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.5 Insurance	**Climate Risk Insurance Model (CRIM)**

Model/ tool type and outputs	This is a linked catastrophe and supply side flood insurance sector model that estimates the influence of climate change scenarios on the pricing of annual and multi-year flood insurance in the Netherlands. Moreover, it estimates developments of financial reserves of both privately funded and public-private flood insurance systems.
Open access?	No
Key data inputs	Data inputs include the expected flood probability and flood damage on a spatial resolution of dike ring areas under climate change and land use change scenarios, as estimated by hydrological models and a flood damage model. Moreover, premiums are based on a loading factor and a cap of a maximum damage amount covered by the private sector in the layered system.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access.
Strengths	Can be used for assessing the impacts of climate change on the pricing of annual and multi-year insurance, and the potential stability of reserves under a private and public-private layered flood insurance system under climate scenarios. This can provide insights into potentially required reforms of flood insurance systems to cope with climate change.
Assumptions/ limitations	The model does not account for the demand side, and hence assumes that flood coverage is mandatory. It does not explicitly model reinsurance and assumes that the insurer does not offer incentives for risk reduction to policyholders, such as premium discounts.
Spatial scale and resolution	Dike ring areas in the Netherlands.
Temporal scale and resolution	Time periods are the years 2015, 2040 and 2100.
Accessibility of outputs	Outputs include tables, figures, and geographical maps with the development of flood insurance premiums under climate change scenarios. Figures can also include the expected developments of financial reserves.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options

Adaptation policy insights	Can be useful for examining the impacts of climate change on flood insurance premiums, and which type of insurance market reforms are required to guarantee financial stability of the insurance system. A main result is that due to the uncertainty of climate change on flood risk, introducing multi-year flood insurance contracts is not advisable. Moreover, an outcome is that a public-private layered flood insurance system provides greater financial robustness than a private system.
Relevant application	CRIM has been used to support the design of a flood insurance system in the Netherlands. A key finding is that due to the uncertainty of climate change on flood risk, introducing multi-year flood insurance contracts is not advisable. Moreover, an outcome is that a public-private layered flood insurance system provides greater financial robustness than a private system.
Main reference(s)	Aerts, J.C.J.H., Botzen, W.J.W. (2011). Climate change impacts on pricing long-term flood insurance: A comprehensive study for the Netherlands. *Global Environmental Change*, 21: 1045-1060.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.sciencedirect.com/science/article/abs/pii/S0959378011000653
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.5 Insurance	**Flood Risk Policy Model**

Model/ tool type and outputs	This is a linked catastrophe and insurance sector model that simulates the incidence of flood losses on flood victims, insurance companies, and the government in Hungary. It also estimates the effects on insurance profits and government budgets. The model simulates the effects of (adaptation) policy interventions, including levees, and three different flood insurance programs: government disaster relief with voluntary cross-subsidized insurance, lower levels of government relief and voluntary flat fee as well as risk-based insurance, and mandatory public insurance. The effects of climate change are accounted for in the flood probability.
Open access?	No
Key data inputs	Input data are flood probabilities as derived from hydrological models, and flood damage in terms of property damage from a catastrophe (flood damage) model.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access.
Strengths	The model can provide insights regarding how the incidence of flood losses on flood victims, insurance companies and the government depends on the adopted flood insurance system.
Assumptions/ limitations	The model contains potentially restrictive assumptions regarding levee failure. The model does not contain a supply side module that, for example, estimates premiums nor include a demand module to simulate demand. It works with assumed percentages of market penetration. Incentives of the insurance scheme for risk reduction are not modelled. The model has a relatively short time horizon and accounts for climate change through the assumption that flood probability increases by 10% in 10 years, while it does not run under different scenarios of climate change or socio-economic change.
Spatial scale and resolution	Palad-Csecsei pilot region in the Upper Tisza basin in Hungary.
Temporal scale and resolution	10-year time horizon and time resolution.
Accessibility of outputs	The model outputs are figures of the simulated decadal distribution of losses under different flood insurance systems.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options

Adaptation policy insights	The model can provide insights regarding how the incidence of flood losses on flood victims, insurance companies and the government depends on the adopted flood insurance system. Based on the model simulation results and a combined stakeholder workshop, it was concluded that the preferred insurance scheme contains flood insurance through the private sector and in which the government only provides financial disaster relief to people with this private insurance coverage. The government would subsidize low-income households to increase the affordability of flood insurance.
Relevant application	The model has been applied in a river basin in Hungary and was used for advising legislation on disaster insurance that was implemented and partly based on the conclusions drawn from the model and stakeholder workshop. It was concluded that the preferred insurance scheme contains flood insurance through the private sector and in which the government only provides financial disaster relief to people with this private insurance coverage. The government would subsidize low-income households to increase the affordability of flood insurance.
Main reference(s)	Linnerooth-Bayer, J., Vári, A., Brouwers, L., (2013). Designing a flood management and insurance system in Hungary: a model-based stakeholder approach. In *Integrated Catastrophe Risk Modeling* (pp. 199-216). Springer, Dordrecht.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset
Websites	https://link.springer.com/chapter/10.1007/978-94-007-2226-2_12
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.5 Insurance	**Hurricane Risk Catastrophe + Supply Insurance Model of Kunreuther *et al.* (no name provided)**

Model/ tool type and outputs	This is a linked catastrophe and supply side insurance sector model that simulates insured hurricane risk in Florida under climate change scenarios, as well as insurance premiums under soft and hard reinsurance market conditions in which, respectively, reinsurance capital is abundant or scarce. Moreover, the model examines how wind-resistant building codes can lower the insurance premiums. Under these different conditions, the model also estimates the degree of capacity private insurers would be willing to provide to cover hurricane risks.
Open access?	No
Key data inputs	Input data are hurricane probabilities, as derived from tropical storm models, and wind damage in terms of property damage from a catastrophe model. The premium pricing rules require information on the degree of insurer risk aversion and how reinsurance premiums depend on soft and hard market conditions.
Key data accessibility/ availability	A catastrophe model (wind damage model) is required to estimate hurricane risk data. Often these models are not open access.
Strengths	The model offers insights into insurance premiums under climate change scenarios and soft and hard reinsurance market conditions and highlight how wind-resistant building codes could lower insurance premiums. It also provides estimates regarding the degree of capacity private insurers would be willing to provide to cover hurricane risks.
Assumptions/ limitations	The model adopts important assumptions regarding insurer’s risk aversion, the influence of reinsurance capital availability on insurance prices and how building codes limit wind damage. A limitation is that it does not include the demand side for insurance, and the model does not examine other adaptation measures in addition to building codes. Although the focus is on hurricane risk, the model captures wind damage only, not flood. Socio-economic change over time is not accounted for.
Spatial scale and resolution	Florida, USA.
Temporal scale and resolution	The years 1990, 2020 and 2040.

Accessibility of outputs	Outputs include exceedance probability-loss curves, tables with insurance prices, and the percentage of loss covered and required surplus for full coverage by insurers.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model provides insights regarding how future insurance premiums depend on soft and hard reinsurance market conditions, and how wind-resistant building codes could lower insurance premiums. Results highlight that climate change may significantly increase premiums of wind insurance coverage, which could result in insurance affordability problems. The adoption of the most recent building codes by all residents could halve premiums and negate the impact of climate change on premiums. Building codes could also be important for guaranteeing the availability of future insurance coverage by the private sector.
Relevant application	This model has been applied in hurricane insurance in Florida. Results highlight that climate change may significantly increase premiums of wind insurance coverage, which could result in insurance affordability problems. The adoption of the most recent building codes by all residents could halve premiums and negate the impact of climate change on premiums. Building codes could also be important for guaranteeing the availability of future insurance coverage by the private sector.
Main reference(s)	Kunreuther, H., Michel-Kerjan, E., Ranger, N. (2013). Insuring future climate catastrophes. *Climatic Change*, 118(2): 339-354.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://link.springer.com/article/10.1007/s10584-012-0625-z
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.5 Insurance	**Flood Catastrophe + Supply Insurance Model of Hudson *et al.* (no name provided)**

Model/ tool type and outputs	This is a linked catastrophe and supply side flood insurance sector model that simulates premiums of a public-private flood insurance system in France and Germany under scenarios of climate change and socio-economic development. The link between insurance and incentives for adaptation is explicitly modelled, which supports the examination of how discounts on flood insurance premiums investments can be incentivized through flood-proofing homes by households. The model can evaluate the affordability of flood insurance premiums and examines potential trade-offs between charging risk-based premiums and premium affordability.
Open access?	No
Key data inputs	Input data are flood probabilities as derived from hydrological models, and flood damage in terms of property damage from a catastrophe (flood damage) model. Moreover, information on individual perceptions of flood risk is input for the consumer behaviour module. Other input data includes the lifespan and costs and benefits of flood-proofing measures.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access.
Strengths	A strength of the model is the explicit link between insurance incentives and adaptation investments by policyholders, which supports the evaluation of the level of flood risk reduction through public-private insurance systems that aim to incentivize flood-proofing through risk-based premiums with discounts for policyholders.
Assumptions/ limitations	The model was established to simulate a public-private flood insurance system with mandatory purchase requirements, and therefore is not applicable to voluntary private insurance. The empirical basis for the household decision rule that determines investments in flood-proofing measures is limited.
Spatial scale and resolution	The spatial resolution is the NUTS 2 level, an EU statistical region, for Germany and France, although most results are presented on the country level.
Temporal scale and resolution	Years 2015 and 2040.
Accessibility of outputs	Outputs include tables with the average annual flood insurance premiums, the average annual risk reduction obtained from flood-

	proofing measures, and of costs of a voucher scheme to limit problems with the unaffordability of premiums.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model provides insights regarding the effectiveness of stimulating policyholders to adopt adaptation measures through charging risk-based premiums and premium discounts. Results highlight that these incentives can limit flood risk by 12% in Germany and 24% in France by 2040. However, risk-based premiums may be unaffordable for about 20% of households in flood-prone areas. This implies that government policies are required to limit problems with the unaffordability of flood insurance, such as offering insurance vouchers to low-income households in flood-prone areas.
Relevant application	The model has been applied to flood risk of all main river basins in Germany and France. Results highlight that these incentives can limit flood risk by 12% in Germany and 24% in France by 2040. However, risk-based premiums may be unaffordable for about 20% of households in flood-prone areas. This implies that government policies are required to limit problems with the unaffordability of flood insurance, such as offering insurance vouchers to low-income households in flood-prone areas.
Main reference(s)	Hudson, P., Botzen, W.J.W., Feyen, L., Aerts, J.C.J.H. (2016). Incentivising flood risk adaptation through risk based insurance premiums: trade-offs between affordability and risk reduction. *Ecological Economics*, 125: 1-13.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.sciencedirect.com/science/article/abs/pii/S0921800916301240
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.5 Insurance	**Flood Catastrophe Model + EU Solidarity Finance of Hochrainer-Stigler *et al.* (no name provided)**

Model/ tool type and outputs	The model is an application of a catastrophe model simulating the impacts of flood events on the EU solidarity fund budget. Based on threshold criteria, the model estimates whether funding criteria for a flood event are likely to be met, the subsequent estimates of the annual fund payments and the probability of fund depletion. The model can examine how reforms of the EU solidarity fund, such as changes in aid thresholds and greater intertemporal risk distribution, impact these budget criteria. This supports attaining greater insights regarding whether additional risk transfer instruments, such as reinsurance or catastrophe bonds, are desirable for the EU budget.
Open access?	No
Key data inputs	Input data are flood probabilities derived from hydrological models, and flood damage in terms of property damage from a catastrophe (flood damage) model.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access.
Strengths	The model can provide insights regarding how EU solidarity fund reforms impact the budget, which can derive whether additional risk transfer instruments, such as reinsurance or catastrophe bonds, are desirable for the EU budget.
Assumptions/ limitations	The influences of climate change or socio-economic development on flood risk are not considered. A limitation with this model is that only flooding is considered, while multiple impacts hazards can be eligible for EU solidarity funding. The model also does not account for the possibility of flood events that impact multiple countries at the same time. The influence of risk reduction regulations of the EU on flood risk are not explicitly modelled.
Spatial scale and resolution	Flood risk is estimated at the country scale for all EU member states, while implications for the EU solidarity fund are at the EU budget scale.
Temporal scale and resolution	Annual outputs from 2002 up to 2012.
Accessibility of outputs	The main model output is the annual depletion probability of the EU solidarity fund.

Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options
Adaptation policy insights	The model can provide insights regarding how EU solidarity fund reforms can impact the budget requirements, which can derive whether additional risk transfer instruments, such as reinsurance or catastrophe bonds, are desirable for the EU budget.
Relevant application	The model was used for evaluating reforms of the EU solidarity fund that were adopted in 2014. A main finding is that reforms of the EU solidarity fund that support greater intertemporal risk distribution reduced the annual depletion probability of the fund from 3.57% to 3.03%. The risk of depletion could be reduced further by increasing contributions from member states or by engaging in risk transfer, such as purchasing reinsurance or catastrophe bonds.
Main reference(s)	Hochrainer-Stigler S., Linnerooth-Bayer J., Lorant, A. (2017). The European Union Solidarity Fund: an assessment of its recent reforms. *Mitigation and Adaptation Strategies for Global Change,* 22(4): 547-563.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://link.springer.com/article/10.1007/s11027-015-9687-3
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.5 Insurance	**Flood Catastrophe Model for Insurance Reformation of Hudson (no name provided)**

Model/ tool type and outputs	This model uses a catastrophe model of flood risk in Europe to estimate the influence of reforming flood insurance markets towards risk-based pricing on the affordability of flood insurance coverage. It provides insights regarding the affordability of flood insurance under climate change scenarios, which can be useful information for designing adaptation policies for limiting problems with unaffordability of insurance for low-income households.
Open access?	No
Key data inputs	Input data are flood probabilities derived from hydrological models, and flood damage in terms of property damage from a catastrophe (flood damage) model. Moreover, data on the local income distribution is used for determining the affordability of insurance.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access. Income distribution data are used from Eurostat and are open access.
Strengths	The model provides insights regarding the affordability of flood insurance under climate change scenarios under different definitions of insurance affordability.
Assumptions/ limitations	Income inequality is assumed to remain constant over time. A limitation is the assumption that premiums do not have loading factors for risk aversion by insurers where insurance is provided by the private sector. The demand side of flood insurance, as well as the relationship between insurance and risk reduction, are not modelled.
Spatial scale and resolution	Spatial scale is the country level for all EU member states.
Temporal scale and resolution	Years 2010 and 2080.
Accessibility of outputs	Outputs include maps of the development of risk-based premiums and affordability of flood insurance in the EU under climate change scenarios.
Adaptation policy cycle stages	2) Assessing risk and vulnerability to climate change; 3) Identifying adaptation options
Adaptation policy insights	This model provides insights regarding the influence of reforming flood insurance markets towards risk-based pricing on the affordability of flood insurance coverage. This can be useful

	information for designing adaptation policies for limiting problems with unaffordability of insurance for low-income households.
Relevant application	This model has been applied to examine future affordability of risk-based flood insurance premiums in EU member states. Results indicate that, on average, flood insurance premiums across Europe could more than double by the year 2080 due to climate change. This rise in premiums may result in substantial problems with the affordability of future flood coverage, and it is argued that this requires the implementation of adaptation policies to address concerns regarding insurance unaffordability, such as subsidies, vouchers, tax credits, or flood protection.
Main reference(s)	Hudson, P. (2018). A comparison of definitions of affordability for flood risk adaption measures: a case study of current and future risk-based flood insurance premiums in Europe. *Mitigation and Adaptation Strategies for Global Change*, 23(7): 1019-1038.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://link.springer.com/article/10.1007%2Fs11027-017-9769-5
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.5 Insurance	**Flood Risk Catastrophe + Supply Insurance Model of Reguero *et al.* (no name provided)**

Model/ tool type and outputs	This model combines a catastrophe model of flood risk in Dominica with a supply side insurance model to estimate the influence of nature-based adaptation solutions, and in particular, reef restoration, on insurance premium savings. The model supports the performance of a cost-benefit analysis of nature-based adaptation solutions.
Open access?	No
Key data inputs	Input data includes flood probabilities derived from hydrological models, and flood damage in terms of property damage from a catastrophe (flood damage) model, the costs of a reef restoration project and the resulting degree of risk reduction, the lifespan of the reef restoration in place, the insurance premium loading factor and the risk level covered by the insurance.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data and the risk reduction level of nature-based adaptation solutions. Often these models are not open access.
Strengths	The model estimates the effects of nature-based adaptation solutions on insurance premiums and coverage and can be used to obtain insights regarding the economic desirability of implementing nature-based adaptation solutions.
Assumptions/ limitations	The risk reduction level from a hypothetical reef restoration project is assumed to illustrate the functioning of the model. Changing risk from climate change is not explicitly modelled. Insurance supply is modelled through only a private primary insurer, while the demand side is not modelled.
Spatial scale and resolution	A country-level analysis of Dominica.
Temporal scale and resolution	The time period is across five hypothetical years.
Accessibility of outputs	Outputs include figures of the loss-probability curve and the risk reduction effect of the reef restoration project, and figures and tables of the development of the insurance premium, insurance coverage, and benefits and costs of the reef restoration project.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options

Adaptation policy insights	The model provides insights regarding the premium savings that can be obtained from nature-based adaptation solutions and their economic desirability.
Relevant application	The model was applied to a hypothetical reef restoration project in Dominica. On average, it was found that reef restoration projects yield benefits that exceed the costs six times over across a 25 years lifespan.
Main reference(s)	Reguero, B.G., Beck, M.W., Schmid, D., Stadtmüller, D., Raepple, J., Schüssele, S., Pfliegner, K. (2020). Financing coastal resilience by combining nature-based risk reduction with insurance. *Ecological Economics*, 169: 106487.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.sciencedirect.com/science/article/abs/pii/S0921800918315167
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.5 Insurance	**Public Sector Flood Risk Catastrophe Model + Supply Insurance Model of Unterberger *et al.* (no name provided)**

Model/ tool type and outputs	This model combines a catastrophe model of flood risk to public sector infrastructure and public buildings in Austria. Further, it contains a supply side insurance model to estimate the impacts of flooding on government budgets under climate change and socio-economic development scenarios, and how formalized insurance arrangements can limit the pressure of floods on government budgets: public sector, private, and public-private insurance compensation arrangements for flood risk are simulated and their desirability evaluated. Moreover, the model estimates how insurance incentives to limit public infrastructure risk through premium discounts can limit burdens on public sector budgets, as well as the influence of improved flood protection.
Open access?	No
Key data inputs	Input data includes flood probabilities derived from hydrological models, and flood damage in terms of damage to public infrastructure and public buildings from a catastrophe (flood damage) model, the costs of flood-proofing buildings and the risk reduction it delivers, the lifespan of the flood-proofing measures in place, and the insurance premium loading factor under different compensation arrangements.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data and the risk reduction of flood-proofing buildings. Often these models are not open access.
Strengths	The model offers insights regarding the type of insurance arrangements which can effectively limit the pressure of floods on public sector budgets, as well as the benefits of providing financial incentives for risk reduction through insurance.
Assumptions/ limitations	The model only accounts for riverine flood risk, yet other natural disasters, which are not incorporated, could also impact public sector budgets. Moreover, it supports capturing the impact of direct damages on public budgets, while indirect economic damages, such as lost tax revenues, may also be important to consider.
Spatial scale and resolution	The spatial scale is the 99 political districts of Austria.
Temporal scale and resolution	Years 2010, 2020, 2040, 2060, and 2080.

Accessibility of outputs	Outputs include figures of the development of annual expected flood damage to public infrastructure and public buildings over time, and tables of the total expected burden on government budgets and a multi-criterion scoring of the desirability of the different compensation arrangements.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model offers insights regarding the type of reforms of insurance arrangements which can effectively limit the pressure of floods on public sector budgets, as well as the benefits of providing financial incentives through insurance for implementing adaptation measures, such as flood-proofing buildings.
Relevant application	The model has been used for evaluating the desirability of flood insurance arrangements for the public sector in Austria. The results highlight that switching from an ad-hoc public compensation system to a formalised insurance system provides greater certainty for government budgets and incentives for implementing adaptation measures that limit flood risk.
Main reference(s)	Unterberger, C., Hudson, P., Botzen, W.J.W., Schroeer, K., Steininger, K. (2019). Future public sector flood risk and risk sharing arrangements: An assessment for Austria. *Ecological Economics*, 156: 153-163.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.sciencedirect.com/science/article/pii/S0921800917317895
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.5 Insurance	**Integrated Catastrophe Risk Management (ICRM) Model**

Model/ tool type and outputs	This model combines a catastrophe model of flood risk in an outer dike ring area in the Netherlands with estimations of quantile-related risk functions and stochastic optimization procedures in order to evaluate location-specific insurance policies. The model evaluates the insurability of flood risk by simulating demand and supply, which provides insights regarding the optimal premium and coverage levels at a location, given safety constraints across stakeholders including insurers, households, companies and the government.
Open access?	No
Key data inputs	Input data are flood probabilities as derived from hydrological models, and flood damage in terms of property and business interruption damage from a catastrophe (flood damage) model.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access.
Strengths	The model accounts for skewed catastrophic loss distributions, which may result in a greater robust risk and flood insurance premium estimations.
Assumptions/ limitations	Climate change impacts on risk are not modelled. The model assumes that transaction or administrative costs by the insurer are zero. A limitation is that while the model aims to maintain limited insurer insolvency, it does not explicitly model risk transfer options for insurers, such as acquiring reinsurance, which is only indirectly inferred from the results. Moreover, insurance demand is not based on a standard micro-economic theory or calibrated based on empirical data, and purchase of coverage is not explicitly estimated. Potential links between insurance and the implementation of risk reduction measures are not modelled.
Spatial scale and resolution	The model simulates for the outer dike ring areas in the Rijnmond-Drechtsteden region, The Netherlands. The spatial resolution is 100m by 100m.
Temporal scale and resolution	Years 2000, 2050 and 2100.
Accessibility of outputs	Outputs include maps and figures of flood insurance premiums, compensation and payments for insurance.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options

Adaptation policy insights	The model can provide insights regarding premiums and insurability of flood risk, but it does not explicitly examine flood insurance market reforms or risk reduction measures.
Relevant application	The model has been applied to evaluate the insurability of flood risk in outer dike ring areas in the Rijnmond-Drechtsteden region in the Netherlands. The results highlight the advantages of the robust premium estimation by the model, for example, because it guarantees solvency of the insurance program and reduces the need for other risk transfer and risk reduction measures.
Main reference(s)	Ermolieva, T., Filatova, T., Ermoliev, Y., Obersteiner, M., de Bruijn, K.M., Jeuken, A. (2017). Flood catastrophe model for designing optimal flood insurance program: Estimating location-specific premiums in the Netherlands. *Risk Analysis*, 37(1): 82-98.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.onlinelibrary.wiley.com/doi/10.1111/risa.12589
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.5 Insurance	**Riverine Flood Catastrophe Model + EU Solidarity Finance of Jongman *et al.* (no name provided)**

Model/ tool type and outputs	This model uses a catastrophe model of riverine flood risk in Europe to estimate the impacts of climate change on insured flood losses, capital requirements by insurers, uninsured flood losses, and expected flood-related claims for the EU solidarity fund and the fund's depletion probability. The model is used to evaluate the adaptation strategies: increasing insurance penetration, for instance, through mandatory purchase requirements; increasing the capacity of the EU solidarity funds; and flood protection infrastructure.
Open access?	No
Key data inputs	Input data are flood probabilities derived from hydrological models, flood protection standards per river basin and flood damage from a catastrophe (flood damage) model.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access.
Strengths	The flood risk estimates account for flood protection within river basins and for correlations of flood events across basins using copulas.
Assumptions/ limitations	The model focuses on riverine flood risk only, yet other hazards, which are not incorporated, could also impact the EU solidarity fund. Insurance demand and supply are not explicitly modelled in estimating future insured flood losses. Links between insurance and risk reduction are not explicitly modelled.
Spatial scale and resolution	Spatial resolution is 100m by 100m for all EU member states. Most results are presented for the aggregated EU level.
Temporal scale and resolution	Years 2000, 2010, 2020, 2030, 2040, 2050.
Accessibility of outputs	Outputs include figures of projections of flood losses over time per financing source and reductions in modelled flood losses under the different adaptation measures.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model provides insights regarding the effectiveness of the adaptation strategies: increasing insurance penetration, for instance through mandatory purchase requirements; raising the

	capacity of the EU solidarity fund; and flood protection infrastructure.
Relevant application	This model was applied to flood risk in all main river basins in the EU. It was found that climate change may significantly increase flood risk: observed extreme flood losses could occur greater than two-fold by 2050. Yet, increasing flood insurance penetration rates from 30% to 50% reduced uninsured flood losses by greater than €10 billion. Moreover, increasing the capacity of the EU solidarity fund could limit uninsured flood losses, however this requires an infeasibly large budget. Increasing flood protection standards to a minimum of 1/100 years for all river basins would reduce flood losses by 30% in 2050.
Main reference(s)	Jongman, B., Hochrainer-Stigler, S., Feyen, L., Aerts, J.C.J.H., Mechler, R., Botzen, W.J.W., Bouwer, L.M., Pflug, G., Rojas, R., Ward, P. (2014). Stress on disaster finance due to correlated flood extremes. *Nature Climate Change*, 4: 264-268.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.nature.com/articles/nclimate2124
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.5 Insurance	**Actuarial Flood Risk Model + Supply Insurance Model of Paudel *et al.* (no name provided)**

Model/ tool type and outputs	This model uses actuarial approaches, including Bayesian Inference, to estimate the probability distributions of flood risk for all dike ring areas in the Netherlands. From this information, the model derives flood insurance premiums and optimal insurance and reinsurance coverage levels under private and public-private insurance systems. The estimations are conducted for the current climate and under scenarios of climate and socio-economic change.
Open access?	No
Key data inputs	Input data are flood probabilities derived from hydrological models, and flood damage from a catastrophe (flood damage) model.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access.
Strengths	A strength of the method is that it provides insights regarding the full probability density of flood damages, which supports a greater precision of estimates of flood insurance premiums. The estimates account for the fat tails of the loss distribution, as is relevant for catastrophic risk.
Assumptions/ limitations	A limitation is that although the method provides insights regarding the uncertainty of flood damage, uncertainty in flood frequency is not considered. Flood insurance demand is not explicitly modelled, nor the link between insurance and risk reduction.
Spatial scale and resolution	The spatial resolution is the dike ring level in the Netherlands.
Temporal scale and resolution	Years 2015 and 2040.
Accessibility of outputs	Outputs include figures of probability density functions of flood losses and required reinsurance levels. Tables of flood insurance premiums, deductible and insurance coverage levels and coverage to premium ratios are also produced.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model provides insights regarding climate change effects on flood insurance premiums and the influence of private and public-private insurance systems on premiums. Moreover, it estimates the optimal allocation of risk in a public-private flood insurance system,

	in terms of deductibles, and insurance and reinsurance coverage levels.
Relevant application	The model has been applied to all dike ring areas in the Netherlands. Climate change may considerably increase flood risk and flood insurance premiums in the Netherlands, unless adaptation measures are implemented to limit flood risk. Due to risk aversion of private insurers, premiums can be considerably above the expected value of flood damage in some dike ring areas. A public-private flood insurance system, in which the government acts as a reinsurer, may be an effective insurance arrangement for maintaining affordable premiums.
Main reference(s)	Paudel, Y., Botzen, W.J.W., Aerts, J.C.J.H. (2013). Estimation of insurance premiums for coverage against natural disaster risk: An application of Bayesian Inference. *Natural Hazards and Earth System Sciences*, 13: 1-18. Paudel, Y., Botzen, W.J.W., Aerts, J.C.J.H. (2015). Influence of climate change scenarios on catastrophe insurance: A case study of flood risk in the Netherlands. *Regional Environmental Change*, 8(2): 116-134. Paudel, Y., Botzen, W.J.W., Aerts, J.C.J.H., Dijkstra, T.K. (2015). Risk allocation in a public-private catastrophe insurance system: an actuarial analysis of deductibles, stop-loss, and premiums. *Journal of Flood Risk Management*, 8: 116-134.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.nat-hazards-earth-syst-sci.net/13/737/2013/nhess-13-737-2013.pdf https://doi.org/10.1007/s10113-014-0736-3 https://onlinelibrary.wiley.com/doi/full/10.1111/jfr3.12082
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.5 Insurance	**Agent-Based Flood Risk + Catastrophe Model of Jenkins *et al.* (no name provided)**

Model/ tool type and outputs	This agent-based model simulates developments in surface water flooding risk in London under scenarios of climate change and socio-economic development. The model is used to examine flood insurance reforms and its integration with flood risk management options, including sustainable drainage systems and property level protection measures, adopted at the local government and household level respectively. Other agents are insurers who establish insurance premiums and deductible levels and decide on whether a property can be reinsured by the joint Government-insurer initiative, Flood Re, property developers, and banks. The model is spatially explicit and simulated at annual time intervals with 100 simulations. It includes a catastrophe model component that estimates flood risk to residential buildings, which can be reduced through adoption of flood risk reduction measures.
Open access?	Yes
Key data inputs	The main input data are flood probabilities derived from hydrological models, and flood damage from a catastrophe (flood damage) model.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access.
Strengths	A strength of this model is that it supports the examination of risk reduction from adaptation decisions of various agents as a response to decisions of other agents, such as households and local governments, and for analysing the influence of the insurance program, Flood Re, on the developments in flood risk.
Assumptions/ limitations	It is assumed that sustainable drainage systems reduce flood risk by 75% and property level protection measures by 35%, while 1% of the households invests proactively in risk reduction measures and 34% invests reactively following a flood. Local governments are assumed to base their risk reduction investments on cost-benefit analyses and invest when the cost-benefit ratio is at least 1 in 5. A limitation is that the empirical basis for the modelled decision rules is limited.
Spatial scale and resolution	The spatial focus is the London Borough of Camden and the resolution is 5km by 5km.
Temporal scale and resolution	Years 1975, 2030, 2050.

Accessibility of outputs	Outputs include figures of the development of flood risk, flood insurance premiums, the percentage of properties that are reinsured in Flood Re, and the number of houses exposed to flooding.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model supports the estimation of risk reduction that can be obtained from adaptation investments and the influence of insurance on developments in risk.
Relevant application	The model was used to evaluate the effects of Flood Re on flood risk in the London Borough of Camden. Flood risk could increase by up to 80% in 2050 as a results of climate change. Building level protection measures and sustainable drainage systems could reduce flood risk by approximately 10% and 15% respectively. The insurance program, Flood Re, was demonstrated to effectively maintain insurance premium affordability, however it increases flood risk by stimulating new housing developments in flood-prone areas. Yet restricting development in flood-prone areas has been demonstrated to be effective in limiting flood risk over time.
Main reference(s)	Jenkins, K., Surminski, S., Hall, J., Crick, F. (2017) Assessing surface water flood risk and management strategies under future climate change: insights from an agent-based model. *Science of the Total Environment*, 595: 159-168. Crick, F., Jenkins, K., Surminski, S. (2018). Strengthening insurance partnerships in the face of climate change–insights from an agent-based model of flood insurance in the UK. Science of the Total Environment, 636: 192-204.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.sciencedirect.com/science/article/pii/S0048969717307738 https://www.openabm.org/model/4647/version/3/view https://www.sciencedirect.com/science/article/pii/S0048969718314165
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.5 Insurance	**Agent-Based Sea Level Rise Flood Risk + Catastrophe Model of Haer *et al.* (no name provided)**

Model/ tool type and outputs	This agent-based model simulates developments in residential flood risk in the Heijplaat neighbourhood, Rotterdam, under a scenario of sea level rise. The model is used to examine how flood-proofing of buildings by households influences developments of flood risk over time. Moreover, the model estimates how the adoption of adaptation measures is influenced by risk reduction incentives provided by insurance through risk based pricing and premium discounts for risk mitigation. The agents are households who decide whether to implement loss-reducing measures, and insurers who establish premiums and discounts for risk reduction. Household behaviour is modelled heterogeneously following behavioural rules based on the micro-economic theories: expected utility theory, prospect theory, and Bayesian learning regarding risk perceptions based on flood experience, media and social networks. The model is spatially explicit and simulates monthly time periods with 100 simulations. It includes a catastrophe model component that estimates flood risk to residential buildings, which can be reduced by adopting flood risk reduction measures.
Open access?	No
Key data inputs	The main input data are flood probabilities derived from hydrological models, and flood damage and risk reduction from flood-proofing estimates from a catastrophe (flood damage) model. Other input data are the costs of flood-proofing measures for building types, the lifespan of flood-proofing and behavioural parameters related to individual risk perceptions, risk aversion, and social networks.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access.
Strengths	A strength of this model is that it supports the examination of risk reduction from adaptation decisions from heterogeneous, and potentially boundedly rational, households that respond to the decisions of other agents. Moreover, the model can analyse the influence of insurance incentives for adopting adaptation measures on this behaviour and resulting flood risk.
Assumptions/ limitations	The main assumptions of this model are related to parameters of the behavioural rules of households that determine whether they purchase flood insurance and adopt flood-proofing measures. For example, these refer to individual over- or underestimation of flood

	risk in response to flood events, media information regarding risk and social networks, risk aversion, loss aversion, and probability weighting. Even though these rules are well founded in micro-economic theories and parameters are derived from literature, a limitation is that they are not calibrated upon data from the case study.
Spatial scale and resolution	The spatial scale is the Heijplaat neighbourhood, Rotterdam, the Netherlands. The resolution is 5m by 5m.
Temporal scale and resolution	Annual time scale between the years 2000 and 2100.
Accessibility of outputs	Outputs include figures of developments in flood risk and the percentage of households with loss-reducing measures.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model supports the examination of risk reduction from adaptation decisions by households, and for evaluating the effectiveness of insurance incentives to stimulate risk reduction by policyholders.
Relevant application	The model was applied in a case study of the Heijplaat neighbourhood, Rotterdam, which is an outer dike ring area in the Netherlands. The model results demonstrated that adaptation behaviour by households can limit flood risk between 19% and 56%. Insurance incentives for risk reduction can strongly influence adaptation decisions and reduce flood risk by approximately 29%.
Main reference(s)	Haer, T., Botzen, W.J.W., de Moel, H., Aerts, J.C.J.H. (2017). Integrating household risk mitigation behaviour in flood risk analysis: An agent-based model approach. *Risk Analysis*, 37(10): 1977-1992.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://onlinelibrary.wiley.com/doi/pdf/10.1111/risa.12740
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.5 Insurance	**Agent-Based Coastal Flood Risk + Catastrophe Model of Han *et al.* (no name provided)**

Model/ tool type and outputs	This agent-based model simulates developments in coastal flood risk in Miami-Dade County, Florida, under different sea level rise scenarios. The model is used to examine the interactions between public and private adaptation decisions. The agents are households who can make decisions regarding elevating their house or purchasing flood insurance. The flood insurance market is simulated through the National Flood Insurance Program (NFIP) as well as private flood insurance providers. Moreover, a government agent can invest in public risk mitigation plans. Household behaviour is modelled heterogeneously following behavioural rules based on Prospect Theory and individual risk perceptions. Risk perceptions depend on the physical flood risk and demographic/socio-economic characteristics. Insurer and government behaviour emulate assumed scenarios in which the government invests in risk mitigation in areas with the highest risk from a constrained budget. Households in areas with public risk mitigation receive premiums discounts through the Community Rating System. The model is spatially explicit and simulates at annual time intervals. It includes a catastrophe model component that estimates flood risk to residential buildings under sea level rise scenarios, which can be reduced by adopting flood risk reduction measures.
Open access?	No
Key data inputs	The main input data are flood probabilities derived from hydrological models, and flood damage from a catastrophe (flood damage) model.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access.
Strengths	A strength of this model is that it supports the examination of risk reduction from adaptation decisions from heterogeneous households and the community, while accounting for how household decisions depend on community actions as well as insurance incentives for risk reduction.
Assumptions/ limitations	The main assumptions of this model are related to parameters of the behavioural rules of households that determine insurances purchases and investments in house elevations. Moreover, the government and policy scenarios are based on assumptions regarding risk reduction levels obtained in a certain area. The

	empirical basis for behavioural rules and scenarios appears limited though.
Spatial scale and resolution	The spatial scale is Miami-Dade County with a parcel-level resolution.
Temporal scale and resolution	The time resolution is 30 years.
Accessibility of outputs	Model outputs include maps of flood risk, insurance costs, insurance coverage, elevation costs, and total annual adaptation costs. A figure of flood insurance purchases and tables with results for adaptation scenarios can also be produced.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model supports the examination of risk reduction from adaptation decisions by households and the community.
Relevant application	The model has been applied to Miami-Dade County, Florida, USA. The results indicated that household adaptation actions mainly occur in high risk areas. A voucher coupling a house elevation program with low interest mitigation loans could increase the number of households adopting risk mitigation measures by 89%, significantly reducing flood risk. Moreover, it addressed issues of house elevation unaffordability and increases insurance uptake rates. If subsidies of NFIP (please expand acronym) premiums are phased out, then demand for private insurance coverage expands. Public adaptation measures appear important to limit flood risk under climate change but reduce risk mitigation activities by households.
Main reference(s)	Han, Y., Peng, Z.R. (2019). The integration of local government, residents, and insurance in coastal adaptation: An agent-based modeling approach. Computers, Environment and Urban Systems, 76: 69-79.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.sciencedirect.com/science/article/pii/S0198971518305362
Manuals/ training/ videos	
Wikipedia page	
Other	

3) Economic models	3.5 Insurance	**Agent-Based River Flood Risk + Catastrophe Model of Haer *et al.* (no name provided)**

Model/ tool type and outputs	This agent-based model simulates developments in residential river flood risk in all European Union member states under scenarios of climate change and socio-economic development. The model is used to examine how flood-proofing of buildings by households and investments in flood protection by governments influence developments of flood risk over time. It also supports the examination of the "levee effect", which implies that household location decisions depend on flood-protection investments by the government that increases the desirability of settlement in a flood protected zone. Moreover, the model estimates how adoption of household level adaptation measures is influenced by risk reduction incentives provided by insurance through risk based pricing and premium discounts for risk mitigation. The agents are households who make decisions regarding implementing loss-reducing measures, insurers who establish premiums and discounts for risk reduction, and governments who are able to invest in flood protection. Household behaviour is modelled heterogeneously following behavioural rules based on subjective expected utility theory, in which their risk perceptions are either rational or boundedly rational depending on the occurrence of flood events. Governments base flood-protection investments on a cost-benefit analysis in either a proactive manner or reactively following flood events. The model is spatially explicit and simulates annual time intervals with 50 simulations of each possible scenario combination. It includes a catastrophe model component that estimates flood risk to residential buildings, which can be reduced by adopting flood risk reduction measures.
Open access?	No
Key data inputs	The main input data are flood probabilities derived from hydrological models, and flood damage and risk reduction from flood-proofing estimates from a catastrophe (flood damage) model. Other input data are the costs of flood-proofing measures for building types and flood-protection measures, the lifespan of flood-proofing and behavioural parameters related to individual risk perceptions and risk aversion.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access.
Strengths	A strength of this model is that it supports the examination of risk reduction at the EU scale from adaptation decisions by

	heterogeneous and potentially boundedly rational households, as well as by governments that respond to decisions of other agents. Moreover, the model can analyse the influence of insurance incentives for adopting adaptation measures on household behaviour and resulting flood risk.
Assumptions/ limitations	The main assumptions of this model are related to parameters of the behavioural rules of governments and of households that determine location decisions, and whether they purchase flood insurance and adopt flood-proofing measures. For example, these rules for households refer to individual over- or underestimation of flood risk in response to flood events, and risk aversion. Even though these rules are well founded in micro-economic theories and parameters are derived from literature, a limitation is that they cannot be calibrated using EU wide data.
Spatial scale and resolution	The spatial focus is all main river basins in EU member states and potentially inundated areas with a grid cell resolution of 30″ x 30″.
Temporal scale and resolution	The time period is annually between 2010-2080.
Accessibility of outputs	Outputs include figures of developments in flood risks and risk reduction by households, and maps of the share of residential buildings protected by flood-proofing, flood-protection by governments, risk reduction by households, and flood risk.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model supports the examination of risk reduction from adaptation decisions by households and governments, and for evaluating the effectiveness of insurance incentives to stimulate risk reduction by policyholders.
Relevant application	The model has been applied to all key river basins at risk of flooding in the European Union. The model results highlight that increasing flood risk by climate change can be significantly offset through adaptation decisions. In the short term, household adaptation can have a greater impact than risk reduction by governments. Moreover, investments in flood-protection by the government increase potential flood damage over time due to the levee effect, which entails lower investments by households in flood damage mitigation measures and increased settlement in flood zones. Stimulating households to limit risk through insurance premium incentives can result in risk reduction by 38%.
Main reference(s)	Haer, T., Botzen, W.J.W., Aerts, J.C.J.H. (2019). Advancing disaster policies by integrating dynamic adaptive behaviour in risk assessments using an agent-based modelling approach. *Environmental Research Letters*, 14:4.

	Haer, T., Husby, T., Botzen, W.J.W., Aerts, J.C.J.H. (2019). The safe development paradox: An agent-based model for flood risk under climate change in the European Union. *Global Environmental Change*, 60: 102009.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://iopscience.iop.org/article/10.1088/1748-9326/ab0770/pdf https://www.sciencedirect.com/science/article/pii/S0959378018314079
Manuals/ training/ videos	
Wikipedia page	
Other	

Annex 4: Other techniques

4) Other techniques	4.1 Other non-standard modelling techniques: Agent-based models and system dynamics	**Agent-Based Flood Risk + Catastrophe Model of Tonn *et al.* (no name provided)**

Model/ tool type and outputs	This agent-based model simulates developments in river flood risk in in Fargo, North Dakota, under climate change scenarios. The model is used to examine how the flood-proofing of buildings by households and their relocation decisions influence flood risk development over time. Moreover, the model estimates how community risk mitigation decisions and communication strategies influence flood risk. The agents are households who make decisions regarding: elevating equipment or their house, can voluntarily relocate to a different area or complain about the risk to the community, or a community who can instigate an information campaign on risk and mitigation options and install a levee. Household behaviour is modelled heterogeneously following behavioural rules based on a combination of risk perceptions, coping appraisals and utility maximization. Risk perceptions depend on indicators of flood experience, risk communication by the community, and previously implemented mitigation measures. Coping appraisals depend on neighbour mitigation, community information, home values and prior mitigation. The community behaviour depends on complaints by residents and flood loss experiences. The model is spatially explicit and runs in annual time intervals with 500 simulations for each climate scenario. It includes a catastrophe model component that estimates flood risk to residential buildings, which can be reduced by adopting flood risk reduction measures.
Open access?	No
Key data inputs	The main input data are flood probabilities derived from hydrological models, and flood damage from a catastrophe (flood damage) model.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required in order to estimate flood risk data. Often these models are not open access.
Strengths	A strength of this model is that it supports the examination of risk reduction from adaptation decisions by heterogeneous households and the wider community that respond to other individuals' decisions.
Assumptions/ limitations	The main assumptions of the model are related to the parameters regarding the behavioural rules of households and the community

	that determine location decisions and whether risk mitigation measures are adopted. For example, individuals are assumed to act when risk perceptions and coping appraisals exceed certain thresholds, which are determined based on expert judgement. It is assumed that communities implement a levee if flood damage exceeds $10 million in a year and the community instigates an information campaign if greater than 5% of the residents complain about flood risk. These values are also based on expert judgment. Vacant parcels are assumed to be occupied with a probability of 0.01 without community mitigation, while this probability is 0.1 with mitigation in place. A robust empirical basis for these assumptions appears to be limited.
Spatial scale and resolution	The spatial scale is Fargo, North Dakota, with a parcel level resolution.
Temporal scale and resolution	The model runs in annual time intervals of 50 years.
Accessibility of outputs	Outputs include figures of development in flood risk over time, tables and maps with average flood damages, maps of the percentage of agents adopting adaptation measures, tables with community adaptation actions and vacancy of plots.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model supports the examination of risk reduction from adaptation decisions by households and the community.
Relevant application	The model has been applied to Fargo, North Dakota in the USA. The findings indicate that both individual as well as community level adaptation measures can significantly limit flood risk. Individual investments in flood-proofing of buildings are predominantly effective in a climate change scenario with low flood risk, while relocation and community risk mitigation measures constitute important actions for reducing flood risk in a high-risk climate change scenario. Many individuals relocate to safer areas when risk increases are substantial. Adaptation behaviour can largely offset the impacts of climate change on flood risk.
Main reference(s)	Tonn, G., Guikema, S., & Zaitchik, B. (2019). Simulating behavioral influences on community flood risk under future climate scenarios. Risk Analysis. doi:10.1111/risa.13428
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://onlinelibrary.wiley.com/doi/abs/10.1111/risa.13428

Manuals/ training/ videos	
Wikipedia page	
Other	

4) Other techniques	4.1 Other non-standard modelling techniques: Agent-based models and system dynamics	**DAnCE4Water**

Model/ tool type and outputs	This agent-based model couples a hydrodynamic simulation package with the urban development agent-based model, DAnCE4Water, to evaluate flood risk reductions from adaptation strategies in Melbourne, Australia under scenarios of climate change and urban development. The 32 combinations of adaptation strategies include infrastructure investments in rainwater harvesting and increases in storm water pipes, urban planning that limits urban sprawl and flood-zoning that repurchases properties with a high flood risk. These measures are optimized along a pathway in a catchment that predominately experiences pluvial flooding. The model is used to examine interactions between adaptation measures in reducing flood risk. The agents are city councils who make decisions regarding zoning and urban planning regulations, developers who built new residential properties based on these regulations, location preferences and pre-defined development patterns, and new or relocated households who can occupy new buildings and install tanks to harvest rainwater. The implementation of adaptation measures depends on assumed scenarios. Cost-benefit analyses assess the economic desirability of these adaptation strategies. The model is spatially explicit and runs in decadal time intervals. It includes a catastrophe model component that estimates flood risk to residential buildings under climate change scenarios, which can be altered through the adoption of flood risk reduction measures and urban development.
Open access?	No
Key data inputs	The main input data are flood probabilities derived from hydrological models, and flood damage from a catastrophe (flood damage) model.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required in order to estimate flood risk data. Often these models are not open access.
Strengths	A strength of this model is that it supports the examination of risk reduction and the economic desirability of spatial planning, flood zoning measures and infrastructure investments under multiple scenarios of future risk and combinations of adaptation options, while accounting for the interaction of the effects of multiple measures on reducing flood risk.
Assumptions/ limitations	A main limitation is that the implementation of adaptation measures in the model is introduced through assumed scenarios instead of using flooding behavioural processes. For instance,

	social processes in the uptake of adaptation measures are not modelled. Moreover, the model assumes no change in development patterns over time, that new developments do not depend on economic conditions and it excludes indirect impacts from floods. Sensitivity of results to key assumptions, such as the assumed discount rate, have not been tested.
Spatial scale and resolution	The model was applied to the Scotchman's Creek catchment in Melbourne, Australia with a parcel level spatial resolution.
Temporal scale and resolution	The time span is between 2010 and 2060, with intervals of 10 years.
Accessibility of outputs	Model outputs include figures of the development in flood risk, maps of building footprints and tables detailing the flood risk under adaptation strategies and indicators of their economic efficiency.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model supports the examination of risk reduction and economic desirability of spatial planning, flood zoning measures and infrastructure investments under multiple scenarios of future risk and combinations of adaptation options.
Relevant application	The model was applied to the Scotchman's Creek catchment in Melbourne, Australia. The results highlight that the performance of adaptation measures depend on the future risk scenario and which other measures are adopted. Adaptive measures are preferable over one-off investments. Urban planning policies are found to have the greatest effect in limiting risk and are economically efficient, while property buy-backs, pipe increases and rainwater harvesting are frequently excessively expensive, although the last two measures are efficient under high-end climate and population change scenarios. Adaptation can offset risk increases in low population growth scenarios, but not under high population growth. New developments can, under certain circumstances, offset the risk reduction obtained from adaptation measures.
Main reference(s)	Löwe, R., Urich, C., Domingo, N.S., Mark, O., Deletic, A. and Arnbjerg-Nielsen, K. (2017). Assessment of urban pluvial flood risk and efficiency of adaptation options through simulations–A new generation of urban planning tools. Journal of Hydrology, 550: 355-367.
Suitability for rapid assessment	The model is computationally intensive; long-term study required for necessary dataset.
Websites	https://www.sciencedirect.com/science/article/pii/S0022169417302962

Manuals/ training/ videos	
Wikipedia page	
Other	

4) Other techniques	4.1 Other non-standard modelling techniques: Agent-based models and system dynamics	**Agent-Based Coastal Risk + Real Estate + Catastrophe Model of McNamara *et al.* (no name provided)**

Model/ tool type and outputs	This agent-based model couples a physical barrier island model of sea level rise and storm surges with an agent-based model of real estimate markets to simulate coastal adaptation strategies to sea level rise and erosion in barrier island communities along the US East coast under climate change scenarios. The adaptation strategies include beach nourishment and dune creation. The model is used to examine the influence of risk development and implementation of adaptation measures on real estate markets. The agents are households. Agents make decisions regarding the cost that they are willing to pay for property, depending on flood insurance costs, expected flood damage costs and net rental income less of tax payments for defences. Moreover, agents decide on how much to invest in defensive engineering measures, based on a cost-benefit trade-off and referendum voting. The real estate market clears depending on bids on properties. The behaviour of agents depends on various risk perceptions, which are a combination of beliefs regarding the risk trends and climate model predictions, in particular, on the rate of coastal erosion, the loss of beach due to storm surges and the frequency of flooding. These expectations depend on the occurrence of loss events. The model simulates in annual time intervals. It includes a catastrophe model component that estimates flood risk to residential buildings under climate change scenarios, which can be altered using beach nourishment and dunes.
Open access?	No
Key data inputs	The main input data are flood probabilities derived from hydrological models, and flood damage from a catastrophe (flood damage) model.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required in order to estimate flood risk data. Often these models are not open access.
Strengths	A strength of the model is that it supports the examination of the implementation of adaptation measures by heterogeneous households, and the influence of these measures and risk changes on real estate market outcomes.
Assumptions/ limitations	The main assumptions of the model are related to the parameters regarding the behavioural rules of households that determine whether they purchase a property or vote for flood defence measures. For instance, these decisions depend on risk

	perceptions, which are a combination of beliefs regarding trends in risk and climate model predictions, in particular, on the rate of coastal erosion, the loss of beach due to storm surges and the frequency of flooding. These expectations depend on the occurrence of loss events, and weightings applied to these components predominately depend on assumptions where the empirical basis is limited.
Spatial scale and resolution	The spatial scale is the barrier islands along the US East coast. The model is not spatially explicit but simulates for 400 agents.
Temporal scale and resolution	The model simulates in annual time intervals of 50 years from present day.
Accessibility of outputs	Model outputs include figures summarising the developments in property values, defensive engineering and the time of house abandonment, real estate market volatility in relation to coastal erosion, and property damage in relation to sea level rise.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model supports the examination of the implementation of adaptation measures by heterogeneous households, and the influence of these measures and risk changes on real estate market outcomes.
Relevant application	The model is illustrated with a hypothetical case of barrier island communities along the US East coast. The results highlight that people are not sufficiently proactive to adapt to changing risk levels when they are not confident in climate model predictions. In contrast, well-informed property owners invest in defensive measures in the short-term yet abandon coastal real estate when critical risk thresholds are exceeded which triggers price fluctuations in the real estate market. Sea level rise induces lower property values and can result in property abandonment. Subsidizing nourishment or flood insurance costs slows the rate of abandonment however this is less effective when sea level rise is high.
Main reference(s)	McNamara, D.E., Keeler, A. (2013). A coupled physical and economic model of the response of coastal real estate to climate risk. Nature Climate Change, 3(6): 559-562.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.nature.com/articles/nclimate1826#Sec3

Manuals/ training/ videos	
Wikipedia page	
Other	

4) Other techniques	4.1 Other non-standard modelling techniques: Agent-based models and system dynamics	**Social Networks in Agricultural Adaptation to Climate Change (SAGA) model**

Model/ tool type and outputs	This spatial economic agent-based model examines the impact of social networks and different behavioural rules on the adoption of irrigation methods by farmers in the Netherlands under climate change scenarios. Moreover, the model assesses the impacts of droughts and adaptation on macro-economic indicators, such as the rate of adaptation, crop production and related income and water demand. The agents are farmers who can invest in freshwater basins and irrigation equipment. Farmers behaviour is modelled according to two scenarios: rational profit maximisers in which farmers learn from past experiences versus heuristic decision makers which base decisions on interactions with their social networks, drought experience, and repetition. The social network rule, farmers characteristics (size and cropping patterns) and risk awareness are calibrated using empirical data from a survey among 142 farmers in the Netherlands. Crop production follows a 10-day cycle, while irrigation investments are determined annually. An agro-economic model called AGRICOM simulates agricultural yields under climate change scenarios. The model is spatially explicit, and each scenario is run 30 times.
Open access?	No
Key data inputs	The main input data are crop yields and survey data for calibrating behavioural rules.
Key data accessibility/ availability	Crop yields can be simulated using an agro-economic model which is typically not open access.
Strengths	A strength of the model is that it can simulate adaptation decisions by heterogenous farmers that respond to the decisions of other individuals through social networks. Moreover, this model estimates how micro-level decisions influence macroeconomic outcomes, such as agricultural income. A strength is that part of the behavioural decision's rules is calibrated using survey data.
Assumptions/ limitations	Although several components of the behavioural rules are calibrated using survey data, behavioural assumptions are still adopted in which the empirical basis is limited, such as related to the income expectations formation. Moreover, crop prices are assumed to remain constant, while climate change may increase drought risks and impact agricultural markets. Dynamics of risk perceptions are not modelled.

Spatial scale and resolution	The model is applied to the Netherlands and the spatial resolution is at the farm level.
Temporal scale and resolution	The time horizon is up to 30 years, results are shown per year.
Accessibility of outputs	Model outputs include figures summarising the development in the adoption of irrigation measures, regional income, cumulative water demand, and shares of farmers adopting different behavioural strategies.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model could provide insights into the adaptation decisions of heterogenous farmers that respond to the decisions of other individuals through social networks, and for estimating how micro-level decisions influence macroeconomic outcomes, such as agricultural income.
Relevant application	The model is applied to the Netherlands. Findings highlight that farmers adopt different strategies for the uptake of irrigation measures: heuristic-based farmers demonstrate slower rates of adopting adaptation measures in the short-term given that they rely on information from social networks and have uncertain expectations regarding drought events. However, this behaviour is suboptimal and results in income loss. In comparison, maximiser agents almost entirely adopt irrigation practices when expected drought losses increase. Adoption of irrigation measures is greater when climate change results in greater risk increases, however this also increases water demand, pressurising water resource. A near optimal state in the long-term can be obtained even with a small proportion of economic rational agents, who could be imitated by heuristic decision makers.
Main reference(s)	van Duinen, R., Filatova, T., Jager, W., van der Veen, A. (2016). Going beyond perfect rationality: drought risk, economic choices and the influence of social networks. The Annals of Regional Science, 57(2-3): 335-369.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://link.springer.com/article/10.1007/s00168-015-0699-4
Manuals/ training/ videos	
Wikipedia page	

Other	

4) Other techniques	4.1 Other non-standard modelling techniques: Agent-based models and system dynamics	**OMOLAND Climate Change Adaptation (OMOLAND-CA) Model**

Model/ tool type and outputs	This agent-based model simulates the impacts of climate change on the adaptive capacity of communities in the South Omo Zone, Ethiopia. In particular, the model examines the impact of diversification of production strategies as an adaptation strategy in rural areas to increasing drought risk from climate change and associated land use change. The agents are individual households who rely on subsistence agriculture of herding and farming. The household adaptation strategy consists of choosing to allocate labour time to a combination of herding and farming, depending on which generates the highest return, and on grazing practices and migrating out of the area. Agent behaviour is modelled according to the Model of Private Proactive Adaptation to Climate Change, which follows Protection Motivation Theory in which actions depend on the level of knowledge and understanding of rainfall levels depending on learning through past experience, perceived probability and severity of risk, and coping appraisals which consists of coping efficacy, self-efficacy and response cost. Moreover, behaviour depends on imitation neighbours. The model includes a crop-yield and live-stock production modules that are influenced by climate change. The model is spatially explicit, has a daily temporal resolution, and simulates 30 repetitions.
Open access?	No
Key data inputs	The main input data are crop yields and livestock reproduction.
Key data accessibility/ availability	Crop yields and livestock reproduction can be simulated using agro-economic and biological models, which are typically not open access.
Strengths	A strength of the model is that it supports attaining insights regarding the diversification of activities by heterogeneous households who engage in subsistence farming as a form of adaptation. The model is comprehensive in terms of modelled behaviour.
Assumptions/ limitations	Data is lacking for calibrating the behavioural rules in the model, resulting in a significant reliance on assumptions and expert judgement. Further, community level adaptation strategies are not considered in the model.
Spatial scale and resolution	The geographical focus is communities in the South Omo Zone, Ethiopia. The spatial resolution is 100m by 100m.

Temporal scale and resolution	The time scale is 50 years and outputs are presented annually.
Accessibility of outputs	Model outputs include figures highlighting developments in household and population size, migration, livestock and crops, and seasonal onset and rainfall predictions by households.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model could provide insights regarding adaptation strategies in terms of the diversification of activities by heterogeneous households who engage in subsistence farming and migration.
Relevant application	The model has been applied to the South Omo Zone, Ethiopia. Results indicate that adaptive capacity reduces particularly after the occurrence of successive drought events, which is apparent from increased migration out of the area. Increased droughts risks cause declines in livestock, triggers migration, and enhances crop cultivation to offset livestock losses.
Main reference(s)	Hailegiorgis, A., Crooks, A., Cioffi-Revilla, C. (2018). An Agent-Based Model of rural households' adaptation to climate change. Journal of Artificial Societies & Social Simulation, 21(4): 4.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	http://jasss.soc.surrey.ac.uk/21/4/4.html
Manuals/ training/ videos	
Wikipedia page	
Other	

4) Other techniques	4.1 Other non-standard modelling techniques: Agent-based models and system dynamics	**Agent-Based Grasslands Management Model of Wang *et al.* (no name provided)**

Model/ tool type and outputs	This agent-based model examines the performance of multiple local institutions in fostering adaptation in the semiarid and arid Mongolian grasslands under climate change scenarios. The three institutional arrangements assessed in the model are sedentary grazing, pasture rental markets, and reciprocal pasture-use groups. Moreover, the model analyses social mechanisms that incentivise the cooperative use of pastures. The agents are sheep shepherds. In sedentary grazing, agents' sheep graze on their own pastures. Agents can migrate in response to droughts and can bid for parcels in pasture rental markets. In reciprocal pasture-use groups, shepherds share pastures, which may result in free riding. Agents can decide to join a cooperation group based on the expected utility of cooperation versus sedentary grazing. The values of some model parameters were based on 751 surveys of herder households and other interviews, while other parameters are based on assumptions. Drought that is affected by climate change influences grass productivity, which is again impacted by overgrazing. The model is hypothetical, simulates in annual time intervals with 30 repetitions.
Open access?	No
Key data inputs	Main input data are grass productivity and survey data for calibrating behavioural rules.
Key data accessibility/ availability	Grass productivity can be simulated using bio-economic models, which are often not open access.
Strengths	A strength of the model is that it can evaluate the performance of multiple local institutions in fostering adaptation by heterogeneous shepherds to increased drought conditions as a result of climate change.
Assumptions/ limitations	Limitations are that the model does not include the influence of market incentives on herders' livestock management behaviours nor sheep fecundity rates. Although some model parameters are calibrated, others are based on expert judgment and assumptions. Overall the empirical basis for the behavioural rules appears to be limited.
Spatial scale and resolution	The model is hypothetical.

Temporal scale and resolution	The time horizon is 20 years with an annual resolution.
Accessibility of outputs	Model outputs include the benefits for shepherds and the number of ecologically healthy land parcels under the various institutional arrangements.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model can provide insights regarding the performance of multiple local institutions in fostering adaptation by heterogeneous shepherds to increased climate-induced drought conditions.
Relevant application	The model has been applied to the semiarid and arid Mongolian grasslands. The findings indicate that reciprocal pasture-use groups constitute a greater effective adaptation strategy than pasture rental markets. If drought risk increases, the benefits of cooperative pasture-use subsequently increase relative to sedentary grazing without cooperation. The development of reciprocal pasture-use groups is promoted with agent diversity and social norms, and cooperation is maintained through kin selection and punishment of free-riders.
Main reference(s)	Wang, J., Brown, D.G., Riolo, R.L., Page, S.E., Agrawal, A. (2013). Exploratory analyses of local institutions for climate change adaptation in the Mongolian grasslands: An agent-based modeling approach. Global Environmental Change, 23(5): 1266-1276.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.sciencedirect.com/science/article/abs/pii/S0959378013001234
Manuals/ training/ videos	
Wikipedia page	
Other	

4) Other techniques	4.1 Other non-standard modelling techniques: Agent-based models and system dynamics	**Agent-Based Diarrhoea Prevalence Model of Mellor *et al.* (no name provided)**

Model/ tool type and outputs	This agent-based model simulates future diarrhoea prevalence due to water consumption of a certain quality in Hubli-Dharwad, India, under climate change scenarios and estimates the effectiveness of adaptation strategies. The agents are 1000 households with children. The agent-based framework combines downscaled global climate model data with weather, water quality, and diarrhoea prevalence data in a quantitative microbial risk assessment model. The model is calibrated with data on longitudinal microbial water quality, child diarrhoea prevalence and weather. The adaptation measures considered in the model are household point-of-use water treatment technologies.
Open access?	No
Key data inputs	The model requires weather, water quality and diarrhoea prevalence data.
Key data accessibility/ availability	Weather data are commonly open access available through meteorological agencies, and water quality data is usually available through other government agencies. Diarrhoea prevalence data may need to be collected through surveys.
Strengths	A strength of the model is that it could provide insights regarding future diarrhoea prevalence due to water consumption of a certain quality under climate change and that it allows for identifying effective adaptation options to limit this health risk.
Assumptions/ limitations	Limitations of the model are that it is only applicable to intermittent piped water supplies in urban or peri urban settings in low-income tropical countries. The model does not account for water accessibility, which is an important determinant of health; economic growth, which may improve infrastructure that limits health risk; or behavioural adaptation measures that may limit health risk.
Spatial scale and resolution	The model is hypothetical and not spatially explicit/ geographically defined.
Temporal scale and resolution	The modelled time periods are 2011−2030, 2046−2065, and 2080−2099, which is also constitutes the temporal resolution of outputs.
Accessibility of outputs	Model outputs include figures of changes in diarrhoea prevalence.

Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model can provide insights into future diarrhoea prevalence due to water consumption quality under climate change and supports the identification of effective adaptation options to limit the health risk.
Relevant application	The model has been applied to Hubli-Dharwad, India. The results highlight that diarrhoea prevalence increases up to 26% by the year 2100, predominately due to increases in rainfall. The results imply that water filters would constitute the preferred adaptation strategy for limiting health risks.
Main reference(s)	Mellor, J., Kumpel, E., Ercumen, A. and Zimmerman, J. (2016). Systems approach to climate, water, and diarrhea in Hubli-Dharwad, India. Environmental Science & Technology, 50(23): 13042-13051.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://pubs.acs.org/doi/abs/10.1021/acs.est.6b02092
Manuals/ training/ videos	
Wikipedia page	
Other	

4) Other techniques	4.1 Other non-standard modelling techniques: Agent-based models and system dynamics	**Agent-Based Diarrhoea Prevalence Model of Cherng *et al.* (no name provided)**

Model/ tool type and outputs	This agent-based model examines how social cohesion can affect disease prevention adaptation strategies within communities exposed to diseases exasperated by climate change, such as diarrhoea. The agents are households with social networks who can decide between two strategies to protect against diseases: one initially provides greater protection, but its effectiveness may reduce due to increasing extreme weather such as floods and droughts; the other is moderately effective but insensitive to weather changes. Households can imitate neighbours who appear to have successfully adapted to historic conditions. If an infection event occurs, households decide to adapt by randomly selecting from the adaptation measures adopted by neighbours. Social networks are calibrated with sociometric data from rural villages in northern coastal Ecuador. Diseases are modelled through an SIS model of enteric pathogen exposure and transmission, which is calibrated using plausible infection trends. Climate change is represented in the model through abstract changes in environmental cycles.
Open access?	No
Key data inputs	The model requires data on social networks, diseases' infection rates and climate/environmental conditions.
Key data accessibility/ availability	Social network data may be obtained through surveys, which are often not open access. Disease infection rates can be modelled. Weather data are often available and open access through meteorological agencies.
Strengths	A strength of the model is that it can examine the effectiveness of adaptation strategies to reduce health risks within communities with varying degrees of cohesion.
Assumptions/ limitations	A limitation is that the social learning procedure is restricted to neighbours only and remains static over time, however social learning may be a dynamic process. Moreover, the adoption of adaptation measures is likely to depend on other factors in addition to neighbour imitation, such as perceived risks and costs and benefits. In general, the model is hypothetical, which may reduce the transferable application to a case study.
Spatial scale and resolution	The model is hypothetical and not spatially explicit/ geographically defined.

Temporal scale and resolution	The model simulates six cycles of a hypothetical time period.
Accessibility of outputs	Model outputs include figures of adaptation and infection trends.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model could provide insights regarding the effectiveness of adaptation strategies to reduce health risk within communities with varying degrees of cohesion.
Relevant application	The model is hypothetical but is calibrated using data from rural villages in northern coastal Ecuador. The model simulations suggest that communities with greater cohesion disseminate the initially optimal strategy at a greater rate than communities with low cohesion, therefore reducing the diversity of adaptation responses and increasing communities' long-term vulnerability to weather changes that limit efficacy of the adaptation measure. Consequently, highly cohesive communities may experience reduced health outcomes.
Main reference(s)	Cherng, S.T., Cangemi, I., Trostle, J.A., Remais, J.V., Eisenberg, J.N. (2019). Social cohesion and passive adaptation in relation to climate change and disease. Global Environmental Change, 58: 101960.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.sciencedirect.com/science/article/abs/pii/S0959378018309270
Manuals/ training/ videos	
Wikipedia page	
Other	

4) Other techniques	4.1 Other non-standard modelling techniques: Agent-based models and system dynamics	**Rainfalls Agent-Based Migration Model – Tanzania (RABMM-T)**

Model/ tool type and outputs	This agent-based model assesses the impact of climate-induced rainfall changes on household income, food production and ultimately, resilience and human migration in three villages in Tanzania. The main agents are households who make decisions in relation to farm labour activities and migration based on the Theory of Planned Behaviour. Factors influencing the propensity to migrate are income, community and personal characteristics, migration experience and networks. The migration decision rule was calibrated using survey data. Climate change informs the model through changes in the mean and variability of rainfall, which affects farm labour activities and food production. Resilience of a household is assessed through surplus income after consumption. The model has a monthly time scale and is in hypothetical and geographically undefined space.
Open access?	No
Key data inputs	The model requires data on rainfall and its effects on crops, social networks and factors influencing migration decisions.
Key data accessibility/ availability	Weather data are commonly open access available through meteorological agencies and crop productivity can be modelled. Social network and migration data may be obtained through surveys, which are often not open access.
Strengths	A strength of the model is that it supports the assessment of the impact of climate-induced rainfall changes on human migration and estimates household resilience.
Assumptions/ limitations	Despite that migration decision-making is calibrated using survey data, these decisions are, in practice, complex due to interconnected processes that are unlikely to be fully captured through the explanatory variables used in the model. Moreover, such processes are site specific, which reduces transferability of the model to other case study areas.
Spatial scale and resolution	The model is hypothetical and not spatially explicit/ geographically.
Temporal scale and resolution	The time horizon is 2050 and model outputs are produced as five-year averages.
Accessibility of outputs	Model outputs include figures of development in resilience of households and migration.

Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model can provide insights regarding the impact of climate-induced rainfall changes on human migration and estimate household resilience.
Relevant application	The model was applied to three villages of Same District, Kilimanjaro Region, Tanzania. The results demonstrate that climate change has a clear impact on resilience, but the effects on migration are less evident. Migration appears to be predominately influenced by demographic and societal changes.
Main reference(s)	Smith, C. D. (2014). Modelling migration futures: development and testing of the Rainfalls Agent-Based Migration Model – Tanzania. Climate and Development, 0(0): 1–15.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://rsa.tandfonline.com/doi/full/10.1080/17565529.2013.872593
Manuals/ training/ videos	
Wikipedia page	
Other	

4) Other techniques	4.1 Other non-standard modelling techniques: Agent-based models and system dynamics	**Agent-Based Migration Model of Kniveton *et al.* (no name provided)**

Model/ tool type and outputs	This agent-based model examines how the combination of climate and demographic changes influence migration from and within Burkina Faso. Agents are individuals. Migration decisions are modelled according to the theory of planned behaviour, which consists of attitudes towards behaviour, subjective norms and perceived behavioural control. In particular, migration decisions are dependent on personal attributes, including social networks, and experienced rainfall variability. These attitudes and networks are calibrated based on survey data and interviews. The model divides Burkina Faso in five zones and migration can occur between these zones or out of the country. Rainfall is driven by regional climate model projections.
Open access?	No
Key data inputs	The model requires data on rainfall, social networks and factors influencing migration decisions.
Key data accessibility/ availability	Weather data are commonly open access and available through meteorological agencies. Social network and migration data may be obtained through surveys, which are often not open access.
Strengths	A strength of the model is that it supports the assessment of the impact of climate-induced rainfall changes on human migration from and within a country.
Assumptions/ limitations	Even though the migration decision is calibrated using survey data, migration decisions are, in practice, complex due to multiple interconnected processes that are unlikely to be fully captured by the rainfall and other explanatory variables used within the model. Moreover, such processes are location specific, which limits the transferability of the model to other case study areas.
Spatial scale and resolution	The resolution of the climate projection is 50km by 50km, while the country is divided into five zones.
Temporal scale and resolution	The time horizon is up to the year 2045, while results are simulated annually.
Accessibility of outputs	Model outputs include figures displaying developments in migration.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options

Adaptation policy insights	The model can provide insights regarding the impact of climate-induced rainfall changes on human migration from and within a country.
Relevant application	The model has been applied to Burkina Faso. Results highlight that the extent of migration is highly non-linearly related to dryer conditions under climate change, and this non-linearity is influenced by population growth. This implies that policies to limit migration should focus both on climate adaptation and demographic developments.
Main reference(s)	Kniveton, D. R., Smith, C. D., Black, R. (2012). Emerging migration flows in a changing climate in dryland Africa. Nature Climate Change, 2(6): 444–447.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.nature.com/articles/nclimate1447
Manuals/ training/ videos	
Wikipedia page	
Other	

4) Other techniques	4.1 Other non-standard modelling techniques: Agent-based models and system dynamics	**Agent-Based Migration Model of Hassani-Mahmooei *et al.* (no name provided)**

Model/ tool type and outputs	This agent-based model examines migration processes that may occur due to climate change in Bangladesh. The agents are district level government agents that determine economic development and individuals who may migrate. Migration decisions are modelled according to a migration threshold that is based on variables that represent push factors, including climate change, pull and intervening factors, as well as perceptions of their social network. The model was calibrated with district level data, including weather, demographic and economic characteristics. The model is spatially explicit and covers the complete population and all districts in Bangladesh. The models run with monthly time intervals and each scenario is simulated 20 times. A model validation exercise highlights how historical observations match the model's predictions of a population within a district.
Open access?	No
Key data inputs	Data on weather, demographic and economic characteristics.
Key data accessibility/ availability	Weather data are commonly open access and available through meteorological agencies. Population data are often accessible through government agencies; however surveys may be required to obtain information regarding demographic data and individual characteristics.
Strengths	A strength of the model is that it considers heterogeneous migration responses to social, economic and environmental factors in an integrated manner.
Assumptions/ limitations	Migration decisions are, in practice, complex due to multiple interconnected processes that are unlikely to be fully captured by the explanatory variables used in the model. Although the model outcomes match historical population trends, the factors of influence on migration are not fully calibrated using empirical relationships.
Spatial scale and resolution	The spatial scale is at the country level and the resolution is at the district level.
Temporal scale and resolution	The time horizon as well as time resolution is the year 2050.
Accessibility of outputs	Model outputs include maps of projected changes in population.

Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model can provide insights regarding migration responses to climate change.
Relevant application	The model has been applied to Bangladesh. The results highlight that between three and 10 million people are expected to migrate away from areas that will be affected by drought, cyclones and floods towards areas in Bangladesh by 2040. Based on these results, it is recommended to target adaptation funds to these areas that appear to be vulnerable to climate change.
Main reference(s)	Hassani-Mahmooei, B., Parris, B. W. (2012). Climate change and internal migration patterns in Bangladesh: An agent-based model. Environment and Development Economics, 17(6): 763–780.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.cambridge.org/core/journals/environment-and-development-economics/article/climate-change-and-internal-migration-patterns-in-bangladesh-an-agentbased-model/3D95A3095E5092CF785F204DC54CCE6E
Manuals/ training/ videos	
Wikipedia page	
Other	

4) Other techniques	4.1 Other non-standard modelling techniques: Agent-based models and system dynamics	**Agent-Based Flood Risk + Catastrophe Model of Jenkins *et al.* (no name provided)**

Model/ tool type and outputs	This agent-based model simulates developments in surface water flooding risk in London under scenarios of climate change and socio-economic development. The model is used to examine flood insurance reforms and its integration with flood risk management options, including sustainable drainage systems and property level protection measures, adopted at the local government and household level respectively. Other agents are insurers who establish insurance premiums and deductible levels and decide on whether a property can be reinsured by the joint Government-insurer initiative, Flood Re, property developers and banks. The model is spatially explicit and simulated at annual time intervals with 100 simulations. It includes a catastrophe model component that estimates flood risk to residential buildings, which can be reduced through adoption of flood risk reduction measures.
Open access?	Yes
Key data inputs	The main input data are flood probabilities derived from hydrological models and flood damage from a catastrophe (flood damage) model.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access.
Strengths	A strength of this model is that it supports the examination of risk reduction from adaptation decisions of various agents as a response to decisions of other agents, such as households and local governments, and for analysing the influence of the insurance program, Flood Re, on the developments in flood risk.
Assumptions/ limitations	It is assumed that sustainable drainage systems reduce flood risk by 75% and property level protection measures by 35%, while 1% of the households invests proactively in risk reduction measures and 34% invests reactively following a flood. Local governments are assumed to base their risk reduction investments on cost-benefit analyses and invest when the cost-benefit ratio is at least 1 in 5. A limitation is that the empirical basis for the modelled decision rules is limited.
Spatial scale and resolution	The spatial focus is the London Borough of Camden and the resolution is 5km by 5km.
Temporal scale and resolution	Years 1975, 2030, 2050.

Accessibility of outputs	Outputs include figures of the development of flood risk, flood insurance premiums, the percentage of properties that are reinsured in Flood Re, and the number of houses exposed to flooding.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model supports the estimation of risk reduction that can be obtained from adaptation investments and the influence of insurance on developments in risk.
Relevant application	The model was used to evaluate the effects of Flood Re on flood risk in the London Borough of Camden. Flood risk could increase by up to 80% in 2050 as a results of climate change. Building level protection measures and sustainable drainage systems could reduce flood risk by approximately 10% and 15% respectively. The insurance program, Flood Re, was demonstrated to effectively maintain insurance premium affordability, however it increases flood risk by stimulating new housing developments in flood-prone areas. Yet restricting development in flood-prone areas has been demonstrated to be effective in limiting flood risk over time.
Main reference(s)	Jenkins, K., Surminski, S., Hall, J., Crick, F. (2017) Assessing surface water flood risk and management strategies under future climate change: insights from an agent-based model. *Science of the Total Environment*, 595: 159-168. Crick, F., Jenkins, K., Surminski, S. (2018). Strengthening insurance partnerships in the face of climate change–insights from an agent-based model of flood insurance in the UK. Science of the Total Environment, 636: 192-204.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.sciencedirect.com/science/article/pii /S0048969717307738 https://www.openabm.org/model/4647/version/3/view https://www.sciencedirect.com/science/article/pii /S0048969718314165
Manuals/ training/ videos	
Wikipedia page	
Other	

4) Other techniques	4.1 Other non-standard modelling techniques: Agent-based models and system dynamics	**Agent-Based Sea Level Rise Flood Risk + Catastrophe Model of Haer *et al.* (no name provided)**

Model/ tool type and outputs	This agent-based model simulates developments in residential flood risk in the Heijplaat neighbourhood, Rotterdam, under a scenario of sea level rise. The model is used to examine how flood-proofing of buildings by households influences developments of flood risk over time. Moreover, the model estimates how the adoption of adaptation measures is influenced by risk reduction incentives provided by insurance through risk based pricing and premium discounts for risk mitigation. The agents are households who decide whether to implement loss-reducing measures, and insurers who establish premiums and discounts for risk reduction. Household behaviour is modelled heterogeneously following behavioural rules based on the micro-economic theories: expected utility theory, prospect theory, and Bayesian learning regarding risk perceptions based on flood experience, media and social networks. The model is spatially explicit and simulates monthly time periods with 100 simulations. It includes a catastrophe model component that estimates flood risk to residential buildings, which can be reduced by adopting flood risk reduction measures.
Open access?	No
Key data inputs	The main input data are flood probabilities derived from hydrological models, and flood damage and risk reduction from flood-proofing estimates from a catastrophe (flood damage) model. Other input data are the costs of flood-proofing measures for building types, the lifespan of flood-proofing and behavioural parameters related to individual risk perceptions, risk aversion and social networks.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access.
Strengths	A strength of this model is that it supports the examination of risk reduction from adaptation decisions from heterogeneous, and potentially boundedly rational, households that respond to the decisions of other agents. Moreover, the model can analyse the influence of insurance incentives for adopting adaptation measures on this behaviour and resulting flood risk.
Assumptions/ limitations	The main assumptions of this model are related to parameters of the behavioural rules of households that determine whether they purchase flood insurance and adopt flood-proofing measures. For example, these refer to individual over- or underestimation of flood

	risk in response to flood events, media information regarding risk and social networks, risk aversion, loss aversion and probability weighting. Even though these rules are well founded in micro-economic theories and parameters are derived from literature, a limitation is that they are not calibrated upon data from the case study.
Spatial scale and resolution	The spatial scale is the Heijplaat neighbourhood, Rotterdam, the Netherlands. The resolution is 5m by 5m.
Temporal scale and resolution	Annual time scale between the years 2000 and 2100.
Accessibility of outputs	Outputs include figures of developments in flood risk and the percentage of households with loss-reducing measures.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model supports the examination of risk reduction from adaptation decisions by households and for evaluating the effectiveness of insurance incentives to stimulate risk reduction by policyholders.
Relevant application	The model was applied in a case study of the Heijplaat neighbourhood, Rotterdam, which is an outer dike ring area in the Netherlands. The model results demonstrate that adaptation behaviour by households can limit flood risk between 19% and 56%. Insurance incentives for risk reduction can strongly influence adaptation decisions and reduce flood risk by approximately 29%.
Main reference(s)	Haer, T., Botzen, W.J.W., de Moel, H., Aerts, J.C.J.H. (2017). Integrating household risk mitigation behaviour in flood risk analysis: An agent-based model approach. *Risk Analysis*, 37(10): 1977-1992.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://onlinelibrary.wiley.com/doi/pdf/10.1111/risa.12740
Manuals/ training/ videos	
Wikipedia page	
Other	

4) Other techniques	4.1 Other non-standard modelling techniques: Agent-based models and system dynamics	**Agent-Based Coastal Flood Risk + Catastrophe Model of Han *et al.* (no name provided)**

Model/ tool type and outputs	This agent-based model simulates developments in coastal flood risk in Miami-Dade County, Florida, under different sea level rise scenarios. The model is used to examine the interactions between public and private adaptation decisions. The agents are households who can make decisions regarding elevating their house or purchasing flood insurance. The flood insurance market is simulated through the National Flood Insurance Program (NFIP) as well as private flood insurance providers. Moreover, a government agent can invest in public risk mitigation plans. Household behaviour is modelled heterogeneously following behavioural rules based on Prospect Theory and individual risk perceptions. Risk perceptions depend on the physical flood risk and demographic/socio-economic characteristics. Insurer and government behaviour emulate assumed scenarios in which the government invests in risk mitigation in areas with the highest risk from a constrained budget. Households in areas with public risk mitigation receive premiums discounts through the Community Rating System. The model is spatially explicit and simulates at annual time intervals. It includes a catastrophe model component that estimates flood risk to residential buildings under sea level rise scenarios, which can be reduced by adopting flood risk reduction measures.
Open access?	No
Key data inputs	The main input data are flood probabilities derived from hydrological models and flood damage from a catastrophe (flood damage) model.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access.
Strengths	A strength of this model is that it supports the examination of risk reduction from adaptation decisions from heterogeneous households and the community, while accounting for how household decisions depend on community actions as well as insurance incentives for risk reduction.
Assumptions/ limitations	The main assumptions of this model are related to parameters of the behavioural rules of households that determine insurances purchases and investments in house elevations. Moreover, the government and policy scenarios are based on assumptions regarding risk reduction levels obtained in a certain area. The

	empirical basis for behavioural rules and scenarios appears limited though.
Spatial scale and resolution	The spatial scale is Miami-Dade County with a parcel-level resolution.
Temporal scale and resolution	The time resolution is 30 years.
Accessibility of outputs	Model outputs include maps of flood risk, insurance costs, insurance coverage, elevation costs and total annual adaptation costs. A figure of flood insurance purchases and tables with results for adaptation scenarios can also be produced.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model supports the examination of risk reduction from adaptation decisions by households and the community.
Relevant application	The model has been applied to Miami-Dade County, Florida, USA. The results indicate that household adaptation actions mainly occur in high risk areas. A voucher coupling a house elevation program with low interest mitigation loans could increase the number of households adopting risk mitigation measures by 89%, significantly reducing flood risk. Moreover, it addresses issues of house elevation unaffordability and increases insurance uptake rates. If subsidies of NFIP (please expand acronym) premiums are phased out, then demand for private insurance coverage expands. Public adaptation measures appear important to limit flood risk under climate change but reduce risk mitigation activities by households.
Main reference(s)	Han, Y., Peng, Z.R. (2019). The integration of local government, residents, and insurance in coastal adaptation: An agent-based modeling approach. Computers, Environment and Urban Systems, 76: 69-79.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://www.sciencedirect.com/science/article/pii/S0198971518305362
Manuals/ training/ videos	
Wikipedia page	
Other	

4) Other techniques	4.1 Other non-standard modelling techniques: Agent-based models and system dynamics	**Agent-Based River Flood Risk + Catastrophe Model of Haer *et al.* (no name provided)**

Model/ tool type and outputs	This agent-based model simulates developments in residential river flood risk in all European Union member states under scenarios of climate change and socio-economic development. The model is used to examine how flood-proofing of buildings by households and investments in flood protection by governments influence developments of flood risk over time. It also supports the examination of the "levee effect", which implies that household location decisions depend on flood-protection investments by the government that increases the desirability of settlement in a flood protected zone. Moreover, the model estimates how the adoption of household level adaptation measures are influenced by risk reduction incentives provided by insurance through risk based pricing and premium discounts for risk mitigation. The agents are households who make decisions regarding implementing loss-reducing measures, insurers who establish premiums and discounts for risk reduction, and governments who can invest in flood protection. Household behaviour is modelled heterogeneously following behavioural rules based on subjective expected utility theory, in which their risk perceptions are either rational or boundedly rational depending on the occurrence of flood events. Governments base flood-protection investments on a cost-benefit analysis in either a proactive manner or reactively following flood events. The model is spatially explicit and simulates annual time intervals with 50 simulations of each possible scenario combination. It includes a catastrophe model component that estimates flood risk to residential buildings, which can be reduced by adopting flood risk reduction measures.
Open access?	No
Key data inputs	The main input data are flood probabilities derived from hydrological models and flood damage and risk reduction from flood-proofing estimates from a catastrophe (flood damage) model. Other input data are the costs of flood-proofing measures for building types and flood-protection measures, the lifespan of flood-proofing and behavioural parameters related to individual risk perceptions and risk aversion.
Key data accessibility/ availability	A catastrophe model (flood damage model) is required to estimate flood risk data. Often these models are not open access.
Strengths	A strength of this model is that it supports the examination of risk reduction at the EU scale from adaptation decisions by

	heterogeneous and potentially boundedly rational households, as well as by governments that respond to decisions of other agents. Moreover, the model can analyse the influence of insurance incentives for adopting adaptation measures on household behaviour and resulting flood risk.
Assumptions/ limitations	The main assumptions of this model are related to parameters of the behavioural rules of governments and of households that determine location decisions and whether they purchase flood insurance and adopt flood-proofing measures. For example, these rules for households refer to individual over- or underestimation of flood risk in response to flood events and risk aversion. Even though these rules are well founded in micro-economic theories and parameters are derived from literature, a limitation is that they cannot be calibrated using EU wide data.
Spatial scale and resolution	The spatial focus is all main river basins in EU member states and potentially inundated areas with a grid cell resolution of 30″ x 30″.
Temporal scale and resolution	The time period is annually between 2010-2080.
Accessibility of outputs	Outputs include figures of developments in flood risks and risk reduction by households and maps of the share of residential buildings protected by flood-proofing, flood-protection by governments, risk reduction by households and flood risk.
Adaptation policy cycle stages	2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options
Adaptation policy insights	The model supports the examination of risk reduction from adaptation decisions by households and governments, and for evaluating the effectiveness of insurance incentives to stimulate risk reduction by policyholders.
Relevant application	The model has been applied to all key river basins at risk of flooding in the European Union. The model results highlight that increasing flood risk by climate change can be significantly offset through adaptation decisions. In the short term, household adaptation can have a greater impact than risk reduction by governments. Moreover, investments in flood-protection by the government increase potential flood damage over time due to the levee effect, which entails lower investments by households in flood damage mitigation measures and increased settlement in flood zones. Stimulating households to limit risk through insurance premium incentives can result in risk reduction by 38%.
Main reference(s)	Haer, T., Botzen, W.J.W., Aerts, J.C.J.H. (2019). Advancing disaster policies by integrating dynamic adaptive behaviour in risk assessments using an agent-based modelling approach. *Environmental Research Letters*, 14:4.

	Haer, T., Husby, T., Botzen, W.J.W., Aerts, J.C.J.H. (2019). The safe development paradox: An agent-based model for flood risk under climate change in the European Union. *Global Environmental Change*, 60: 102009.
Suitability for rapid assessment	Rapid use of model; long-term study required for necessary dataset.
Websites	https://iopscience.iop.org/article/10.1088/1748-9326/ab0770/pdf https://www.sciencedirect.com/science/article/pii/S0959378018314079
Manuals/ training/ videos	
Wikipedia page	
Other	

4) Other techniques	4.3 Semi-quantitative assessments: Multi criteria analysis (MCA)	**NAIADE - Novel Approach to Imprecise Assessment and Decision Environments**

Model/ tool type and outputs	NAIADE belongs to the family of outranking methods and supports the analysis of alternatives by providing a final ranking and the best alternative. However, this 'best' alternative is not necessarily the optimum solution, but a compromise. The impact/ evaluation matrix may include either crisp, stochastic or fuzzy measurements of the performance of an alternative with respect to a judgment criterion, thus it is flexible for real-world applications. NAIADE avoids compensability; hence, a poor performance for one criterion does not compensate for a good performance of another. This model is suitable for economic-ecological modelling, incorporating various degrees of precision of the variables taken into consideration.
Open access?	No, the model appears to be out of order, however the manual is available to replicate the methodology.
Key data inputs	▪ Measures or options to analyse ▪ Information regarding the performance of each measure or option ▪ Criteria for each alternative: metrics may be expressed in the form of either crisp, stochastic, fuzzy numbers or linguistic expressions
Key data accessibility/ availability	▪ Focus groups and interviews ▪ National, sectoral or regional sources to assess regulatory frameworks and policy. If relevant, CAPEX/OPEX (Capital and Operational expenditures) of each measure, when possible, can be obtained from experts (estimates), literature from past projects and developers. ▪ IPCC for climate change projections or local/regional models when available.
Strengths	▪ Can incorporate mixed and incommensurable information of both quantitative and qualitative of various dimensions, such as economic, environmental and social. ▪ Can assess the impact of a given alternative in their original unit. ▪ Can use information affected by different types and degrees of uncertainty, including fuzzy data where the phenomena to manage this cannot be defined in an unambiguous manner, such as indeterminacy.

	▪ Can attribute values to the alternatives' criteria expressed in the form of either crisp (exact and certain), stochastic, fuzzy numbers or linguistic expressions.
Assumptions/ limitations	▪ The model is complex: many parameters need to be determined, such as aggregation and compensation coefficients of alpha and gamma. ▪ Notable level of technical expertise is required for its correct use and understanding. ▪ Fastidious participatory and social process: four preference and indifference thresholds to be defined in agreement with all social actors involved. ▪ No weights can be applied. ▪ No possibility of directly using ordinal criteria.
Spatial scale and resolution	No limitations regarding the geographical coverage.
Temporal scale and resolution	No specific time scale.
Accessibility of outputs	Expected outcome is the single most preferred option and ranking of measures that can support prioritizing actions.
Adaptation policy cycle stages	4) Assessing adaptation options
Adaptation policy insights	The results of this model are a good input when designing adaptation polices as it highlights the single most preferred option, ranking of measures that can help prioritizing actions, a short list of options for further evaluation or characterization of acceptable or unacceptable possibilities.
Relevant application	In 2000, NAIADE was applied to address the perceived problem of under-exploitation of the potential availability of water resources in the town of Troina (eastern Sicily, Italy), through an analysis of different possible alternatives for action. This approach has proven highly effective for discussing multiple preferences and points of view from different stakeholder groups and finding out whether social compromise solutions exist. https://www.weadapt.org/placemarks/maps/view/542
Main reference(s)	https://www.weadapt.org/sites/weadapt.org/files/legacy-new/placemarks/files/50a51de5570ddnaiade.pdf https://www.weadapt.org/knowledge-base/adaptation-decision-making/naiade-novel-approach-to-imprecise-assessment-and-decision-environments https://www.weadapt.org/system/files_force/naiade.pdf?download=1

Suitability for rapid assessment	No - setting up the model and attaining the necessary data can be complex and time consuming.
Websites	http://www.liaise-kit.eu/content/outranking-methods-naiade
Manuals/ training/ videos	https://vimeo.com/143244176
Wikipedia page	

4) Other techniques	4.3 Semi-quantitative assessments: Multi criteria analysis (MCA)	**OPTamos - Options for Participatory Transformation and Sustainability Management**

Model/ tool type and outputs	OPTamos is a Multi-Criteria Evaluation tool which aims to assist in decision-making processes and to promote stakeholder participation and engagement. It is based on Analytical Hierarchy Processes.
Open access?	Yes, there is a new version OPTamos. Free registration, online software. Website is subject to periodic maintenance.
Key data inputs	▪ Goal: defines the aim of the analysis. It is established by the team in charge of the decision-making process. ▪ Options: refers to available alternatives. A list of possible options is elaborated by the team in charge of the process following a thorough literature research, expert consultation and policy analysis. ▪ Criteria: are guiding elements on which decisions are based. An initial list is generated by the team in charge of the process and finalised after stakeholder consultation. ▪ Weights: indicate the relative importance of the different components of the process. The weighting of different options should be evaluated by the relevant stakeholders through public consultation, workshops and interviews.
Key data accessibility/ availability	Goal: defined by the project, aim of the analysis. Options, criteria and weights: can be elaborated by the team working on the project from secondary data, from stakeholder consultation.
Strengths	Supports the efficient handling and processing of large volumes of quantitative and qualitative data generated from stakeholder workshops. This model is flexible for real-world applications. It is a discrete multi-criteria method whose impact/ evaluation matrix may include either crisp, stochastic or fuzzy measurements of the performance of an alternative and with respect to a judgment criterion. It can also support the integration of stakeholder expertise and scientific knowledge.
Assumptions/ limitations	There were no explicit limitations found for this methodology in literature. This tool is good for stakeholder workshops to deliberate on various options for a specific outcome, but these results will be based solely on the opinion of the stakeholders' present. Therefore, the assumption of stakeholders holding good information for an informed judgement is relevant for the quality of these results.

Spatial scale and resolution	No limitations regarding the geographical coverage.
Temporal scale and resolution	No specific time scale.
Accessibility of outputs	The outputs can be directly accessed through the software or exported to Excel.
Adaptation policy cycle stages	4) Assessing adaptation options
Adaptation policy insights	OPTamos combines information provided by stakeholders, producing a final ranking of optional pathways. It is based on the Analytic Hierarchy Process method and, therefore, on pairwise comparisons and supports the use of both quantitative and qualitative data.
Relevant application	▪ The aim of OPTamos is to assist decision processes regarding land-use in the context of multi-stakeholder settings. It has been developed and used in the EU project, FPY ROBIN (Role of Biodiversity in Climate Change Mitigation). ROBIN has assessed the role of biodiversity in terrestrial ecosystems in South and Mesoamerica in mitigating climate change. It has evaluated socio-ecological consequences of changes in biodiversity and ecosystem services under climate change. ▪ Applied to a land use related decision in the Cuitzmala watershed, in the state of Jalisco in Mexico: the outcomes from this approach resulted in acceptable land management options for the entire area of the watershed that satisfied criteria generated by the stakeholders themselves and to finally develop an action plan.
Main reference(s)	▪ http://robin-decisionsupport.aau.at/ ▪ Grima, N., Singh, S. J., & Smetschka, B. (2017). Decision making in a complex world: Using OPTamos in a multi-criteria process for land management in the Cuitzmala watershed in Mexico. Land use policy, 67, 73-85. ▪ https://www.researchgate.net/profile/Simron_Singh/publication/289674156_Social_Multi-Criteria_Evaluation_SMCE_in_Theory_and_Practice_Introducing_the_software_OPTamos/links/5691a53e08aee91f69a51fc0.pdf
Suitability for rapid assessment	The model itself / software can be of rapid use, however collecting the necessary data can be time consuming.
Websites	http://robin-decisionsupport.aau.at/

Manuals/ training/ videos	http://robin-decisionsupport.aau.at/files%20uploaded/OPTamos%20step-by-step%20user%20guide.pdf
Wikipedia page	
Other	

4) Other techniques	4.3 Semi-quantitative assessments: Multi criteria analysis (MCA)	**PROMETHEE**

Model/ tool type and outputs	PROMETHEE is an outranking method. It is a well-established decision support system which manages the appraisal and selection of a set of options on the basis of several criteria, with the objective of identifying the benefits and limitations of the alternatives and obtaining a ranking among these. Various PROMETHEE tools and modules have been developed to date. For analysing evaluations, the three Promethee tools predominately used are: PROMETHEE I for partial ranking, PROMETHEE II for complete ranking GAIA plane for visualisation
Open access?	No, a license is required.
Key data inputs	Options to be evaluated Criteria of evaluations Preference function, and the preference/indifference thresholds. Weights
Key data accessibility/ availability	Goal: defined by the project, aim of the analysis. Options, criteria and weights: can be elaborated by the team working on the project from secondary data, from stakeholder consultation.
Strengths	▪ Supports group level decision-making given that it constitutes a useful platform for debate and consensus building. ▪ The model can incorporate both qualitative and quantitative criteria. Criteria scores can be expressed in their own units. ▪ Can manage uncertain and fuzzy information.
Assumptions/ limitations	▪ PROMETHEE suffers from the rank reversal problem when a new alternative is introduced (De Keyser and Peeter, 1996). Rank reversal occurs whenever the relative ranking of two alternatives in the global ranking is reversed when a third alternative is removed from the set. ▪ PROMETHEE does not provide the option to structure a decision problem. In the case of multiple criteria and options, it subsequently may become difficult for the decision maker to obtain a clear view of the problem and to evaluate the results. ▪ Until recently, PROMETHEE did not provide any formal guidelines for weighing, but assumed that the decision-maker is able to weigh the criteria appropriately. ▪ The method in which the preference information is processed is complicated and hard to explain to non–specialists.

Spatial scale and resolution	No limitations regarding the geographical coverage.
Temporal scale and resolution	No specific time scale.
Accessibility of outputs	The outputs can be directly accessed through the software; however a fee is charged.
Adaptation policy cycle stages	4) Assessing adaptation options
Adaptation policy insights	PROMETHEE can be used in the stage of recognizing and investigating the nature of a problem only to a limited extend, since it cannot structure a decision problem. It delivers a ranking of options which facilitates the selection of a policy option, but it is less suitable for the implementation and the evaluation of an implemented policy.
Relevant application	With the objective to develop a set of tools designed to guide forest manager's decisions to improve forest sustainability, Waaub *et al.* (2000) applied PROMETHEE to compare strategic planning forest scenarios in Quebec, Canada. The approach was used in a process of negotiation in a collaborative environment and facilitated the participation of stakeholders.
Main reference(s)	http://www.promethee-gaia.net http://www.ivm.vu.nl/en/Images/MCA4_tcm234-161530.pdf Brans, J. P., & De Smet, Y. (2016). PROMETHEE methods. In Multiple criteria decision analysis (pp. 187-219). Springer, New York, NY. Behzadian, M., Kazemzadeh, R. B., Albadvi, A., & Aghdasi, M. (2010). PROMETHEE: A comprehensive literature review on methodologies and applications. European journal of Operational research, 200(1), 198-215.
Suitability for rapid assessment	No - setting up the software and attaining the necessary data can be complex and time consuming.
Websites	http://www.promethee-gaia.net http://www.ivm.vu.nl/en/Images/MCA4_tcm234-161530.pdf
Manuals/ training/ videos	http://www.promethee-gaia.net/files/VPManual.pdf
Wikipedia page	https://en.wikipedia.org/wiki/Preference_ranking_organization_method_for_enrichment_evaluation#cite_note-Figueria-1

Other	

Annex 5: How to use the information (principals and methods)

5) How to use the information (principals and methods)	5.3 Decision support systems (DSS)	**DESYCO - DEcision support SYstem for Coastal climate change impact assessment**

Model/ tool type and outputs	DESYCO is a DSS which integrates heterogeneous data, including socio-economic, hydrological, environmental and ecological information, and finds wider application within climate adaptation and environmental management. For example, low-lying coastal plains and islands, river basins and groundwater systems, and in the frame of marine areas.
Open access?	Available upon request
Key data inputs	The DSS integrates climate data such as temperature, rainfall and extreme events; biophysical; socio-economic including population and tourism; geomorphological such as erosion and subsidence; hydrological including groundwater, lakes and rivers; environmental such as protected areas and wetlands; ecological data such as marine biological systems and species habitats; and raster and vector data.
Key data accessibility/ availability	Data can be collected through various sources such as open access databases, including: https://www.imf.org/external/pubs/ft/weo/2019/01/weodata/ index.aspx or climate change projections provided by Regional Climate Models (RCMs), historical observations and monitoring data.
Strengths	DESYCO is flexible given that it can be readily applied to aid risk mapping and adaptation assessment in case studies with different geographical and decisional contexts; it may be applied for a range of climate-related problems across the land-sea interface of coastal zones, and at broader spatial scales and resolutions of national, supranational and continental scales according to the purposes of the analysis and the availability of climate and hazard models.
Assumptions/ limitations	The conceptual approach and methodological assumptions underlying the RRA framework may be considered too simplistic for the end-users to trust the reliability of the results. A detailed plan of action, including the definition of how, when and by whom specific adaptation measures should be implemented should be

	based on a more detailed, data intensive and quantitative risk assessment process.
Spatial scale and resolution	DEYSCO was developed on regional (sub-national) scale however can be adapted to finer (i.e. local scale) or larger scales (national and international).
Temporal scale and resolution	Scenarios for 2070-2100.
Accessibility of outputs	Outputs include hazard, exposure, vulnerability, risk and damage maps which can be used for facing a wide range of risk assessment and management issues, relevant for coastal, marine and water management; several statistics (tabular results, graphs and indicators) can be also derived from the spatial maps, facilitating results' understanding and communication to the end-users.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options; 6) Monitoring and evaluation.
Adaptation policy insights	▪ Adopts a common and cross-sectoral regional risk assessment methodology to identify and rank risk patterns across a range of impacts and targets, such as coastal erosion and flooding, saltwater intrusion into groundwater, water quality and ecosystems deterioration, and damages to human assets and infrastructures. ▪ Integrates multi-disciplinary and heterogeneous information and scenarios (climate, environmental and socio-economic) into a structured Multi-Criteria Decision Analysis (MCDA) process based on a trade-off between expert judgement and stakeholder perspectives. ▪ Captures, manipulates and processes spatial and geo-referenced data commonly owned by public authorities, including digital elevation models, land use and land cover maps, population and critical infrastructures data and maps of protected areas and habitats, using an open source software. ▪ Adopts a framework that is scalable and replicable, supporting users to address evolving decision-makers' needs, such as new regulatory frameworks or updated risk assessment methodologies. ▪ Facilitates the communication, training and dialogue among expert and end-users, mainstreaming climate risk assessment into spatial planning.
Relevant application	Low-lying coastal plains and islands in the North Adriatic Sea, the Gulf of Gabes and the Republic of Mauritius; river basins and groundwater systems within the Upper Plain of Veneto and Friuli-Venezia Giulia and the Marche Region; and in the frame of marine areas. Results provide damage maps as combination of risk and

	value maps which provide relative estimations of the potential social, economic and environmental losses.
Main reference(s)	Torresan, S., Critto, A., Rizzi, J., Zabeo, A., Furlan, E., & Marcomini, A. (2016). DESYCO: A decision support system for the regional risk assessment of climate change impacts in coastal zones. Ocean and Coastal Management, 120, 49–63. https://doi.org/10.1016/j.ocecoaman.2015.11.003
Suitability for rapid assessment	Rapid use of the DSSs once populated, however long-term study is required for the collection and pre-processing of the input data.
Websites	https://www.cmcc.it/models/desyco
Manuals/ training/ videos	
Wikipedia page	
Other	

5) How to use the information (principals and methods)	5.3 Decision support systems (DSS)	**THESEUS**

Model/ tool type and outputs	THESEUS DSS proposes the conceptual framework based on the Source-Pathway-Receptor-Consequence (SPRC) model, adopting scenarios for the present (2010), and short (2020s), medium (2050s) and long-term (2080s). Physical processes, such as floods and coastal erosion and environmental and socio-economic processes, are modelled in order to rank critical facilities in relation to social vulnerability; estimate physical damage for structures and define the touristic impacts. It integrates the GIS-based methodology for planning sustainable coastal defence strategies and addresses technical, social, socio-economic and environmental aspects, including climate, environmental and socio-economic scenarios.
Open access?	Yes
Key data inputs	The DSS integrates physical data, including storm surge, wind driven waves and tides; socio-economic such as commercially important features; and environmental data including habitat extent, protected sites and key species.
Key data accessibility/ availability	Data can be collected through various sources such as open access databases, including: https://data.worldbank.org/ or climate change projections provided by Regional Climate Models (RCMs), historical observations, monitoring data, expert judgment and literature.
Strengths	THESEUS is an open-source tool with rapid run-time and quick response; good for preliminary risk assessment and planning phases. THESEUS DSS was developed on top of an integrated simulation model suitable for performing 'What if' analyses based on scenarios. This analysis can support investigating how management strategies and scenario sensitive variables and parameters influence risk at the selected coastal site. The policy analysis mainly focuses on the consequences of changing coastal management options. The different components of this analysis can be seen and changed interactively by means of the user interface.
Assumptions/ limitations	The model contains no representation of risk perception; cost-benefit analysis is difficult to incorporate; high spatial resolution data is required; considers only linear interdependence of the mitigation options. Seasonal effects are not considered in the present DSS modelling. It provides coastal managers with an overview of the drivers, pressures, impacts and response options in different time intervals,

	however it is not expected to replace detailed design tools. It raises awareness of the implications of different policy decisions, but it does not prompt the selection of specific policies. It should be a tool for aiding decision making but it cannot provide a straightforward decision since a) it does not overcome the representation of the social perception of risk and the resilience of society; and b) it includes a strong uncertainty component in the prediction of both physical processes and consequences.
Spatial scale and resolution	THESEUS is applied at the local level with intermediate spatial scales of 10–100 km.
Temporal scale and resolution	Temporal scale is short (2020), medium (2050) and long-term (2080) scenarios with short-, medium- and long-term time spans of 1–10–100 years.
Accessibility of outputs	Outputs are geographic specific. Intermediate maps of specific results, for example, flood depth, land value loss and life losses, are shown with their own scale; the results of hydraulic, social, economic and ecological vulnerability and the overall risk assessment map are given as normalised-quantitative indicators. User friendly interface, outputs accessible to understand for non-technical audience.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 3) Identifying adaptation options; 6) Monitoring & evaluation
Adaptation policy insights	▪ The tool raises awareness of the implications of different policy decisions; however, it does not prompt the selection of specific policies. ▪ The policy analysis mainly focuses on the consequences of changing coastal management options, which may be seen and changed interactively by means of the user interface.
Relevant application	Cesenatico (Emilia-Romagna, Italy) - application of THESEUS provided an Integrated risk assessment map.
Main reference(s)	Zanuttigh, B. *et al.* (2014) 'THESEUS decision support system for coastal risk management', Coastal Engineering. Elsevier B.V., 87, pp. 218–239. doi: 10.1016/j.coastaleng.2013.11.013.
Suitability for rapid assessment	The rapid access to input data is dependent on the case study.
Websites	http://www.vliz.be/projects/theseusproject
Manuals/ training/ videos	
Wikipedia page	

Other	

5) How to use the information (principals and methods)	5.3 Decision support systems (DSS)	**Tyndall Coastal Simulator**

Model/ tool type and outputs	Tyndall Coastal Simulator is based on a series of linked climate models (CM) within a nested framework which recognises three spatial scales: (i) the global (GCM) scale; (ii) the regional scale and (iii) the Simulator Domain, a physiographic unit such as a coastal sub-cell. The models provide feedback for each other and describe a wide array of natural processes and variables linked with coastal dynamics, such as sea level, tides, surges, waves, sediment transport, coastal morphology; and different climate scenarios, as well as the range of uncertainty.
Open access?	No - only accessible to the Tyndall Research Centre
Key data inputs	The model uses climate data such as temperature, rainfall and extreme events; socio-economic such as population and tourism; environmental including protected areas, wetlands and habitats; geomorphological such as erosion and subsidence; hydrological including groundwater, lakes and lagoons; and physical data such as waves.
Key data accessibility/ availability	Data can be collected through various sources such as open access databases, including https://data.worldbank.org/ or climate change projections provided by Regional Climate Models (RCMs), historical observations, monitoring data, expert judgment and literature.
Strengths	It describes a wide array of natural processes and variables linked with coastal dynamics, including sea level, tides, surges, waves, sediment transport and coastal morphology.
Assumptions/ limitations	At the Simulator scale, two fundamental challenges are apparent. Firstly, to extend the Simulator Domain to embrace multiple sub-cells involves linking diverse geomorphic elements where scientific understanding often focuses on qualitative rather than quantitative. This would need to include the interaction between wave-dominated coasts and estuaries. Secondly, to link the results of the Simulator beyond shoreline management planning to all the decisions that are influenced by coastal change and flood risk requires further research, including potentially coupling the physical and socio-economic dynamics.
Spatial scale and resolution	Three spatial scales: (i) the global (GCM) scale; (ii) the regional scale and (iii) the Simulator Domain (a physiographic unit, such as a coastal sub-cell).

Temporal scale and resolution	100 years projection with annual/ decadal resolution or a final value at the end of the projection.
Accessibility of outputs	The simulator includes a dedicated GIS-based user-friendly interface, which requires users to be familiar with GIS.
Adaptation policy cycle stages	1) Preparing the ground for adaptation
Adaptation policy insights	It explores the impacts of climate change on the coast to address questions of adaptation policies.
Relevant application	Exploration of changes along the Norfolk (UK) shoreline, where cliffs are easily and well-known to be eroded at an average rate of up to 1 m/yr.
Main reference(s)	Mokrech, M., Hanson, S., Nicholls, R.J. *et al.* The Tyndall coastal simulator. J Coast Conserv 15, 325–335 (2011). https://doi.org/10.1007/s11852-009-0083-6
Suitability for rapid assessment	Rapid use of mode; access to input data depends on the case study.
Websites	https://tyndall.ac.uk/
Manuals/ training/ videos	
Wikipedia page	
Other	

5) How to use the information (principals and methods)	5.3 Decision support systems (DSS)	**SimCLIM - Simulator model System for Climate Change Impacts and Adaptation**

Model/ tool type and outputs	SimCLIM explores current and potential risks related to climate change and natural hazards, such as sea level rise, and coastal erosion and flooding. The open-framework software model considers 30 years of daily rainfall data (1961-1990) and future scenarios of drier conditions by 2050, producing spatially interpolated risk maps highlighting risk level according to four categories: low or no risk, moderate risk, high risk and extreme high risk.
Open access?	Yes - demonstration version is available.
Key data inputs	The model integrates climate data such as temperature, rainfall and extreme events; hydrological including groundwater, lakes and rivers; and socio-economic data such as population and tourism.
Key data accessibility/ availability	Data can be collected through various sources such as open access databases, including: https://www.imf.org/external/pubs/ft/weo/2019/01/weodata/index.aspx or climate change projections provided by Regional Climate Models (RCMs), historical observations and monitoring data.
Strengths	SimCLIM is flexible in structural modification and in study area - can be customised and maintained by users. It can also be useful in analysing the effects of, and adaptation to, climatic variability and change on water supply systems at a specific location.
Assumptions/ limitations	Final decisions are a matter of weighing and balancing multiple factors such as risk acceptance, costs, future discounting, uncertainties, and perceived efficacy of the actions, which are beyond the realm of a model such as SimCLIM.
Spatial scale and resolution	The spatial scale is based on the user choice from a global to local scale.
Temporal scale and resolution	The model can create climate scenarios for a year of interest, such as 2050, with annual/ decadal resolution or a final value at the end of the projection.
Accessibility of outputs	Outputs are maps of the simulation's output. These are accessible for a non-technical user to interpret.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options

Adaptation policy insights	SimCLIM is effective for adaptation policies examining the adaptations to climate variability and change, including extreme climatic events. SimCLIM supports the assessment of adjustments to natural variability as well as in identifying the incremental risks and evaluating adaptation to climate change.
Relevant application	South-East Queensland and Brisbane (Australia) - here, SimCLIM analysed the effects of, and adaptation to, climatic variability and change on water supply systems.
Main reference(s)	Torresan, S., Critto, A., Rizzi, J., Zabeo, A., Furlan, E., & Marcomini, A. (2016). DESYCO: A decision support system for the regional risk assessment of climate change impacts in coastal zones. Ocean and Coastal Management, 120, 49–63. https://doi.org/10.1016/j.ocecoaman.2015.11.003
Suitability for rapid assessment	The "open-framework" allowed SimCLIM to transition from the realm of the specialist into a tool that can also be used by planners, consultants, policymakers and educators.
Websites	http://www.climsystems.com
Manuals/ training/ videos	https://www.youtube.com/watch?v=z-A-jpkl6TI
Wikipedia page	
Other	

5) How to use the information (principals and methods)	5.3 Decision support systems (DSS)	**DIVA - Dynamic and Interactive Vulnerability Assessment**

Model/ tool type and outputs	The DIVA method consists of two parts: (i) a modelling framework, providing a general a-priori conceptualisation of the system, and (ii) a semi-automated development process. The tool supports decision makers by assessing a wide range of climate change scenarios such as sea-level rise, coastal erosion and flooding.
Open access?	Yes
Key data inputs	The tool uses climate data such as temperature, rainfall and extreme events; hydrological including groundwater, lakes and rivers; morphological including erosion and subsidence; and socio-economic data such as population and tourism.
Key data accessibility/ availability	Data can be collected through various sources such as open access databases, for example: https://data.worldbank.org/ or climate change projections provided by Regional Climate Models (RCMs), historical observations, monitoring data, expert judgment and literature.
Strengths	DIVA is flexible in study area; integrates expert knowledge and feedbacks; algorithm and data are continuously updated; easily available tool.
Assumptions/ limitations	Integrate models are difficult to validate because of the lack of data; doesn't provide GIS functionality at the expert level; a set of drivers and processes with relevant contributions to coastal vulnerability are not included because of limitations in available data, models and resources. While DIVA was not originally designed as a decision-support tool for coastal planners and managers, there is a high demand for DIVA-like tools that operate at a resolution that is high enough for decision-making in the face of sea-level rise and associated hazards. Furthermore, the use of DIVA by people with detailed local knowledge of particular coastal areas has also revealed inconsistencies in the data as all data in DIVA has been derived from public global databases. Another limitation is that the DIVA Graphical User Interface (GUI) does not provide GIS functionality at the expert level. It is technically a minor operation to import and export to and from standard GIS tools, yet this functionality is not currently available via the GUI. Developing such and other advanced functionality available via the GUI would, however, be costly.

Spatial scale and resolution	DIVA can be applied at the local, national, regional and global scale. Resolution of outputs depends on the input data.
Temporal scale and resolution	2100 scenario with annual/ decadal resolution or a final value at the end of the projection.
Accessibility of outputs	The model's output has multiple components that are not objectively comparable and unsuitable for aggregation into a single measure. Only the monetary components of the output can be readily compared and added up, which is the basis for a 'cost–benefit' adaptation strategy. The tool does not produce a single measure or index of vulnerability. The comparison of the various components of the output is left to the user's own judgement.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options; 5) Implementation
Adaptation policy insights	DIVA provides updated policy-relevant information regarding coastal vulnerability.
Relevant application	DIVA contributed to a number of policy reports, such as "The Future Oceans? Warming Up, Rising High, Turning Sour" by the German Advisory Council on Global Change and a report to the United Nations Framework Convention on Climate Change (UNFCCC) on adaptation options for coastal areas. It has been, and is being used, within several EU-funded projects such as PESETA, BRANCH, ADAM and CLIMATECOST, as well as within an integrated vulnerability assessment of coastal areas of South-East and East Asia funded by the Asian Pacific Network.
Main reference(s)	Hinkel, J., & Klein, R. J. T. (2009). Integrating knowledge to assess coastal vulnerability to sea-level rise: The development of the DIVA tool. Global Environmental Change, 19(3), 384–395. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2009.03.002
Suitability for rapid assessment	The model rapid and accessible - DIVA is used in the education of undergraduate and graduate students.
Websites	http://www.dinas-coast.net
Manuals/ training/ videos	
Wikipedia page	
Other	

5) How to use the information (principals and methods)	5.3 Decision support systems (DSS)	**DITTY-DSS Information technology tool for the management of Southern European lagoons**

Model/ tool type and outputs	DITTY DSS, due to its flexible characteristics and structure, is adjustable to application within a range of different geographical and socio-economic contexts. By integrating a GIS database, it supports users to graphically define the area of concern and to assess the effects of different spatial allocations under two- and three-year timeframe scenarios.
Open access?	No
Key data inputs	The DSS integrates morphological data; socio-economic such as population, GDP and tourism; geographical raster and vector; hydrological including groundwater, lakes and rivers; and ecological data such as habitats and protected areas.
Key data accessibility/ availability	Data can be collected through various sources such as open access databases, for example, https://data.worldbank.org/ or climate change projections provided by Regional Climate Models (RCMs), historical observations, monitoring data, expert judgment and literature.
Strengths	Quick response; easy to use; evaluation in almost-real-time the effects of possible decisions; flexible in study area (European perspective); drives the entire study (not only at the end).
Assumptions/ limitations	The discrete approach with respect to the control options and the external factors: when control options and external factors vary in continuous sets, gridding of these sets suffers from a number of drawbacks. There is no guarantee that the final decision is truly optimal, since evaluation of points outside the considered grid could in principle change the outcome of the decision process. It heavily relies on the availability of models of the cause–effect relations in the system under study. If models with these characteristics are not available or cannot be developed, the DITTY structure is not applicable. The mechanism underlying this DSS structure is not completely automatic, rather it requires user's participation and supervision.
Spatial scale and resolution	The spatial scale is local while the resolution depends on the input data.
Temporal scale and resolution	Alternative scenarios. The model provides two- and three-year projections, with 1995-2005 as reference years.

Accessibility of outputs	Provides a ranking of the evaluated alternatives by means of simple matrix calculations and pairwise comparisons. The "models" block represents a suitable interconnection of the models used to describe the system behaviour and its vulnerability, making simulations and predictions of, for example, the physical, chemical and biological, as well as the economic and social variables of the system, which are understandable for a non-technical user.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options; 6) Monitoring & evaluation
Adaptation policy insights	Integrated policy making requires a holistic assessment of benefits and limitations; maintaining the current situation. Data and information obtained from the models can be used to inform a Multi Criteria Analysis (MCA - see section 4.3). Robustness of the decision with respect to external factors are beyond the control of the decision-maker.
Relevant application	Sacca di Goro lagoon (Italy) - The structure of DITTY-DSS supported the integration and management of the input information provided by different mathematical and analytical models of a lagoon ecosystem in a clear and structured manner. This included biogeochemical, hydrodynamic, ecological and socio-economic models.
Main reference(s)	Mocenni C., Casini M., Paoletti S., Giordani G., Viaroli P., Comenges JM.Z. (2009) A Decision Support System for the Management of the Sacca di Goro (Italy). In: Marcomini A., Suter II G., Critto A. (eds) Decision Support Systems for Risk-Based Management of Contaminated Sites. Springer, Boston
Suitability for rapid assessment	Rapid use of mode; access to input data depends on the case study.
Websites	https://cordis.europa.eu/project/id/EVK3-CT-2002-00084
Manuals/ training/ videos	
Wikipedia page	
Other	

5) How to use the information (principals and methods)	5.3 Decision support systems (DSS)	**KRIM: Decision Support System**

Model/ tool type and outputs	The KRIM DSS provides orientation and action-taking knowledge for coastal risk management and protection under climate change conditions. By using a 2050 climate scenario, the consequences of an accelerated sea level rise and intensified extreme events are analysed together with adaptation options for the natural and the social structures located within the coastal region.
Open access?	No, prototype 2003.
Key data inputs	The tool uses climate data such as temperature, rainfall and extreme events; hydrological including groundwater, lakes and rivers; and socio-economic data including population and tourism.
Key data accessibility/ availability	Data can be collected through various sources such as open access databases, for example, https://www.imf.org/external/pubs/ft/weo/2019/01/weodata/index.aspx or climate change projections provided by Regional Climate Models (RCMs), historical observations and monitoring data.
Strengths	KRIM is the only DSS considering extreme events scenarios in its analysis to support the development of robust coastal management strategies. It enables an integration of results of sub-projects, models and relevant knowledge; stimulate interdisciplinary research and trans-sectoral interactions; and supports a participative policy-making process with an innovative use of information technology and the internet.
Assumptions/ limitations	KRIM is not flexible.
Spatial scale and resolution	The spatial scale is regional while the resolution depends on the case study input data.
Temporal scale and resolution	The temporal scale depends on the case study input data with annual/ decadal resolution or a final value at the end of the projection.
Accessibility of outputs	Information for non-technical users. It simulates an interactive dialog with interested citizens, policy makers and decision-makers on the consequences of sea level rise on coastal protection management. The DSS uses the internet as a medium for such dialog. With an appropriate choice of the informatics framework, group specific user-interfaces for the DSS can be designed. With these specific user-interfaces the presentation of information,

	results and analysis capabilities of the system can be customized according to the role of the user in the decision-making process.
Adaptation policy cycle stages	1) Preparing the ground for adaptation
Adaptation policy insights	The integral representation of knowledge regarding both the physical and social science processes in a dynamic system promotes a decision support system as a useful tool for both integrative scientific analysis and a participative policy making process.
Relevant application	Weser-Jade-Region (Bremen, Germany) - KRIM was used to assess the impacts related to extreme events and natural hazards, such as typhoons and cyclones.
Main reference(s)	Kraft, D. (2003) 'Aufbau eines Entscheidungsunterstuetzungssystems fuer das Kuestenzonenmanagement: Konzeption und Entwicklung eines DSS aus kuesten-oekologischer Sicht.
Suitability for rapid assessment	The rapid access to input data depends by the case study.
Websites	http://www.krim.uni-bremen.de
Manuals/ training/ videos	
Wikipedia page	
Other	

5) How to use the information (principals and methods)	5.3 Decision support systems (DSS)	**CVAT - Community Vulnerability Assessment Tool**

Model/ tool type and outputs	CVAT evaluates i) community vulnerability and related community-based hazard mitigation strategies to withstand hurricane hazards in the New Hanover County, North Carolina; ii) the vulnerability of critical facilities, economic sectors, society, and the environment to coastal hazards such as hurricanes, coastal flooding and erosion and tsunamis in the Maui County, Hawaii, validating the ease of adapting the methodology to other geographic locations and hazard types; iii) risks and vulnerabilities of multiple hazards such as extreme wind events, floods, earthquakes, tornadoes, snow/ice, temperature extremes and environmental hazards at a state-wide scale, and subsequently the corresponding level of risk in various regions throughout the state.
Open access?	Yes (prototype)
Key data inputs	The tool integrates climate data including temperature, rainfall and extreme events; hydrological such as groundwater, lakes and rivers; and socio-economic data including population and tourism.
Key data accessibility/ availability	Data can be collected through various sources such as open access databases, for example, https://data.worldbank.org/ or climate change projections provided by Regional Climate Models (RCMs), historical observations, monitoring data, expert judgment and literature.
Strengths	CVAT is flexible in study area - it is readily adaptable for any geographic location; maps facilitate the community understanding and action needed; flexible for any type of hazard; and facilitates community expert collaboration to develop effective strategies for reducing or eliminating disaster-related damages.
Assumptions/ limitations	It may be challenging to engage and maintain the appropriate stakeholders to sustain the momentum of the process; communities might not have adequate expertise or resources to collect and integrate data; probability data are not consistent among different hazard types and data are not always available at the local scale.
Spatial scale and resolution	Results may be achieved using a geographic information system or static maps with overlays and handwritten data.
Temporal scale and resolution	The temporal scale and resolution are dependent on the case study and input data.

Accessibility of outputs	Output constitutes a map of targets and natural hazard risk areas, which are implemented in a GIS software. Users therefore need to be familiar with GIS software. However, a desktop user-friendly interface is available.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options; 5) Implementation; 6) Monitoring & evaluation
Adaptation policy insights	A community level vulnerability assessment can support prioritisation of adaptation options and policy decision-making at the local and grassroots level, as well as provide input data for a broader national assessment.
Relevant application	New Hanover County (North Carolina); Maui County (Hawaii); Rhode Island **-** CVAT analysis results provide a baseline to prioritize mitigation measures and to evaluate the effectiveness of those measures over time.
Main reference(s)	Flax, L. K., Jackson, R. W. and Stein, D. N. (2002) 'Community Vulnerability Assessment Tool Methodology', (November), pp. 163–176
Suitability for rapid assessment	Unknown
Websites	https://trid.trb.org/view/728144
Manuals/ training/ videos	
Wikipedia page	
Other	

5) How to use the information (principals and methods)	5.3 Decision support systems (DSS)	**WADBOS: Decision Support Systems**

Model/ tool type and outputs	WadBOS supports integrating socio-economic, hydrological, environmental and ecological data to create three sub-models for socio-economics, ecology and the landscape. It simulates for three different possible time steps of a tidal cycle, one month, one-year and a 10-years scenario.
Open access?	Yes - demonstration version available online.
Key data inputs	The DSS uses hydrological data including groundwater, lakes and rivers; socio-economic such as population and tourism; and environmental data such as protected areas, wetlands and habitats.
Key data accessibility/ availability	Data can be collected through various sources such as open access databases, for example: https://data.worldbank.org/ or climate change projections provided by Regional Climate Models (RCMs), historical observations, monitoring data, expert judgment and literature.
Strengths	The strong linkages and feedback loops between the individual models highlight mistakes within the model formulation with greater ease than when the same models are applied in isolation; flexible - the methodology is transferrable to other coastal zones at a local, national, regional and global scale.
Assumptions/ limitations	The DSS is not completed - there are missing information or policy criteria for policy makers such as acceptability, responsive and appropriateness; there is uncertainty regarding the validity and correctness of the scientific knowledge incorporated within the DSS; the DSS uses different spatial scales and resolutions than desirable for the formulation of policy as greater detailed information is required; calibration is difficult and time consuming; not flexible; policy makers have reported not being satisfied with the user-friendliness and transparency of the instrument; it does not account for the quality of the model in terms of calibration and predictive capabilities, and as such it should not be used for actual policy making purposes.
Spatial scale and resolution	WADBOS can be applied at the local or regional scale, and the resolution is dependent on the case study and input data.
Temporal scale and resolution	10 years scenario with a final value at the end of the projection.

Accessibility of outputs	Outputs are presented in the form of text, time graphs and linked MS Excel tables. All the variables calculated at the compartment and the cellular levels are available as dynamic maps, updated on a monthly basis.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options; 5) Implementation; 6) Monitoring & evaluation
Adaptation policy insights	WADBOS assists decision-making for precise policy measures to be implemented and analysis of policy documents.
Relevant application	Wadden Sea, the Netherlands - results show scenarios construction and analysis, sensitivity analysis and multi-criteria decision analysis.
Main reference(s)	Engelen, G., Uljee, I. and van de Ven, K. (2005) 'WadBOS: Integrating Knowledge to Support Policy-making for the Wadden Sea.
Suitability for rapid assessment	Unknown
Websites	http://www.riks.nl/projects/WadBOS
Manuals/ training/ videos	
Wikipedia page	
Other	

5) How to use the information (principals and methods)	5.4 Real option analysis	**Decision Support Tool**

Model/ tool type and outputs	Real Options Analysis (ROA) is a decision making under uncertainty approach. It quantifies the investment risk associated with uncertain future outcomes. It is particularly useful when considering the value of flexibility of investments, either over the timing of the capital investment, or the flexibility to adjust the investment as it progresses over time, i.e. allowing a project to adapt, expand or scale-back in response to unfolding events.
Open access?	Decision support tool - thus the method commonly available.
Key data inputs	Depends on application, but does normally require probabilities or probability-like data or assumptions.
Key data accessibility/ availability	Uses other data sources, thus depends on source availability.
Strengths	Allows for quantitative economic analysis of the value of flexibility and learning. Provides a structured method to conceptualise and visualise the concept of adaptive management.
Assumptions/ limitations	The application requires inputs related to probability or probabilistic-like assumptions for climate change and the identification of decision points. It is therefore not so applicable under situations of (deep) uncertainty, where probabilistic information is low or missing. The derivation of probabilities for climate information is a major assumption, especially where this involve scenario uncertainty (i.e. different RCPs), though it also involves some form of assumption to derive a probability from an ensemble of climate models. It also requires the identification of decision points for (dynamic) aspects of climate change and need to match these decision points to equivalent climate data.
Spatial scale and resolution	Project level.
Temporal scale and resolution	Depends on model inputs used.
Accessibility of outputs	Output is expected net present value (for options).
Adaptation policy cycle stages	4) Assessing adaptation options
Adaptation policy insights	Real Options Analysis provides information on whether to invest now or wait for more information, or for the benefits of flexibility in

	investment for later updates. The outputs can be an economic net present value that shows alternative options, allowing this to be used to help prioritise choices.
Relevant application	Dobes (2008) (2010) Real options in the Mekong Delta, Vietnam, with a comparison of net present values of two housing alternatives, with option for houses with raiseable floors. Scandizzo (2011) ROA to assess value of hard infrastructure, restoration of mangroves and coastal zone management options in Mexico. Linquiti and Vonortas (2012) ROA to assess investments in coastal protection using real options with case studies in Dhaka and Dar-es-Salaam. Kontogianni *et al.* (2013) ROA for value of maintaining flexibility (such as scaling up or down, deferral, acceleration or abandonment) to engineered structures in Greece. Gersonius *et al.* (2013) ROA for urban drainage infrastructure in England. Dawson *et al.* (2018) ROA of railways investment for Dawlish in the UK. Woodward *et al.* (2014) Considers the best time to invest in flood risk strategies for the Thames Estuary (UK), using RAO to assess flexible adaptive measures for potential flood risk management. Jeuland and Whittington (2014) ROA to water investment planning on the Blue Nile to identify flexibility in design and operating decisions for a series of large dams. van der Pol *et al.* (2013) ROA for Dike Investments. Skourtos *et al.* (2016) ROA for city of Bilboa. Dittrich *et al.* (2018) ROA for forestry.
Main reference(s)	▪ Watkiss, P. and Hunt, A, Blyth, W (2013). Real Options Analysis: Decision Support Methods for Adaptation, MEDIATION Project, Briefing Note 4. Funded by the EC's 7FWP. Available at https://www.weadapt.org/sites/weadapt.org/files/legacy-new/knowledge-base/files/1202/5204fe5fd75f9real-options-analysis.pdf ▪ Dobes, L., 2008: Getting Real about Adapting to Climate Change: Using 'Real Options' to Address the Uncertainties. In: Agenda, Volume 15, Number 3, 2008, p. 55-69. ▪ Dobes, L (2010). Notes on Applying Real Options to Climate Change Adaptation Measures, with examples from Vietnam. Research Report No. 75. November 2010. ▪ Scandizzo, P.L., (2011). Climate Change Adaptation and Real Option Evaluation. CEIS Working Paper No. 232. Available at SSRN: https://ssrn.com/abstract=2046955 or http://dx.doi.org/10.2139/ssrn.2046955 ▪ Kontogianni, A., C.H. Tourkolias, D. Damigos and M. Skourtos (2013). Assessing sea-level-rise costs and adaptation benefits

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Suitability for rapid assessment	a. Quick access to input data/ previous studies Previous studies can provide information on possible options of delay or flexibility, through there may be issues on the appropriateness of transferability. b. Rapid use of models and methods ROA has a complex methodology, which typically requires high volumes of data and resources. A more qualitative approach combined with the use of decision trees can be taken, which is of benefit when significant amounts of data are unavailable.

	There are some examples of simple xls for guidance, but these still require considerable primary information to allow analysis.
Websites	https://www.weadapt.org/sites/weadapt.org/files/legacy-new/knowledge-base/files/1202/5204fe5fd75f9real-options-analysis.pdf
Manuals/ training/ videos	https://www.weadapt.org/sites/weadapt.org/files/legacy-new/knowledge-base/files/1202/5204fe5fd75f9real-options-analysis.pdf
Wikipedia page	
Other	

5) How to use the information (principals and methods)	5.4 Real option analysis	**ECONADAPT**

Model/ tool type and outputs	Real Options Analysis (ROA) is a decision making under uncertainty approach. ECONADAPT is an Excel based model with examples and a work sheet, and it quantifies the investment risk associated with uncertain future outcomes. It is particularly useful when considering the value of flexibility of investments, either over the timing of the capital investment, or the flexibility to adjust the investment as it progresses over time. This supports a project to adapt, expand or scale-back in response to unfolding events.
Open access?	Yes
Key data inputs	Input data depends on application, but it frequently requires probabilities or probability like data or assumptions, and all input data for a project to support quantification and valuation.
Key data accessibility/ availability	Will depend on the application. No generic data sources available for this.
Strengths	ECONADAPT supports the quantitative economic analysis of the value of flexibility and learning. It provides a structured method to conceptualise adaptive management and can support data analysis.
Assumptions/ limitations	The application requires inputs related to probability or probabilistic-like assumptions for climate change and the identification of decision points. This method is therefore not applicable under situations of deep uncertainty, where probabilistic information is scarce or missing. The derivation of probabilities for climate information is a significant assumption, especially where this involve scenario uncertainty, such as different RCPs, though it also involves some form of assumption to derive a probability from an ensemble of climate models. It also requires the identification of decision points for dynamic aspects of climate change and need to match these decision points to equivalent climate data.
Spatial scale and resolution	Project level.
Temporal scale and resolution	Depends on model inputs used.
Accessibility of outputs	Output is the expected net present value for adaptation options.
Adaptation policy cycle stages	4) Assessing adaptation options
Adaptation policy insights	Real Options Analysis provides information regarding the optimal timing for investment, or whether to invest in options that provide

	greater future flexibility. The outputs can be an economic net present value that highlights alternative options to support decision making.
Relevant application	ECONADAPT was applied to case studies in Greece and Bilboa.
Main reference(s)	Kontogianni, A., C.H. Tourkolias, D. Damigos and M. Skourtos (2013). Assessing sea-level-rise costs and adaptation benefits under uncertainty in Greece. Environmental Science & Policy. Vol 37: 61-78. http://dx.doi.org/10.1016/j.envsci.2013.08.006. Skourtos, M., Damigos D, Kontogianni A., Tourkolias C., Markandya, A., Abadie, L. M, Sainz de Murieta, E., Galarraga, I., Wellman, J. and A. Hunt (2016). Future values for adaptation assessment. Deliverable 2.2, Econadapt FP7 research project. Available at https://econadapt.eu/sites/default/files/docs/Deliverable%202-2%20approved%20for%20publishing_0.pdf
Suitability for rapid assessment	a. Quick access to input data/ previous studies Previous studies can provide information regarding the possible options of delay or flexibility, though there may be issues on the appropriateness of transferability. b. Rapid use of models and methods ROA is a complex methodology, which typically requires high volumes of data and resources. A greater qualitative approach combining decision trees can be adopted, which beneficial when significant quantities of data are unavailable. Some Excel examples are available for guidance however these still require considerable primary information to support analysis.
Websites	https://econadapt-toolbox.eu/tool-real-options-analysis#overlay-context=real-options-analysis
Manuals/ training/ videos	
Wikipedia page	
Other	

5) How to use the information (principals and methods)	5.6 Dynamic adaptive policy pathways (DAPP)	**Dynamic Adaptive Policy Pathways (DAPP)**

Model/ tool type and outputs	Dynamic Adaptive Policy Pathways (DAPP) is an approach for decision making under deep uncertainty (DMDU) that explicitly includes decision-making over time. The essence is proactive and dynamic planning in response to how the future actually unfolds. It explores alternative sequences of decisions or actions (development or adaptation pathways) under multiple futures and illuminates the path-dependency of options. The output is a plan for action.
Open access?	Yes
Key data inputs	In general, future climate scenarios and demographic outlooks are required. DAPP is a flexible approach, there is no specific data required. The DAPP method can be used on different levels. If models are used, these models have their own data requirements.
Key data accessibility/ availability	Future scenarios can be based on information from official sources such as IPCC for climate change projections and the national planning department for demographic outlooks.
Strengths	▪ The DAPP process yields a plan for action. This describes which actions to take in the short-term to meet policy objectives and keep long-term options open, which developments to monitor, and under which conditions next actions should be taken to stay on track. ▪ DAPP is a flexible, generic analytical approach which is often first carried out qualitatively based on expert judgement, followed by a more detailed model-based assessment. ▪ Flexibility: Where resources and data permit, model-based assessments can be used to establish tipping points and pathways, such as through stress testing, sensitivity analyses and ensemble generation. In the absence of models or reliable quantitative data, expert judgement and more qualitative assessments can be applied with local experts and stakeholders. When objectives cannot be translated into clear target indicators and values, relative values can be used.
Assumptions/ limitations	More given by the underlying models and tools than by the DAPP method itself, therefore not mentioned here.
Spatial scale and resolution	Flexible, depends on the system and the chosen models and tools.
Temporal scale and resolution	Flexible, depends on the system and the chosen models and tools.
Accessibility of outputs	An action plan, given as a metro-map or a decision tree.

Adaptation policy cycle stages	3) Identifying adaptation options, 4) Assessing adaptation options
Adaptation policy insights	An action plan with the alternative sequence of decisions or actions under multiple futures, path-dependency of options.
Relevant application	▪ The Netherlands: Dutch Delta Programme. ▪ Bangladesh: Bangladesh Delta Plan 2100. ▪ EU: RISES-AM- research project mapping out the risks of climate change, sea-level rise and extreme storm impacts at local, regional and global levels. ▪ Philippines: Economic Analysis Integrating Uncertainty into Adaptation Investment Decisions. ▪ United States: Miami flood resilience. ▪ United States: San Francisco water supply. ▪ Thailand: Development of a Flood Early Warning System and an Adaptive Flood Risk Management plan for Sukhothai district / Yom River Basin.
Main reference(s)	Haasnoot, M., Kwakkel, J. H., Walker, W. E., ter Maat, J. (2013). "Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world." Global Environmental Change, 23(2), 485–498. Lawrence, J., M. Haasnoot (2017) What it took to catalyse uptake... Env. Sc. & Policy, 10.1016/j.envsci.2016.12.003 Haasnoot, M., J. Schellekens, J.J. Beersma, H. Middelkoop, J.C.J. Kwadijk, (2015) Transient scenarios for robust climate change adaptation illustrated for water management in the Netherlands. Env. Res. Let. 10.1088/1748-9326/10/10/105008 Kwakkel, J. H., M. Haasnoot, W. E. Walker. 2014. Developing dynamic adaptive policy pathways: a computer-assisted approach for developing adaptive strategies for a deeply uncertain world. Clim. Change 2014:1-14. 10.1007/s10584-014-1210-4
Suitability for rapid assessment	Building adaptation pathways needs extensive information on performance of individual actions under various SLR and climate change scenarios. It also requires stakeholder involvement in identification and selection of actions. The analysis can be conducted as either expert or model based. The latter is not suitable for rapid analysis. An expert-based exercise as an exploration can be conducted in a half-day workshop, provided there is sufficient knowledge represented. The application of the pathway generator tool is accessible and fast.
Websites	http://pathways.deltares.nl

Manuals/ training/ videos	http://deltagame.deltares.nl https://publicwiki.deltares.nl/display/AP/Pathways+Generator
Wikipedia page	http://www.coastalwiki.org/wiki/Climate_adaptation_policies_for_the_coastal_zone#Adaptation_pathways
Other	https://agwaguide.org/about/CRIDA/

Annex 6: Multi-disciplinary

Multi-disciplinary	Multidisciplinary (including extreme events, ecosystems, biodiversity, climate change impacts and water quality)	**Random Forest (RF)**

Model/ tool type and outputs	RF provides a useful tool for data classification and regression.
Open access?	Yes
Key data inputs	Vector features (points in a n-dimension space).
Key data accessibility/ availability	Data can be collected through various sources of information, for example, open access population databases or climate change projections provided by regional climate models, historical observations, expert judgment and literature.
Strengths	RF provides greater accuracy and robustness than the individual classifiers due to: (1) it can effectively manage large databases; (2) it can incorporate thousands of input variables without deletion of the variable; (3) it creates an internal unbiased estimation of the generalized error; (4) it can estimate the importance of each variable for classification; (5) it can compute proximities between pairs of cases utilized in locating outliers; (6) such ensembles demonstrate robust and accurate performance on complex datasets with limited fine-tuning in the presence of multiple noisy variables.
Assumptions/ limitations	One of the key disadvantages of the decision tree is the large variance in its results, yet RF may resolve this issue by averaging multiple trees. However, due to the cascading effect, this might constitute a greater challenge to interpret the resulting output. Moreover, decision trees are slower than other methods in the testing phase.
Spatial scale and resolution	Local/ national/ regional depending on the scale/resolution of the input data.
Temporal scale and resolution	Idealized scenarios depending on the scale/resolution of the input data.
Accessibility of outputs	The model outputs are accessible for any end-user.

Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options; 6) Monitoring & evaluation
Adaptation policy insights	Futures scenarios based on large datasets, such as big data, can provide greater robust alternatives for supporting adaptation policies.
Relevant application	Detection of shoreline evolution in relation to tsunami events through remotely sensed data: extraction of changed pixels from the output images of regression analysis.
Main reference(s)	Eisavi, V. and Homayouni, S., 2016. Performance evaluation of random forest and support vector regressions in natural hazard change detection. *Journal of Applied Remote Sensing*, *10*(4), p.046030.
Suitability for rapid assessment	Rapid use of the model once completed, however long-term study is required for input data collection and model training, calibration and validation.
Websites	https://scikit-learn.org/stable/index.html
Manuals/ training/ videos	
Wikipedia page	
Other	

Multi-disciplinary	Multidisciplinary (including extreme events, ecosystems, biodiversity, climate change impacts and water quality)	**Support Vector Machine (SVM)**

Model/ tool type and outputs	SVM provides a useful tool for data classification and regression. SVM can learn boundaries and develop linear separator between classes.
Open access?	Yes
Key data inputs	Vector features (points in an n-dimension space).
Key data accessibility/ availability	Data can be collected through various sources of information such as open access population databases or climate change projections provided by regional climate models, historical observations, expert judgment and literature.
Strengths	SVM is greater suited to situations with limited reference points. It can readily incorporate a significant quantity of input features and learn non-linear relationships between multiple features.
Assumptions/ limitations	When there is a large training set and the model is sensitive to noisy data, the computation of SVM can be complex.
Spatial scale and resolution	Local/ national/ regional depending on the scale/resolution of the input data.
Temporal scale and resolution	Idealized scenarios depending on the scale/resolution of the input data.
Accessibility of outputs	Moderate accessibility.
Adaptation policy cycle stages	1) Preparing the ground for adaptation; 2) Assessing risks and vulnerability to climate change; 3) Identifying adaptation options; 4) Assessing adaptation options; 6) Monitoring & evaluation
Adaptation policy insights	Futures scenarios based on large datasets, such as big data, can provide greater robust alternatives for supporting adaptation policies.
Relevant application	Assessment of urban flood susceptibility in flood-prone areas with limited flood inventories.
Main reference(s)	Zhao, G., Pang, B., Xu, Z., Peng, D. and Xu, L., 2019. Assessment of urban flood susceptibility using semi-supervised machine learning model. *Science of The Total Environment*, *659*, pp.940-949.

Suitability for rapid assessment	Rapid use of the model once completed, however long-term study is required for input data collection and model training, calibration and validation.
Websites	https://scikit-learn.org/stable/index.html
Manuals/ training/ videos	
Wikipedia page	
Other	

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