WATExR

Climate seasonal prediction for adapting water resources to extreme events

European Research Area for Climate Services

JPI Climate

WP 3 – Integrative tools

Report on the new QGIS plug-ins, with examples of impact models being executed with seasonal climate prediction through the plug-in

Date

December 2018

Authors:

The entire WATExR consortium has contributed to the material of this report.

Table of Contents

1. Introduction

In WATExR, two main objectives are to 1) integrate cutting-edge seasonal climate prediction and ecosystem impact models in co-developed advanced tools; and to 2) implement these tools in a standardized, user-friendly GIS environment. These objectives seek to ensure that the developments of WATExR will live beyond the lifespan of the project, while also enabling further developments and applications by developers and end-users outside of the WATExR project consortium. Work package 3 (WP3) is at the core of these objectives, and focus on the actual development of these tools, represented by a series of software workflows that may be adapted to and applied by the individual developers and end-users. WP3 include training of developers for producing software workflows, documentation of the workflows, training of end-users in application of the developed workflows, and release of the developed software solutions through open platforms such as Github or Gitlab.

This report (Deliverable 3.1) aims to document the choice of software workflows for each individual site-partner in WATExR, and to briefly demonstrate working examples of how impact models, which are embedded in the workflows, may be executed with seasonal climate prediction data through the software. The demonstration will aid end-users in understanding the potential usefulness of seasonal predictions by impact models, and may also help identify further development aspects, which may need attention for the remainder of the WATExR project and beyond.

2. Software workflows in WATExR

Software workflows in WATExR are developed in collaboration with the project's end-users, and each site-partner seeks to take into account the specific needs of the individual end-users. Interactions between developers and end-users (the latter also referred to as co-developers) have been organized in WP1, and face-to-face interactions have been accomplished by organizing events coinciding with the first two hands-on meetings of the project. The resulting choices of software solutions, which are outlined in this deliverable, therefore balance the requests and needs of the end-users against the resources available to the developers in the project. At the time of writing this deliverable, the software workflows for the Danish and Spanish sites have matured the most, and we therefore used these for the demonstration of the software workflow in operation for producing seasonal impact predictions.

2.1 Software workflow for Danish site: Lake Arreskov and its catchment

The Danish study site is the shallow, eutrophic, Lake Arreskov and its catchment (Nielsen et al. 2014), situated in the upper parts of the catchment to the Odense Fjord estuary. The Danish end-user is the Danish Ministry for the Environment (MFE), and key challenges, which they would like the WATExR solutions to address include:

- Compliance with the EU Water Framework Directive (WFD) with focus on:
    - phytoplankton and the proportion of blue-green algae
    - fish and the proportion of piscivorous fish
    - the presence or absence of submerged vegetation
- Interpretation and communication (to the public) of the mechanisms of extreme events, including:
    - dynamics of hypoxia formation and how this may cause fish kills and internal nutrient load

The Danish end-user is interested in an impact model solution, which can readily be adapted to any other lake and catchment in Denmark. Through the developer/end-user interactions, the Danish partners have agreed on a software solution comprising the SWAT model (Soil and Water Assessment Tool) for describing the catchment dynamics, including water discharge and nutrient loads to Lake Arreskov, and the WET model (Water Ecosystems Tool) for describing the ecosystem dynamics within the lake (Fig. 1).

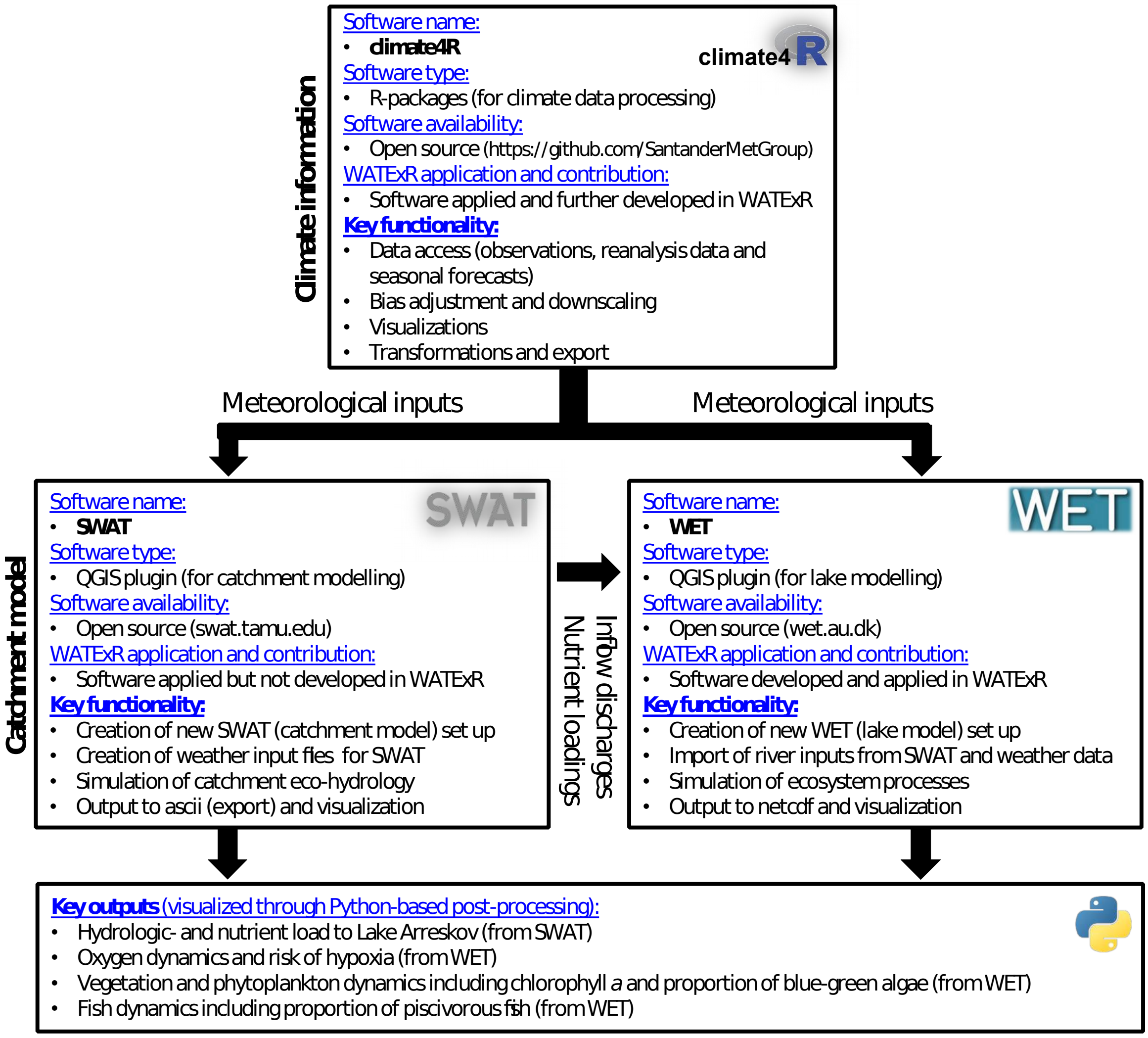

Figure 1. The workflow, and key functionality of its software components, for enabling seasonal predictions for Lake Arreskov and its catchment.

The key software components in the workflow for producing seasonal predictions for Lake Arreskov and its catchment include:

- **climate4R:** for downloading (packages loadeR and loadeR.ECOMS), bias-correcting (package downscaleR) and formatting (packages transformeR and convertR) reanalysis climate data and seasonal climate predictions. The open source climate4R (Iturbide et al. 2019) framework includes a series of R packages (illustrated in Fig. 2), which among other functionalities allow acquisition of required meteorological information hosted by the Santander Met Group Thredds Data Server including pseudo-observations (e.g. EWEMBI), reanalysis (e.g. ERA-Interim) and climate seasonal forecasts (e.g.

System4) for any location in the world. The visualizeR package (Frías et al. 2018) from climate4R can also be utilized for visualization and communication of probabilistic seasonal forecasts.

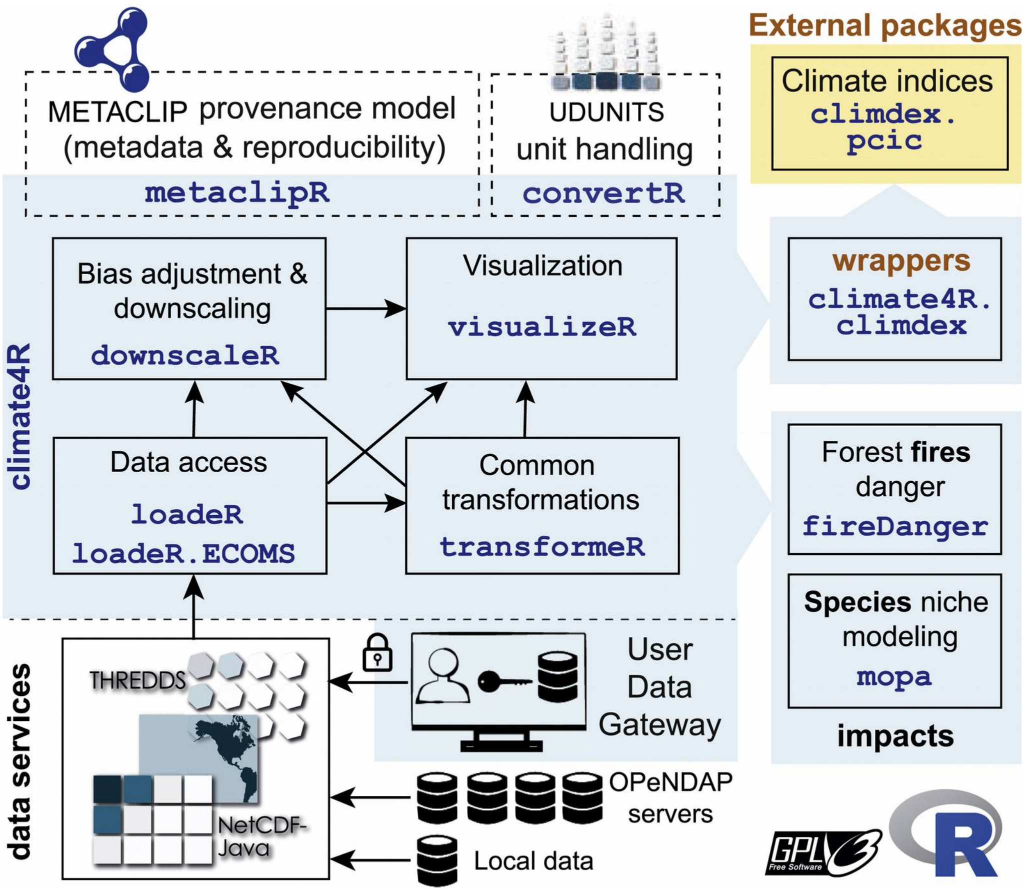

Figure 2. Schematic illustration of the climate4R framework (from Iturbide et al. 2019) consisting of three layers: (a) Data services building on NetCDF-Java and THREDDS in order to load local or remote (exposed via a THREDDS OPeNDAP service) data, and also datasets from the in-house Santander User Data Gateway (UDG); (b) The climate4R R bundle for data access and post-processing, formed by four core packages for data loading, transformation, downscaling (including bias correction) and visualization; (c) External packages, which are connected to climate4R via specific wrapper packages.

In WATExR, different R scripts have been further developed to readily produce meteorological input data in the format required for both SWAT and WET. Depending on the users' choice of seasonal forecast product, climate4R allows access to different seasonal climate forecast systems, process these seasonal forecasts into a homogeneous data format, and export a number of ensemble members that may be used to produce probabilistic predictions through the impact model chain. The different components of climate4R are freely available, and may be accessed through: https://github.com/SantanderMetGroup.

- **SWAT (Soil and Water Assessment Tool):** for simulating the water discharge, sediment and nutrient loads entering Lake Arreskov. As extreme weather events, such as extreme rainfall, may result in periodically extreme nutrient loads to lakes, a catchment model which attempts to simulate both water discharge and stream phosphorus and nitrogen loads is required. SWAT (Arnold et al. 2012) is an open source eco-hydrological model, which may be applied based on globally, and freely available GIS data, including digital elevation maps (e.g. SRTM or Aster), land cover maps (e.g. GlobCover) and soil maps (e.g. Harmonized World Soil Database). SWAT can therefore be applied to any catchment in the world. If more detailed maps are available, as is the case for Denmark, these may also be applied for producing potentially more reliable estimates of stream discharge and nutrient loads. The model is applied through a freely available QGIS plugin, and may be accessed through: swat.tamu.edu.
- **WET (Water Ecosystems Tool):** for simulating the hydrodynamics and ecosystem dynamics of Lake Arreskov. WET (Nielsen et al. 2017) is an open source QGIS plugin, which currently assume a one-dimensional domain of a lake or reservoir. It can simulate the ecosystem components that the Danish end-user has an interest in, including oxygen concentration, zooplanktivorous, benthivorous and piscivorous fish, zooplankton, zoobenthos, phytoplankton (including blue-green algae) and submerged vegetation. The development of WET was onset by the WATExR project, and it currently enables a link to the SWAT model, whereby river discharge and nutrient loads predicted by SWAT can easily be read into WET. The software is freely available, and may be accessed through: wet.au.dk.

2.1.1 Demonstration of seasonal predictions based on impact models for the Danish site

As an example of how seasonal predictions can be run through an impact model chain, we here demonstrate an ensemble run based on the System4 (S4) forecast system by the European Centre for Medium-Range Weather Forecasts (ECMWF). S4 has produced retrospective forecasts (also referred to as hindcasts) starting on the 1st of every month for the years 1981-2010. The hindcast dataset is comprised of an ensemble of 15 members. The Climate4R framework can be utilized for bias correction using observational data, such as the EWEMBI pseudo-observations or ERA-interim reanalysis data, when the time series of local observations are short or incomplete. The bias-corrected ensemble outputs can then be propagated through the impact modelling chain as if it was a real-time seasonal prediction. In this example, to simulate a real seasonal prediction situation, we combined reanalysis data (to allow impact model warmup) with seasonal prediction data. As an example of application of the workflow developed for this case study (Fig. 2) we show the results obtained for the summer of 2001 (Fig. 3 and Fig. 4); further details on seasonal forecast model skills can be found in deliverable 2.2.

From past experience with SWAT, which includes the relatively inert dynamics of soil phosphorus pools, we know that 5-10 years of model warmup/spinup may be required before the model produces good outputs for phosphorus stream loads. In this demonstration, we therefore run both the SWAT and WET tools based on the ERA-interim reanalysis data for the 10 year period January 1990 to April 2001 as model warmup, and then the following 4 months (May-August) based on the seasonal predictions from S4 (of which the first month is considered a reinitialization month, and the latter three months represent the “target season”).

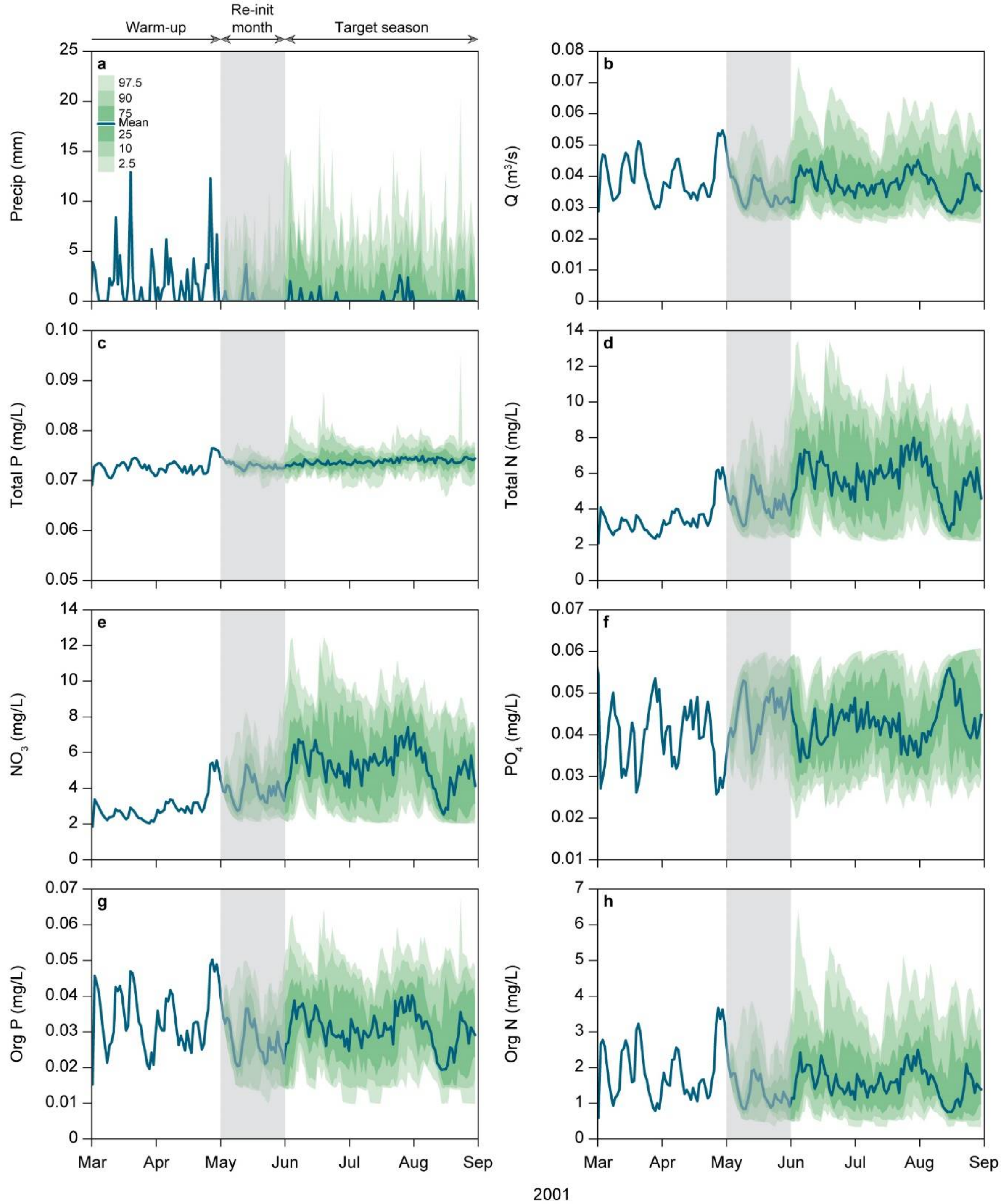

Figure 3. Demonstration of a seasonal prediction for the catchment of Lake Arreskov (output from the SWAT model), which are then read into the lake model (WET). The blue line represent the single time series output from the warmup period based on forcing by the ERA-interim reanalysis data (1991 to April 2001), and then the mean value of the 15-member ensemble based on the S4 seasonal weather prediction data. The green shaded area represents different percentiles of the prediction, derived from the ensemble.

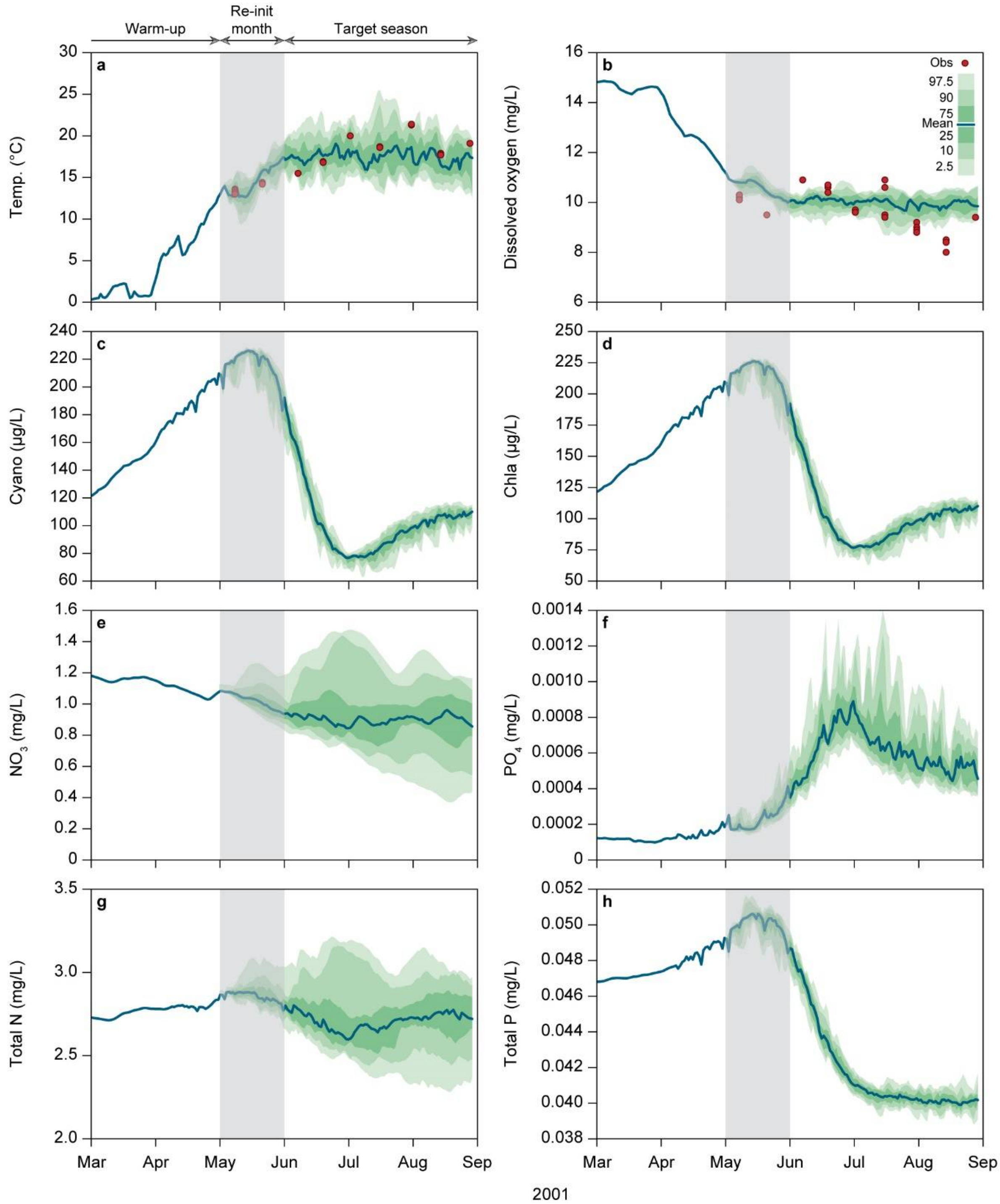

Figure 4. Demonstration of a seasonal prediction for Lake Arreskov in Denmark (output from the GOTM-FABM-PCLake model that is implemented in the WET QGIS plugin). The blue line represent the single time series output from the warmup period based on the forcing by the ERA-interim reanalysis data (1991 to April 2001), and then the mean value of the 15-member ensemble based on the S4 seasonal weather prediction data. The green shaded area represents different percentiles of the prediction, derived from the ensemble. Red dots for temperature and oxygen represent examples of actual observations from the lake.

2.2 Software workflow for Spanish site: Sau Reservoir and its catchment

The Ter river basin has an area of 1680 m² and is the main source of water for the Sau Reservoir (capacity of 165 hm3 and mean inflow of 10 m³/s), which is a recreational and water supply system for Barcelona metropolitan area (ca. 3 million people). This particular watershed was selected because there is an increasing interest, from the stakeholders and society in general that depends on water supply from this area, to attempt to have a seasonal prediction of water flows and water quality of the reservoir.

The Spanish end-user is the ATLL Concessionària de la Generalitat de Catalunya, which is the water supply company for Barcelona and the main user of the water stored in the Sau Reservoir. They would like the WATExR solutions to include:

-A friendly and useful tool to visualize and use seasonal forecasting variables related to water quality variables in the target reservoirs.
-Specifically, they want a tool to support them in making decisions under extreme climatic event conditions.
-Taking into account the common limitation of using seasonal forecasting, they would like to enable different potential scenarios on the workflow to check the system response and help them make decisions.

The Spanish end-user is interested in an impact model solution, which can readily be used to take decisions and help in the water management. Through the developer/enduser interactions, the Spanish partners have agreed on a software solution comprising mHM (mesoscale Hydrologic Model) for describing the catchment dynamics, including water discharge to Sau Reservoir, and GOTM (General Ocean Turbulence Model) for describing the dynamics within the lake (Fig. 5).

The key software components in the workflow for producing seasonal predictions for Sau Reservoir and its catchment include:

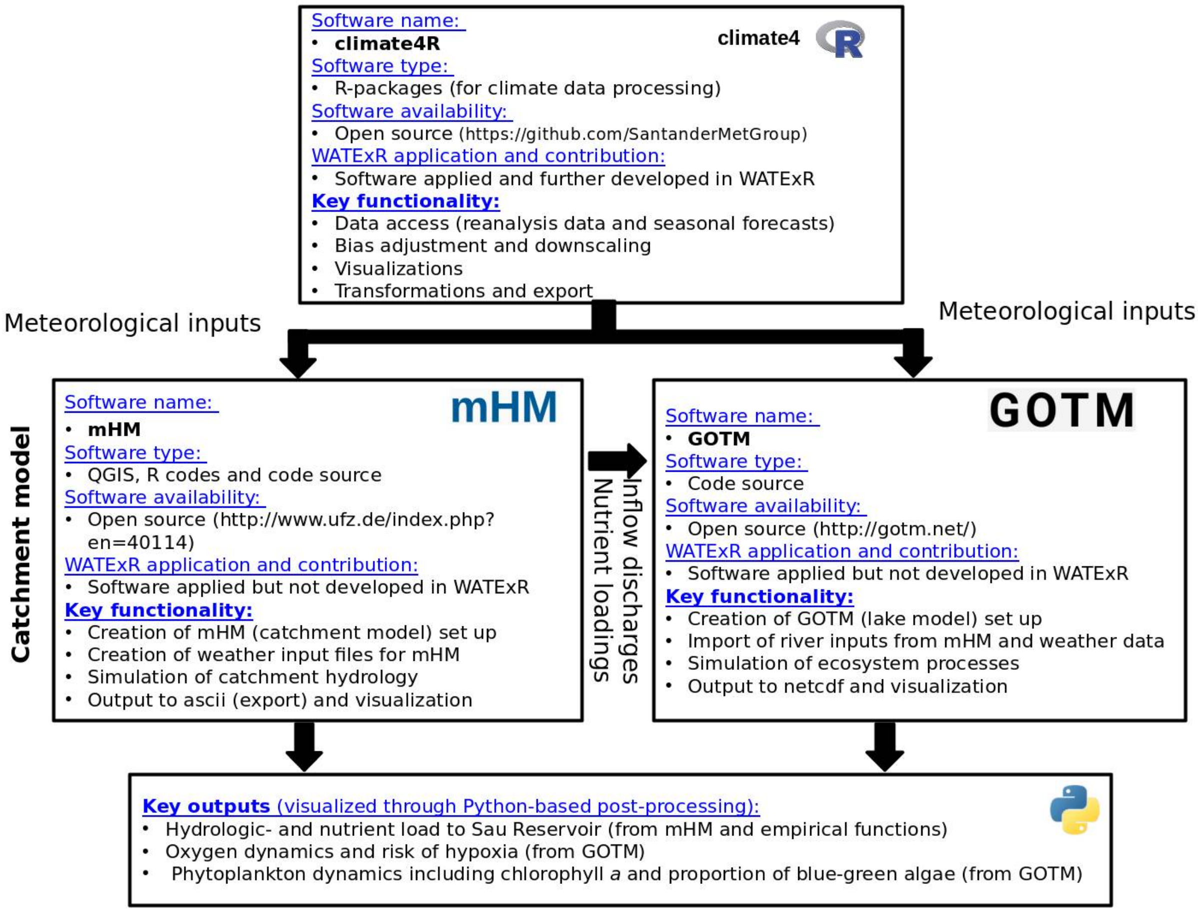

Figure 5. The workflow, and key functionality of its software components, for enabling seasonal predictions for the Sau Reservoir and its catchment.

- **climate4R:** for downloading, bias-correcting and formatting reanalysis climate data and seasonal prediction data. For more details, see Section 2.1.
- **mHM (mesoscale Hydrologic Model):** The mHM v5.9 was used to implement the hydrological simulations in the Ter river. This is a spatially distributed model (successfully tested in several watersheds around the world) with grid pixel as the main hydrological unit and a multiscale parameter regionalization approach. It has the capacity to represent the most relevant physical processes in hydrological modeling (e.g, soil moisture dynamics, infiltration and surface runoff, subsurface processes, canopy interception, snowmelt processes). Apart from being driven by meteorological variables (precipitation, temperature and potential evaporation), it also depends on land cover, leaf area index (LAI), soil and hydrogeologic maps.

- **GOTM (General Ocean Turbulence Model):** for simulating the hydrodynamics and ecosystem dynamics of Sau Reservoir. GOTM is an open source ocean model (adapted to lake), which currently assume a one-dimensional water column model for studying hydrodynamic and biogeochemical processes in marine and limnic waters. It models the state-of-the-art of the main physical processes: vertical turbulent fluxes of momentum, heat and dissolved and particulate matter.

2.2.1 Demonstration of seasonal predictions based on impact models for the Spanish site

As a demonstration and validation of how seasonal predictions may work in a longer-term perspective, we here demonstrate a collection of ensemble runs based on the EWEMBI observations data combined with the S4 forecast system by ECMWF. For every season (108 in total) in the time range (1983-2009), the following workflow was implemented for the Sau Reservoir site, to obtain hydrological (discharge) forecast data: (i) the model was warmed up with 5 years data using EWEMBI (pseudo-observations), (ii) then a simulation (reinitialisation) using one month previous to the target season was run using EWEMBI data, and finally (iii) the three months of the target season were simulated using S4 and CFSv2 (seasonal weather prediction data).

For example, to simulate the boreal autumn of 2005: we used data from September 2002 to July 2005 from EWEMBI (warm-up) + August 2005 from EWEMBI (reinitialisation) + September 2005 to November 2005 from S4 and CFSv2. In a post-processing step, the three months of the target season were extracted for each of the 108 simulated target seasons, and then merged into one time series plot (Fig. 6).

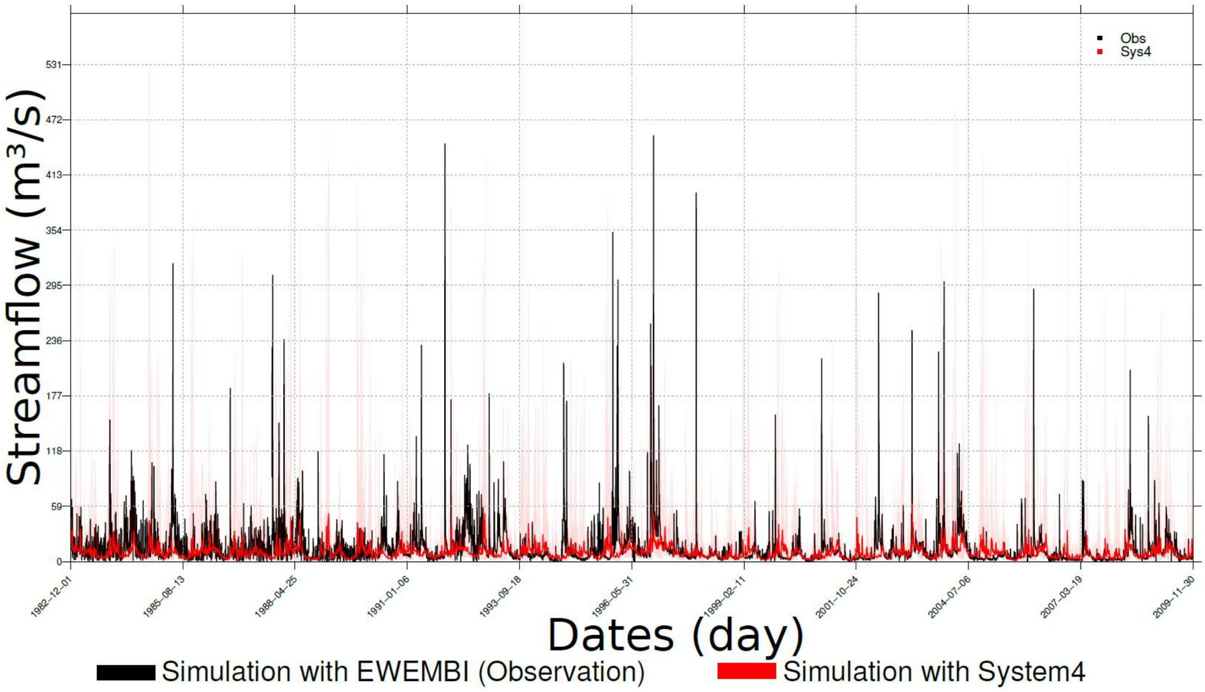

Figure 6. Demonstration of simulated discharge going into the Sau Reservoir (output from the mHM catchment model). The black line represents the simulated discharge when using EWEMBI data as forcing, while the red line represents the mean of the 15-member ensemble based on the S4 seasonal prediction data. The red shaded area represents the total span of the ensemble.

2.3 Software workflow for Irish site: Burrishoole catchment

The Burrishoole catchment (~100 km^2) drains into the Northeast Atlantic through Clew bay on the west coast of Ireland (53° 56'N, 9° 35' W). Burrishoole contains approximately 474 ha of wetted area (449 ha lacustrine, 25 ha fluvial), which has been the focus of intensive ecological monitoring since the 1970s.

The Irish end-user, the Marine Institute (MI), are responsible for monitoring three diadromous fish species (European eel (*Anguilla anguilla*), Atlantic salmon (*Salmo salar*) and sea trout (*Salmo trutta*)). To facilitate monitoring, fish trapping facilities at the only two freshwater outflows from the catchment have been in place since 1970, which has afforded the Marine Institute with a multi-decadal complete census of daily downstream (mature eel, and juvenile salmon and sea trout smolts) and upstream (mature salmon and sea trout) fish movements.

Under the framework of WATExR, the MI would like build on previous work to further understand the timing of three migration events that are closely associated with environmental conditions: (i) catadromous silver eel spawning migration (autumn); (ii) salmon smolt seaward migration (spring); and (iii) sea trout smolt seaward migration (spring).

Specifically, the MI would like to further understand:

- The extent to which daily counts of migrating fishes are predictable; and, by extension, the extent to which seasonal meteorological predictions provide model forcing/driving data that are useful for predicting migration phenology (e.g., in terms of start, peak and end date of migration periods).

The Irish partners have agreed on a workflow to deliver seasonal fish migration phenology forecasts for Burrishoole, which comprises three primary software components (Fig. 7):

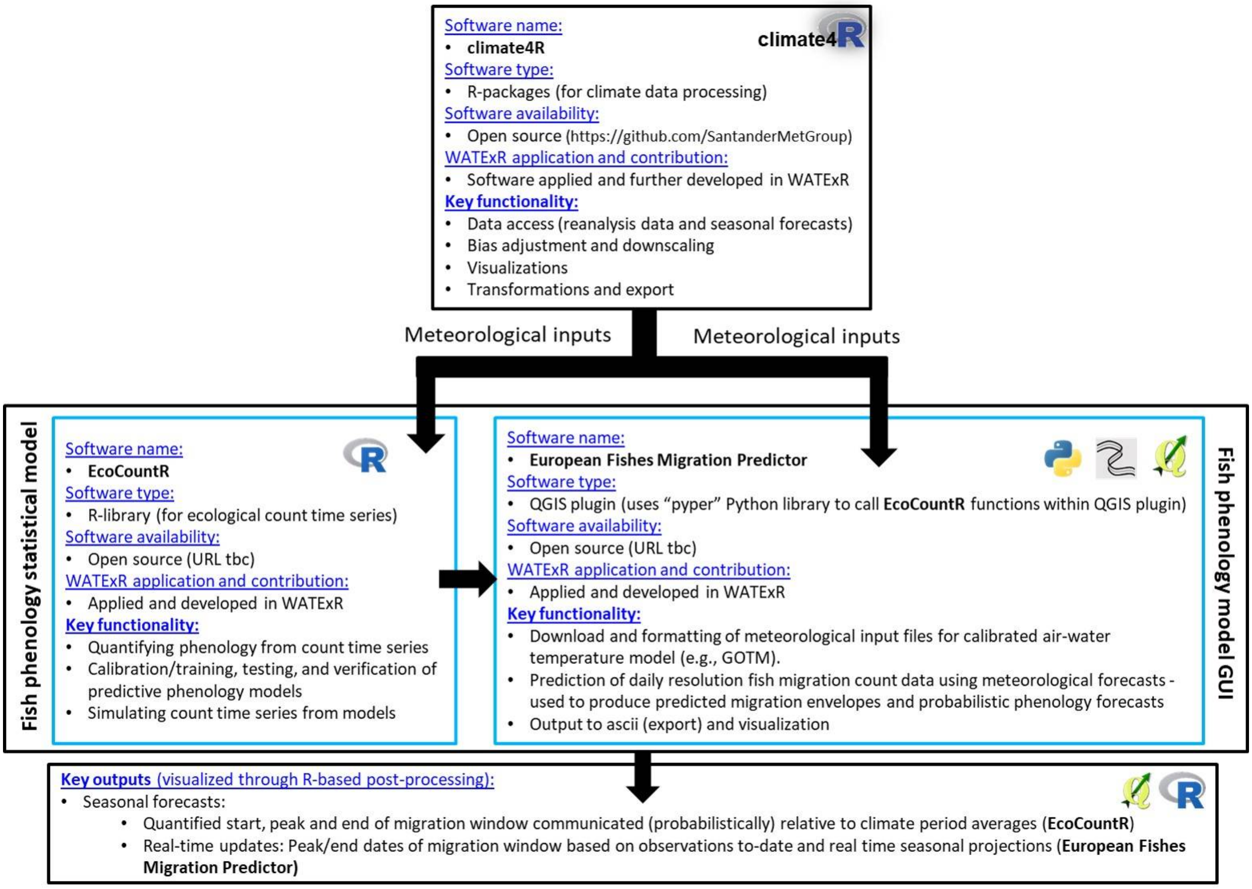

Figure 7. The workflow and the key functionality and outputs of its software components for enabling seasonal predictions for fish migration phenology at the Burrishoole catchment.

- **climate4R:** for downloading, bias-correcting and formatting reanalysis climate data and seasonal prediction data. For more details, see Section 2.1.
- **EcoCountR:** EcoCountR is an R based library of functions being developed by the Irish partners (R Core Team, 2018) and will comprise a selection of data processing and statistical analyses functions for the probabilistic forecasting of ecological time series with a current focus on the migration phenology of diadromous fishes. EcoCountR will allow end-users to: (i) quantify associations between environmental conditions and daily fish counts; (ii) quantify migration phenology (start, peak and end dates of migration period) from a time series, and (iii) predict migration phenology from a meteorological forecast at the daily time step and illustrate probabilistic

predictions from ensemble seasonal projections (for modelling workflow and details of other extensions/functionality to EcoCountR (e.g., water temperature modelling through GOTM and/or GR4J) and R packages used in the development of EcoCountR see WATExR D2.1)

- **European Fishes Migration Predictor (EFMaP):** EFMap is a QGIS (QGIS Development Team, 2019) plugin that allows end users to input meteorological (seasonal) predictions to forecast the migration phenology of diadromous fishes via an under-the-hood R script. The Python based QGIS plugin communicates with R through Python's pyper module with the aim of delivering a climate4R-EcoCountR modelling workflow. The forecast delivered by the plugin will be illustrated through a series of plots that will tell the user whether migration phenology (in terms of start, peak and end of migration period/waves) are expected to occur earlier, later or no different to the long term average. An indication of forecast uncertainty, specifically "trust" (based on hindcast simulation performance) will be emphasized.

2.4 Software workflow for Norwegian site: Lake Vansjø and its catchment

The Norwegian study site is Lake Vansjø and its catchment, referred to as Morsa. Morsa lies in south-eastern Norway, in one of the most agricultural areas of the country. The Norwegian end-user is the Morsa river basin authority, who are responsible for EU Water Framework Directive (WFD) implementation in the catchment and wider area, and are a partnership organisation representing many interested parties in the catchment. Key challenges of interest to the end-user to be addressed in WATExR include:

- Compliance with the WFD (i.e. achieving good or better ecological status), with a focus on:
    - In-lake concentrations of total P (TP) and phytoplankton abundance (using biovolume and chlorophyll-a as proxies)
    - Phytoplankton trophic index (PTI), an index of plankton species composition with respect to eutrophication status
    - Abundance of cyanobacteria
- Risk of poor bathing water quality due to potentially toxic cyanobacterial blooms
- Advance warning of whether the season is likely to be particularly dry or wet, to inform lake water level regulation
- Drinking water quality, in particular lake water colour.

The Norwegian partners have agreed on a workflow to produce seasonal predictions for Lake Vansjø, which comprises the following software components (summarised in Fig. 8):

- **climate4R:** for downloading, bias-correcting and formatting reanalysis climate data and seasonal prediction data. For more details, see Section 2.1.

- **BN (a Bayesian Network):** A Bayesian Network is a probabilistic graphical model that represents a set of discretised variables and their conditional probabilities in a casual network. In Lake Vansjø, the BN represents the quantitative relationships between meteorological data, catchment and lake variables affecting variables of interest (e.g. discharge and nutrient fluxes to the lake, nutrient concentrations within the lake, water temperature, time of year, etc.), and the variables related to management targets (WFD status, cyanobacterial bloom and water colour). The structure of the BN is developed according to expert knowledge and analysis of observed data. BN parameters (the conditional probabilities) are then set by 'training' on observed data or, where this is lacking or sparse, simulated data from two process-based models, SimplyP (a catchment hydrology, sediment and nutrient model) and MyLake (a lake model). Given a seasonal climate forecast, the BN can be used to predict lake variables of interest in a probabilistic way, consistent with the probabilistic nature of the seasonal climate forecasts. The underlying probabilities may be updated as more observed data becomes available, meaning the performance of the forecasting system can improve through time.

The model is applied through a freely-available QGIS plugin. This plugin interacts with the climate4R package to download, bias correct and reformat seasonal forecast data. It then runs the BN to produce forecasts for the coming season. This forecast information is presented in a user-friendly way, using layout and charts agreed on between co-developers.

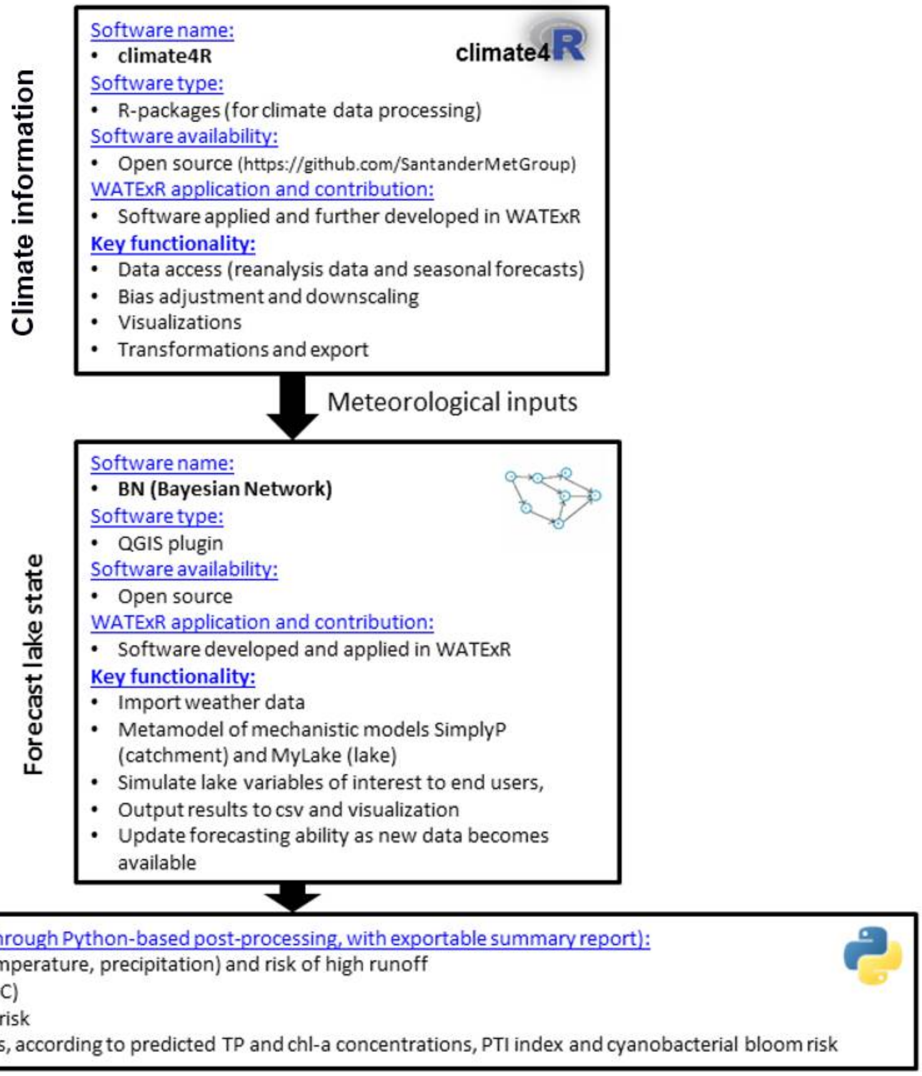

Figure 8. The workflow, and key functionality of its software components, for enabling seasonal predictions for Lake Vansjø and its catchment.

2.5 Software workflow for Swedish site: Lake Erken

The Swedish Lake Erken site plays a key role as an “outreach” and ISIMIP site of the WATExR project. The end-user target is mainly students, who will visit the Erken Laboratory. This lab focuses on the long-term monitoring of water quality, climate effects on aquatic systems, circulation of nutrients, and population and community dynamics in lakes. An objective of the WATExR project is to implement several of the ISIMIP lake model case studies and climate scenarios into the WET QGIS plugin (Fig. 9). This will be then available for students who visit the Lake Erken lab, and allow them to work with models in an entry-level and accessible way, and also to get an understanding of how climate scenarios may impact lakes in the long-term.

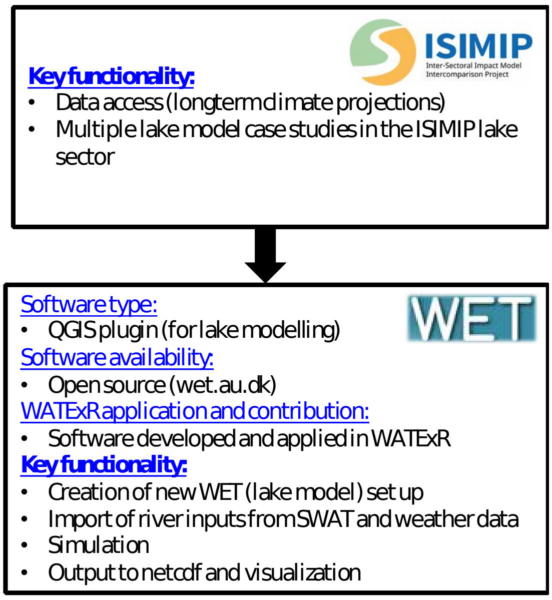

Figure 9. The workflow, and key functionality of its software components, for enabling seasonal predictions for Lake Erken.

The workflow for the Swedish site will therefore be:

- **ISIMIP:** downloading already formatted climate data and lake models of the ISIMIP lake sector.
- **Water Ecosystems Tool (WET):** Implementation of lake models and climate scenarios into WET. For more details on WET, see Section 2.1.

2.6 Software workflow for German site: Wupper reservoir and its catchment

The Wupper Reservoir is located in on the river Wupper, whose catchment is a part of the Rhine river catchment. The reservoir serves as a flow controlling and flood protection system as well as a recreational area. The reservoir's upstream catchment area of 212 km^2 is highly populated and the river upstream of the reservoir is regulated through a network of reservoirs on both the Wupper and its tributaries. It is characterized as slightly eutrophic and dimictic, its water level fluctuates widely (Scharf, 2008). It receives treated sewage water as well as effluents from combined sewer overflows.

The German end user is the Wupperverband, who is responsible for the management of the catchment of the Wupper River and operates 14 reservoirs in total.

Key challenges of interest to the end-user to be addressed in WATExR include:

- Developing a seasonal prediction toolset for optimal management decision making especially for the cases of extreme events.
- Providing discharge supplement of a sufficient quality to the downstream river in times of low discharge in order to dilute downstream WWTP effluents and maintain benthic communities
- Prediction and, if possible, avoidance of cyanobacterial blooms, which largely occur during hot summers and large water level drawdowns → avoidance of too severe water level drawdowns during times of low water availability through adaptive water transfers (see below)
- Exploiting the upstream reservoir network in order to optimize the management water quantity as well as water quality of Wupper Reservoir (coupled reservoir systems management)

The German end user is interested in optimizing the reservoir network management by implementing seasonal forecasts in order to improve decision making, particularly during extreme events and with respect to projected future changes within the Wupper catchment. The German partners have agreed on a workflow solution for an integrated modeling of the reservoir/catchment system that comprises the following software components, presented in (Fig. 10).

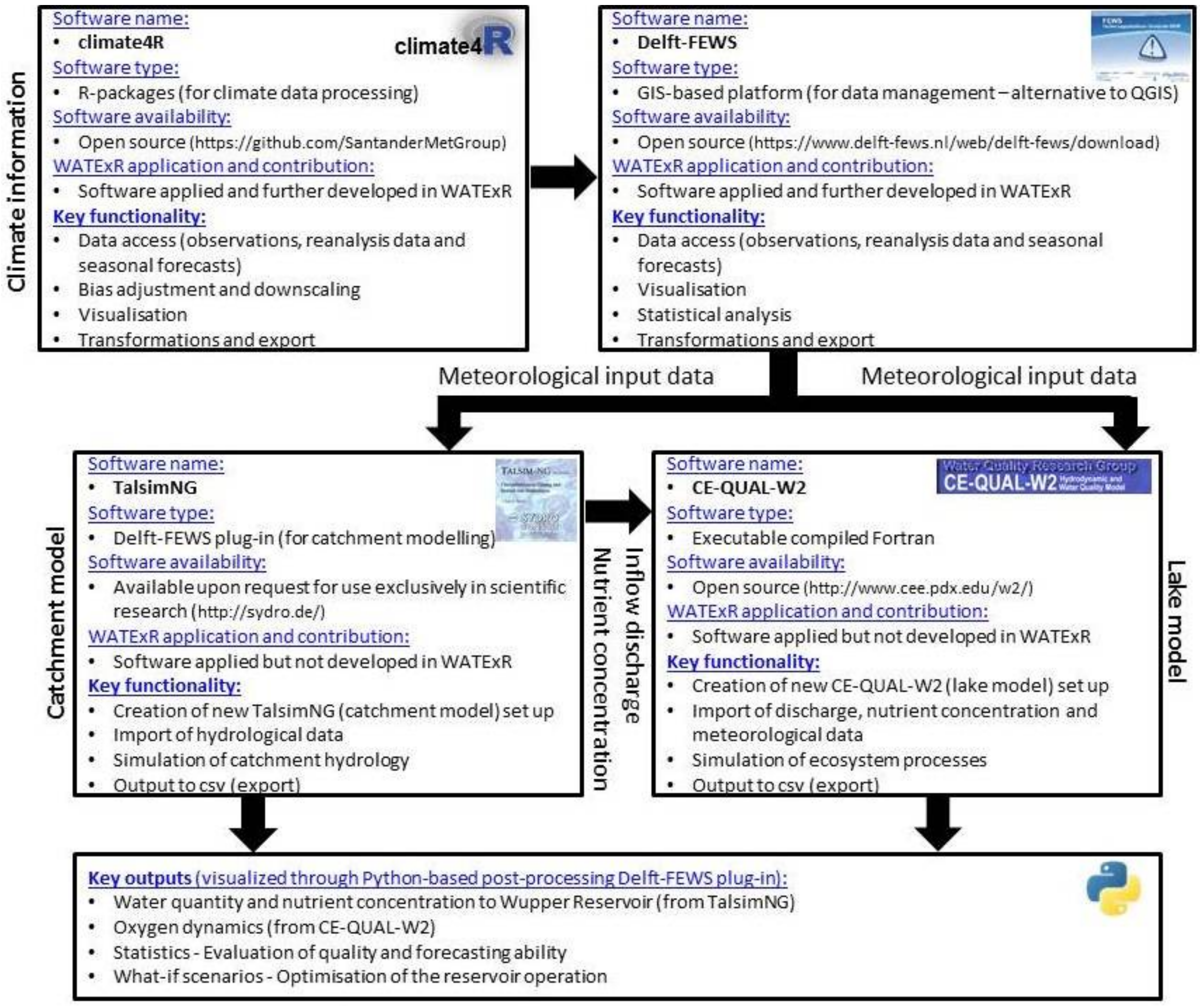

Figure 10. The workflow, and key functionality of its software components, for enabling seasonal predictions for Wupper reservoir and its catchment.

- **climate4R**: for downloading, bias-correcting and formatting reanalysis climate data and seasonal prediction data. For more details, see Section 2.1.
- **Delft-FEWS (Delft-Flood Early Warning System):** Delft-FEWS is a time series management platform with a GIS interface, alternative to QGIS, already in operation in Wupperverband. An important advantage of Delft-FEWS is the combination of time series (temporal component) and GIS interface (spatial component). Delft-FEWS is an open source, script based software and enables working with climate, water quality and hydrological data of various

formats (NetCDF, GRIB, Radar data, csv etc.). Additionally, it contains modules of both water quantity and water quality data analysis. Delft-FEWS integrates handling (retrieving, storing and processing) of datasets with simulation models in an operational manner. The integration of simulation models within the Delft-FEWS platform takes places through model plug-ins. Within WATExR, Delft-FEWS is the platform that connects the hydrological model, the lake model, and the seasonal forecasting time series.

- **TALSIM-NG (TALSIM Next Generation):** for simulating the catchment and the reservoir network and providing the lake model with hydrological inflow data and nutrients fluxes. The inflow reaching the reservoir is regulated through a network of reservoirs upstream, where some of the reservoirs supply the others in the cases of necessity. These reservoir-borne flows are operated via a set of operational conditions and these rules cannot be described through a lumped hydrological catchment model but require a tailored model like TALSIM (SYDRO, 2016). TALSIM-NG includes a runoff-model for the catchment hydrology and a dynamic reservoir volume model for simulating coupled reservoir systems.
  The software is operating standalone through a Delft-FEWS plug-in. TALSIM-NG is a closed source software. However, the executable file, the file containing Metadata as well as the user interface of TALSIM-NG are made available for the WATExR research project. The use of the TALSIM-NG software is limited to research projects only and requires prior agreement with SYDRO Consult (http://sydro.de/).

- **CEQUAL-W2:** for simulating the hydrodynamics and ecosystem dynamics within Wupper Reservoir. CEQUAL-W2 is a two dimensional, laterally averaged model. It has the advantage of simulating the complex longitudinal gradients and dynamics within canyon-like reservoir. It models the main hydrophysical processes, biogeochemical cycles of NPC and Si, as well as the planktonic food web and algal dynamics.

2.7 Software workflow for Australian site: Mt. Bold Reservoir and its catchment

The Australian study site is Mt. Bold reservoir located in the Lofty Ranges in South Australia. The Australian end-user is the South Australian Water Corporation which would like the WATExR solutions to address:

- Level of water within the reservoir
  - Water is pumped from the Murray River to prevent levels of water getting too low and the pumping of this water is a large cost to their operations
  - Supplies water to the citizens of Adelaide
- Concentrations of phosphorus in the outtake (i.e. the bottom)
  - The Happy Valley reservoir downstream experiences algal blooms and this is where the drinking water treatment plant is located

The Australian end-user is interested in a user-friendly interface that allows them to switch between lake and river models to assess the forecasts along the model chain. From interactions with the stakeholder they have agreed on using a program based in R but presented within a QGIS plugin to enable spatial interactions (Fig 11).

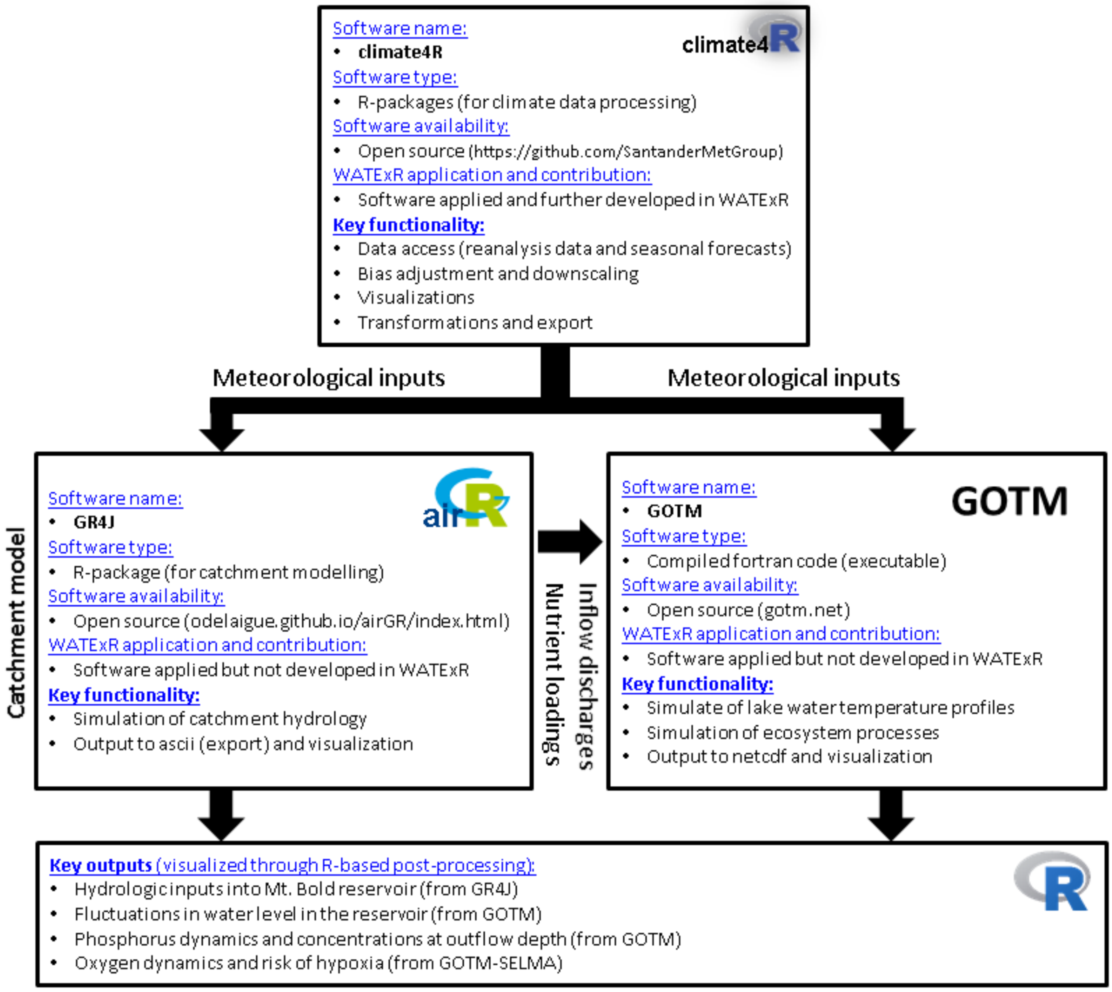

Figure 11. The workflow, and key functionality of its software components, for enabling seasonal predictions for Mt Bold reservoir and its catchment.

The key software components in the workflow for producing seasonal predictions for Mt. Bold and its catchment include:

- **climate4R:** for downloading, bias-correcting and formatting reanalysis climate data and seasonal prediction data. For more details, see Section 2.1.
- **GR4J:** for simulating the water discharge entering Mt. Bold. As extreme weather events, such as extreme rainfall, may result in periodically extreme discharges to lakes, a catchment model which attempts to simulate water discharge is required (Perrin *et al.*, 2003). GR4J is openly available as part of the airGR package for R (Coron *et al.*, 2017) or as an Excel spreadsheet from

its website (https://webgr.irstea.fr/en/modeles/journalier-gr4j-2/fonctionnement_gr4j/) . It a simple lumped hydrological model based on four parameters and has been used for a variety of different hydrological regimes (Crochemore *et al.*, 2017; Santos *et al.*, 2018).

- **GOTM (General Ocean Turbulence Model):** for simulating the hydrodynamics and ecosystem dynamics of Mt. Bold reservoir. GOTM is an open source one-dimensional domain of a lake or reservoir (Burchard et al., 2006). It can be coupled with FABM (Framework for Aquatic Biogeochemical Models) to allow it to simulate biogeochemical processes within the water column dynamically (Bruggeman & Bolding, 2014). This can be used to simulate the chemical concentrations that the end-used has an interest in i.e. phosphorus. The source code for both GOTM and FABM is freely available on GitHub: https://github.com/gotm-model and https://github.com/fabm-model/fabm

3. References

1. Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., Van Griensven, A., Van Liew, M.W., Kannan, N., Jha, M.K. 2012. SWAT: Model use, calibration, and validation. Transactions of the ASABE. 55(4):1491-1508.
2. Bruggeman, J., & Bolding, K. (2014). A general framework for aquatic biogeochemical models. *Environmental Modelling and Software*, *61*, 249–265. https://doi.org/10.1016/j.envsoft.2014.04.002.
3. Burchard, H., Bolding, K., Kühn, W., Meister, A., Neumann, T., & Umlauf, L. (2006). Description of a flexible and extendable physical-biogeochemical model system for the water column. *Journal of Marine Systems*, *61*, 180–211. https://doi.org/10.1016/j.jmarsys.2005.04.011.
4. Coron, L., Thirel, G., Delaigue, O., Perrin, C., & Andréassian, V. (2017). The suite of lumped GR hydrological models in an R package. *Environmental Modelling and Software*, *94*, 166–171. https://doi.org/10.1016/j.envsoft.2017.05.002.Crochemore, L., Ramos, M. H., Pappenberger, F., & Perrin, C. (2017). Seasonal streamflow forecasting by conditioning climatology with precipitation indices. *Hydrology and Earth System Sciences*, *21*(3), 1573–1591. https://doi.org/10.5194/hess-21-1573-2017.
5. Frías, M.D., Iturbide, M., Manzanas, R., Bedia, J., Fernández, J., Herrera, S., Cofiño, A.S., Gutiérrez, J.M. (2018). An R package to visualize and communicate uncertainty in seasonal climate prediction. *Environmental Modelling & Software*, 99, 101-110. https://doi.org/10.1016/j.envsoft.2017.09.008
6. Iturbide, M., Bedia J., Herrera, S., Baño-Medina, J., Fernández, J., Frías, M.D., Manzanas, R., San-Martín, D., Cimadevilla, E., Cofiño, A.S., Gutiérrez, J.M. 2019 The R-based climate4R open framework for reproducible climate data access and post-processing. *Environmental Modelling & Software*, 111, 42-54.
7. Nielsen, A., Bolding, B., Hu, F., Trolle, D. 2017. An open source QGIS-based workflow for model application and experimentation with aquatic ecosystems. *Environmental Modelling & Software*, 95, 358-364.
8. Nielsen, A., Trolle, D., Olesen, J.E., Bjerring, R., Søndergaard, M., Janse, J.H., Mooij, W.M. and Jeppesen, E. 2014. Effects of changes in climate and nutrient loading on the water quality of shallow lakes assessed by ensemble model runs. *Ecological Applications,* 24(8): 1926-1944.

9. Perrin, C., Michel, C., & Andréassian, V. (2003). Improvement of a parsimonious model for streamflow simulation. *Journal of Hydrology*, *279*(1–4), 275–289. https://doi.org/10.1016/S0022-1694(03)00225-7.
10. QGIS Development Team, 2019. QGIS Geographic Information System. Open Source Geospatial Foundation Project.
11. R Core Team, 2018. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
12. Santos, L., Thirel, G., & Perrin, C. (2018). Continuous state-space representation of a bucket-type rainfall-runoff model: a case study with the GR4 model using state-space GR4 (version 1.0). *Geosci. Model Dev*, *11*, 1591–1605. https://doi.org/10.5194/gmd-11-1591-2018.
13. Scharf, Wilfried. 2008. Development of the fish stock and its manageability in the deep, stratifying Wupper Reservoir. *Limnologica - Ecology and Management of Inland Waters*, 38(3-4), 248-257.
14. SYDRO, 2016. TALSIM-NG (Talsim Next Generation) – River Basin Modelling and Water Resources Modelling. SYDRO Consult GmbH, May 2016. http://sydro.de/sydro/wp-content/uploads/2017/07/2016_05_02_TalsimNG_brochure_en.pdf