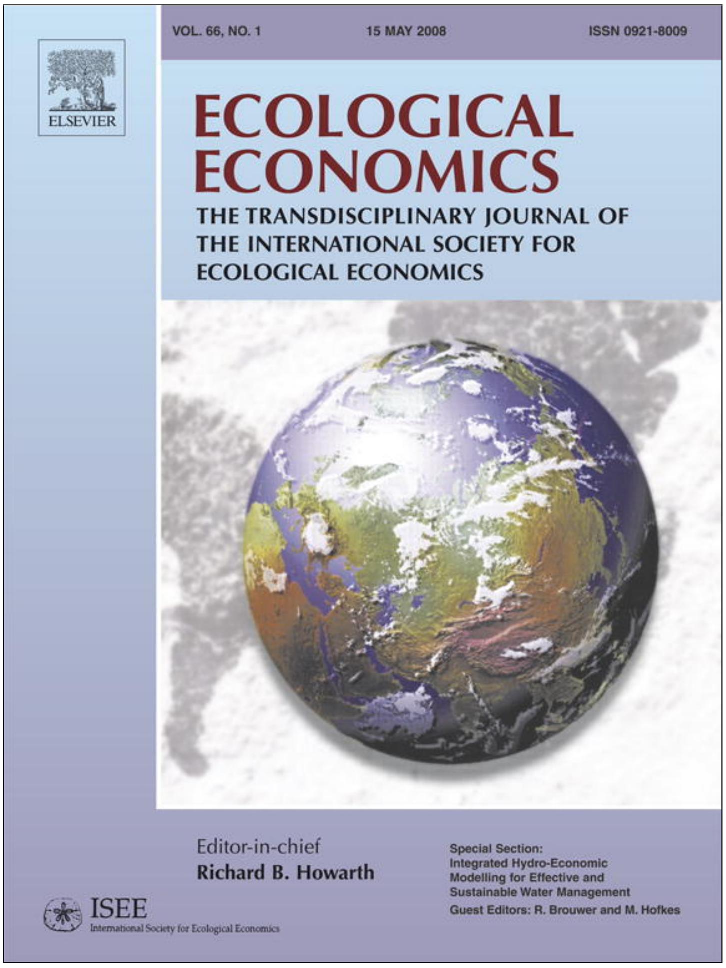
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Integrated hydrodynamic and economic modelling of flood damage in the Netherlands

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ABSTRACT

This paper presents a model developed in the Netherlands for the estimation of damage caused by floods. The model attempts to fill the gap in the international literature about integrated flood damage modelling and develop an integrated framework for the assessment of both direct hazard-induced damages and indirect economic damages such as the interruption of production flows outside the flood affected area, as well as loss of life due to flooding. The scale of damage assessment varies from a specified flood-prone area in a river basin or a coastal region to the country's entire economy. The integrative character of the presented model is featured by the combination of information on land use and economic data, and data on flood characteristics and stage-damage functions, where the geographical dimension is supported by modern GIS to obtain a damage estimate for various damage categories. The usefulness of the model is demonstrated in a case study estimating expected flood damage in the largest flood-prone area in the Netherlands.

1. Introduction

The catastrophic flooding in the United States after hurricane Katrina in late august 2005 illustrated the destructive power of flood events. Apart from the human suffering, this event caused enormous economic damage in the states of Louisiana and Mississippi. The preliminary estimate of total direct damages associated with this catastrophe is $90 billion (USACE, 2006). Especially the city of New Orleans was severely affected. An estimate of direct property and infrastructure damage due to flooding was published in a report in June 2007 by the Interagency Performance Evaluation Team (IPET, 2007). The report conveyed that flood damage to residential property in New Orleans is estimated at US$16 billion and damage to public structures, infrastructure and utilities (like roads, railroads, water defences, electricity network, drainage etc.) at US$7 billion. A year after the devastating hurricane rushed through the city, New Orleans has got merely a half of its pre-calamity population back (see Liu et al., 2006), and about 66% two years after the disaster. The return of the population to the city is yet accompanied by low business confidence and thus a slow pace of business activity revival reflected through high unemployment rates. While 67% of the houses had flood insurance, payments on the claims are another problem (Kok et al., 2006).

Hurricane Katrina illustrates the extreme vulnerability of modern societies situated in flood-prone areas when exposed to a flood hazard. It makes one think of other low-lying developed urban and industrial areas similar to New Orleans like the coastal areas of the Netherlands and Japan that also have a high potential to suffer extensive damages from flooding. For such areas it is important to have insight in the possible damages to support decision-making regarding flood management strate-

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gies and the determination of appropriate protection levels. In this paper, we will focus on an integrated modelling approach to flood disaster modelling and the impacts of floods on life and livelihood. The main objective of this paper is to present and demonstrate the integrated hydrodynamic and economic model developed in the Netherlands to predict and assess the damage due to catastrophe flooding. First we will provide a brief description in Section 2 of the particular situation in the Netherlands with regard to water management and flood protection on which the logic of our model is based. Next in Section 3 a number of conceptual matters will be addressed connected to damage classification and modelling based on a review of selected international literature. The choice of the modelling approach requires special attention. In Section 4, we will present a first effort at building an integrated model for the assessment of economic flood damage in the Netherlands, which is essentially based on the use of geographically related information in damage modelling. The estimation of direct damage costs is developed furtherst, but of particular interest is also the modelling of the indirect economic damage and the estimation of the number of potential fatalities. In Section 5, we will present an example of the actual as well as potential application possibilities. Concluding remarks and recommendations are given in Section 6.

2. Flood management in the Netherlands

We will first of all briefly describe the specific situation in the Netherlands with respect to flood protection, as this has been an important drive behind the modelling philosophy and the choice for a suitable modelling framework. More than half of the country is situated below sea level and, if unprotected, would be permanently threatened by flooding from the sea, rivers and lakes (see Fig. 1).

The flood-prone areas in the Netherlands are divided in so-called dike ring areas (see Fig. 1). These are the areas protected against floods by a series of water defences (dikes, dunes, hydraulic structures) and high grounds. For most dike ring areas the land level is below the water level. Safety standards have been derived for each of the dike ring areas. The fundamental principles underlying the determination of these standards were identified by the Delta Commission. This Commission was installed to investigate the possibilities of a new approach towards flood protection after the 1953 flood disaster, which caused major damages in the south-western part of the country, and the killing of over one thousand people. The Commission came up with proposals for new flood defence works and new safety standards for the entire country. van Dantzig (1956) developed a general formula for the optimal level of flood protection through dikes, requiring investments at regular intervals. His formula gives a fixed exceedance probability after each investment in the relevant safety structure, i.e. the probability that the water level exceeds the top of the dike, resulting in overflow and breaching of the dike and thus flooding of the land behind the dike. A so-called design level with a certain exceedance probability is used to express the required height of the dike. The current design criteria and the safety evaluation of flood defences are based on these design levels. The safety levels of

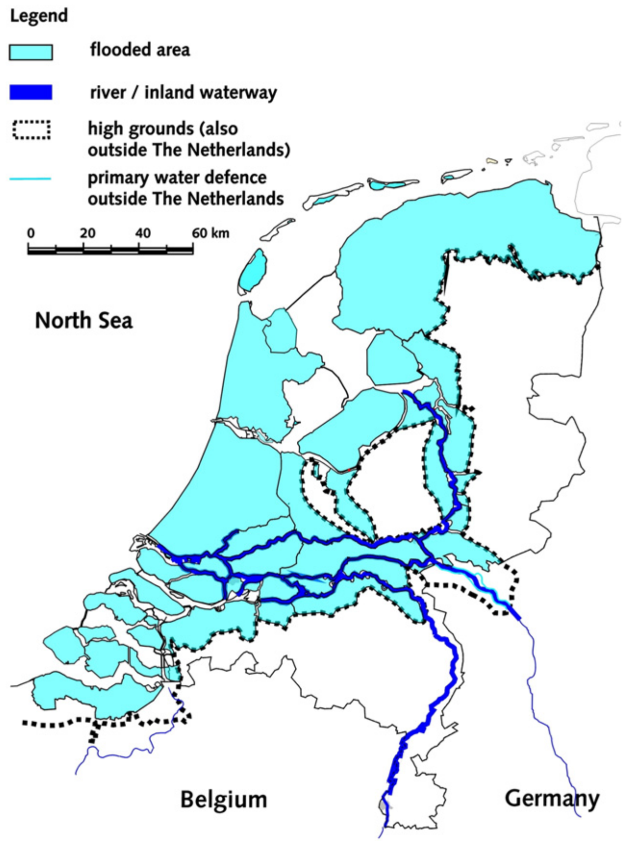

Fig. 1 – Flood-prone areas in the Netherlands.

flood defences per dike ring area are laid down in the Flood Protection Act of 1996. The height of these standards depends on the economic value of the area and the source of flooding (coast or river). For coastal areas, design levels have exceedance frequencies of 1/4000 per year and 1/10,000 per year. For the river basins the safety standards are set at 1/1250 per year and 1/2000 per year. Some smaller dike ring areas in the Meuse river basin in the south-east of the country have a safety standard of 1/250 per year.

Most of the economic values in the Netherlands are located in the low-lying western part of the country, which is also the most flood-prone part. In these areas, failure of one of the elements in the flood defence system will most likely lead to the flooding of large parts of the dike ring area from the rivers Rhine and Meuse, the North Sea and the big lake in the centre of the country, the IJsselmeer. A serious flood in this part of the Netherlands thus would mean “something very big”, i.e. a disaster with severe consequences for the whole country. Here, we may think of an event similar in scale to that of Katrina (Kok et al., 2006).

The current safety standards have mostly been derived in the 1960s. Since then, the population and economic value in the dike ring areas have grown enormously. A recent review of the flood defence policy (RIVM, 2004) concluded that these standards are no longer proportional to the protected economic and societal values. In addition, flood protection policy mainly focuses on the prevention of floods by means of flood defence works. More recently, more attention is paid to the (reduction of the) consequences of flooding. In connection to that, also the concept of risk has received renewed attention in the Netherlands (Brouwer and Kind, 2005).

The concept of risk is a product of probability and impact, consequence, or damage and requires that attention is paid to both its components, i.e. the probability of flooding *and* the consequences of flooding. These developments imply that more attention is also given to the analysis of flood damage. In this context, the current paper focuses on some of the basic building blocks for what can be seen as an integrative (modular) approach to flood damage modelling in the direction of flood risk management.

3. Classification and modelling of damage

Discussing catastrophic flooding on a large scale, it is important to keep in mind that a major flood in a modern economy like the Netherlands is expected to bring about a whole gamut of consequences. In Table 1 we provide a classification of various types of damages characterising flood events. We make a distinction between direct damages inside the flooded area and indirect damages that occur outside the flooded area. Another distinction is made between tangible damages that can be priced, and intangible damages for which no market prices exist.

Table 1 – Different dimensions of flood damages

	Tangible and priced	Intangible and unpriced
Direct	• Residences	• Fatalities
	• Capital assets and inventory	• Injuries
	• Business interruption (inside the flooded area)	• Inconvenience and moral damages
	• Vehicles	• Utilities and communication
	• Agricultural land and cattle	• Historical and cultural losses
	• Roads, utility and communication infrastructure	• Environmental losses
	• Evacuation and rescue operations	
	• Reconstruction of flood defences	
	• Clean up costs	
Indirect	• Damage for companies outside the flooded area	• Societal disruption
	• Adjustments in production and consumption patterns outside the flooded area	• Psychological traumas
	• Temporary housing of evacuees	• Undermined trust in public authorities

The spectrum of consequences or rather damages that a flood brings about includes economic, political, social, psychological, ecological and environmental damages, all of which are often intertangled in a complex network of modern societies. Each of them alone cannot represent an intricate disaster phenomenon, rather all of them together contribute to the compound picture of disaster consequences. In fact, each of the mentioned damage dimensions needs a model of its own. To get a good overview of the variety of disaster effects due to catastrophic flooding in a country like the Netherlands, where a substantial part of the highly industrialised economy becomes dysfunctional, an integrated framework is required that enables the inclusion of various types of complementary models and the interpretation of model results in a consistent manner (Brouwer and van Ek, 2004). In the Netherlands separate approaches exist focusing on the estimation of physical damage (Kok et al., 2005), environmental damage (Stuyt et al., 2003), loss of life (Jonkman and Kelman, 2005; Jonkman, 2007), public health impacts (Ahern et al., 2005), and economic damage (van der Veen et al., 2003; Steenge and Bočkarjova, 2007). An integrated, unifying approach is missing.

One of the aspects that we shall concentrate on in this paper is economic damage modelling and assessment. Here, a number of issues surface. There is a substantial body of international literature that provides evidence of extensive expertise in the field of damage estimation. However, experts and academics disagree about the methods and models to be applied. First of all, numerous definitions of damage exist (see for example Cochrane, 2004 or Rose, 2004). The division of damage into direct and indirect, and tangible and intangible in Table 1 is commonplace, but interpretations and delineations of what is considered a direct and indirect impact differ. Second, various perspectives exist regarding damage appraisal, such as financial and economic valuation based on market values or imputed values accounting for the depreciation of assets (based on historical values or replacement values),[1] while variation is also found regarding the scale of analysis, be it micro-, meso-or macro-level (see also Messner et al., 2006). Moreover, varying temporal and spatial scales may be applied in practice when modelling flood damage and damage estimates may be associated with considerable uncertainty (Merz et al., 2004).

Direct damages associated with the physical impacts of a hazard are generally estimated by what is referred to as unit damage functions or stage-damage functions, which are conceptually similar to dose–response functions or fragility curves used in other disciplines. In the case of flooding, damage functions are determined using a specified relationship between flood characteristics (usually depth) and the extent of economic damage. The estimation of direct physical damages involves two related steps. The first is the estimation of structural damages to objects, such as buildings (e.g. Kelman and Spence, 2004), while the second step is the monetisation or 'pricing' of these physical damages. Stage-damage curves were first proposed in the USA in the 1960s (White, 1964; Kates, 1965). Since then methods for flood damage estimation have been developed in several other countries, see for example Penning-Rowsell and Chatterton (1977), Parker et al. (1987), Dutta et al. (2003). Most stage-damage functions include water depth as the main determinant of direct damage. Kreibich et al. (2005) and Thieken et al. (2005) also investigate the influence of other factors, such as flood duration, contamination and preparedness for flood damage based on data for the 2002 floods in Germany.

Economic damages connected to business interruption, usually attributed to the affected area and thus by some authors defined as part of the direct damages, and loss of

[1] See for example van Ast et al. (2003) for a discussion of various valuation methods.

connectivity within the broader economic network, like a country or a region, usually referred to as indirect effects,[2] require a different approach. Here, a modelling framework is needed that captures the working of an economic system, as well as any disturbances therein. Modelling frameworks used for total economic damage assessments include variants of general equilibrium models (Rose, 2004), input-output models (Cole, 2004; Okuyama et al., 2004; Santos and Haimes, 2004), macro-models (Freeman et al., 2004; Mechler, 2004), micro-simulations, and linear programming.[3] One framework much in use in academic research are input–output (I–O) based models to evaluate losses as a result of disturbed links between economic actors. I–O models are known for their simplicity and reflect the economic structure by means of transactions between productive output sectors, final demand requirements and primary factor inputs. Productive sectors in an I–O model are described by a technology, based on the inputs they require to produce a good or service. The data for I–O models are directly obtained from the input-output tables usually assembled by a national bureau of statistics. I–O models are demand-driven, which means that changes in demand trigger changes in input requirements of productive sectors, and thus total output, which is obtained by means of a multiplier.[4] For modelling disruptions caused by major calamities the standard framework can be modified. For example, Santos and Haimes (2004) propose a modification to an I–O model that reflects the extent of an economy's inoperability after a calamity. Okuyama et al. (2004) provide an I–O model that includes a time element, distinguishing between various production modes and including recovery stages. Steenge and Bočkarjova (2007) put forth a three-stage I–O approach to large-scale effect modelling, marking the disequilibrium, recovery and preparedness to flooding. Finally, Cole (1995, 2003, 2004) suggests using an extension of the I–O model into a so-called Social Accounting Matrix (SAM), where a variety of actors can be included.

For consistent decision-making it is desirable to have a more or less standardized approach for damage assessment on a higher aggregation level, such as a river basin or even a complete country. With this in mind, governments in several countries have developed standardized methods for the estimation of damage due to flooding. Examples are the HAZUS methodology developed in the USA (FEMA, 2003), the guidelines for cost-benefit analysis (CBA) developed in the UK (MAFF, 1999, 2000), and Australia (BTRE, 2001). While the Australian approach discusses direct damages, it ignores indirect economic losses assuming perfect substitutability within an economic system. The HAZUS software provides an account of a wide range of damages, including direct and indirect economic losses, yet the assumptions behind the modules can be contested like the stability of life cycle demand or the flexibility of producers behind the adjustments following the demand–supply manipulations of the I–O transactions table. The MAFF approach has a solid theoretical background, pointing at the distinction between stocks and flows, and double-counting related to this distinction. It offers a framework for CBA to support decision-making related to flood prevention measures.

The Netherlands have some specific features which require special attention. First, given the unusual high safety standards compared to some of the surrounding countries we are rather dealing with major flood events, contrary to relatively smaller scale events in for example Belgium. Furthermore, the Netherlands are organised in so-called dike rings, which are the appropriate unit of analysis. It is essential to consider the physical and economic (inter)connections between those dike rings on country level to portray the total effect of a flood. Finally, Dutch flood management is hinging on the risk minimisation principle, which is related to but different from a CBA approach. Meyer and Messner (2005a,b) in their review of flood damage evaluation methods used in four European countries (United Kingdom, Netherlands, Germany, Czech Republic) point to a number of differences, which complicate the application of a standard model outside its original context, including the objective of the flood damage evaluation (e.g. CBA or risk analysis), the damage categories considered, the level of detail, the scale of the analysis, and the application of basic evaluation principles.

In conclusion and following Chen et al. (2003) in the context of bush fires, we point out the importance of having a common framework that includes the various elements of flood-induced damages in a consistent way and is dictated by the needs of policy and decision-making. A damage model in support of policy-making needs to reflect the complexity of effects and impacts of a major flood in a modern industrialised society. Lack of such a decision-support tool for *ex-ante* analysis and post-disaster planning may lead as to inadequate preparedness, as to inability to steer recovery processes stimulating the revival of the economy, which has been argued is the case of hurricane Katrina (US House of Representatives, 2006). The next section tries to fill the gap in flood damage modelling by presenting the key building blocks of an integrated flood damage model in development.

4. Integrated flood damage modelling in the Netherlands

The fundamental element of the integrated flood damage model is a database, which explicitly and simultaneously

[2] For example, van der Veen et al. (2003) describe indirect effects as effects which occur as a result of dislocations suffered by economic sectors not sustaining direct damage (referring to both suppliers and customers of the affected businesses). For further discussion of direct and indirect losses, see for instance Bočkarjova et al. (2007) and Bočkarjova (2007).

[3] In addition, some (re)insurance companies also develop methods to assess the financial losses of a flood (i.e. the insured values), see for example Kron (2002) and Munich Re (2005a,b). These models have a different theoretical underpinning than the models discussed above as they are primarily based on actuarial principles.

[4] Total output of each sector consists of intermediate consumption (which is used for production of other goods and services), and final demand. The essence behind an I–O multiplier is that due to the change, e.g. a decrease, in final demand of a particular good also the intermediate input requirements of the producer of this good will decrease accordingly. This means, that this producer (or sector) will demand less inputs from which this good is produced, thus affecting the supplying sectors throughout the economy, each of which will produce less of its respective output.

illuminates the spatial component describing the hazard and each of the loss categories included in the analysis (Kok et al., 2005). Thus, the starting point for any analysis is geographical information covering the identified area affected by a hazard and the asset categories in each unit of this area. The integrated character of the approach is the combination of various modules in a consistent manner within one geographical area through a common geographical attribute. In this section, we mainly concentrate on the estimation of direct physical damage, followed by a description of the approach to estimate indirect economic damage and the loss of life.

4.1. *Direct physical damages*

The procedure for the estimation of direct physical damage is visualized in Fig. 2. The procedure comprises three main elements: 1) determination of flood characteristics; 2) assembling information on land use data and maximum damage amounts; 3) application of stage-damage functions. We shall discuss these elements in more detail below.

Flooding patterns are simulated on the basis of the hydrodynamic model SOBEK 1D–2D (Delft Hydraulics, 2003). The model gives insight in the development of the flood flow over land resulting from a breach in the flood defence. The mathematical model consists of a two-dimensional flow model that is based on the Saint Venant equations. In order to be able to run the model a lot of input data are required to represent the flood-prone area, the location of the breach(es) and the hydraulic load outside the breach, i.e. height and duration of the high water level. In the simulation of flood flows it is important to account for the roughness and geometry of the flooded area like land elevation, land use, location of water courses, including the so-called line elements, such as local dikes, roads, and railways. These obstacles might create barriers that significantly influence the flood flow and the size of the flooded area, thereby dividing the area in smaller compartments.

The hydrodynamic model generates output information about the development of the flood flow over time and provides insight in flood characteristics, such as water depth, flow velocity and the rate at which the water rises. All these characteristics can be depicted on a map. In reality multiple breaches can occur simultaneously in one area, and these may result in higher damages compared to a single breach, as large amounts of water are allowed to flow into the dike ring area. For flood events characterised by the occurrence of multiple breaches it is likely that larger areas become flooded, as evidenced by several historical flood disasters, such as the 1953 flood in the Netherlands and the recent flooding of New Orleans after hurricane Katrina.

Because an area can get flooded in multiple ways, various flood scenarios are often constructed, simulating one or a set of multiple breaches in the dike ring and the resulting pattern of flooding. For a single dike ring different flood scenarios are possible, covering different breach locations or combinations of multiple breach locations. Generally, several typical dike failure mechanisms are distinguished for river dikes (Rijkswaterstaat, 2005) such as overtopping, piping, macro-instability at land side, instability of dike cover, and sliding off at riverside.

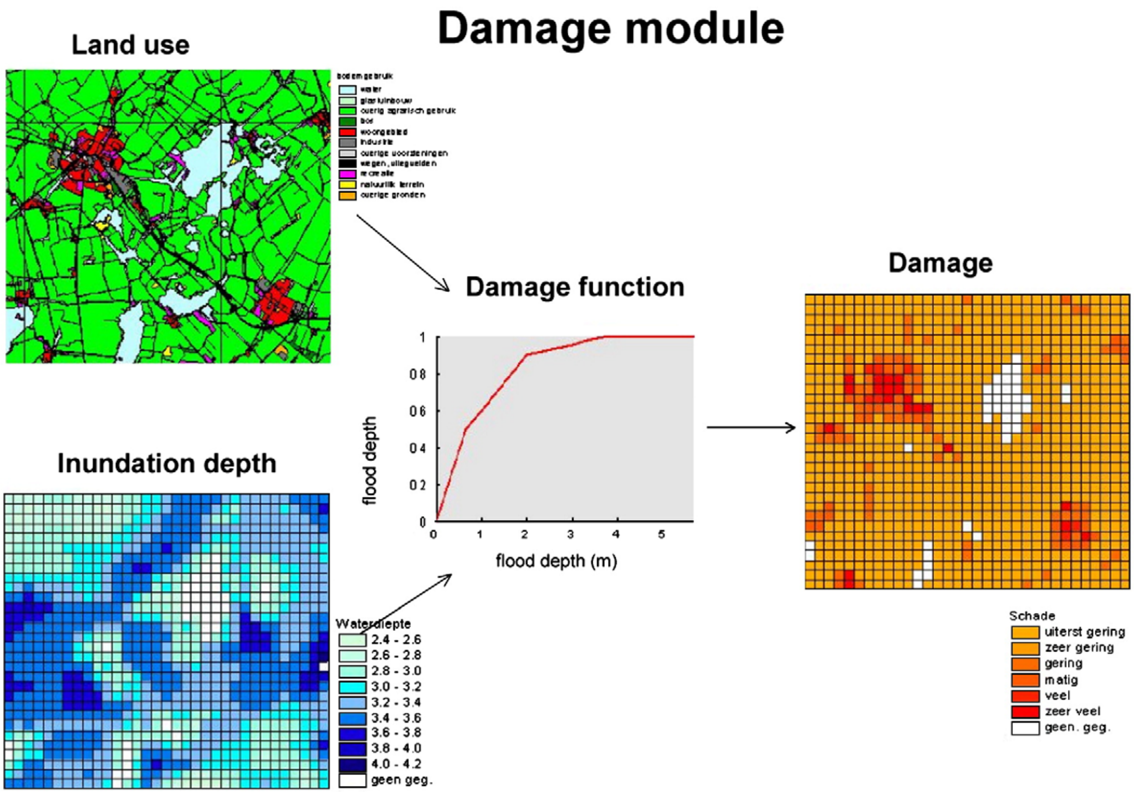

Fig. 2 – Schematization of the assessment of direct physical damages due to catastrophe flooding (source: Rijkswaterstaat).

The hydraulic conditions of the sea or river and the increase of the breach in the flood defence determine the volume of water that flows into the area (see for example Visser, 1998; Zhu, 2006, who developed models for breach growth in dikes). The inflow volume, in turn, determines the flow velocity, water depth and the extent of the area flooded, which are consequently related to the economic damage involved.

Five main categories of assets at risk are distinguished in the direct physical damage assessment: general land use (for example urban area), infrastructure (for example railroads), households (house types), companies (for example industry) and public utilities and facilities (for example pumping stations). Various sources of data are used to determine the amount of maximum damage for different asset categories (Table 2).

The direct physical damages are determined by means of a maximum damage amount per damage object (e.g. a building, a square meter of land, or a meter of road). This value is assumed the same countrywide for the same type of object. Currently, site-specific conditions or regional differentiation are not accounted for in the assessment procedure. The direct damages due to business interruption are determined based on the value added per working place. For the estimation of direct damage to objects, stage-damage functions have been developed for different types of land use. These are used to estimate the fraction of maximum damage as a function of selected flood characteristics like water depth and flow velocity. The following equation describes how the elements in the direct damage model are combined to estimate the total of physical damages in a flooded area:

$$D = \sum_{i}^{m} \sum_{r}^{n} \alpha_i(h_r) D_{\max,i} n_{i,r}, \qquad (1)$$

where:

$D_{\max,i}$	maximum damage amount for an object or land use category i;
i	damage or land use category;
r	location in flooded area;
m	number of damage categories;
n	number of locations in flooded area;
h_r	hydraulic characteristics of the flood at a particular location;
$\alpha_i(h_r)$	stage-damage function that expresses the fraction of maximum damage for category i as a function of flood characteristics at a particular location r ($0 \leq \alpha_i(h_r) \leq 1$);
$n_{i,r}$	number of objects of damage category i at location r.

For each of the damage categories in Table 2, a specific stage-damage function is estimated and used in the direct physical damage assessment by correlating historical damage data with flood depth. Hence, the functions are derived based on empirical flood damage data from the past such as the

Table 2 – Direct damage categories, measurement units, maximum damage costs (price level 2000) and data sources

Damage category	Damage sub-category	Measurement unit	Maximum direct damage amount [€]	Data source
Land use	Agriculture	m^2	2	CBS land use
	Greenhouses		40	CBS land use
	Urban area		49	CBS land use
	Intensive recreation		11	CBS land use
	Extensive recreation		9	CBS land use
	Airports		1230	CBS land use
Infrastructure	Motorways	m	2100	National Road Database
	Major roads		980	National Road Database
	Other roads		270	National Road Database
	Railways		25,000	Rail-NS
Households	Low-rise housing	Object	172,000	Bridgis dwelling types
	Middle-rise housing		172,000	Bridgis dwelling types
	High-rise housing		172,000	Bridgis dwelling types
	Single-family houses		241,000	Bridgis dwelling types
	Farms		402,000	Bridgis dwelling types
	Vehicles		1050	Manual input combined with Bridgis persons file
Companies	Mineral extraction	Value added per working place	1,820,000	D&B employment database
	Industry		279,000	D&B employment database
	Electric companies		620,000	D&B employment database
	Construction		10,000	D&B employment database
	Trading and catering		20,000	D&B employment database
	Banking and insurance		90,000	D&B employment database
	Transport and communications		75,000	D&B employment database
Other	Pumping stations	Object	750,000	Water Information System
	Water purification installations		11,000,000	Water Information System

Source: Briene et al. (2002).

Explanatory notes: CBS: Statistics Netherlands; D&B: Dun and Brandstreet. Maximum damage costs are based on the replacement value of damaged objects (see also Messner et al., 2007).

catastrophic flood in 1953 in the Netherlands (see Duiser, 1982), and later events, like local flooding caused by high discharges in the river Meuse in 1993, combined with existing literature and expert judgment. More recent flooding events like the Elbe flood in 2002 and the flood in New Orleans in 2005 are expected to provide important updates of the fit of the damage functions. An example of a damage function is given in Fig. 3 for damages to houses and their contents. The figure shows that the flood damage is 100% if the water depth exceeds 4.5 m. Similar specific damage functions are estimated for each damage sub-category, correlating direct physical damage to the flood depth.

To estimate the total direct damage, information on flood characteristics and land use are integrated and combined with the stage-damage functions (see Fig. 2). Based on the local flood conditions the damage level by land use category is estimated as a fraction of the maximum damage (see Eq. (1)). GIS offers the possibility to relate the information about flood characteristics, (maximum) damage and the damage functions in a spatial context (see Fig. 2). This is done by means of an overlay of data coming form different sources based on a common spatial attribute, which can be an (x,y) coordinate or a zip code. A grid of 100×100 m is usually used for the simulation of flood scenarios and corresponding flood damage. However, higher grid resolutions can also be applied, like 25×25 m, which is for example used in the Netherlands for the assessment of damage in the coastal zone due to erosion during storm surges. Within each grid cell, information becomes available about the number of houses, the number of jobs, land use etc. affected by the flood scenario. Damage values can be aggregated across grid cells to the appropriate level of analysis like a municipality, province, river basin or the entire country and visualized in maps, see e.g. (ICPR, 2001). Besides displaying the estimated damage as a spatial distribution of damage intensities over an area in a map, the output can be also displayed in a table format presenting the number of flooded objects and damage values per damage category and as a single total economic value. The model is operated and maintained by the Dutch Directorate General of Public Works and Water Management (Rijkswaterstaat) within

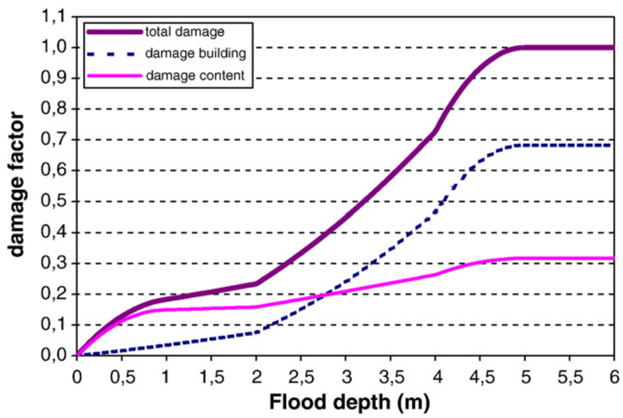

Fig. 3 – Relation between flood depth and damage factor for houses, distinguishing between damage to building and house content.

the Dutch Ministry of Transport, Public Works and Water Management and publicly available.

4.2. *Modelling of indirect economic losses*

To estimate indirect economic damage connected to interruptions in business flows, a model is needed that is able to capture and analyse the interconnectedness between economic agents making up an economic system on the one hand, and the impact of stochastic shocks on this system of interconnected activities on the other hand, including (multi-stage) economic adjustment processes resulting in new equilibria. For the purpose of determining the indirect economic losses associated with a major flood in the Netherlands, the model based on Bočkarjova et al. (2004) and Steenge and Bočkarjova (2007) has been proposed, which is essentially of an I–O type, but is specifically adopted for the analysis of major hazards in modern economies. The model incorporates a spatial dimension, so that geo-referenced input can be used, and is based on a three-step procedure.

The first step is to get a good overview of the nature of the post-catastrophe disruptions. Here, the output of the direct damage module, which identifies and categorises lost objects per locality, can be used as an input for the indirect damage estimation module. In this indirect modelling exercise, we look at an economy as a circular flow, represented by an I–O system. We start from the notion of balance, or equilibrium, which is interrupted by a calamity, like a major flood. We then interpret damage in terms of the disruption of existing links within and between the various sectors in the regional and national economy as parts of the productive activities in the flooded area become temporarily unavailable. Using the technical equations for labour and sectoral output, we are able to establish in a systematic manner and within the I–O logics which part of intermediate as well as final demand 'drops out' of the circular flow as a result of the calamity, and which part stays intact. This results in a new set of sectoral equations, referred to as the Basic equation, which provides a reflection of the out-of-equilibrium situation in the entire economy in the form of a systematic 'inventarisation' of the remaining production capacity. The Basic equation represents an economic system that still has to find its new balance and internal proportions.

In the second stage of the indirect damage module post-disaster imbalances are addressed. During this stage, the Basic equation from stage one becomes the point of departure for an investigation of the options open to an economy when entering the post-disaster recovery. Many policy tracks are possible, including a return to equilibrium in terms of the pre-disaster proportions. Other possibilities include various (temporary) adjustments to the new circumstances both in terms of production and consumption patterns. Given that the estimation of indirect business interruption damages can be carried out under various assumptions regarding market flexibility, government intervention, and post-calamity adjustment scenarios, such an analysis will result in a range of possible outcomes. In this *ex-ante* setting, the comparison of the modelled post-disaster outcomes with the situation without a calamity offers the basis for an estimation of the economy-wide impacts in terms of decreased transactions translated in a decrease of value added, production or consumption values of directly and indirectly affected activities, but possibly also an increase of value added in the sectors with high post-disaster (reconstruction) demand and spare production capacities. The results of such an analysis depend largely on the simulated conditions, as well as the adapting abilities of the economy.

During the third stage, CBA can be carried out using multiple pre-disaster conditions to investigate the effect of pre-disaster adaptation and mitigation, post-disaster policy measures and recovery paths on the total expected costs of a catastrophe. This type of analysis hence enables us to assess the feasibility of particular *ex-ante* preventive measures comparing their benefits (i.e., avoided losses) to the additional costs, as production facilities and residential areas become damaged or protected depending on the flood scenario investigated.

4.3. *Modelling of loss of life*

Alongside economic damage expectations, policy and decision-makers are also interested in the potential number of fatalities associated with a hazard. Some authors like Smith (1996) even define a disaster in terms of the number of victims, thus stressing the importance of the human factor in hazard analysis. At the moment, the model also includes a module to estimate the loss of life caused by a flood (Jonkman and Cappendijk, 2006; Jonkman, 2007). An estimate of the number of fatalities due to a flood event is based on: 1) information regarding the flood characteristics; 2) an analysis of the exposed population and evacuation possibilities; and 3) an estimate of mortality among the exposed population.

Information regarding the flood characteristics is obtained from flood simulations using the hydrodynamic model described before. Relevant flood characteristics include water depth, the rate at which the flood water rises, and the flow velocity. The exposed population equals the number of inhabitants of the flooded area minus the part of the population that is able to evacuate the area or find shelter elsewhere in the area. To analyse evacuation, we use the model developed by van Zuilekom et al. (2005). The mortality rate equals the number of people killed divided by the number of people exposed and is determined by so-called mortality functions which relate observed mortality from real floods to specified flood characteristics, such as water depth, flood water rise rate and flow velocity. Three zones are distinguished to account for different flood characteristics and mortality patterns (Fig. 4): a breach zone where the flood defence breaks, a zone with rapidly rising floodwater and a rest zone. The breach zone is usually characterised by collapsed buildings and a high mortality rate due to high flow velocities just behind the breach. The zone with rapidly rising waters is also characterised by a relatively high mortality rate, because people are less likely to reach a shelter at higher grounds or higher floors of buildings. For each zone a mortality function has been derived based on observations from historical disasters, including the disaster flood in 1953 in the Netherlands.

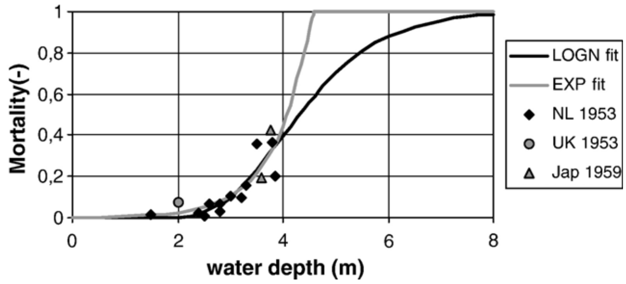

Fig. 5 – Observed and fitted mortality functions for the zone with rapidly rising flood waters (Jonkman, 2007).

An example of a mortality function for the rapidly rising zone is shown in Fig. 5. Based on this method the loss of life can be estimated for a given flood scenario. The loss of life estimates are presented as a separate output of the model and are not monetised.

5. Example: assessment of flood damage in South Holland

In this section an example is presented to demonstrate the usefulness of the flood damage model. It shows how information from different disciplines (hydraulic engineering and economics) is combined in a single case study. We demonstrate the model's ability to present information with the help of maps, including the spatial distribution of the direct and indirect damages and the number of victims as a result of a specified flood scenario simulation in a specific flood-prone area.

We present the results of the estimated *direct* damage costs due to catastrophic flooding in South Holland (dike ring 14 in

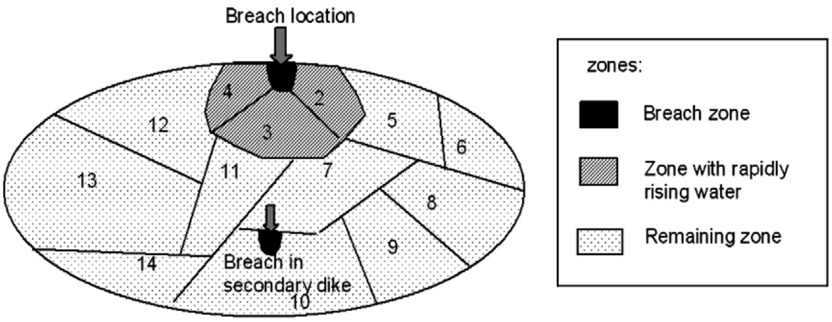

Fig. 4 – Hazard zones for loss of life estimation (Jonkman, 2007).

Fig. 1). This is the most important dike ring area in the Netherlands, both in terms of protected population and economic values. It includes the capital Amsterdam, the port of Rotterdam, the seat of the government in the Hague, and the international airport Schiphol. Potential breach locations in South Holland are shown in Fig. 6 with red dots. Approximately 3.6 million people live and work in this area (about a quarter of the total population in the Netherlands).

The area of South Holland is threatened by floods due to storm surges on the North Sea and riverine flooding given its location in the delta of the Rhine. The area is protected by a sophisticated flood defence system that consists of sand dunes along the coast and dikes along the rivers. As part of the Delta works carried out after the catastrophic flooding in 1953, storm surge barriers have been constructed in the river system like the Maeslant barrier near Hoek van Holland to prevent that storm surge on the North Sea lead to flooding in the lower river system. Depending on the location of a breach, substantial parts of the dike ring can inundate as the area includes some of the lowest lying parts of the Netherlands, up to almost 6 m below mean sea level. In combination with the intensity of social and economic activities this implies, that this area has a high damage potential in case a dike breach takes place.

The flood damage depends on the location of the breach, the size of the breach, the peak flow and the duration of the flood wave and the area's topography. Here, we present the results of one flood scenario, featuring a double breach at The Hague and Ter Heijde (see Fig. 6) caused by a high storm surge on the North Sea. As mentioned, flooding caused by multiple breaches is expected to be most devastating and this also proves to be true for the simulated event presented here,

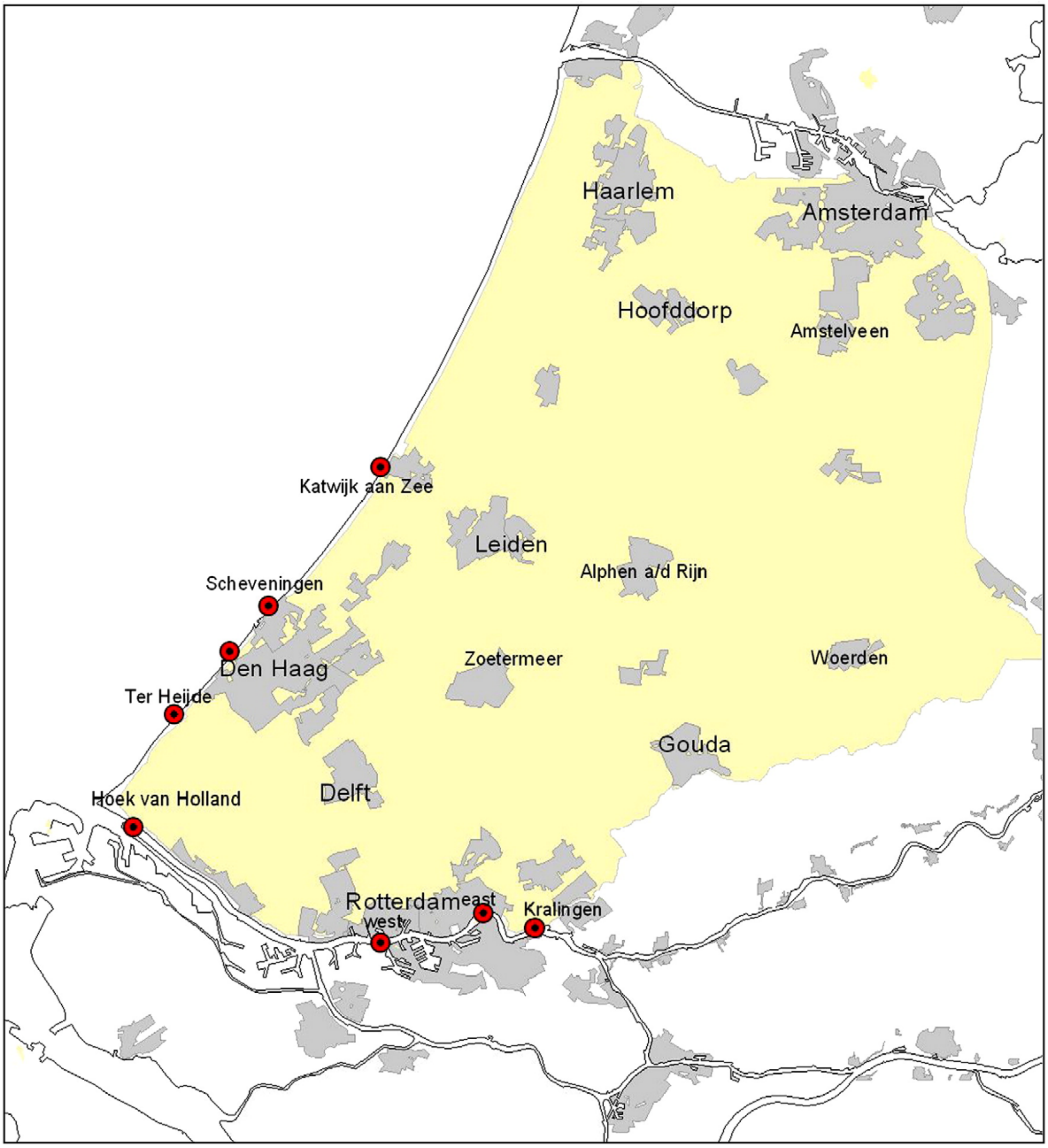

Fig. 6 – Overview of potential breach locations in the dike ring area South Holland.

leading to the inundation of an area of almost 370 km^2. Fig. 7 shows the results of the flood simulation with the hydrodynamic model SOBEK in terms of water depth throughout the affected area associated with the specific flood scenario and as core input into the flood damage modelling exercise, while Fig. 8 shows the spatial distribution of the direct physical damage intensities for this flood scenario. Flood water depth is highest near Delft and Scheveningen. The highest damage intensities occur in the urban areas near The Hague and Rotterdam, where the concentration of economically valuable capital assets is very high.

Table 3 gives an overview of the total direct damage by damage category. The total damage is estimated at almost 24 billion euro (6.5% of GDP, 2000), the largest fraction of which (70%) is associated with direct physical damages to residential property. Other substantial damage categories include direct damage to businesses (11%), commercial and public property (10%) and agricultural losses (8%). The damage to vehicles is very small. It is assumed that many vehicles will be evacuated, but this assumption has to be investigated further. Moreover, not all relevant damage categories are yet included in the model. For example, the burden of evacuation and clean up costs, environmental costs is currently not yet part of the model.

Due to the lack of consistency in the direct damage cost data in the current model version and the necessary economic data for an indirect economy-wide assessment, we are not able to present any reliable and robust estimations of the indirect damage caused elsewhere in the country as a result of the temporary shutdown of production in the flooded area for this specific flood scenario of a double dike breach at The Hague and Ter Heijde. Results of the application of the three-step I–O approach outlined in Section 4.2 to estimate the extent of indirect damage in the case of a flood simulation in central Holland caused by a breach in the dike east of Rotterdam (see

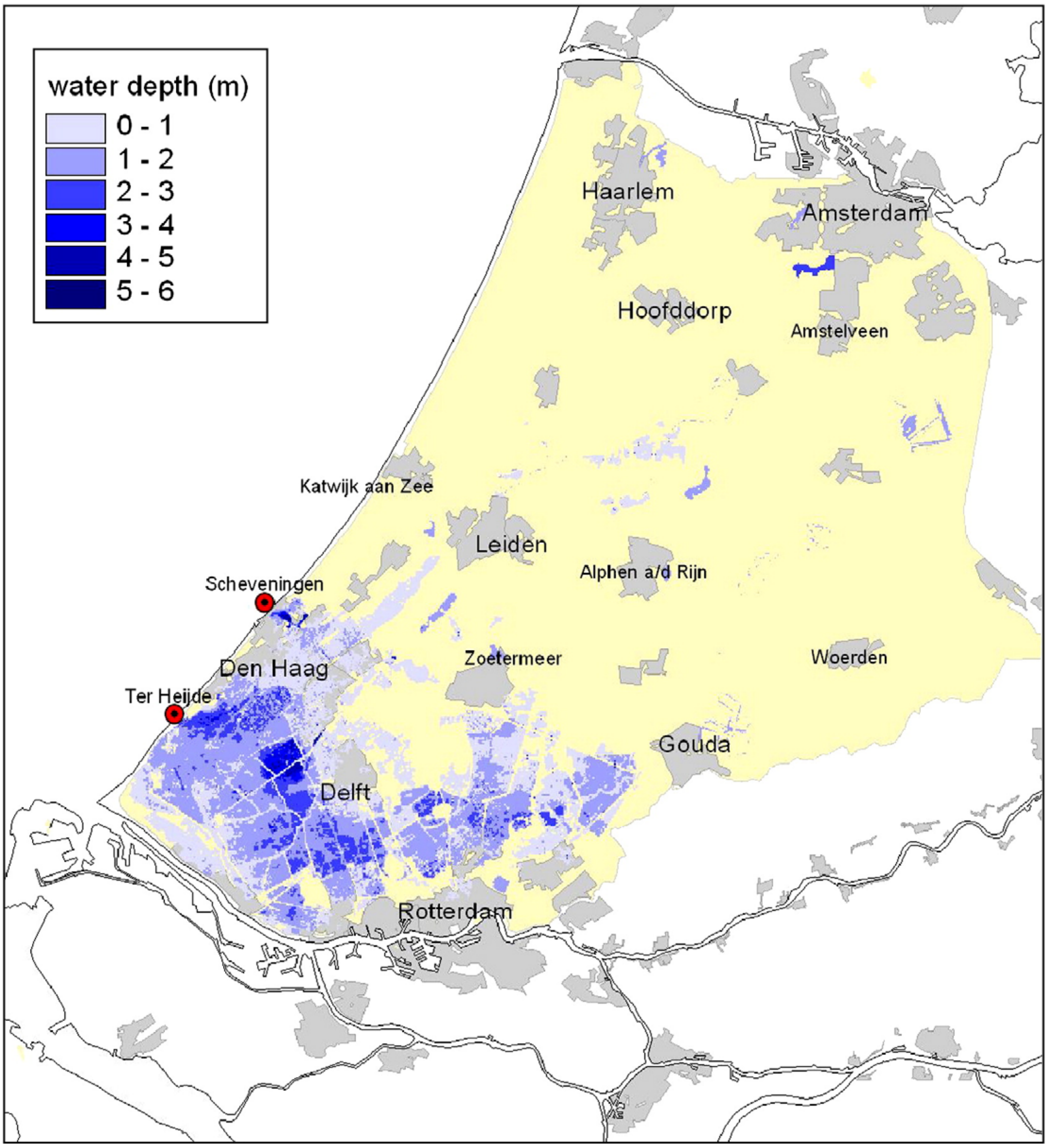

Fig. 7 – Flood water depth simulated with the hydrodynamic model SOBEK 1D–2D as a result of a double breach flood scenario at Ter Heijde and The Hague in South Holland.

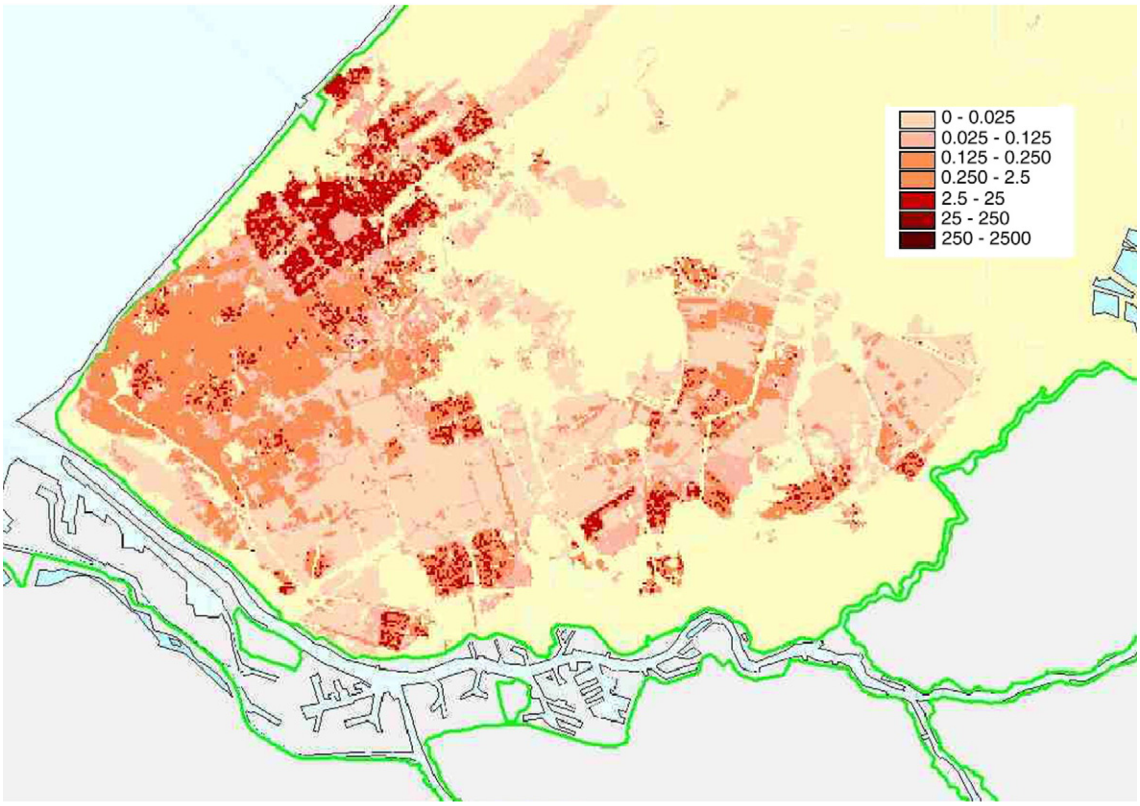

Fig. 8 – Direct damage intensity per hectare for the double breach flood scenario at The Hague and Ter Heijde.

Fig. 6) varied, depending on the economic recovery scenario, between 2.5 and 5% of GDP (Bočkarjova et al., 2007).[5]

A number of other possible dike breach and flood scenarios in the area of South Holland (as shown in Fig. 6) were simulated (see Rijkswaterstaat, 2005), resulting in direct damages varying between €2 and €37 billion. This shows that there can be substantial variation in damage estimations for different scenarios within one dike ring. The nature and extent of the flood catastrophe and thereby the estimation of the associated damage for dike rings highly depend on the location of the dike breach, the area's topography, and the spatial distribution of the protected economic assets within the flood-prone area Furthermore, this finding implies that no single damage estimate should be taken at face value without further careful consideration and examination of the particular assumptions and flood characteristics behind the model exercise, making it hard if not impossible to generalize and transfer flood risk and flood damage assessments across situations and contexts.

In addition to the estimation of the direct physical damage and a rough preliminary assessment of possible indirect economic effects, also the potential number of fatalities has been estimated using the approach described in the previous Section 4.3. The simulated flood scenario is expected to affect approximately 700,000 inhabitants (20% of the total number of inhabitants in South Holland). The time available for evacuation, i.e. expected time between the prediction of the breaches and the actual dike breaches, for this severe scenario of a double dike breach is expected to be limited, and estimated at 10 to 20 h. Analysis with the evacuation model developed by van Zuilekom et al. (2005) shows that the time necessary for a complete evacuation of large parts of South Holland is substantially higher than the available time. It is therefore expected that only a small fraction of the population can be evacuated from the inundated area under this flood scenario. The number of fatalities under these underlying assumptions is then estimated with the available mortality functions, and is expected to amount to approximately 3000 deaths, most of which will occur in the areas with high flood depths south of The Hague (the darker areas in Fig. 7). Such a high death toll combined with the enormous economic damage expectations shows how catastrophic a major flood may turn out in a

Table 3 – Direct damage by category for the flood scenario with simultaneous breaches at The Hague and Ter Heijde

Direct damage category	Direct damage (million euro)	% of total damage
Residential property	16,000	69
Commercial and public buildings	2300	10
Vehicles	40	0
Infrastructure	300	1
Airports	500	2
Agriculture	1900	8
Businesses	2700	11
Total	23,740	100

[5] van der Veen and Logtmeijer (2005) present a map of so-called hotspots in the Netherlands, i.e. locations where flood damages are expected to cause most indirect losses.

densely populated country below sea level like the Netherlands in the face of climate change.

6. Discussion and conclusions

In this paper, an integrated hydrodynamic–economic model is presented which is used in the Netherlands to estimate the economic damage as a result of major catastrophic floods under typical low probability–high impact conditions. Although unlikely given current protection and safety levels in the Netherlands, the probability of catastrophic floods may increase significantly due to the unpredictable variability introduced by climate change. At the same time the impacts of catastrophes like the one that hit the city of New Orleans in 2005 are expected to increase due to the accumulation of economic wealth and capital in flood-prone areas throughout the world. The model presented here exemplifies a complex, multi-staged approach, reflecting the intricate nature of the problem at hand. Natural hazards, especially ones with large-scale impacts, as we presented in an example in this paper, are complex events and trigger the emergence of multiple types of effects in modern, developed societies. In terms of order of magnitude, the social and economic consequences of the flood simulation presented in this paper are comparable with the damage caused by the flooding in New Orleans after hurricane Katrina. In some flood simulation scenarios the estimated damage and number of casualties is expected to be even higher in the Netherlands than they were in New Orleans. This finding urges for pro-active measures to prepare and anticipate future catastrophes in flood-prone parts of the Netherlands, i.e. about a half of the country lying below sea level, in order to prevent a major catastrophe and decrease the extent of potential damage.

In the near future more fine-tuned scenario analysis of flood projections and economic development in different dike ring areas is needed to support policy- and decision-making in the context of flood risk management, spatial planning and further economic development. A highly topical policy question is whether further economic and spatial development in the most low-lying areas of the country are desirable, and which types of future development are expected to not undermine sustainable development in the long run in the face of climate change and sea level rise. For most parts of the country more than one flood scenario is possible, and this may lead to a wide range of variation in damage estimates. To manage the high level of uncertainty and provide a feasible range of values for flood risks derived from the model for reliable use in CBA of flood protection scenarios as in Jonkman et al. (2004), Brouwer and van Ek (2004), Brouwer and Kind (2005) or Eijgenraam (2006), multiple flood scenarios have to be constructed for dike ring areas, combined with probabilistic methods to assess the likelihood of the different flooding scenarios actually occurring (Vrijling, 2001). Another potential field of application is flood insurance. Unlike many other countries, the Netherlands do not have a system of flood insurance. Floods are considered an 'uninsurable risk'. Yet, in recent studies (Botzen and van den Bergh, 2006) the potential for private insurance of flood damages in the Netherlands has been addressed. This has created a lot of interest in the method for direct flood damage estimation on the part of insurers to determine insurance premiums for various types of objects like factories and residential dwellings.

The modelling approach described in this paper allows for the integration of different types of flood risk and flood damage related data using geographical information as the key binding element. In a GIS environment, various data sources related to topography, land use, economic activities, and other objects and line elements can be overlaid and analysed. Combined with hydraulic and hydrological information about flood characteristics based on hydrodynamic simulations the developed flood damage model provides an indication of the expected spatial distribution of damages and casualties for specified flood scenarios. Although the current model mainly captures direct physical damage and the estimation of loss of life, work is under way to extend the model by including other damage aspects in a consistent manner and connecting interruptions in economic flows of goods and services to more comprehensive economy-wide models. One of the key methodological challenges here is to account for stochastic shocks in economic system modelling and the inclusion of economic adaptation and mitigation processes in time in dynamic modelling procedures. Lessons from Katrina teach us that recovery processes taking place after a calamity require substantial attention, also in pre-disaster planning. Literature on economic disaster analysis (e.g. Rose and Liao, 2005; 2006; Bočkarjova, 2007) points to the importance of building up resilient communities those are able to resume their activities and quickly return to 'normal'.

In this sense the model is still 'under construction', and there are a number of serious caveats, which will have to be addressed to arrive at a more comprehensive and complete integrated decision-support model in the future. These include the extension to include indirect effects of large-scale catastrophes, but also the update of the existing generic damage functions, and the regionalization of these damage functions to adequately fit local and regional conditions as in the hydrodynamic flood simulation model. In conclusion, we have every reason to believe that the developed model but with its strong empirical basis and possibilities to extend its scope in terms of types of damages covered, has ample potential for further theoretical and empirical advancement and application in the Netherlands and beyond, for instance in the context of international river basin management.

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