

# Informing River Basin Management on Flood and Drought Risks Taking Future Uncertainties into Account

Aline te Linde, Hans de Moel, and Jeroen Aerts

**Abstract** Severe dry periods (droughts) receive less attention than floods and storms in natural hazard risk assessments. This is remarkable as droughts (heat waves) cause the most casualties of all natural hazards in Europe. The combination of socio-economic developments and climate change poses a challenge to water managers to not only mitigate flood and drought probabilities but also consider measures that a priori alleviate the damage of extreme floods and droughts. This chapter describes how climate scenarios and socio-economic scenarios can be combined to assess future flood risks. Furthermore, several ways are explained of dealing with uncertainty in an approach that may inform river basin managers on flood and drought risks. Finally, an example of drought risk assessment is provided for the Netherlands. The chapter concludes that cooperation with social and economic sciences is a prerequisite for a strategy that best informs river basin management on flood and drought risks. By applying such a strategy, river basin management could involve information on flood and drought risks to assess urgency and priority of a priori risk reduction measures.

**Keywords** Drought risk • Flood risk • River basin management • Scenarios

---

A. te Linde (✉)

Institute for Environmental Studies, Vrije Universiteit Amsterdam, De Boelelaan 1087, 1081 HV Amsterdam, The Netherlands

Twynstra Gudde, Stationsplein 1, 3818 LE Amersfoort, The Netherlands

e-mail: [aln@tg.nl](mailto:aln@tg.nl)

H. de Moel • J. Aerts

Institute for Environmental Studies, Vrije Universiteit Amsterdam, De Boelelaan 1087, 1081 HV Amsterdam, The Netherlands

## Contents

1	Introduction .....	198
1.1	Economic Losses, Natural Hazards and Uncertainty .....	198
1.2	Frequency of Natural Hazards .....	199
2	Flood Management in Europe .....	201
2.1	Future Flood Risk Assessment .....	202
2.2	Dealing with Uncertainty in a Risk-Informed Approach .....	203
3	An Outlook to the Assessment of Drought Risk .....	205
4	Conclusions and Recommendations .....	205
	References .....	206

## 1 Introduction

### 1.1 *Economic Losses, Natural Hazards and Uncertainty*

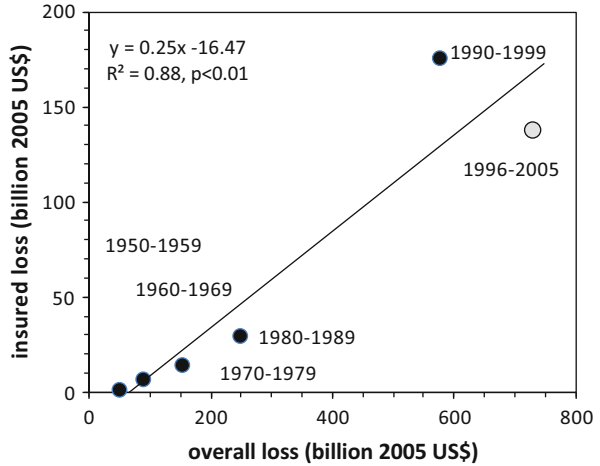
The global economic losses caused by natural disasters have increased in recent decades. After adjustment for inflation and increased prosperity, the average overall damage in the 1950s amounts to about 50 billion Euros (converted to 2007 values). This rose to about 700 billion Euros in the 1990s [1, 2]. The insured losses increased to about 140 billion US\$ on average (Fig. 1).

According to the United Nations, more than two thirds of the world's large cities are vulnerable to rising sea levels and extreme river discharges, exposing millions of people to the risk of extreme floods and storms [3]. In Europe, floods constitute to about 38 % of the total losses of all natural hazards. This makes it, together with windstorms, the most costly natural disaster [4]. In England, for example, floods occurred due to extreme precipitation and caused 8 billion Euro damage in the year 2007 [5]. In 2002, floods in the Elbe basin caused nearly 15 billion Euro damage [6, 7].

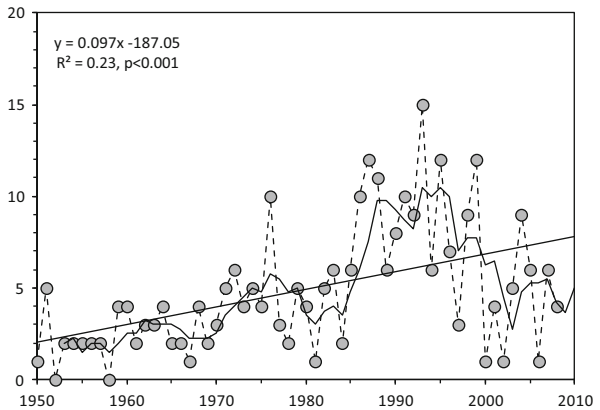
Severe dry periods receive less attention than floods and storms in risk assessments of natural hazards. This is remarkable as they cause the highest numbers of casualties of all natural hazards in Europe [4].

Figure 2 displays an increase in large natural catastrophes worldwide since 1950. This includes an increase in the number of hydrological and climate-related events. Climate events include heat wave, freeze, wildland fire and drought. According to the United Nations Environment Programme (UNEP: [8]), water stress exists in many places in Europe, resulting in serious water shortages, flooding, pollution and ecosystem damage. Several studies conclude that in the last decades, the drought situation in Europe got more severe, due to an increase in frequency, duration or intensity of low flows (e.g. [9] and see also [10], this volume). The European Environment Agency (EEA: [4]) estimates that the dry and hot summer of 2003 in Europe caused 10 billion Euros of economic losses to farming, livestock and forestry. The heat wave of 2003 also resulted in considerable loss of life in Europe. Some estimates indicate that more than 52,000 people died, although the heat affected mainly elderly people [11].

**Fig. 1** Decadal economic losses due to natural hazards in the period 1950–2005. Plotted are the insured losses versus the estimated overall loss (2005 values; source Munich RE, 2008)



**Fig. 2** The number of large (Category 6) natural catastrophes, including a 4-year running mean. Category 6 catastrophes are defined as causing more than 1,000 fatalities, more than 100,000 homeless and/or situations when overall loss and/or insured losses are of exceptional proportions (Adapted from Munich RE, 2008)

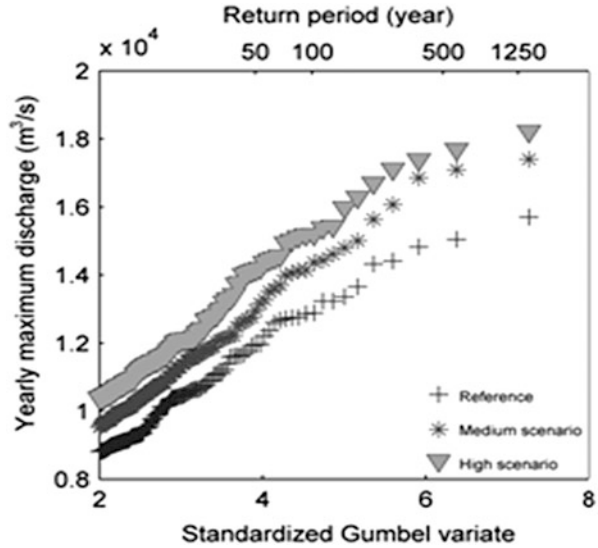


### 1.2 Frequency of Natural Hazards

The latest report by the Intergovernmental Panel on Climate Change (IPCC) indicates that global warming will intensify the global hydrological cycle ([12], and see Fig. 1 in [13], this volume). As a consequence, the magnitude and frequency of extreme precipitation events are expected to increase. This may lead to an increased flood probability in Europe [14, 15]. Also the frequency and duration of extreme droughts are expected to increase in Europe, in particular in Mediterranean areas [16].

Dankers and Feyen [17] made a pan-European assessment of the changes in flood frequency under changing climate conditions. In several rivers in north-west Europe, the current, flood return period of once every 100 years may in the future be 50 years or even less. Recent findings in the Rhine River basin suggest that—if no

**Fig. 3** Extreme value plots of yearly maximum discharges of the Rhine at the German-Dutch border. As input for the rainfall-runoff model served 1,000 years of daily meteorological input data that were obtained by a weather generator (Beersma et al. 2001). Displayed are 1,000 years of simulated yearly maximum discharges for the reference situation and two climate change scenarios for the year 2050 (Source: Te Linde et al. [19])



extra defence measures are implemented—the probability of flooding will increase with a factor of 2.5–5 in 2050 [18] (Fig. 3).

Observed and projected trends of climate impacts, differentiated for four regions in Europe, do show some discrepancy (Table 1). Both observations and projections agree on an increase of river floods in two temperate regions, whereas droughts only increase in the projections of the maritime climate and Mediterranean regions.

Apart from climate change, socio-economic developments play an important role in the vulnerability to extreme flood and drought events. Within the next 30 years, the United Nations predict that the number of people living in cities will increase to 60 % of the world’s population, resulting in even more people living in highly exposed areas [20]. Worldwide, water withdrawal intensified in the second half of the twentieth century. This is a direct result from population growth and intensified industry and agriculture [21]. Some scenarios project the world water withdrawal in 2025 to be 1.4 times higher than in 1995. Hence, socio-economic trends further amplify the possible damage of future floods as more people move towards low-lying flood-prone areas and urban areas, and the increase and concentration of people increases water stress.

The combination of socio-economic developments and climate change poses a challenge to water managers to not only mitigate flood and drought probabilities but also consider measures that a priori alleviate the damage of extreme floods and droughts [12]. Examples of a priori measures are early warning, spatial planning, different crop growth and insurance. Furthermore, future projections are highly uncertain and it appears difficult to simulate how flood and drought risks will develop in the future under various combinations of climate change and socio-economic scenarios (conform [22]).

**Table 1** Observed (obs) and projected (scen) trends in climate and impacts for northern (Arctic and boreal), temperate (maritime climate, central/eastern) and southern (Mediterranean) regions of Europe (adapted from [4])

Indicator	Northern	Temperate	Southern	
	Arctic and boreal obs/scen	Maritime climate obs/scen	Central/ eastern obs/scen	Mediterranean obs/scen
Atmosphere and climate				
Global and European temperature	+/+	+/+	+/+	+/+
European precipitation	+/+	+/o	o/o	-/-
Temperature extremes in Europe				
Heat waves in Europe	+/+	+/+	+/+	+/+
Precipitation extremes in Europe	+/+	+/+	+/+	+/+
Water quantity, river floods and droughts				
River flow	+/+	o/+	o/+	-/-
River floods (number of events)	o/-	+/+	+/+	o/+
River flow drought	o/-	o/+	o/-	o/+
Economic consequences of climate change				
Direct losses from weather disasters	+/+	+/+	+/+	+/+

+ = increasing; - = decreasing; o = no significant changes (or diverging trends within the region)

The remaining part of this chapter reports on the progress in flood-risk-informed management in Europe, addressing two aspects of future flood management that may deserve additional attention in research and drought-risk assessments: (1) the combined use of climate and socio-economic scenarios in future flood risk assessments and (2) several ways of dealing with uncertainty in a risk-informed approach. Finally, an outlook is provided to the assessment of drought risk, with an example from the Netherlands.

## 2 Flood Management in Europe

Until recently, flood management in Europe relied strongly on technical engineering capacity [23]. This has a historical basis; water managers have developed the subject area and designed hydro-morphological structures on the basis of flood safety standards [24]. For example, the flood embankments along the river Rhine have been designed to withstand floods that only occur once every 200–500 years in Germany and once every 1,250 years in the Netherlands [19]. While flood defences have provided protection against river flooding, continued socio-economic developments behind these defences resulted in an increase in flood risk. Moreover, not only the amount of economic and social capital increased, but developments

behind flood defences occurred in increasingly more hazardous places because the most safe and obvious places had already been occupied [25].

However, since the near floods in 1993 and 1995 along the river Rhine, the 2002 flooding along the Elbe and various floods in the Danube during the last 15 years, flood management has been exploring new approaches that go beyond technical measures such as dikes or canalization. This new way of thinking is referred to as flood-risk-informed management [26, 27]. Flood risk is defined here as the product of probability and consequence (e.g. damaged property and loss of life), i.e. the expected loss per year [28]. The EU supports the transition towards a risk-informed approach in the implementation of the EU Floods Directive (2007/60/EC). This Directive sets out several actions on preliminary flood risk assessment, development of flood risk maps and the preparation of basin-wide risk management plans, to be completed at river basin scale by the end of 2015 (see also [29], this volume). Many European Union member states have already collated information and maps on flood hazard (potentially damaged area), but information and maps on flood risk are still rare [30]. The EU Green Paper on adaptation to climate change [31] also stresses the importance of looking beyond defensive measures. It states that concrete adaptation actions should range from relatively inexpensive soft measures (i.e. raising awareness, public planning) to much more costly defence and relocation measures (i.e. higher dykes, storm surge barriers, relocation of ports and urban centres [31]).

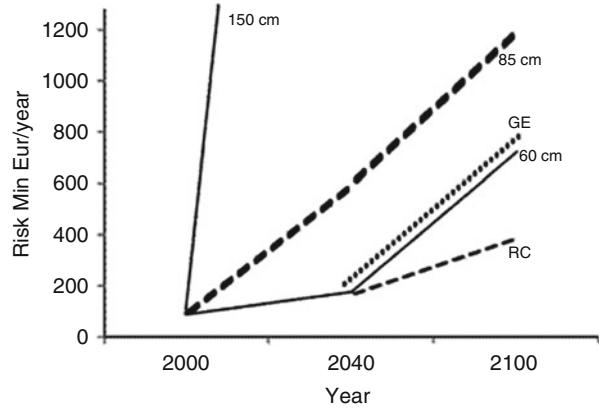
## 2.1 *Future Flood Risk Assessment*

Infrastructures (buildings, roads, sewer, electricity cables etc.) resulting from spatial developments as well as most flood defence measures are supposed to last for long periods of time. Thus, their planning and management requires insight in likely future necessities. As flood risk is by no means static, it is therefore important to anticipate on expected future changes in flood risk. Feyen et al. [32] estimated future flood risk in Europe, averaged over NUTS2<sup>1</sup> level. They used a hydrological model and inundation maps, depth-damage functions and different levels of flood protection based on the gross domestic product (GDP) per country. The impacts of both climate and land use change were included, and they estimated an average increase in expected annual damage for all European countries from 6.5 billion Euros in 2000 to 18 billion Euros in 2100 (converted to 2006 values). More detail is necessary to be able to map flood risk at the scale of individual countries. Flooding probabilities in the Netherlands, for example, are much lower than the once every

---

<sup>1</sup>The Nomenclature of Territorial Units for Statistics (NUTS) is a geocode standard for referencing the subdivisions of countries for statistical purposes. NUTS regions are based on existing national administrative subdivisions. The population bandwidth for NUTS2 regions is 800,000–3 million, but this is not applied rigidly

**Fig. 4** Prognosis of flood risk (expressed as Mln Euro damage/year) for the Netherlands. The relative influence of sea level rise (60, 85 and 150 cm in 100 years) on flood risk is compared with the influence of urban development, according to two scenarios: RC (B2, low economic growth) and GE (A1, high economic growth) (adapted from Aerts et al. [33])



100-year protection level that Feyen et al. [32] adopted. Safety levels in the Netherlands vary from flooding once every 1,250 years in the eastern part to once every 10,000 years in coastal areas.

At a national scale, Aerts et al. [33] have studied the independent influence of both climate change and socio-economic developments on flood risk in the Netherlands. For this purpose, a wide range of scenarios concerning climate change and land use developments were studied. Effects of climate change were modelled using three combined sea level rise and river discharge scenarios, which together influence flood probability. Furthermore, changes in urban development were assessed using two SRES scenarios (see Table 1 in [34], this volume), namely, low economic growth (B2 or Regional Communities) and high growth (A1 or Global Economy) [cf. 22, 34] (Fig. 4).

The results indicate that a moderate rise in sea level of 60 cm results in a similar increase in potential damage as a high economic growth scenario. Climate change effects only dominate for high increases in sea level, which is above 85 cm in the year 2100. These results highlight the importance of flood adaptation policies that limit both flooding probabilities as well as potential damage of flood disasters.

## 2.2 Dealing with Uncertainty in a Risk-Informed Approach

While clearly important, it is by no means straightforward to take future changes into account in a risk-informed approach. Long-term trends are inherently uncertain, hence difficult to translate into specific or necessary investment demands for daily operational river basin management. The prime source of uncertainty in flood (risk) prediction is the reliability of extreme value statistics [35]. Floods are very rare events, having return periods that are usually far outside the length of the period of the used observed time series data. One of the ways of dealing with this shortage of data is to statistically expand the existing set of observed data from

decades to centuries or even millennia. Te Linde and Aerts [36] used a weather generator model to create 1,000 years of daily precipitation and temperature data [37], in order to simulate daily discharges and annual maximum flood peaks. In this way discharges corresponding to design safety level return periods (i.e. flooding acceptable once every 100 years or once every 1,250 years) can be estimated using interpolation instead of extrapolation.

As the future is inherently unknown, scenarios are often used to explore possible or plausible futures (conform [34] and see also [34], this volume) and make better informed decisions in the present. Such scenarios represent different views on future societal development and provide images of how important driving variables are expected to change. It is of key importance that these variables are internally consistent, meaning that they should logically match within and among scenarios [22, 38, 39]. Furthermore, the scenarios applied would ideally cover the full width of conceivable future situations. Since any single scenario is equally plausible, all scenarios should be included in decision-making. The studies of Te Linde et al. [18] and Aerts [33] are both examples of scenario-based flood risk studies.

A more formal way of dealing with uncertainties is to perform statistical uncertainty analyses of the assessment models. Formal uncertainty analyses are common in integrated assessment models and many approaches exist (see e.g. [40]). In the commonly used Monte Carlo approaches, the assessment model is ran many times using different sets of random input parameter values, which are all varied within their own uncertainty range (see e.g. [41]). This will not result in a single number, but in a distribution of outcomes representing the many possible outcomes of the model given the uncertainties included. While a distribution has clear advantages over a limited set of scenarios, there are also some distinct disadvantages. Most importantly, depending on the model in use, such uncertainty assessments may require large computational capacity, which can become both time consuming and expensive. Furthermore, the uncertainty surrounding the input data must be quantified a priori, which is an inherent complication since the uncertainty ranges are generally estimates [42].

Full uncertainty analyses are used in early warning systems to estimate the bandwidth around water level predictions [43]. Furthermore, many efforts are being put in ensemble studies of climate models (e.g. the PRUDENCE [14] and ENSEMBLES [44] projects<sup>2</sup>) in order to get a better grip on the uncertainties and distribution of future climate parameters. Combining all these efforts into a full uncertainty analysis of the overall flood risk is a challenging task which is only recently starting to be picked up. Overall, uncertainty can be seen as one of the main remaining challenges in flood management [42], especially in risk-informed approaches that try to account for future changes.

---

<sup>2</sup> See: <http://prudence.dmi.dk/>



**Table 2** Expected annual damage to agriculture and shipping (Mln Eur/year) (Adapted from: De Bruijn [45])

	Current (2000)	2050 (1 °C rise)	2050 (2 °C rise)
Expected annual damage to agriculture	351	488	624
Expected annual damage to shipping	90	175	280

### 3 An Outlook to the Assessment of Drought Risk

Just like flood risk, drought risk can be defined as the product of probability and consequence (e.g. damaged property and loss of life) and expressed in expected damage or loss per year. Few studies, though, seem to have attempted this. De Bruijn [45] made a quick scan for the Netherlands. Although densely populated, there is usually sufficient water in the Netherlands to meet the needs of all water use sectors (e.g. drinking water, agriculture, cooling water for power plants, naval transport over the river, industry and nature). The summer of 2003, though, caused severe and costly problems for water management: low river water levels hampered inland shipping; water quality deteriorated due to high temperatures and intruding brackish water; irrigation water for agriculture was restricted and power plants had to cut down their production because of a limited cooling capacity of the remaining river water.

Damages were estimated for two different climate change scenarios (1 or 2 °C temperature rise in 2050; Table 2). It is evident that in the current situation agriculture and shipping already suffer yearly damage. Apparently, both sectors have adapted or seem to cope with these annual damages [46]. Compared to the present situation, the expected damage to agriculture is estimated to increase with a factor of 1.4–1.8 and to shipping with a factor of 2–3. These projections remain inherently uncertain. Economic developments in the agricultural sector, for example, are influenced severely by world market prices, which are highly uncertain. Although estimated drought risk seems substantial, a first mitigation analysis shows that it is feasible and cost-effective to implement adaptation measures to cope with increased drought risk in 2050 in the Netherlands [47].

### 4 Conclusions and Recommendations

Dealing with natural hazards—like droughts and floods—in a risk-informed approach, which also takes future developments into account, is becoming more and more important in a wealthier and increasingly more densely populated world. Flood management is moving away from being the sole domain of engineers. Cooperation with social and economic sciences is—as further underpinned in book Section C—a prerequisite for successful risk-informed strategies. Integrating these different fields of research is one of the major challenges in informing river

basin management on flood and drought risks taking future uncertainties into account. Such risk-informed river basin management could help basin managers to distinguish between urgency and priority of risk reduction measures. Due to the huge investments, we desire a long lifetime of infrastructure (roads, buildings, sewers, electricity cables, etc.) and defensive structures. Thus, it should be accounted for future trends related to the hazard (e.g. climatic change), damage (infrastructure) and loss (human lives). Furthermore, the uncertainties of assessments, particularly those related to scenario-based future outlooks, should be assessed and communicated adequately in order to enable better informed decisions.

## References

1. Kunreuter H (2009) Reducing losses from catastrophe risks through long-term insurance and mitigation. *Social Res* 75(3):905–930
2. Munich Re (2008) Annual Review 2008
3. Rosenzweig C, Solecki WD, Hammer SA, Mehrotra S (2011) First assessment report of the Urban Climate Change Research Network. Cambridge University Press, Cambridge
4. EEA, WHO, JRC (2008) Impacts of Europe's changing climate – 2008 indicator-based assessment, European Environment Agency, Copenhagen, Denmark, EEA No 4/2008. [http://reports.eea.europa.eu/eea\\_report\\_2008\\_4/en](http://reports.eea.europa.eu/eea_report_2008_4/en)
5. ABI (2007) Summer floods 2007: learning the lessons. Association of British Insurers, London
6. Thielen AH, Müller M, Kreibich H, Merz B (2005) Flood damage and influencing factors: new insights from the August 2002 flood in Germany. *Water Resour Res* 41:1–16
7. Thielen AH, Petrow T, Kreibich H, Merz B (2006) Insurability and mitigation of flood losses in private households in Germany. *Risk Anal* 26:383–395
8. UNEP (2004) Freshwater in Europe – facts, figures and maps. United Nations Environment Programme/DEWA Europe, Châtelaine, Switzerland
9. Demuth S, Stahl K (2001) Assessment of the regional impact of droughts in Europe. Final Report to the European Union, ENV-CT97-0553, Institute of Hydrology, University of Freiburg, Germany
10. von der Ohe PC, Apitz SE, Arbačiauskas K, Beketov MA, Borchardt D, de Zwart D, Goedkoop W, Hein M, Hellsten S, Hering D, Kefford BJ, Panov VE, Schäfer RB, Segner H, van Gils J, Vegter JJ, Wetzel MA, Brack W (2014) Status and causal pathway assessments supporting river basin management. In: Brils J, Brack W, Müller-Grabherr D, Négrel P, Vermaat JE (eds) Risk-informed management of European river basins. Springer, Heidelberg
11. Larsen J (2006) Setting the record straight: more than 52,000 Europeans died from heat in summer 2003, Eco-Economy Update (Washington, DC: Earth Policy Institute, 26 July 2006)
12. IPCC (2007) Climate change 2007: the physical science basis. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
13. Négrel P, Merly C, Gourcy L, Cerdan O, Petelet-Giraud E, Kralik M, Klaver G, van Wirdum G, Vegter J (2014) Soil – sediment – river connections: catchment processes delivering pressures to river catchments. In: Brils J, Brack W, Müller-Grabherr D, Négrel P, Vermaat JE (eds) Risk-informed management of European river basins. Springer, Heidelberg

14. Christensen JH, Christensen OB (2007) A summary of the PRUDENCE model projections of changes in European climate by the end of this century. *Clim Change* 81:7–30
15. Milly PCD, Dunne KA, Vecchia AV (2005) Global pattern of trends in streamflow and water availability in a changing climate. *Nature* 438:347–350
16. Kundzewicz ZW, Mata LJ, et al. (2007) Freshwater resources and their management. climate change 2007: impacts, adaptation and vulnerability. In: Parry ML, Conziani OF, Palutikof JP, van der Linden P, Hanson, CE. Contribution of working group II tot the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 173–210
17. Dankers R, Feyen L (2008) Climate change impact on flood hazard in Europe: an assessment based on high resolution climate simulations. *J Geophys Res* 113
18. Te Linde AH, Aerts JCJH, Bakker AMR, Kwadijk JCJ (2010) Simulating low probability peak discharges for the Rhine basin using resampled climate modeling data. *Water Resour Res* 46, WRR3512
19. Te Linde AH, Bubeck B, Dekkers JEC, De Moel H, Aerts JCJH (2011) Future flood risk estimates along the river Rhine. *Nat Hazard Earth Syst Sci* 11:459–473
20. Nicholls RJ, Hanson S, Herweijer C, Patmore N, Hallegatte S, Corfee-Morlot J, Château J, Muir-Wood R (2008) Ranking port cities with high exposure and vulnerability to climate extremes exposure estimates. OECD Environment Working Papers No. 1, 19/11/2008.
21. Oki T, Valeo C, Heal K (2006) Hydrology 2020: an integrating science to meet world water challenges. IAHS, Wallingford, Oxfordshire, IAHS Publication 300
22. Busch G (2006) Future European agricultural landscapes – what can we learn from existing quantitative land use scenario studies. *Agric Ecosyst Environ* 114:121–140
23. Commission of the European Communities (2004) Communication. Flood risk management, Flood prevention, protection and mitigation. COM(2004)472 final
24. Aerts JCJH, Droogers P (2004) Adaptation for river basin management. CABI publishers, Wallingford, p 260
25. De Moel H, Aerts JCJH, Koomen E (2011) Development of flood exposure in the Netherlands during the 20<sup>th</sup> and 21<sup>st</sup> century. *Glob Environ Change* 21(2):620–627
26. De Bruijn K, Klijn F (2009) Risky places in the Netherlands: a first approximation for floods. *J Flood Risk Manage* 2:58–67
27. Wheeler H, Evans E (2009) Land use, water management and future flood risk. *J Land Use Policy* 26:S251–S264
28. Smith K (2001) Environmental hazards: assessing risk and reducing disaster, 3rd edn. Routledge, London
29. Brils J, Barceló D, Blum W, Brack W, Harris B, Müller D, Négrel P, Ragnarsdottir V, Salomons W, Slob A, Track T, Vegter J, Vermaat JE (2014) Introduction: the need for risk-informed river basin management. In: Brils J, Brack W, Müller-Grabherr D, Négrel P, Vermaat JE (eds) Risk-informed management of European river basins. Springer, Heidelberg
30. De Moel H, Van Alphen J, Aerts JCJH (2009) Flood maps in Europe – methods, availability and use. *Nat Hazard Earth Syst Sci* 9:289–301
31. Commission of the European Communities (2007) Green Paper. Adapting to climate change in Europe – options for EU action. COM(2007)354 final
32. Feyen L, Barredo JI, Dankers R (2009) Implications of global warming and urban land use on flooding in Europe. In: Shannon N (ed) Water and urban development paradigms – feyen. Taylor and Francis Group, London
33. Aerts JCJH, Bannink B, Sprong TA (2008) Aandacht voor veiligheid. <http://www.adaptation.nl>. IVM Report. VU University, Amsterdam
34. Vermaat JE, Salomons W, Gilbert AJ, Hellmann F (2014) Downscaling scenarios as an exploratory tool for river basin management – an introduction. In: Brils J, Brack W, Müller-Grabherr D, Négrel P, Vermaat JE (eds) Risk-informed management of European river basins. Springer, Heidelberg

35. Apel H, Thielen AH, Merz B, Blöschl G (2004) Flood risk assessment and associated uncertainty. *Nat Hazard Earth Syst Sci* 4:295–308
36. Te Linde AH, Aerts JCJH (2008) Simulating flood-peak probability in the Rhine basin and the effect of climate change. In: Samuels P, Huntington S, Allsop W, Harrop J (eds) *Proceedings of the European conference on flood risk management: research and practice (FloodRisk 2008)*. Oxford, 30 September–2 October 2008
37. Beersma JJ, Buishand TA, Wöjcik R (2001) Rainfall generator for the Rhine basin; multi-site simulation of daily weather variables by nearest-neighbour resampling. Generation of hydro-meteorological reference conditions for the assessment of flood hazard in large river basins. In P Krahe, D Herpertz (eds). Lelystad, The Netherlands, International Commission for the Hydrology of the Rhine basin (CHR). CHR-Report no. I-20:69–77.
38. Lorenzoni I, Jordan A, Hulme M, Turner RK, O’Riordan T (2000) A co-evolutionary approach to climate impact assessment: part I. Integrating socio-economic and climate change scenarios. *Glob Environ Change* 10:57–68
39. Van Vuuren DP, Lucas PL, Hilderink H (2007) Downscaling drivers of global environmental change: enabling use of global SRES scenarios at the national and grid levels. *Glob Environ Change* 17:114–130
40. Kann A, Weyant JP (2000) Approaches for performing uncertainty analysis in large-scale energy/economic policy models. *Environ Model Assess* 5:29–46
41. Crosetto M, Tarantola S, Saltelli A (2000) Sensitivity and uncertainty analysis in spatial modelling based on GIS. *Agric Ecosyst Environ* 81:71–79
42. Hall JW (2003) Handling uncertainty in the hydroinformatic process. *J Hydroinf* 5:215–232
43. Weerts AH, Diermanse F, Reggiani P, Werner M, Van Dijk M, Schellekens J (2003) Assessing and quantifying the combined effect of model parameter and boundary uncertainties in model based flood forecasting. *Geophys Res Abstr* 5:14564
44. Van der Linden P, Mitchell JFB (2009) Summary of research and results from the ENSEMBLES project. The Met Office Hadley Centre, Exeter
45. De Bruijn K (2009) Future flood risk and drought. Report 1002158 Deltares, Delft
46. Jonkeren OE (2009) Adaptation to climate change in inland waterway transport. Ph.D. thesis, VU Amsterdam
47. Deltares (2008) Omgaan met droogteschade. Kosteneffectiviteit van grootschalige maatregelen tegen droogteschade als gevolg van G + en W + klimaatscenario’s. Report T2499. Deltares, Delft