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Alternative water management options to reduce vulnerability for climate change in the Netherlands

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Abstract Urbanization, land subsidence and sea level rise will increase vulnerability of the urbanized low-lying areas in the western part of the Netherlands. In this article possibilities are explored to reduce vulnerability of these areas by implementing alternative water management options. Two main water management fields are distinguished, water supply and flood control. A four-component vulnerability framework is presented that includes threshold capacity, coping capacity, recovery capacity, and adaptive capacity. By using the vulnerability framework it is shown that current water supply and flood control strategies in the Netherlands focus on increasing threshold capacity by constructing higher and stronger dikes, improved water storage and delivery infrastructure. A complete vulnerability decreasing strategy requires measures that include all four capacities. Flood damage reduction, backup water supply systems and emergency plans are measures that can contribute to increasing coping capacity. Recovery capacity can be increased by multi-source water supply, insurance, or establishing disaster funds. Adaptive capacity can be developed by starting experiments with new modes of water supply and urbanization. Including all four components of the vulnerability framework enables better understanding of water and climate related vulnerability of urban areas and enables developing more complete water management strategies to reduce vulnerability.

Keywords Vulnerability · Water management · The Netherlands · Flood control · Climate change

1 Introduction

Almost half of the Netherlands lies below sea level (Fig. 1) and more than half of its population and capital are concentrated in this heavily urbanized area. By continuous draining and pumping, the ground level in this area has subsided well under the mean sea

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Fig. 1 Illustration of areas in the Netherlands below mean sea level (Source: http://www.news.bbc.co.uk/2/hi/americas/4597288.stm)

level. In this area, water levels are managed artificially by installing water storage capacity and pumping capacity in a so-called polder system. Climate change, sea level rise, population growth and ongoing urbanization result in increased vulnerability of the low-lying areas in the Netherlands because it will result in increased flooding frequency, increased damage, and it may also lead to increased use of water, energy and other resources. Due to climate change, urban areas will have to cope with more variability of water resources, in particular the water resources from the river Rhine. Moreover, flood levels from rivers and sea will increase by sea level rise and higher design discharges. This will make urban areas increasingly vulnerable to the impacts of climate change.

Vulnerability is often defined as the sensitivity of a system to exposure to shocks, stresses and disturbances, or the degree to which a system is susceptible to adverse effects (White 1974; IPCC 2001; Turner et al. 2003; Leurs 2005), or the degree to which a system or unit is likely to experience harm from perturbations or stress (Schiller et al. 2001). The system under consideration can be a community or region. The vulnerability concept is widely used in studies on risks and natural hazards, and often also includes social, and political dimensions. Stress and disturbances on a system can be both exogenous and endogenous, ranging from changes in the environment to changes in society. Some vulnerability approaches consider threats from both inside and outside the considered system, as well as the capacity of the considered system to cope with these threats. Moreover, they consider coupled human-environment systems or the reflexive relation between human society and the environment, instead of only human systems and environmental threats (Fraser et al. 2003; Turner et al. 2003; Leurs 2005). In the risk glossary of United Nations University, Thywissen (2006) concludes: “vulnerability is a dynamic, intrinsic feature of any community (or household, region, state, infrastructure or any other element at risk) that comprises a multitude of components. The extent to which it is revealed is determined by the severity of the event.”

The concept of vulnerability pays attention to both disturbances and system response. The ability of a system to attenuate stresses or cope with consequences through various strategies is one of the main determinants of system response and system impact (Schiller et al. 2001). According to Blaikie et al. (1994) vulnerability is: “the characteristics of a person or a group in terms of their capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard.” It involves a combination of factors that determine the degree to which someone’s life and livelihood is put at risk by a discrete or identifiable event in nature or society. Also other authors (Timmerman 1981; Bogard 1989; Dow 1992; Suarez 2002) link vulnerability to the capacity to act against disturbances and developments. These capacities relate to a complex set of characteristics that include initial well being, self-protection, group protection, hazard preparedness and presence of political networks and institutions (Cannon et al. 2002). A focus limited to perturbations and stresses is insufficient to understand the impact on systems (Turner et al. 2003). Thus, to understand vulnerability requires including the abilities and capacities of the system under consideration. In addition, dealing with uncertainty is important to understand the vulnerability of a system. Today, a system may be functioning well but possible future developments might increase vulnerability if a system is not able to adjust to these developments. Cannon et al. (2002) argue that vulnerability has to include some predictive quality and conceptualize what could occur to an identifiable population, in case of a future disaster. Therefore, an important aspect of vulnerability is the capacity of communities and societies to adapt to uncertain future developments.

Frameworks that are often used to examine vulnerability take environmental disturbances on exposed human systems into account (Schiller et al. 2001; Turner et al. 2003). In practice, however, the exposed system may amplify, attenuate, and create stresses and disturbances. This is illustrated by the fact that a drought can be caused by low river flow, bad water management or both. Low river flow in itself can again be caused by natural variation of weather, or activities such as deforestation or upstream reservoir construction. Flood damage might be caused by high water levels only. However, often it will be a combination of lack of risk awareness, failing warning systems, lacking or non functioning emergency plans, insufficient maintenance of flood defense, urbanization in flood prone areas and high water levels that cause flood damage and determine its severity.

Also in other complex systems, such as ecosystems there is a connection between vulnerability of the system and human practices. Environmental management practices can decrease coping capacity of ecosystems and make them more vulnerable to exogenous forces, such as hurricanes and fires (Scheffer et al. 2001). These examples illustrate that we are dealing with coupled human and environmental systems and that an artificial distinction between environmental hazards and human vulnerability does not contribute to fully understanding complex interactions between human and environmental systems.

2 A vulnerability framework

The literature review in the introduction section shows that vulnerability can be considered as the ability to build a threshold against disturbances. Moreover, most reviewed definitions include the ability to cope with disturbances as a determining factor of vulnerability. Some approaches also take the capacity to recover from disturbances into account and include future elements in the approach toward vulnerability (Blaikie et al. 1994; Cannon et al. 2002; Turner et al. 2003). This article aims to develop a comprehensive view on climate change vulnerability of the Netherlands, concerning water management. Therefore, vulnerability is defined in this article, as a combination of the aforementioned components: threshold capacity, coping capacity, recovery capacity and adapting capacity. This vulnerability framework will be elaborated by examples of climate impacts on flood control and water supply, the two main components of current water management practice in the Netherlands. Although this article focuses on water management and climate change, this framework could as well be applied elsewhere to other natural hazards such as earthquakes. Table 1 illustrates the four capacities framework.

2.1 Threshold capacity

Threshold capacity is the ability of a society to build up a threshold against variation in order to prevent damage. In flood risk management, examples are building river dikes and increasing flow capacity to set a threshold against high river flow. In case of water supply, examples are constructing storage reservoirs to increase damage threshold in case of droughts. The objective of building threshold capacity is prevention of damage. The time horizon lies in the past; past disaster experiences of society are the guiding principle to determine the height of the threshold. In the Netherlands, for ages dikes were constructed that had the same height as the highest experienced flood. The dimensions of a water resources reservoir are determined by historic droughts and water use levels. As a result, the uncertainty of the height of the threshold is relatively low. The ability of a society to build, operate, and maintain threshold capacity is determined by its social, institutional, technical, and economic abilities. In the Netherlands, the responsibility of maintenance of flood defense and water delivery infrastructure is clear. Water boards are responsible for maintaining flood defense; water utility companies are responsible for safe and efficient delivery of drinking water.

Table 1 Description of type, hazard frequency, time orientation, uncertainty and responsibility of the four components of the vulnerability framework

Component	Type	Frequency of hazard	Time orientation	Uncertainty of hazard magnitude	Responsibility
Threshold capacity	Damage prevention	High	Past	Low	Clear
Coping capacity	Damage reduction	Medium	Instantaneous	Low	Not clear
Recovery capacity	Damage reaction	Medium	Instantaneous/ future	Low	Not clear
Adaptive capacity	Damage anticipation	Low	Future	High	Undefined

2.2 Coping capacity

Coping capacity is the capacity of society to reduce damage in case of a disturbance that exceeds the damage threshold. For flood management coping capacity of society is determined by the presence of effective emergency and evacuation plans, the availability of damage reducing measures, a communication plan to create risk awareness among inhabitants, and a clear organizational structure and responsibility for disaster management. For water supply, the availability of emergency and backup water facilities that can be used in case of droughts and disasters, are important determinants of coping capacity. The objective of developing coping capacity is reduction of damage. The time orientation is instantaneous, because in case of emergencies, only 'here and now' is important. The uncertainty is low, because the magnitude of the hazard is clear at the time society has to deal with it. Also for coping capacity the ability of a society to build, operate and maintain it is determined by its social, institutional, technical and economic abilities. There is a large range of coping capacity options and in the Netherlands threshold exceeding events for water management do not occur frequently. As a result, it is not clear who is responsible for damage reduction in case of emergencies. Multiple factors such as firefighters, water boards, municipalities, and other government agencies are involved.

2.3 Recovery capacity

The recovery capacity is the third component and refers to the capacity of a society to recover to the same or an equivalent state as before the emergency. For flood control, it is the capacity of a flooded area to reconstruct buildings, infrastructure, and dikes. For water supply, it is the capacity to achieve a functioning water supply and sanitation system. The objective of developing and increasing recovery capacity is to quickly and effectively respond after a disaster. The time horizon is instantaneous right after the disaster but will change gradually toward a focus on the future. Although economical damage estimates might be difficult, the uncertainty of the hazard magnitude will be relatively low compared to the possible future hazard, because the effects will still be noticeable. The economic capacity of the country to finance the reconstruction determines the recovery success to a large extent. However, institutional ability and technical knowledge are also important. A society that is able to recover from impacts of hazards will be less vulnerable for these hazards. Recovery time might range from weeks to decades, depending on the spatial scale and disaster magnitude. Recovering from the Katrina hurricane in New Orleans will probably take years. Although in the Netherlands it is clear who is responsible for reinstalling the flood control and water delivery infrastructure, it is not entirely clear who is financially responsible for compensating the hazard impacts. In the past, the Dutch government often refunded flood damage to house owners. However, also people themselves or insurance companies could be responsible in some cases.

2.4 Adaptive capacity

Adaptive capacity is the capacity of a nation, a community living in a river basin, or even the world to cope with, and adjust to uncertain future developments and catastrophic, not frequently occurring disturbances, like extreme floods and severe droughts. Therefore, the time orientation lies in the future. Although a system may be functioning well, at present, human and environmental developments, both from inside or outside the considered system, can put a system under strain and threaten its future functioning. Examples are climate change, population growth, and urbanization. For flood control, the problem of adapting to uncertain future developments can be illustrated by an example of land use. Although future risks from river or sea floods are unknown, land use decisions that determine future vulnerability are presently being taken. For water supply, a good example is salt-water intrusion. The sea level and river discharge in 2050 are unknown; hence also the future problem of salt-water intrusion into the Dutch river delta is unknown. However, decisions to construct inlets for drinking water production points in this delta are currently being made.

The objective of developing adaptive capacity is to anticipate on future developments and impacts by constructing a robust living and working environment. The uncertainty of the nature and magnitude of future hazards and impacts are high and the frequency of occurrence is low, which is also illustrated in Fig. 2. The capacity to adapt to these uncertain developments also determines the vulnerability of a system. Although the exact size and nature of changes are unknown, solutions will have to be developed for long time horizons and financial and spatial reservations to allow for adaptations will have to be made. The IPCC (2001) has made a list of categories of determinants of the adaptive capacity of society:

1. The range of available technological options for adaptation.
2. The availability of resources and their distribution across the population.
3. The structure of critical institutions, the derivative allocation of decision-making authority, and the decision criteria that would be employed.
4. The stock of human capital including education and personal security.
5. The stock of social capital including the definition of property rights.
6. The system’s access to risk spreading processes.
7. The ability of decision-makers to manage information, the processes by which these decision makers determine which information is credible, and the credibility of the decision makers themselves.
8. The public’s perceived attribution of the source of stress and the significance of exposure to its local manifestations.

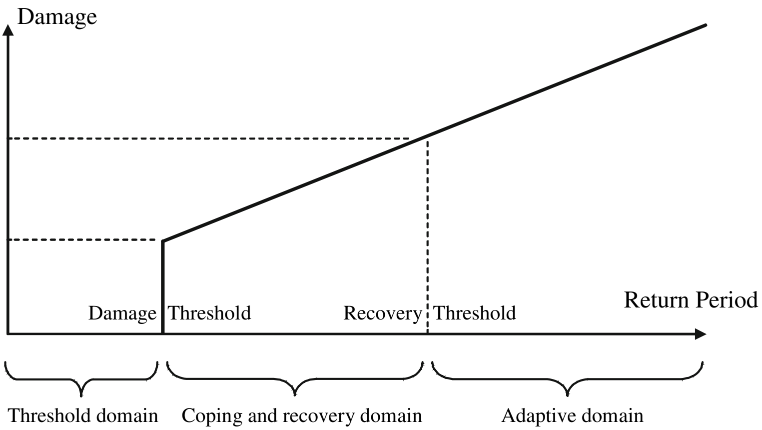

Fig. 2 The four components and three domains of the vulnerability framework illustrated by a damage return period graph. The three domains are interrelated, changes in one domain affect the other domains, resulting in an overall change in vulnerability

The list points the large number of options available for society to increase its adaptive capacity, varying from technical options (1) to insurance policy (6) or communication strategies (8). The range and variety of possible adaptive options are large and the number of involved organizations in the adaptive capacity determinants is also large. Consequently, there is not a clear picture about who is responsible for strengthening adaptive capacity. Moreover, there is societal disagreement about the developments, the problems, and the solutions that are relevant for adaptive capacity.

3 Complex interactions between vulnerability components

It is a societal objective to become less vulnerable to all kinds of hazards, long term and short term. However, to decrease vulnerability is a complex task. Vulnerability components are highly connected. Consequently, increasing one vulnerability component often decreases one or more of the other components resulting in higher, rather than reduced vulnerability. The connection between vulnerability components is illustrated. Figure 2 presents a conceptual damage return period graph. As a result of dike construction or reservoir construction, environmental variations with low return periods will cause no damage. This is the threshold domain in Fig. 2.

Even if thresholds have been built, there will be some occasions when the threshold will be exceeded. Then, coping with hazard impacts and recovering from them is necessary. This is the coping and recovery domain in which damage reduction is the prime goal. Finally, there are very unlikely events with very long return periods where the expected damage is so extreme that recovery is neither feasible nor possible. These types of occasions, we want to prevent by adapting. Therefore, this is the adaptive domain. Figure 2 illustrates that by increasing the threshold domain, for instance by building higher and stronger dikes for flood control or by building reservoirs for water resources, the coping and recovery domain becomes smaller. However, these domains are important; by coping and recovering people become aware of risks. An approach that only focuses on increasing threshold capacity results in a system that is increasingly vulnerable to rarely occurring disasters. Disasters that cause damage will occur less frequently, but the ones that do occur will cause more damage. Consequently, for a complete vulnerability reducing strategy, attention should be paid to all components and domains of vulnerability.

4 Vulnerability of flood defense

Evaluation of flood defense in the Netherlands is founded on safety design standards that are based on a probability of exceedance of a certain water level. The design standards are given in Fig. 3. These safety design standards are the threshold capacity of society against flooding.

Flood disasters of the past have led to a process of continuously increasing the height and strength of dikes. Due to this process, the damage threshold return period has become very high. The damage threshold is an average statistical return period of the design water level. Based on this design water level, the height of dikes is determined. The return period design standard varies from $T = 10{,}000$ year for coastal flooding in the densely populated Randstad area, to $T = 4{,}000$ year in the less densely populated areas and

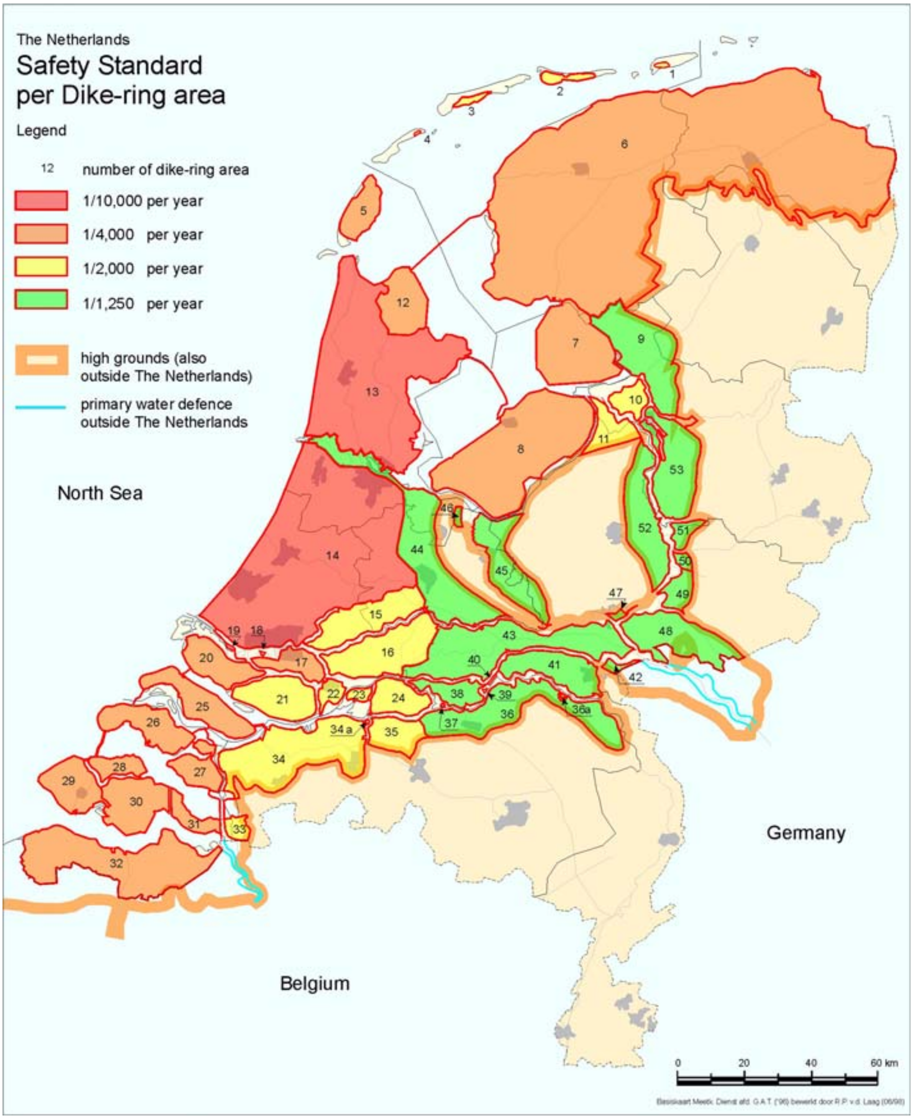

Fig. 3 Safety standards of Dutch flood defense system. In the densely populated western part of the country, the design return period is highest, $T = 10{,}000$ years. In the other parts of the country, the design resturn period is lower, $T = 4000$ years, $T = 2{,}500$ years, and $T = 1{,}250$. From these design standards, water levels have been derived that have been used to determine the height of the dikes (Source: Ministerie van Verkeer en Waterstaat 2005)

$T = 2{,}000$ year, and $T = 1{,}250$ year in the areas that are prone to river flooding. One could argue that this threshold is also the recovery threshold because the expected damage in case of sea defense failure is 400 billion Euros which is larger than the Dutch yearly available national budget (Ale 2006). However, this damage amount would be in case of complete inundation of the low-lying areas of the Netherlands, which is not impossible but extremely unlikely. In the “Flood Risks and Safety in the Netherlands” project Floris (Ministerie van Verkeer en Waterstaat 2005), the expected damage of dike failures for multiple locations in multiple scenarios has been calculated. Expected damage figures range from 1.9 billion euro in case of a single dike failure in Scheveningen up to 37.2 billion euros in case of three simultaneous sea dike failures. The number of expected fatalities range from 100 in case of an expected flood, one single dike failure and organized evacuation, up to 5,090 in case of three simultaneous dike failures, an unexpected flood and no evacuation (Jonkman 2007). The annual probability of flooding is much higher than the design standards, ranging from $T = 2{,}500$ years in Zuid-Holland to $T = 100$ years in the rivers region. This is due to the fact that dike failures often take place by other mechanisms than dike overtopping in case of high water levels.

Heavily urbanized areas will be increasingly vulnerable for natural hazards (Mitchell 1999). The estimated amount of required new houses in the Netherlands in the period until 2030 varies from 1 to 1.5 million in various scenarios (VROM et al. 2005). In the Netherlands urbanization, continued land subsidence and sea-level rise will result in increased flood risk vulnerability. This will result in an increasingly densely populated, increasingly low-lying area under an increasing sea level. Under these conditions, increasing damage thresholds by further rising and strengthening of dikes, will not give absolute certainty that future disastrous flooding events will have no negative impacts. On the contrary, absolute security is impossible and statistically there will always be occasions where the threshold will be exceeded and where coping and recovering is necessary. In the Netherlands, there is a change from water-level-based design standards to a more integrated risk-based approach that includes more failure mechanisms than only dike overtopping and takes into account the impacts of flooding in addition to flood hazards. This opens up possibilities for measures and strategies that decrease flood impacts by increasing coping capacity and recovery capacity in addition to increasing threshold capacity. Moreover, adaptive measures to counter uncertain changes to both more variability of the water level and gradual changes in the mean water level are necessary. High amounts of invested capacity in low-lying areas and a high threshold capacity have made the Netherlands highly vulnerable to floods with a high return period. Therefore, for a complete vulnerability strategy, attention should be paid to all four components of vulnerability and measures should be included that increase coping capacity, recovery capacity, and adaptive capacity.

5 Vulnerability of water resources

In the western part of the Netherlands, urban areas depend on external river water resources, in particular the Rhine, for their water supply. In the eastern part, mainly ground water is used. In this chapter vulnerability of water resources in the Netherlands is analyzed by addressing possible future developments.

Recent climate scenarios of the Royal Netherlands Meteorological Institute are presented in Table 2. Detailed information about the climate change scenarios for the Netherlands can be found in the scientific report (KNMI 2006). Two main driving forces were selected to construct the scenarios by running combined simulations of both General Circulation Models and a Regional Climate Model. The first driving force is global temperature change. For the low (G) scenarios, global temperature increase is +1°C in 2050 and +2°C in 2100. For the high (W) scenarios, global temperature increase is +2°C in 2050 and +4°C in 2100. The second driving force is the change of the mean seasonal regional atmospheric circulation. This driving force determines the Dutch regional climate to a large extent. Predominantly western atmospheric circulation, very similar to the current

Table 2 Four scenarios for climate change in the Netherlands in 2050 relative to 1990. Two driving forces were selected to construct the scenarios, the change in the atmospheric circulation pattern and the global temperature change. In the + scenarios there is a strong change in the atmospheric circulation pattern. In the other scenarios this change is weak. The G scenarios have a relatively small global temperature increase, the W scenarios have a higher global temperature increase (KNMI 2006)

2050		G	G+	W	W+
Global temperature increase in 2050		+1°C	+1°C	+2°C	+2°C
Change of atmospheric circulation		Weak	Strong	Weak	Strong
Winter	Mean temperature	+0.9°C	+1.1°C	+1.8°C	+2.3°C
	Precipitation	+4%	+7%	+7%	+14%
Summer	Mean temperature	+0.9°C	+1.4°C	+1.7°C	+2.8°C
	Precipitation	+3%	−10%	+6%	−19%
	Potential evaporation	+3.4%	+7.6%	+6.8%	+15.2%
Sea level	Absolute increase	0.15–0.25 m	0.15–0.25 m	0.20–0.35 m	0.20–0.35 m

situation, results in a relatively mild and temperate climate whereas a change towards more eastern circulation conditions would change the regional climate into a more continental climate with dry and hot summers. In the + scenarios (G+ and W+), a strong decrease of the western atmospheric circulation takes place in summer. As a result, warm, dry continental air is transported to the region. In winter, the + scenarios adopt a slight increase in western circulation. For the other two scenarios (G and W), in summer a small increase of western circulation flow takes place. In winter, there is no change compared to the current situation. The four scenarios were designed to span a large part of possible futures in order to deal with the uncertainty of future changes. Based on current insights that are derived from current climate models, the probability that the future climate will be within the range of the four scenarios is estimated at 80% (KNMI 2006). Therefore, there is not a 'most likely' scenario and all four scenarios should be used to develop water management options.

In the + scenarios summer droughts will occur more frequently, resulting from lower precipitation and higher evaporation. The resulting water shortages can be partly covered by a higher precipitation amount in winter. In that case, however, water storage capacity should be available. In the Netherlands, limited terrain level differences are available for water storage and the current water management practice is characterized by artificially maintaining water levels at fixed targets in polder water systems, thus limiting the potential for water storage. In the other two scenarios (G and W), the expected increase in evaporation is only a little higher than the increase in precipitation. However, even in case of these two scenarios, the frequency of droughts may increase. A higher temperature will probably lead to rising water use for agricultural, energy (cooling) and residential purposes (Drunen 2006). A higher water level will lead to increased seepage of brackish groundwater into the Dutch polders under sea level which will in its turn increase the demand for fresh water to flush the polder water systems (Oude Essink 2001; de Bruin and Schultz 2003). Unfortunately, the exact size of these effects of climate change on water management in the Netherlands is not known. More research, well outside the framework of this study, is needed to quantify these effects more precisely.

In addition to internal water resources, such as precipitation, also external water resources will be affected by climate change. At present, large rivers, in particular the Rhine, generate a relative constant supply of water to the Netherlands during summer.

This constant flow consists for a considerable part of snowmelt from its Alpine catchment. Melting off peaks usually occurs in June (van de Ven 1996). However, the mean temperature in Europe is expected to increase, which would generate an earlier snowmelt that will increase the possibilities of water shortages in summer. The expected summer discharge of the Rhine will decrease with 10% in an average climate scenario and even 60% in a dry scenario (NMP 2004). As mentioned, another effect of climate change is sea level rise, this effect, combined with land subsidence and lower river discharge in summer can result in problems with salinity. Consequently, water intake from rivers in delta areas will become more difficult and the chance of water shortage will increase. The exceedance frequency of a year with very high salinity in the delta, increases with 80% in an average climate scenario (RIZA 2005). As a result, water inlets will have to be closed more often.

All mentioned developments in this chapter, summer river discharge, precipitation, and sea level rise are characterized by wide margins of uncertainty. At present, little is known about the specific effects of climate change on water management in the Netherlands. However, the size of changes and precise effects may be uncertain, the direction of change is not. All mentioned developments and effects in this chapter contribute to more frequently occurring droughts in the future (RIZA 2005). Therefore, cities that continue to depend only on one single external water resource, either river water resources or external groundwater resources, will be increasingly vulnerable to droughts.

6 Toward reduced vulnerability

It is important for countries in general, to become less vulnerable for flooding and droughts. For that purpose, all four components of vulnerability should be taken into account. Not only strengthening and raising dikes, but also investing in risk communication, emergency plans, and experimenting with other modes of urbanization. Not only focusing on better and more efficient water storage and delivery infrastructure but also on demand management, water saving technology and decentralized, more flexible water supply. This adds diversity to the options society has available to face uncertain future developments and disturbances. In many fields of science, strengthening diversity as vulnerability reducing measure has been advocated. Examples of these fields are ecology, corporate management sciences, public management sciences, and economics.

According to the Panarchy theory, human and natural systems are more capable to cope with and adjust to shocks and disturbances, if they are more diverse (Gunderson and Holling 2001). The Panarchy theory was developed by landscape ecologists that applied the theory to a broader context and by studying social systems. However, also in other scientific disciplines diversity as a strategy to reduce risks is mentioned.

In economics for instance, portfolio management is used to reduce risk to investments for future uncertain disturbances. By building a portfolio of investments with a low-mutual correlation the investor minimizes effects of disturbances on his returns. Fraser et al. (2005) have shown that applying the concept of financial portfolio management offers insight in reducing the vulnerability of urban supply chains, in their case food supply of urban areas.

In corporate management sciences, the interlinkages among diversity, vulnerability and supply chains of resources and products are studied as well. In “The Resilient Entreprise”, Sheffi (2005) shows that diversity and flexibility in the supply chain of companies, can give them competitive advantages over their rivals in case of unanticipated disturbances such as fires, strikes or terrorists attacks. More diversity leads to a company less vulnerable to uncertain future disturbances. The recovery capacity of a company to bounce back after a disturbing event is enhanced by building in redundancy and flexibility.

In public management sciences, diversity is also an important aspect. An approach to deal with complex problems under conditions of high uncertainty is transition management (Rotmans 2003), which focuses on realizing a societal transformation to decreased vulnerability. Transitions typically take a generation or more to develop. Transition experiments are small-scale experiments aimed at sustainable system innovation. For highly complex problems, it is impossible to develop the solution beforehand. After all, the effects of climate change are uncertain, and so are the available future technologies and their consequences. Therefore, experimenting and learning by doing is necessary. By executing transition experiments, learning with new modes of supply, takes place rather than optimizing existing infrastructure. The information and experience gained by these experiments provide diversity to society and are used to improve other experiments until enough information is available for a transition of the water system from centralized to decentralized water supply.

What could a diversity increasing, vulnerability reducing water management strategy look like? Based on the four-component vulnerability framework, Table 3 gives the following vulnerability decreasing measures for water supply and flood control.

Current vulnerability reducing strategies of water supply companies mainly focus on threshold increasing measures and little on coping-capacity measures. Examples of threshold capacity measures are improved water storage and delivery infrastructure. This is not a complete vulnerability strategy. This article identifies options to add coping, recovery, and adaptive components to current strategies in order to achieve a complete vulnerability strategy. In order to quantify the effectiveness of these options to reduce vulnerability for climate change is not yet possible because (1) there is no information yet about the specific impacts of climate change on local urban water systems in the Netherlands and (2) information about the effectiveness of new local concepts for water supply and flood control is lacking, since most research is aimed at optimizing the current water management infrastructure. Therefore, within the scope of this article, vulnerability reducing options will be discussed by using the vulnerability framework to contribute to future research on the effectiveness of these options.

The expected changes, described in Chapter 5, indicate more frequently occurring dry spells, a higher sea level and lower river discharge. Therefore, the probability increases

Table 3 Overview of vulnerability decreasing options for water supply and flood control classified according to the four components of vulnerability

	Water supply	Flood control
Threshold capacity	More water storage	Higher and stronger dikes
	More efficient water delivery infrastructure	Increased river capacity
Coping capacity	Emergency plans	Emergency plans and timely flood warning
	Backup water supply facilities	Improved communication of risks to inhabitants
Recovery capacity	Multi source water supply	Insurance
	Disaster funds	Disaster funds
Adaptive capacity	Experimenting with other modes of water supply	Experimenting with other modes of urbanization

that conventional drinking water production by centralized drinking water treatment plants in the Dutch river delta will be hindered. In such a situation, water use restrictions, low water reservoir levels, and decreasing drinking water quality will occur. Not only residential water use will be affected, but also industry, shipping, electricity plants and agriculture. This will result in huge economic losses. In 1976, the driest year in recent history, the total estimated economic damage was multiple billions of Euros and disruption of drinking water supply occurred (RIZA 2005). The statistical return period of the 1976 drought is 100 years, however in 2050, the return period of a comparable dry year is estimated to be 45–60 years (RIZA 2005).

During a drought such as 1976, the measures indicated in Table 3 would mitigate damage. In urban areas, local water resources such as recycling of effluent and stormwater would easily compensate for the lack of river water resources and rainfall. Stormwater, for instance, is a relatively clean source that is not yet used for drinking water production. This source has the potential to make urban districts self-supporting with regard to their water supply (de Graaf and van de Ven 2005). However, stormwater is mostly converted to wastewater in combined sewer systems. By using local resources in addition to centralized supply, urban districts in the country would not depend on one single external source but instead use a combination of local stormwater, river water, recycled effluent and regional surface water. Emergency plans and backup emergency facilities, such as water trucks and backup water supply points in each city would also reduce damage and secure water supply for the population. Moreover, recovery to a normal water supply condition would take place more quickly as cities would not be depending on external water resources only. The societal knowledge and experience that would have been built by small scale experiments with other modes of supply would enable society to switch to alternative local sources if conventional external sources are scarce.

The drought example illustrates the importance of building experience with new modes of water supply. Our current large scale, centralized water supply may be optimal during normal supply and demand conditions, however, the system is not necessarily the best choice during droughts. Therefore, this system should be supplemented with a system that utilizes local water resources to become more flexible and less vulnerable. Demonstration projects and transition experiments with local urban water resources are needed. By executing these types of transition experiments, society's options increase in face of uncertain future developments. Moreover, executing transition experiments is a search and learning process for involved actors to deal with new roles, responsibilities and organizational arrangements. A transition process to multi-source local water supply has consequences for the local water system, the local built environment and the responsible organizations, such as municipalities and water boards. This requires new roles for municipalities, water boards and residents. By actively participating in the execution of transition experiments, these actors can contribute to reduce vulnerability. In the current situation of large scale, centralized water supply, these actors are not yet actively involved.

Also in flood control, the emphasis seems to be on increasing threshold capacity to reduce vulnerability. Examples are constructing higher and stronger dikes and increasing the discharge capacity of rivers. Chapter 4 mentioned that a simultaneous failure of three dikes could lead to more than 5000 fatalities and 37.2 billion Euro damage. In such a situation, the measures indicated in Table 3 would mitigate damage. Timely flood warning and improving risk communication would make residents better prepared to cope with flooding. These factors are critical to reduce loss of life (Jonkman 2007). The current potential for evacuation in the Netherlands is limited, however, this would be different in the future if there would be more local shelter and emergency refuge areas. Improving recovery capacity could be done by insuring flood risks, which is not common practice in the Netherlands at this moment. Insurance is a risk spreading mechanism that provides financial means after a disaster. Disaster funds work in the same way and would strengthen the ability to reconstruct the urban environment and re-establish normal economic activities after the disaster by providing financial means. An adaptive measure, finally, would for example be experimenting with other modes of urbanization that do not or less, increase flood risk. Such modes of urbanization would be wetproofing and dryproofing of buildings, building on mounds, building on piles or constructing floating cities. Adaptive measures would have two mitigating effects: (1) Buildings and the urban infrastructures are more resistant against the impacts of flooding and (2) local refuge areas are created that provide shelter for residents during floods.

A broad range of actors such as insurance companies, construction companies, municipalities, and residents should be involved to successfully develop a complete vulnerability strategy that consists of the measures mentioned in Table 3. Also in this case, starting an explorative learning process by experimenting with more climate robust concepts of urbanization, increases society's options in face of uncertain future development.

7 Concluding remarks

The objective of this article was to identify alternative water management options to decrease vulnerability of urban areas to climate change. A four-component vulnerability framework was presented in this article. This framework consists of threshold capacity, coping capacity, recovery capacity and adaptive capacity. Threshold capacity is the ability to build up a threshold against variability in order to prevent damage. Coping capacity is the capacity of society to reduce damage in case of a disturbance that exceeds the damage threshold. Recovery capacity is the third component and refers to the capacity of a society to recover to the same or an equivalent state as before the disturbance. Adaptive capacity is the capacity to cope with, and adjust to uncertain future developments and catastrophic, not frequently occurring disturbances like extreme floods and severe droughts. The vulnerability components are strongly interrelated; increasing one component typically leads to the decrease of one or more other components.

Based on this framework it can be concluded that current strategies for water supply and flood control management mainly focus on the first component of vulnerability, threshold capacity. Developments such as climate change, urbanization and land subsidence will increase the vulnerability of urban areas. These developments are characterized by wide margins of uncertainty. Various fields of science highlight the importance of increasing diversity in face of uncertain future developments to reduce vulnerability.

For a diversity increasing, vulnerability decreasing strategy it is necessary to include all four components of vulnerability: threshold capacity, coping capacity, recovering capacity and adaptive capacity. Emergency plans and improved risk communication are possible coping capacity increasing measures. Multi-source water supply contributes to an increased coping and recovering capacity of water supply systems in case of droughts. Insuring flood risks or setting up disaster compensation funds could increase recovery capacity in flood risk management. Pilot and transition experiments are important as a first step in order to increase adaptive capacity for uncertain future developments. Including all four components of the vulnerability framework enables better understanding of water and climate related vulnerability of urban areas and enables developing more complete water management strategies to reduce vulnerability.

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