Lessons learnt from adaptation planning in four deltas and coastal cities
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ABSTRACT

Deltas and coastal cities around the world face the need to adapt to uncertain future changes. We compared adaptation planning on flood risk management in four cases based on three main elements of adaptive planning: to prepare for a wide range of plausible future scenarios; to respond to change with robust and flexible actions; and to monitor critical changes to be able to reassess the plan accordingly. Differences can be observed in the implementation of these elements. Good practices could be distinguished: cases consider a wide range of future scenarios; short-term decisions are coupled with long-term options while envisioning these options and possibilities for switching between them through adaptation pathways; opportunities originating from other agendas to achieve multiple objective investments are seized; and the system’s resilience is improved by a wide variety of measures. At the same time some barriers for using adaptive planning approaches were identified: the use of a wide range of scenarios is only accepted in an exploratory phase of planning. Structural flood protection measures taken in the past do constrain future choices. The potential for monitoring and reassessment of options is hampered by the fact that trends in some variables cannot be detected.

Key words | adaptive management, cities, climate change, deep uncertainty, deltas, flood risk

INTRODUCTION

The world’s river deltas and coastal cities are increasingly vulnerable due to pressures from climate change, relative sea level rise, and population growth (Mulder et al. 2009; Svyitski et al. 2009; Vörösmarty 2009; Renaud et al. 2013). Therefore, in densely populated deltas and estuaries such as the lower Rhine delta in the Netherlands, the Thames estuary in the UK, the Hudson in New York, and the Ciliwung delta on Java (Indonesia), spatial planning is challenged to enable socioeconomic developments and well-designed water management to provide services such as flood risk management, fresh water supply, and good environmental conditions. Decisions on water management and spatial developments are needed to prepare for future changes. However, uncertainties about the future, the dynamic nature of deltas, and the interaction between the environment and society make such decisions less than straightforward. Decisions avoiding adverse impacts and seizing opportunities are preferred, as the implementation of actions takes time and some actions that may have been possible in the past or at present may not be possible in the future.

Plans are often crafted to operate within a certain range of conditions. But this traditional approach of engineering based on the assumption of a more or less stationary climate is quickly losing ground (Milly et al. 2008).

Experience demonstrates that if this range is too small, such plans have unintended impacts or do not achieve their objectives if the future turns out differently. In case of severe uncertainties (sometimes called deep uncertainties), robust policies and adaptive policies are needed. Robust policies perform well under a wide range of plausible futures, while adaptive policies can be adapted once the future unfolds differently than foreseen. Walker et al. (2015) discriminate
between static and dynamic robustness. The first can also be regarded as the robustness (Mens et al. 2011) of the (physical) system, the latter as the flexibility of the adaptation plan. In some studies (Wardekker et al. 2009), resilience is also regarded as a characteristic of the system under consideration.

Several approaches to develop for such adaptive plans have been proposed in the literature (e.g. Walker et al. 2001; Lempert et al. 2005; Albrechts 2004; Pahl Wostl et al. 2007; Hallegatte 2009; Swanson et al. 2010; Reed & Ranger 2012; Haasnoot et al. 2013). Not only in research but also in practice, planners are increasingly developing adaptive policies to deal with uncertainties (Swanson & Bhadwal 2009).

Considerable efforts have been made to compare adaptation approaches among different areas in the world. These comparisons focused on flood risk strategies (e.g. Wilby & Keenan 2012; Ward et al. 2013), climate proofing of coastal cities (Aerts et al. 2009), vulnerability and adaptive capacity of deltas (Bucx et al. 2010), or deltaic tipping points (Kwadijk et al. 2010; Renaud et al. 2015).

In this paper we expand on these previous studies by analyzing flood risk management policies and the related adaptation planning approaches applied to deal with uncertain future changes for four deltas and coastal cities in developed and developing countries. The main research question is: How are elements of specifically adaptive planning applied (or not applied) to flood risk management in practice?

Central elements of adaptive planning are (Sayers et al. 2012): responses to changes are effective under the widest set of all plausible future scenarios; responses do not foreclose future options or unnecessarily constrain future choice; relevant changes are foreseen through targeted monitoring and scenarios of the future are continuously being reassessed; and policies, strategies, and structure plans are appropriately redefined. We add to this the element of ‘no or low regret’. No regret options in case of uncertainties are actions that have properties such as robustness, flexibility, and reversibility (Refsgaard et al. 2009).

More specifically, the following three main sub-questions, reflecting the main elements of adaptive planning, are investigated using four case studies:

(1) How is the ‘widest set’ of plausible future scenarios defined and used in the assessment of strategies within the four cases?

(2) How are robustness and flexibility being considered? Are actions chosen to remain flexible with respect to uncertain future changes and/or to create a robust system that may better cope with extreme events? In other words, how is ‘low regret’ of decisions safeguarded?

(3) How is monitoring and reassessment accounted for in the plan?

The questions correspond with the logical triad: what to prepare for, how to respond, and what to monitor?

The four cases considered are as follows:

- Dutch Delta Program (DP), planning for adaptation in flood risk management for the Rhine-Meuse delta in the Netherlands.
- Thames estuary 2100 (TE2100) project in the UK, having delivered a plan for flood risk management in the Thames delta.
- PlaNYC 2013. The renewed initiative to adapt New York City after Hurricane Sandy to increasing flood risks (New York City Office of the Mayor 2013).
- Jakarta Coastal Defence Strategy (JCDS). The project for better protecting against increasing flood risks due to subsidence and sea level rise (JCDS 2011).

We review and compare the activities on adaptation planning in the four cases on how they tackle the three elements of adaptive planning. Are the chosen approaches fit for purpose? What lessons can be learnt for application in other cases?

**APPROACH FOR COMPARING FOUR DELTAS AND COASTAL CITIES**

The deltas and coastal cities discussed in this paper share, to some extent, the characteristics that they are highly populated, highly dynamic in terms of economic activity, and share challenges with respect to combined (potential future) effects of sea level rise, river flooding, and soil subsidence. All four cases can be regarded as ‘hotspots’ where climate and socioeconomic changes coincide, but with different challenges in the short and long term. In addition, in all cases there is an active policy and research community jointly working on meeting these challenges. The information on adaptation planning is drawn from the authors’
experiences (all are involved in advising governments on adaptation planning in one of the cases) and their colleagues in working on the adaptation planning.

A general procedure to make an adaptive plan and comply with the aims as described by Sayers et al. (2022) is given by the ‘dynamic adaptive policy pathways’ framework (Haasnoot et al. 2013) that combines the approach of adaptive policy making (Kwakkel et al. 2010) and adaptation pathways (APs) (Haasnoot et al. 2012). The framework consists of the steps as depicted in Figure 1. In short: (1) analyze the policy agendas to identify the main objectives now and in the future. Identify the external developments that these objectives are most vulnerable for and consequently define scenarios. (2) Assess what amount of change can the system handle: what is the critical level (adaptation tipping point; Kwadijk et al. (2010)) before the objectives are not met any more? Assess when this occurs by using the scenarios. Besides critical levels that may be a threat to objectives, opportunities may be defined that may help to achieve objectives. Determine possible adaptation actions and by iterative assessment select successful actions (e.g. actions that increase the success of the policy). (3) Once a set of action seems adequate, potential pathways (a sequence of actions) can be constructed and subsequently one or more preferred pathways can be selected as input for a dynamic adaptive plan (4). The aim of this plan is to keep the preferred pathway open as long as possible. For this purpose, contingency actions and triggers for contingency action are specified and after implementation of the plan (5), the variables inducing these triggers are monitored (6).

To compare the cases systematically for the three main research questions a list of questions (Table 1) was made based on the stepwise approach by Haasnoot et al. (2013).

**FOUR DELTAS AND COASTAL CITIES WITH DIFFERENT CHALLENGES**

**Thames estuary (TE2100)**

The Thames estuary is dominated by the London metropolitan area with over 15 million inhabitants. The tidal river Thames serves as a major transport route for the city, one of the UK’s major ports. Flood protection standards are high as compared to the rest of the UK with most of the estuary protected to 1/1,000 years. The current flood defense system mainly consists of walls, embankments, flood gates, and the Thames Barrier. The main drivers for adaptation
are climate change and rising sea level, increase in development of the flood plain, and an aging flood defense system. The Thames Estuary 2100 project (TE2100) was established in 2002 with the aim of developing a long-term tidal flood risk management plan for London and the Thames estuary. The project covers the tidal Thames from Teddington in West London, through to Sheerness and Shoeburyness in Kent and Essex. A key driver for the project was the need to develop an adaptable long-term plan in the context of a changing estuary. The project was aimed at tackling tidal flood risk but was multidisciplinary in its approach. The project developed options in an iterative fashion through three main phases of development with stakeholder engagement at each phase. The second stage presented high-level options in the form of possible pathways or route maps which can cope with an increase in maximum water level from today’s level all the way to a revised worst case of a 2.7 m increase.

The final draft plan was derived from these options with a planning assumption of 0.9 m increase in water levels by the end of the century. It recommends particular policies for different parts of the estuary. In the main these policies will maintain the current level of flood risk or improve it. Given these planning assumptions it will not be necessary to build a new Barrier or substantially rebuild the existing one until 2070. The plan lays out how planned measures can be adapted if critical indicators such as the actual or predicted rate of sea level rise change significantly in the future (http://www.environment-agency.gov.uk/homeandleisure/floods/104695.aspx).

**New York**

Located on one of the world’s largest natural harbors within the Hudson river estuary, the New York City Metropolitan Area’s population is the United States’ largest, with 18.9 million people. The city serves as the world’s leading financial center and the country’s main economic center. New York has a long experience in dealing with risks of natural hazards, such as flooding events. The greatest flood risks are caused by storm surges as a result of hurricanes or north-eastern storms in combination with high tides (New York City Panel on Climate Change (NPCC) 2013). Between 1900 and 1999, severe hurricanes of category 5 struck the New York area six times (Neuman et al. 1999). Most notable are the recent Hurricane Sandy and the hurricane of 21 September 1938. Although single events cannot be attributed to climate change, it is recognized that due to sea level rise coastal flooding events may increase in strength and frequency. Since the late 1990s, accelerated sea level rise and exacerbated coastal flooding associated with climate change has been seriously considered by New York City (Rosenzweig et al. 2011; New York City Panel on Climate Change (NPCC) 2013).

The approximately 600-mile-long coastline and densely populated complex urban environment in combination

| Table 1 | List of questions for each step in the adaptive planning framework used to describe the cases |
|---------------------------------------------|--------------------------------------------------------------------------------------------------|
| Step (Figure 1) | Question/indicator |
| Step 1 Scenarios | Which developments are included in the scenarios? (climate, socioeconomic, subsidence)  |
| What type of scenarios are used and how many? (predictive, normative, explorative)  |
| What are the time scale and temporal nature of the scenarios? (projection years, which horizon, discontinuous or trends)  |
| Impact assessment | What are the main vulnerabilities and opportunities?  |
| How are impacts assessed?  |
| Steps 2 and 3 Strategy development | What (type of) measures are determined?  |
| What (type of) strategies are included? (robustness, resilience, flexibility, structural, non-structural, green, gray, etc.)  |
| (How) is timing of actions included?  |
| Step 4 Adaptive plan | How are promising strategies determined and translated into a plan?  |
| How is the robustness and/or flexibility of the plan safeguarded? What do investment paths look like?  |
| Steps 5 and 6 Implementation and monitoring | How is monitoring and reassessment included in the definition of the plan?  |
with potential hazards puts it in the top 10 of populations vulnerable to coastal flooding world-wide (Le Blanc & Linkin 2010). The vulnerability of the main sectors and communities has been well established by the NPCC and at a state level by the Climaid initiative (Rosenzweig et al. 2012b).

In 2007 the city’s sustainability plan PlaNYC was launched including several measures that make the city more resilient to flooding, such as creating wetlands and flood-resilient new developments. The impacts of Sandy proved that these investments were just, but the huge damage caused by the storm also pressed to redouble the action. Therefore only recently, in June 2013, the Mayor of New York launched a US$20 billion (10^9) urban-planning initiative that seeks to prepare the city for extreme weather and rising tides in the decades to come until 2050 (New York Times 2013). The coastal protection plan follows a multi-layer approach consisting of 37 initiatives across the area (New York City Office of the Mayor 2013).

**Delta Program in the Netherlands**

The Rhine-Meuse delta in the Netherlands is a river delta that has originated from marine and fluvial sediments but over the last 1,000 years mainly has been shaped by humans. The digging of canals, drainage systems, creation of polders, the embankment of rivers, and coastal protection has brought prosperity to the delta. In this way the Dutch were able to control water levels and reduce the frequently occurring floods. On the other side, the lack of new sedimentation and extensive drainage has caused land subsidence in substantial parts of the country below sea level (see Figure 2).

With the first delta plan, which started in 1960 and was finished in 1997, one of the best protected deltas in the world was created, with high safety standards and extensive dams and barriers. About 9 million people now live well protected in areas prone to flooding (high risk and very low probability). The DP (Delta Program 2012), which started in 2010, aims to prepare a set of strategic decisions for sustainable flood risk protection and fresh water supply under future change. The time horizon is 2100.

In the DP the flood risk issues to be solved are three-fold. First, there is the current mismatch between protection standards and the present performance of dikes in some parts of the country. Secondly, there is the question of whether the increasing socioeconomic developments since the 1960s should lead to higher protection levels (Kind

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**Figure 2** | Sea level rise and land subsidence for a typical low lying polder in the Netherlands (Van de Ven 1993).
Thirdly, there is the question of how to adapt to future changes in climate (e.g. increasing river peak discharges and sea level rise) and socioeconomic changes. Although the program is directed toward flood and drought risks, it is highly multi-sectoral in its approach. The program is initiated by national government and executed for a large part in regional sub-programs where interests of different governmental and non-governmental parties meet. The approach of joint fact finding is used to include stakeholders and science in the decision-making process. The program deliberately follows an adaptive planning approach called ‘Adaptive Delta management’ (Delta Program 2012; Van der Brugge et al. 2012). The main decisions were made at the end of 2014.

**Jakarta Coastal Defence Strategy**

Jakarta is located on the north coast of Java, Indonesia. The city of Jakarta itself has 9.5 million inhabitants. Together with the daily commuters from the suburban areas, the daytime population is over 12.5 million (JCDS 2014). Jakarta is rapidly developing. There are many threats to the urban development, including uncontrolled urbanization, heavy traffic problems, water pollution, supply of drinking water, and flood risks (e.g. Steinberg 2007). In this paper we concentrate on the latter. Flood risks in Jakarta can be characterized by flooding from the sea, from rivers, and from rainfall.

The flood problem in Jakarta is being aggravated by many drivers, both physical and socioeconomic in nature. In terms of physical changes, rapid land subsidence is a key problem in Jakarta (Figure 3). Land subsidence in the coastal parts of the city has occurred at 1–15 cm per year in recent years, with more rapid subsidence in some areas (Abidin et al. 2011). Land subsidence has four possible causes, namely, groundwater extraction, construction loads, natural consolidation of alluvium soil, and geotectonic adjustments. In Jakarta, groundwater extraction for water supply is believed to be the most dominant (Chausard et al. 2013). Hence, while land subsidence may be seen as a physical change in the system, it is clearly driven by socioeconomic activities in the region. Another major

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**Figure 3** | Land subsidence in Jakarta compared to the flooding event induced by the 18.6 year tidal cycle in 26 November 2007. The upper blue line shows that expected effect of sea level rise is only marginal. The full colour version of this figure is available in the online version of this paper.
contributing factor to past flooding in Jakarta has been the lack of drainage and/or storage capacity in the city’s waterways, partly due to them being clogged up by sediments eroded from upstream and by solid waste (e.g. Steinberg 2007). On top of these problems, climate change may bring an additional increase in hazard frequency and magnitude in the future, both due to increased sea level and increased precipitation intensity frequency (Ward et al. 2013). At the same time, major socioeconomic development in Jakarta and the surrounding region has led to a massive increase in exposure and vulnerability over recent decades. Over the last half century, Jakarta’s population has risen rapidly from 2.7 million in 1960 to 9 million in 2007 (Badan Pusat Statistik; BPS Jakarta 2010). The gross domestic product of Indonesia is projected to grow by ca. 4.5% per year between 2005 and 2030. Hence, the population and value of assets exposed to flooding is increasing rapidly.

The overall aim of JCDS is to protect Jakarta against coastal flooding. To do this, a strategic plan has been developed that ‘integrates effective technical solutions to prevent flooding (dikes, retention ponds, and pumps) with additional measures to make the technical solutions sustainable (piped water supply, sewerage and sanitation, and resettlement) and with investment opportunities to make the overall plan financially feasible based on internal cross-subsidies and public-private partnership (land reclamation, toll roads, and deep seaport)’. An important aspect of the plan is integration. It therefore also aims to solve drinking water shortages, river pollution, and traffic jams, and to turn Jakarta into an ‘attractive place to live, work, and invest’. At first, three alternative adaptation strategies were developed, namely, on-land solution with open rivers basically enforcing the existing seawalls; offshore solution with open rivers, adding new offshore polders to the previous; and offshore solution with closed rivers, adding an offshore sea wall creating new retention space in addition (see also Figure 6). Then a preferred Strategic Direction was developed, drawing on key elements from the three strategies, with the idea of ‘...phasing the implementation of this action plan in logic stages with tangible short-, medium- and long-term targets, and by integrating additional measures into this action plan with the purpose of looking beyond the flood problems and technical solutions at opportunities for revitalization and redevelopment of the coastal zone of Jakarta’.

### ANALYSIS

Table 2 summarizes the findings on the research questions per case.

**How is the ‘widest set’ of plausible future scenarios defined and used in the assessment of strategies within the four cases?**

According to Sayers’ characterization of adaptive planning approaches, the effect of adaptation responses has to be measured against the widest set of plausible futures. How has this been worked out in the four cases?

For the TE2100 project, plan NYC and the DP the main climate parameters that have been considered by the project teams in assessing impacts and strategies are sea level rise, storm surges, and river discharges. Dedicated scenarios for these parameters were derived in cooperation with the (international) scientific community (Lowe et al. 2009; Horton et al. 2010; Katsman et al. 2011; New York City Panel on Climate Change (NPCC) 2013). Both plausibility and probability were the main motivations to arrive at a set of scenarios for sea level rise. Not only the most likely scenarios were derived (from ensemble climate model runs based on Intergovernmental Panel on Climate Change (IPCC) emission scenarios), but also plausible and imaginable ‘what if’ scenarios. For Jakarta future projections of subsidence have got the most attention.

**Sea level rise and subsidence**

For the DP in the Netherlands a likely range for SLR (sea level rise) between 35 and 85 cm for 2100 was derived, which is very near to the 90 cm planning assumption for the other North Sea estuary of the Thames. In the TE2100 project, however, initially a high-end SLR scenario of 2.7 m (this scenario consists of a max 2 m increase in sea level and 0.7 m increase in storm surge) for the end of the century was used. In a preceding study to the DP in the Netherlands, a higher maximum plausible SLR of 1.3 m was also estimated which does not include a possible climate change induced storm surge increase (Delta Committee 2008). This high-end SLR scenario caused considerable scientific and public debate because, in the
perspective of some, too much emphasis was put on this extreme upper boundary without stressing the full uncertainty range. According to Van den Hurk et al. (2015), ‘the scientific desire to communicate an objective uncertainty range is not always compatible with the political need to create a sense of urgency’ (see also Jeuken et al. 2011). Once this sense of urgency had been raised, the 1.3 m SLR scenario was later on abandoned by the start of the Delta Program, because it was chosen to proceed with the ‘formal’ Dutch climate scenarios (Van der Hurk et al. 2006) which span a large plausible range but not necessarily including the high-end projections.

In the New York City case, projections for sea level rise are derived using 24 General Circulation Models using two IPCC emission scenarios (RCP4.5 and RCP8.5) with the addition of ranges of local and global factors like thermal expansion, ice melt, gravitational effects, etc., resulting in a range of sea level rise for 2050 between 30 and 60 cm (middle range 25-75%) up to almost 80 cm (high-end 90%) (New York City Panel on Climate Change (NPCC) 2013).

Standard sea level rise scenarios for Jakarta (or Indonesia) are not yet available, and scenarios are generally prepared on an ad hoc basis, for example based on findings from IPCC (2012) or by extrapolating past trends into the future. Moreover, in terms of coastal flooding, climate change is seen as a relatively minor threat compared to subsidence, at least in the short- to medium-term (e.g. Ward et al. 2011). For JCDS, therefore, scenario development mainly considered land subsidence until 2040. In contrast to the TE2100 and DP, there is only one predictive scenario used for sea level rise. However, two additional scenarios of land subsidence were also developed to assess the possible effects of two subsidence control measures.

### Storm surge

In the TE2100 and Dutch DP cases no trends in storm surges are projected. Current extreme event statistics are added to SLR projections. On top of a climate change induced SLR, coastal flood defense measures in the Netherlands have to meet extreme storm surge criteria with return times of 1/10,000 years. The statistical range of storm surge levels is 1.5–2 m larger than the margins in
high-end SLR projections for the Dutch coast. For the North Atlantic Basin of the coast of NYC, the NPCC states ‘that it is more likely than not that there will be an increase in the most intense hurricanes’ (New York City Panel on Climate Change (NPCC) 2013). Based on their hurricane models and available scientific analysis and projections on trends in hurricane intensity and frequency, Swiss Re Reinsurance Company was able to calculate future storm statistics (New York City Office of the Mayor (2013), Figure 4).

Precipitation

Changes in precipitation processes and estimates of associated hydrological consequences are highly uncertain but crucial for flood and drought risk management in the Netherlands. Coupled climate-hydrological models give a large range of possible outcomes, although they mostly agree on an increase of peak discharges under climate change for the Netherlands. Besides SLR, multiple scenarios for precipitation and associated low and peak river discharges have therefore been derived for the DP (Bruggeman et al. 2011). Past statistics are being incorporated and extrapolated to derive relevant return periods for extreme events (Beersma & Buishand 2004).

Socioeconomic changes

For the DP, scenarios have been expanded with scenarios for economic and population growth until 2100, and land use until 2050. TE2100 uses specific socioeconomic scenarios on the future of London and the Thames estuary. These scenarios are used for evaluation of strategies with methods such as cost benefit and multi-criteria analyses. Scenarios for linear population increase were derived for the City of Jakarta for the period 2010–2030. With an increase in the population living in the City of Jakarta from 9.6 million in 2010 to 12.6 million in 2030, and an increase in the population living in river catchments draining into Jakarta from 14.9 million in 2010 to 28.2 million in 2030, this scenario serves to stress the urgency of planning city expansion in conjunction with flood protection measures. The risk projections presented in the resilience plan for NYC (Figure 4) do not explicitly

Figure 4 | Growth in expected annual losses (10^9 $/year) from storm surge and wind based on calculations of Swiss Re taken from the resilience plan for NYC (New York City Office of the Mayor 2013).
incorporate socioeconomic changes (New York City Office of the Mayor 2013).

And how are they used?

Both European cases clearly represent a different situation: the planning time horizon is much longer, observations show weak trends in SLR but no trends in river discharges, and no major recent hazards occurred. Therefore scenarios are solely based on climate and hydrological model calculations and much attention has been paid to the scientific basis and plausibility. The use of a wider range of climate and socioeconomic scenarios is encouraged and is common practice in the assessment of strategies.

From all cases, only the TE2100 project really has explored adaptation options under high-end scenarios for sea level rise. Such high impact and low probability scenarios have aided in exploring the long-term robustness of the plan.

For Jakarta, only one sea level rise has been projected based on one scenario and no changes in hazard due to possible changes in rainfall intensity have been simulated. Studies suggest that the impacts of climate change on flood impacts may be relatively small in the coming decades compared to land subsidence. For example, Ward et al. (2011) developed a model to assess economic assets exposed to a 1/100 year coastal flood event under the current situation, and in the year 2100 as a result of sea level rise and land subsidence. They found that, if land subsidence is not addressed and the rate continues unchecked, and the sea level rises by 59 cm over the 21st century, the value of assets exposed would increase by a factor of 4 between today and 2100. Relative to land subsidence, the impacts of sea level rise are small, yet by no means insignificant, contributing alone to an increase in exposed assets by a factor of 1.7. Hence, the limited treatment of climate change in the scenarios for JCDS up to 2030 can be considered a response to the expected dominant impact of land subsidence on that time-frame. Scientifically broadly supported and regionally specific climate scenarios are currently lacking for Indonesia, but will be valuable for the assessment of longer-term climate impacts after 2030.

While the climate science (New York City Panel on Climate Change (NPCC) 2013) behind the resilience plan for NYC is presenting a full range of scientifically plausible scenarios, the plan itself is hardly communicating the full range but instead presenting central estimates of flood risk increase based on calculations from Swiss Re (New York City Office of the Mayor 2013). In fact, the ensemble model output is treated as a log-normal statistical distribution. In addition the high-end (90 percentile) of the range is used for illustrative purposes. For instance, estimates are given saying a current 1/100 year flood could happen five times more often under a high-end SLR projection for 2050. A connection is made between tolerance levels of sectors and what range of change to consider in the assessment. The high-end estimate could for instance be more appropriate for critical infrastructure operators (New York City Office of the Mayor 2013). It is not clear from the plan how the scenarios were or are going to be used to assess the individual measures or strategies.

We may learn from the above that not necessarily always is a full range of plausible scenarios applied and that scenario use is dependent on the following:

‘Perceived uncertainty’. The level of uncertainty perceived in the dominant drivers for change is strongly guiding scenario use. When confronted with severe uncertainty, a larger range of scenarios is used than when confronted with clear and significant observed trends as seen for subsidence in Jakarta.

‘Tolerance levels’. The lower the tolerance levels, or the higher the risks involved of assets, people and critical infrastructure to be protected, the larger the need to assess adaptation measures against more high-end climate projections.

‘Policy scope’. There are different underlying purposes for using scenarios in a policy process. In the cases we encountered: communication to stress urgency and raise support; exploring long-term options; and planning and designing for short-term action. Stressing urgency obviously benefits from presenting the high end of the range (while being transparent on the full range of uncertainty), whereas policy exploration benefits from considering a wide range. For adaptation design and planning a scenario should be agreed upon representing a sort of acceptable risk level. The three purposes also pose a logical sequence in a policy making process.
How are robustness and flexibility being considered? How is ‘low regret’ of decisions safeguarded?

**Robustness and resilience**

The plan for NYC (New York City Office of the Mayor 2013) is proposing 37 initiatives to start with. The total plan is distributed over the different levels of flood risk management: flood protection by barriers, flood walls and levees, but also ‘softer’ measures like beach nourishment to reduce the probability of floods, spatial planning (risk zoning, buy-out programs, and better protecting critical infrastructure) and flood-robust building (in retrofitting, new building, and adjustments of building codes), and improvements in emergency response and economic recovery to reduce exposure and vulnerability to flooding. The large heterogeneity and some planned redundancy in the solutions proposed will increase the robustness and resilience of the system in a similar manner as explained by Mens et al. (2011) and Wardekker et al. (2009). The risk of failure is distributed over many elements of the flood risk management system. So if one element fails, the whole system does not collapse. The phased implementation of various smaller projects in addition will make it easier to attract financing and get things going and expand in the future when needed and when additional funding is obtained. In addition, measures are quite well supported by local stakeholders and often based on recent experience, as some measures were already implemented before and were seriously tested by Hurricane Sandy.

**Flexibility**

Flexibility is in this context a characteristic of the plan that enables coping with uncertain futures. More specifically: decisions in the near future on concrete actions for adaptation to climate change should not foreclose future options to react differently and switch or add actions if climate or societal changes ask for it; and on the other hand when it is decided to postpone adaptation actions (i.e. there is no urgency yet), developments that take place in the near future should not foreclose future options for adaptation.

To be able to tackle this complexity it is necessary to envision and link possible short-term decisions and long-term options for adaptation and their timing across relevant interfering policy domains. In the cases studied we encountered several examples of how to achieve this.

In all cases, critical thresholds or adaption tipping points (Kwadijk et al. 2010) – describing under what conditions current or alternative policies might fail – are considered. These thresholds are related to acceptable return periods for flood events in risk-based approaches translated to design criteria for the flood protection infrastructure. For the TE2100 and DP, thresholds play a major role in the phasing of the potential actions within the plan. Consecutive actions are combined in APs (Haasnoot et al. 2012) or route maps that show the connection between a short-term decision and longer-term options (Figure 5).

In the Jakarta case, there is only one such pathway which has been assembled from originally three alternatives (see Figure 6), consisting of a few main categories of measures: measures to prevent flooding and measures to decrease the amount of subsidence in three phases until 2030. The plans under development in the DP (for example see Figure 7) and the TE2100 plan (see Figure 5) contain multiple pathways and allow switching between different options in the future. NPCC developed a risk management approach for New York called Flexible Adaptation Pathways (Rosenzweig et al. 2013) inspired by the TE2100 route maps. In the final resilience plan for New York issued by the mayor, mainly the flexibility of phased implementation of the many adaptation actions is stressed without measuring up explicitly the timing of actions against sea level rise as was done for the Thames.

In the DP in the Netherlands, spatial reservations (Room for the river 2012) have been made which keep room for river actions (orange branches in Figure 7) open for a long time until design discharges of 18,000 m³/s (in the Dutch risk-based approach this represents a discharge that occurs with a return period of 1/1,250 years). Switching between more dike reinforcements and more room for the river, in fact both actions that are part of current strategy, remains possible to cope with long-term projected climate changes.

The TE2100 case can be seen as an example of a well-founded decision to postpone action. The APs show that there is still time to act, and if new insights are available, adjusting the strategy and switching to other options is possible.
The flexibility of a plan can be increased if measures can be implemented stepwise, or if there is the possibility of switching to other measures. Flexibility in the flood risk management strategies encountered in the cases is often limited by the lifetime and nature of the measures: structural flood protection measures like barriers and dams are implemented for many decades. Both the TE2100 and the DP case may now seem relatively flexible into the future only because new large-scale structural measures can be postponed. But also the flexibility of dike improvements is limited because single large investments in dike improvements are much more cost-effective than multiple smaller stepwise investments. Soft flood protection measures such as making room for rivers and coastal sand nourishment and measures reducing the consequences of flooding (like flood proofing urban strategies) are better suited to be implemented in small steps.

In the TE2100 and DP, these kinds of measures contribute only partly to the plan, which mainly consists of improving the existing flood safety system of dams, barriers, and dikes. The New York plan promises a wider variety of adaptation actions and more balance between structural, green adaptation, and non-structural measures.

**Combining agendas**

In the DP there are several short-term decisions defined in the water domain (i.e. redefinition of safety standards, water quality, and shipping issues) that are being connected to the long-term climate change questions. For example, where dikes need to be enforced because of maintenance, the expected increase in water levels due to climate change can be taken into account in the design. Another example is that the planned...
works to increase the sluice capacity for current shipping needs can be combined with creating extra drainage capacity for possible future needs because of a changing climate (Stratelligence 2012). In both examples, initial investment costs have to be made only once. Potential overcapacity due to future uncertain development is shared by more than one investment agenda. In this way these short-term decisions may also serve as an opportunity or incentive to make a first low regret step in the implementation of an adaptive plan.

Jakarta clearly uses short-term urgency and, like the DP, matching of different agendas for short-term action while at the same time presenting an extendable plan for the longer term. Urgent short-term measures are planned first (e.g. improving the water supply system and improving the coastal defenses) to reduce the worst problems already in progress. In all three stages of the coastal defense plan, flood protection measures are combined with spatial planning measures to extend living and working space in polders and to improve traffic circulation. Investments serve multiple purposes which may make them more easily financed and executed.

While other investment agendas may help the implementation of adaptation plans, it is also important to be aware of other agendas or autonomous developments that may hamper and lock out future actions. In the past, spatial developments (see Figure 8) have narrowed down easy options for adaptation. Investments in the past for the Netherlands, but also for example in drainage and dikes in Jakarta, have drawn a lot of economic activity to the low lying parts of the deltas. These autonomous developments may make it difficult to switch to pathways that promote substantial different

Figure 6 | Adaptation pathways map for the River Rhine-Waal Branch (Haasnoot 2013). The actions that are planned to be carried out in the near future consist of some dike strengthening and actions aimed at lowering of the water level by giving more space to the river (gray line). These actions are insufficient to control the flood risk over a longer time span. Therefore, five policy options were defined. The first option consists of actions that result in lowering of the water level during a flood by giving more space to the river (e.g. lowering of flood plains; orange lines). It is expected that these actions can only solve part of the problem. If they would start with the implementation of these actions, eventually other actions would be needed. These actions include dike strengthening (yellow lines) (either with a large increase in one action or in succeeding smaller steps), development of ‘unbreachable dikes’ (green lines) (e.g. De Brujin et al. 2013), adaptive construction of houses and other buildings (blue line), or application of very large measures, such as the development of a ‘Green River’ i.e. a new river reach that will only be flooded during extreme events (red line). As it is not very likely that this type of action will be selected now, the first part of this route is made transparent. The full colour version of this figure is available in the online version of this paper.
solutions. It is recognized nowadays in the UK and also in the Netherlands that influencing the spatial development patterns by instruments like risk zoning, spatial reservations, and building codes may serve as measures to reduce flood risks (e.g. De Bruijn & Klijn 2009).

Monitoring and reassessment

According to Sayers, the third characteristic of an adaptive plan is that ‘relevant changes are foreseen through targeted monitoring and scenarios of the future are continuously being reassessed; plans are appropriately redefined’. A good monitoring system should be in place for representative triggers and signposts (Walker et al. 2001; Dewar et al. 1993). Triggers can be based on information on the past or current situation (such as monitoring results), but also information about the future, such as new scientific insights on future climate or new population estimates. Next to monitoring direct drivers for change, monitoring scientific progress, the success of implemented adaptation policies and action are of key importance.

All plans underpin the importance of monitoring. But because most of the plans are still within the pre-implementation phase monitoring has not been worked out in detail yet. TE2100 has progressed furthest, and a number of key indicators (triggers) have been defined that should be monitored. One of the main indicators is sea level rise that has the potential for early detection of accelerated trends.

The Netherlands has the tradition of evaluating the national water policies from time to time. For this purpose a national monitoring strategy and system is in place. It is expected that the Delta decisions that will result from the DP will require adoption of the future monitoring strategy.

One of the main recommendations for New York is to ‘develop a system of indicators and monitoring co-generated by stakeholders and scientists to track data related to climate risks, hazards, and impacts to better inform climate change-related decision-making in New York City’.
Lessons learnt from adaptation planning

Adaptation planning in four cases around the globe concerning flood risk management in deltas and coastal cities has been compared on three main supposed characteristics of adaptive planning: to prepare for a wide range of plausible future scenarios (climate, subsidence, and socioeconomic), to respond to uncertain change with a robust and flexible set of actions, and to monitor critical changes to be able to reassess the plan accordingly. All four cases follow purposely an adaptive planning approach to arrive at an adaptation strategy, but differences can be observed in the implementation. These differences can be related to the context of the cases. To conclude, what main ingredients for successful adaptation planning are looming? There will always be limitations in long-term planning due to the degree of uncertainty in the drivers for change, due to a limited scope (in terms of objectives, stakeholders, spatial and temporal scale) of the planning process or due to past and currently ongoing policies and existing laws. Decision makers in the field have to deal with that as well as possible. So far, the cases in this paper provide little experience in implementation of measures. Therefore there are few evidence-based findings yet, except for some individual measures in New York. But by analyzing the practice of planning and comparing it to existing literature on dealing with uncertainties we were able to at least give some directions on which theoretical concepts can be operationalized better than others (good practices), what limitations are encountered, and what mistakes should be avoided.

In response to the first research question on how is the ‘widest set’ of plausible future scenarios defined and used in the assessment of strategies, we observed the following: logically a wider range of scenarios is used in the cases where the perceived uncertainty of future drivers for change is largest, as is the case in the TE2100 and DP. This is especially the case when projected changes are not supported by clear observed trends or by recent hazard experience. Also, the phase of planning is important. To stress potential urgency, the outer limits of plausibility are used. However, for design (and acceptable cost) of measures a lower upper scenario range is more desirable. To explore options for adaptation a range of scenarios is used. The plausibility of scenarios in all cases is supported by sound science. All cases show good practices of these different uses. In the case of Jakarta, the issues are extremely pressing and urgent, and the trend of subsidence is clear. This may explain why this project explored fewer different climate and sea level rise scenarios, and hence this is not necessarily indicative that the plan is not robust with respect to climate change.

To safeguard the ‘low regret’ content of the adaptation plan, the second research question, we encountered three main strategies: flexibility, mainstreaming, and robustness/resilience. All cases contain examples of all three strategies but different accents can be distinguished in each case.

The cases of TE2100 and DP highlight how short-term decisions are explicitly coupled with long-term options using APs or route maps with clearly marked thresholds defining when to decide to switch from one action to another, this ensures maximum flexibility.

The Jakarta case provides the best example on how short-term decisions are part of a phased implementation of a ‘multi-objective’ plan. The city’s demand for spatial development of infrastructure, and new areas for housing and business creates the opportunity for financing the combined large investments in flood defenses, roads, and polder areas.
in this way reducing the flood risk. However, the long-term possible consequences of climate change remain underexposed. In general, developing countries where poverty and short-term vulnerabilities dominate over long-term concerns, the long-term planning approaches may need to be tailored to be effective (Ranger & Garbett-Shiels 2011). In these countries, long-term planning is much less practiced, because as the Jakarta case shows, other (more urgent) problems exist. The challenge is to design actions that are also able to cope with potential future conditions (robust actions or design actions that leave room for adaptation if needed) and seize opportunities once they arise. Therefore, it is even more important to link (potential) future actions to current problems, for example by searching for win-win options.

The third strategy encountered is increasing resilience (and in this way robustness), as is best illustrated by the plaNYC case, which is not only directed at designing adaptation actions for a certain amount of climate change but also to make the city stronger to protect against, cope with, and recover from uncertain future flood hazards.

Flood risk management actions taken in the past can be quite decisive for the attractiveness of future options. With a very robust flood protection system already in place in the Netherlands, the largest added value in terms of risk reduction per euro invested appears to come from improving this very same protection system and less from investing in planning, building, and emergency response measures (Jeuken et al. 2013; Slootjes & Jeuken 2013). Large cities in low lying deltas, especially below sea level, must be protected against flooding from sea with barriers, levees, and other structural measures. These measures are robust, mainly since they incorporate large safety margins and increase the resistance of the system. As shown, the flexibility of these measures is limited. In these cases, flood risk strategies that aim more at increasing the resilience of the systems are additional to the existing flood protection strategies.

On the third research question, ‘how is monitoring and reassessment included in the plans?’ the main conclusion is that the importance is recognized, that the main climate drivers for change are being considered in monitoring plans, other key triggers are being defined and, since not all relevant variables are suitable for early trend detection, progress in science and climate projections should also be monitored. However, there is little experience yet to be collected, for example on how monitoring can be used to implement or improve strategies.

ACKNOWLEDGEMENTS

Philip Ward was also funded by Knowledge for Climate/ Delta Alliance project HSINT02a. Ad Jeuken was also funded by the EU-FP7 project BASE.

REFERENCES

Abidin, H. Z., Andreas, H., Gumilar, I., Fukuda, Y., Pohon, Y. E. & Deguchi, T. 2011 Land subsidence of Jakarta (Indonesia) and its relation with urban development. Natural Hazards 59 (3), 1753–1771.

Aerts, J., Major, D. C., Bowman, M. J., Dircke, P. & Marfai, M. A. 2009 Connecting Delta Cities. Coastal Cities, Flood Risk Management and Adaptation to Climate Change. VU University Press, Amsterdam.

Albrechts, L. 2004 Strategic (spatial) planning reexamined. Environment and Planning B: Planning and Design 31 (5), 743–758.

Beersma, J. J. & Buishand, T. A. 2004 Joint probability of precipitation and discharge deficits in the Netherlands. Water Resources Research 40, W12508.

BPS Jakarta 2010 Jakarta Dalam Angka 2010. Badan Pusat Statistik Propinsi DKI Jakarta, Jakarta, Indonesia.

Bruggeman, W., Haasnoot, M., Hommes, S., te Linde, A. & van der Brugge, R. 2011 Delta Scenarios. Exploration of Physical and Socio-economic Developments in the 21st Century, Based on the KNMI and WLO Scenarios, for Use in the Delta Program 2011–2012 (in Dutch). Report 1204151.002, Deltares, Delft.

Bucox, T., Marchand, M., Makaske, B. & Van de Guchte, C. 2010 Comparative Assessment of the Vulnerability and Resilience of 10 Deltas. Synthesis Report. Delta Alliance Report Number 1, Delta Alliance International, Delt, Wageningen.

Chaussard, E., Amelung, F., Abidin, H. & Hong, S.-H. 2013 Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction. Remote Sensing of Environment 128 (21), 150–161.

De Bruijn, K. M. & Klijn, F. 2009 Risky places in the Netherlands: a first approximation for floods. Journal of Flood Risk Management 2 (1), 58–67.

De Bruijn, K., Klijn, F. & Knoeff, J. 2013 Unbreachable embankments? In pursuit of the most effective stretches for reducing fatality risk. In: Comprehensive Flood risk Management. Research for Policy and Practice. Proceedings of the 2nd European Conference on Flood Risk Management (F. Klijn & T. Schweckendiek, eds). CRC Press, Taylor & Francis Group, London, UK, p. 436.
Delta Committee 2008 Working together with water: A living land builds for its future. Findings of the Dutch Delta Committee. Ministerie van Verkeer en Waterstaat, The Hague, The Netherlands. http://www.deltacommisie.nl/en/advisie (accessed December 2013).

Delta Program 2012 Werken aan de Delta (in Dutch). Delta programma 2012.

Dewar, J. A., Builder, C. H., Hix, W. M. & Levin, M. H. 1995 Assumption-Based Planning: A Planning Tool for Very Uncertain Times. RAND, MR-114-A, Santa Monica, CA.

Dieremanse, F. L. M., Kwadijk, J. C. J., Beckers, J. V. L. & Crebas, J. I. 2010 Statistical trend analysis of annual maximum discharges of the Rhine and Meuse rivers. In: BHS Third International Symposium, Managing Consequences of a Changing Global Environment, Newcastle.

Haasnoot, M. 2015 Anticipating Change: Sustainable Water Policy Pathways for an Uncertain Future. PhD Thesis. University of Twente, Enschede.

Haasnoot, M., Middelkoop, H., Offermans, A., van Beek, E. & Van Deursen, W. P. A. 2012 Exploring pathways for sustainable water management in river deltas in a changing environment. Climatic Change 115 (3–4), 795–819.

Haasnoot, M., Kwakkel, J. H. & Walker, W. E. 2013 Dynamic adaptive policy pathways: a new method for crafting robust decisions for a deeply uncertain world. Global Environmental Change 25 (2), 485–498.

Hallegraeff, S. 2009 Strategies to adapt to an uncertain climate change. Global Environmental Change 19 (2), 240–247.

Horton, R., Gornitz, V., Bowman, M. & Blake, R. 2010 Climate observations and projections. In: NPCC. Climate Change Adaptation in New York City: Building a Risk Management Response (C. Rosenzweig & W. Solecki, eds). Annals of the New York Academy of Science, New York, NY, pp. 41–62.

IPCC 2012 Managing the risks of extreme events and disasters to advance climate change adaptation. In: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G-K. Plattner, S. K. Allen, M. Tignor & P. M. Midgley, eds). Cambridge University Press, Cambridge, UK and New York, NY, USA, p. 582.

JcDS 2011 Jakarta Coastal Defence Strategy. Agenda. JCDS, Jakarta, Indonesia.

Jeukens, A., te Linde, A., Woelders, L. & Kwadijk, J. 2011 On the use of water scenarios in the Dutch Delta Program. In: BFG Veranstaltungen of the Euraqua Symposium, 4/2011. BFG, Koblenz.

Jeukens, A., Kind, J. & Gauderis, J. 2013 Cost-benefit analysis of flood protection strategies for the Rhine-Meuse delta. In: Comprehensive Flood Risk Management. Research for Policy and Practice. Proceedings of the 2nd European Conference on Flood Risk Management (F. Klijn & T. Schweckendiek, eds). CRC Press, Taylor & Francis Group, London, UK, p. 436.

Katsman, C. A., Sterl, A., Beersma, J. J., van den Brink, H. W., Church, J. A., Hazeleger, W., Kopp, R. E., Kroon, D., Kwadijk, J., Lammersen, R., Lowe, J., Oppenheimer, M., Plag, H.-P., Ridley, J., von Storch, H., Vaughan, D. G., Vellinga, P., Vermeersen, L. L. A., van de Wal, R. S. W. & Weisse, R. 2011 Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta – the Netherlands as an example. Climatic Change 109 (3–4), 617–645.

Kind, J. M. 2014 Economically efficient flood protection standards for the Netherlands. Journal of Flood Risk Management 21 (103–117).

Kwadijk, J. C. J., Haasnoot, M., Mulder, J. P. M., Hoogvliet, M. M. C., Jeukens, A. B. M., van der Krogt, R. A. A., van Oostrom, N. G. C., Schelfhout, H. A., van Velzen, E. H., van Waveren, H. & de Wit, M. J. M. 2010 Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. Wiley Interdisciplinary Reviews: Climate Change 1 (5), 729–740.

Kwakkel, J., Walker, W. E. & Marchau, V. 2010 Classifying and communicating uncertainties in model-based policy analysis. International Journal of Technology, Policy and Management 10 (4), 299–315.

LeBlanc, A. & Linkin, M. 2010 Insurance. In: NPCC. Climate Change Adaptation in New York City: Building a Risk Management Response (C. Rosenzweig & W. Solecki, eds). Annals of the New York Academy of Science, New York, NY, pp. 41–62.

Lempert, R. J., Popper, S. & Bankes, S. 2005 Shaping the Next One Hundred Years: New Methods for Quantitative, Long Term Policy Analysis. Report MR-1626-RPC. RAND, Santa Monica.

Lowe, J. A., Howard, T. P., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S. & Bradley, S. 2009 UK Climate Projections Science Report: Marine and Coastal Projections. Met Office Hadley Centre, Exeter, UK.

Mens, M. J. P., Klijn, F., de Bruijn, K. M. & van Beek, E. 2011 The meaning of system robustness for flood risk management. Environmental Science & Policy 14 (8), 1121–1131.

Milly, P., Betancourt, J., Falkenmark, M., Hirsch, R., Kundzewicz, Z., Lettenmaier, D. & Stouffer, R. 2008 Stationarity is dead: whither water management. Science 319 (5863), 573–574.

Mulder, J. P. M., van der Spek, A. J. F. & van der Meulen, M. J. 2009 Coastal zones and climate change: a sediment perspective on adaptation. Coastal Engineering 56 01/2009, 4053–4064.

Neumann, C. J., Jarvinen, B. R., McAdie, C. J. & Hammer, G. R. 1999 Tropical Cyclones of the North Atlantic Ocean, 1871–1998. Historical Climatological Series 6-2. National Climatic Data Center, Asheville, NC, p. 206.

New York City, Office of the Mayor 2013 PlaNYC: A Stronger, More Resilient New York. June 11 2013.

New York City Panel on Climate Change 2013 Climate risk information 2013: observations, climate change projections, and maps. Prepared for Use by the City of New York Special Initiative on Rebuilding and Resiliency (C. Rosenzweig & W. Solecki, eds). New York.

New York Times 2013 Bloomberg outlines $20 billion storm protection plan. New York Times 11 June 2013.
Pahl-Wostl, C. 2007 Transition towards adaptive management of water facing climate and global change. Water Resources Management 21 (1), 49–62.

Ranger, N. & Garbett-Shiels, S.-L. 2011 How Can Decision-Makers in Developing Countries Incorporate Uncertainty About Future Climate Risks Into Existing Planning and Policy-Making Processes? Tech. rep., Centre for Climate Change Economics and Policy Grantham Research Institute on Climate Change and the Environment in collaboration with the World Resources Report. www.worldresourcesreport.org (accessed December 2013).

Reeder, T. & Ranger, N. 2002 How Do You Adapt in an Uncertain World? Lessons from the Thames Estuary 2100 Project. World Resources Report, Washington, DC. http://www.worldresourcesreport.org/files/wrr/papers/wrr_reeder_and_ranger_uncertainty.pdf, 13 November 2012, online (accessed December 2013).

Rensgaard, J., Arnbjerg-Nielsen, K., Drews, M., Halsnæs, K., Jeppesen, E., Madsen, H., Markandya, A., OleSEN, J., Porter, J. & Christensen, J. 2009 The role of uncertainty in climate change adaptation strategies – a Danish water management example. Mitigation and Adaptation Strategies for Global Change 18 (3), 337–359.

Renaud, F. G., Syvitski, J. P. M., Sebesvari, Z., Werners, S. E., Kremer, H., Kuenzer, C., Ramesh, R., Jeuken, A. & Friedrich, J. 2013 Tipping from the Holocene to the Anthropocene: how threatened are major world deltas? In: Aquatic and marine systems (C. Vörösmarty, C. Pahl-Wostl & A. Bhaduri, eds). Current Opinion in Environmental Sustainability 5 (6), 644–654.

Room for the river 2012 From higher dykes to river widening. Project brochure available at http://www.ruimtevoordevier.nl/media/88721/rvdr_corp_brochure_eng_def_.pdf (accessed December 2013).

Rosenzweig, C., Solecki, W. D., Blake, R., Bowman, M., Faris, C., Gornitz, V., Horton, R., Jacob, K., LeBlanc, A., Leichenko, R., Linkin, M., Major, D., O’Grady, M., Patrick, L., Sussman, E., Yohe, G. & Zimmerman, R. 2012a Developing coastal adaptation to climate change in New York City infrastructure: process, approach, tools and strategies. Climatic Change 106 (1), 93–127.

Rosenzweig, C., Solecki, W., DeGaetano, A., O’Grady, M., Hassol, S. & Grabhorn, P. 2013b Responding to Climate Change in New York State: the ClimAID Integrated Assessment for Effective Climate Change Adaptation. Synthesis Report. New York State Energy Research and Development Authority (NYSERDA), Albany, New York. Report, pp. 11–18.

Sayers, P. B., Galloway, G. E. & Hall, J. W. 2012 Robust decision-making under uncertainty – towards adaptive and resilient flood risk management infrastructure. In: Flood Risk (B. Sayers, ed.). ICE Publishing, UK, pp. 281–302.

Slootjes, N. & Jeuken, A. 2013 Costs and Effects of Promising Strategies for the Delta Program Rijnmond-Drechtsteden (in Dutch). Deltares Report 1207828.004. Deltares, Delft.

Steinberg, F. 2007 Jakarta: environmental problems and sustainability. Habitat International 31 (3–4), 354–365.

Stratelligence 2012 Handreiking adaptief deltamanagement. Tech. rep., Stratelligence Decision Support, in assignment of the Staff of the Delta commissioner. https://deltaprogramma.pleio.nl/file/view/13008692/100812-handreiking-adm-definitief-concept-2pdf (accessed December 2013).

Swanson, D. A. & Bhadwal, S. 2009 Creating Adaptive Policies: A Guide for Policy-making in an Uncertain World. Sage Publications Pvt Ltd, UK.

Swanson, D., Barg, S., Tyler, S., Venema, H., Tomar, S., Bhadwal, S., Nair, S., Roy, D. & Drexhage, J. 2010 Seven tools for creating adaptive policies. Technological Forecasting and Social Change 77 (6), 924–939.

Syvitski, J. P. M., Kettner, A. J., Overeem, I., Hutton, E. W. H., Hannon, M. T., Brakenridge, G. B., Day, J., Vorosmarty, C., Saito, Y., Giosan, L. & Nicholls, R. 2009 Sinking deltas due to human activities. Nature Geoscience 2, 681–686.

Van de Ven, G. P. 1991 Man-made Lowlands: History of Water Management and Land Reclamation in the Netherlands. Uitgeverij Matrijs, Utrecht.

Van den Hurk, B., Klein Tank, A., Lenderink, G., Van Ulden, A., Van Oldenborgh, G. J., Katsman, C., Van den Brink, H., Keller, F., Bessembinder, J., Burgers, G., Komen, G., Hazeleger, W. & Drijfhout, S. 2006 KNMI Climate Change Scenarios for 2006. Tech. Rep. WR2006-01, KNMI, De Bilt.

Van den Hurk, B., Klein Tank, A., Katsman, C., Lenderink, G. & te Linde, A. 2013 Vulnerability assessments in the Netherlands using climate scenarios. In: Climate Vulnerability 5, 257–266.

Van der Bruggen, R., Roosjen, R., Morselt, T. & Jeuken, A. 2012 Adaptive Delta Management. Water Governance 2/2012.

Vörösmarty, C. 2009 Battling to save the world’s river deltas. Bulletin of the Atomic Scientists 65 (2), 31–43.

Walker, W. E., Rahman, S. A. & Cave, J. 2001 Adaptive policies, policy analysis, and policymaking. European Journal of Operational Research 128 (2), 282–289.

Walker, W. E., Haasnoot, M. & Kwakkel, J. H. 2012d Adapt or perish: a review of planning approaches for adaptation under deep uncertainty. Sustainability 5 (3), 955–979.

Wardekker, J. A., de Jong, A., Knoop, J. M. & van der Sluijs, J. P. 2009 Operationalising a resilience approach to adapting an urban delta to uncertain climate changes. Technological Forecasting and Social Change 76 (6), 987–998.

Wilby, R. L. & Keenan, R. 2012 Adapting to flood risk under climate change. Progress in Physical Geography 36 (3), 348–378.

First received 15 December 2013; accepted in revised form 30 October 2014. Available online 4 December 2014