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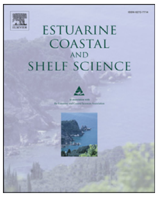

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Damming deltas: A practice of the past? Towards nature-based flood defenses

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ABSTRACT

There is extensive experience in adaptive management of exposed sandy coastlines through sand nourishment for coastal protection. However, in complex estuarine systems, coastlines are often shortened through damming estuaries to achieve desired safety levels. The Dutch Deltaworks illustrate that this approach disrupts natural sediment fluxes and harms ecosystem health, which negatively affects derived ecosystem services, such as freshwater availability and mussel and oyster farming. This heavily impacts local communities and thus requires additional maintenance and management efforts. Nevertheless, the discussion on coastline shortening keeps surfacing when dealing with complex coastal management issues throughout the world. Although adaptive delta management accompanied by innovative approaches that integrate coastal safety with ecosystem services is gaining popularity, it is not yet common practice to include adaptive pathways, a system-based view and ecosystem knowledge into coastal management projects. Here, we provide a first attempt to integrate ecosystem-based flood risk reduction measures in the standard suite of flood risk management solutions, ranging from structural to non-structural. Additionally, for dealing with the dynamic and more unpredictable nature of ecosystems, we suggest the adaptive delta management approach that consists of flexible measures, measurable targets, monitoring and intervention, as a framework for embedding ecosystem-based alternatives for flood risk mitigation in the daily practice of engineers and coastal planners.

1. Flood risk management along estuarine coastlines

Many coastal areas and river basins worldwide are flood prone. Keeping the risk of flooding at an acceptable level is an ongoing challenge. Nowadays the range of options to mitigate flood risk is becoming more diverse, varying from non-structural measures, such as early warning systems and zoning, to traditional structural measures, such as levees, dams, flood detention areas and pumping stations (U.S. Army Corps of Engineers, 2013). The impact of structural measures on natural processes is large and often results in undesirable side effects, such as land subsidence or disturbance of ecosystem functioning and a loss of ecosystem services, with large consequences for local communities. Therefore, the potential of more nature-based flood defense solutions, such as oyster reefs, salt marshes and mangroves, that are thought not to have such negative effects on the natural environment, is actively being explored (Day et al., 2007; Barbier et al., 2008; Borsje et al., 2011; van Slobbe et al., 2013; Cheong et al., 2013). Although these studies make a strong case for application of nature-based defenses and provide valuable information underbuilding the efficiency of nature-based defenses, they do not offer ready to use tools for decision makers and coastal managers.

There is extensive experience in adaptive management of exposed sandy coastlines through nourishment (Nordstrom, 2005). However, in complex estuarine systems, coastline shortening by damming estuaries is often chosen as a means to achieve desired safety levels (Saeijs and Stortelder, 1982; Pilarczyk, 2012). The Dutch Deltaworks illustrate that this approach disrupts natural sediment fluxes and may severely harm ecosystem health, which negatively affects ecosystem services such as freshwater availability due to algal growth and mussel and oyster farming due to reduced carrying capacity (Smaal and Nienhuis, 1992). Additional

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maintenance and management efforts are needed in order to reduce impact on local communities. This requires continuous investment (Smits et al., 2006; Verspagen et al., 2006). Nature-based coastal defenses, most likely including a combination of engineered defenses with restored coastal ecosystems that play an important role in attenuating waves and stabilizing shorelines, can provide an adaptive and robust alternative (Borsje et al., 2011; Temmerman et al., 2013). Here, we review effects of the Dutch Deltaworks on the natural estuarine system and on derived services. We discuss whether damming of bays, estuaries and entire delta systems is still desirable and to what extent nature-based solutions might provide a suitable alternative. For including nature-based alternatives into planning and decision making we integrate these measures into a framework that shows possible structural and non-structural measures for flood risk mitigation.

2. Coastal management in the Netherlands

In the Netherlands, coastal zone management is rooted in the geological background of the area (Fig. 1). The current coast mainly originates from marine sediments, deposited after the last ice age and reworked by wave action. Nowadays, after millennia of continuous sea level rise, sediment supply from the inner shelf is limited and shoreline erosion is the norm (van der Meulen et al., 2007). Ongoing sea-level rise will result in continued erosion of beaches and dunes, which represent the first line of defense against flooding for the most densely populated part of the Netherlands (Fig. 1). In order to prevent the coast from receding, the sand volume in the critical part of the coastal profile is regularly assessed and strategically maintained by nourishments with sandy sediment dredged from offshore (van Koningsveld and Mulder, 2004; Mulder et al., 2011).

Natural processes are harnessed for coastal defense purposes and for maintaining the beach and dune system and continuous optimization of nourishment strategies is also part of the adaptive management approach. Initially, sand nourishment was executed on the beach. However, nourishment under water in the active zone where waves transport sediment towards the beach, turned out to be more effective in distributing sediment equally over the beach, while sediment losses are relatively small (Hamm et al., 2002). Currently, large-scale offshore nourishments in a single downstream location, are being explored. The first trial project is called the sand engine and it is large enough to be visible on Google earth as a small peninsula south of The Hague. The sand that constitutes the peninsula is expected to distribute along the upstream coast over several decades, thereby creating an extremely wide beach area over several kilometers (Stive et al., 2013; van Slobbe et al., 2013). This beach area should enhance natural dune formation and additionally, this method should limit frequency of nourishment, thereby reducing disturbance of benthic fauna.

Besides the availability of sand resources for nourishment purposes, several factors are essential for successful adaptive management of sandy coastlines (Van Koningsveld, 2003; Mulder et al., 2011):

1. a monitoring strategy should be in place,
2. clear targets and goals should be defined such as a benchmark coastal volume or coastline position beyond which coastal erosion is not allowed,
3. monitoring is assessed to determine whether defined goals are met,
4. a clear management plan defines what action should be undertaken in relation to monitoring results,
5. and costs for measures should be budgeted for the long-term.

In the end the main challenge for managing sandy coastlines will be to optimize biodiversity by allowing natural dynamic processes while maintaining reasonable safety levels and keeping costs flexible. A similarly effective, robust and adaptive form of

Fig. 1. Coastal management strategies in the Netherlands (51° 32′ 39.84″ N, 3° 53′ 11.23″ E) differ along enclosed coastlines (A) and along more complex estuarine coastlines (A and B). The Dutch Deltaworks close off the major part of the Rhine-Meuse delta, resulting in fragmented water bodies with different management problems (B). Numbers indicate dams and letters indicate water bodies. Different shades of blue indicate different salinities (light blue/light grey water is fresh and dark blue/dark grey water is salt).

coastal management remains to be developed for estuarine systems.

3. Effects of damming estuaries and bays

Compared to sandy coasts, estuarine systems are characterized by a more complex sedimentology composed of sand, clay and peat. The Dutch Deltaworks are a good example of the trial-and-error approach that often is associated with coastal management of estuaries and bays. Devastating floods in 1953, initiated the damming of most of the Rhine-Meuse delta in the Southwest of the Netherlands (Fig. 1) to enhance safety levels. Consequently, the coastline was drastically shortened and former estuarine inlets were transformed into disengaged and stagnant fresh- and saltwater lakes. Although this has increased safety for the local populations, a considerable price is being paid through deterioration of the natural system, loss of ecosystem services, and rigidity of coastal defenses that cannot easily be adapted to future sea level rise scenarios (Smits et al., 2006). Presently, decades after finalization of the Deltaworks, each enclosed former estuary has specific environmental problems, which mainly result from lack of connectivity, reduced tidal flows and disrupted sediment balance (Fig. 2).

Most literature on the effects of dam construction originates from river systems, where extensive damming for water storage and hydropower, resulted in enormous impacts on the whole system by disturbing natural flow regimes and sediment fluxes (Friedl and Wüest, 2002; Le et al., 2007) and by blocking migration of species (March et al., 2003). Impact on the environment of dams and barriers for coastal defense and tidal energy in deltas and bays has received less attention. In this respect the vast body of literature demonstrating the effects of the Dutch Deltaworks forms an exception from which useful lessons can be learned.

Immediately after completion of the Deltaworks the isolated water systems provided services such as flood safety, tourism and freshwater supply for agriculture, but these have increasingly been outweighed and endangered by environmental degradation (Nienhuis et al., 2002) (Fig. 2). Massive blooms of toxic algae, initiated by high nutrient input into stagnant systems, hamper freshwater supply for agriculture (Verspagen et al., 2006). Even in systems where nutrient input is low, such as the saline Lake Grevelingen, lack of flow and mixing causes stratification and anoxic conditions resulting in mortality of benthic flora and fauna (Nienhuis, 1978; van Wesenbeeck et al., 2009) and harm to tourism. Approaches that were innovative at the time of construction, turn out to be less effective than anticipated. An example is the semi-permeable Oosterschelde storm surge barrier (completed in 1989), designed as an alternative to a complete closure dam in order to mitigate detrimental ecological effects of closure. The open barrier has reduced the tidal prism resulting in oversized tidal channels and eroding intertidal flats (Mulder and Louters, 1994). As the barrier blocks sand exchange with the North Sea, intertidal flats and salt marshes are the main sediment source for this infill landward of the barrier. Consequently, intertidal flats and marshes are eroding, resulting in reduced stability of flood defense dikes, increased wave heights and a considerable loss of ecological value, especially for resident and migratory birds (Smaal and Nienhuis, 1992).

Mitigation of the negative effects on the ecosystem of the Dutch Deltaworks has been subject to many studies over the last decades and is found to require considerable investment (Smits et al., 2006). Recent studies investigated the effects of opening up several of the dams and reconnecting the lakes behind them to the sea. Some of these measures have already been implemented (Wijnhoven et al., 2010). Especially in the Eastern Scheldt, many measures in situ have been taken to mitigate the effects of sediment redistribution or intertidal flat erosion. Some of these measures consist of

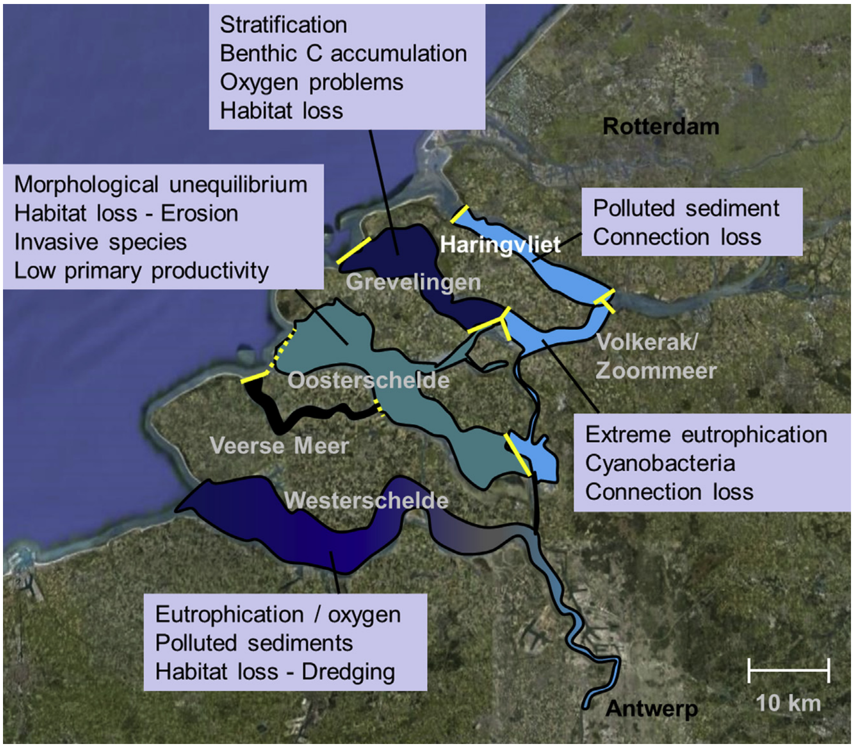

Fig. 2. Water bodies in the South West delta of the Netherlands (Google Earth, 52° 10′ 03.20″ N, 5° 16′ 16.34″ E). For each water body the most urgent ecosystem issues as a result of its' closure or semi-closure are indicated.

construction of small dams to reduce erosion and increase sedimentation. However, ecosystem-based measures are being applied, such as nourishing intertidal flats with sand to mitigate erosion effects (Borsje et al., 2012).

4. Adaptive delta management

With current uncertain future scenarios considering climate change induced sea level rise and increasing peak river discharges, investments in large-scale infrastructural flood defense measures are not viewed enthusiastically. Adaptive delta management is currently being considered as an alternative to such conventional structural planning. Applying adaptive management to deltas is relatively new and the first explicit uses are in the Thames 2100 Estuary Project (TE2100) (Ranger et al., 2013) and in the current Dutch Delta Program (Ministry of Transport, 2010). The Deltaprogram formulates adaptive delta management as a phased decision-making that explicitly and in a transparent manner takes uncertain long-term developments into account. The TE2100 project goes even further in assessing effects of 'deep uncertainty' of climate change on adaptation measures. In both projects adaptive delta management encourages an integral approach to tasking and is aimed at reducing the risk of over- or underinvestment in future flood risk management.

Of special relevance for deltas are "path dependencies" (Haasnoot et al., 2013; Ranger et al., 2013). Historically speaking, draining, dredging and diking were adaptations and modifications of the natural landscape, but they were rigid in form with little flexibility. Modern adaptive delta management envisages elucidating these and alternative solutions under a series of future scenarios in order to make robust decisions. This supports sustainable development, which can be defined as a development that is able to achieve environmental, social and economic targets now and in the future by being robust, i.e., performing satisfactorily under a wide variety of futures, and/or flexible, i.e., it can be adapted to changing (unforeseen) future conditions (Haasnoot et al., 2013; Ranger et al., 2013). One can thus formulate adaptive delta management as a form of uncertainty management of dynamic complex human-environment systems with the goal of sustainable delta development. Clearly the challenge is to find the optimum strategy, which avoids over- and under-investments now and in the future.

Valuable lessons on implementation of adaptive management regimes can be learned from the adaptive co-management (ACM) approach that was specifically designed for management of complex socio-ecological systems and that also anticipates on permanent change and integration of monitoring and experimental results into the decision process (Plummer and Armitage, 2007; Armitage et al., 2008). Although adaptive delta management needs further definition and elaboration, it is already clear that low-regret measures for flood risk management and climate change adaptation will play an important role in dealing with uncertainty (Ministry of Transport, 2010; Environmental Agency, 2012; Ranger et al., 2013). Low-regret measures are typically defined by their rapid and low cost reduction of risks under a wide range of scenarios (Cheong et al., 2013; Ranger et al., 2013). In contrast, hard engineering measures, such as dams or levees, are relatively rigid and adaptation to alternative boundary conditions requires a considerable investment.

Adaptive measures can entail both non-structural and structural interventions (Fig. 3). Non-structural interventions consist of early-warning systems and zoning measures and have minimal impact on the natural environment. Structural interventions are infrastructural interventions, such as dams, sluices and levees. Additionally, we distinguish nature-based measures that are generally structural as they require a physical presence, but that make use of regulating ecosystem services, such as wave attenuation, current reduction and stabilization, in their design. They can contribute to flood risk reduction in several ways: by dissipating wave energy, directly functioning as a barrier against flooding and by stabilizing the coastline (Fig. 3). Nature-based measures can be used in combination with other measures, both infrastructural, such as levees and dikes, but also with non-structural measures such as zoning or early warning systems (Cheong et al., 2013). In general, flood risk management plans entail sets of measures and make use of combinations.

In order to achieve minimal impact of (green) structural interventions on natural systems and avoid the problems of the past, guidelines for green structural interventions should emphasize; 1) connectivity of sediment exchange between river, sea and estuary (Smits et al., 2006) and ensuring sediment flows and balances as a basis for long term development of sedimentary coasts (Nicholls, 1989), 2) ecological integrity of the estuarine system by maximizing openness and mixing (Smits et al., 2006) and 3) respect, enhance and integrate regulating ecosystem services that reduce flood risk, meanwhile enhancing production (e.g., fisheries) and cultural (e.g., landscape) ecosystem services. Basically, this also entails making maximal use of the ecosystem engineering capacity of species, in dissipating waves and trapping sediment, and is often referred to as ecological engineering (Borsje et al., 2011; Gedan et al., 2011; Cheong et al., 2013).

Ecological engineering is currently developing as one of the more popular adaptive and no-regret strategies for flood risk mitigation and climate change adaptation (Cheong et al., 2013). Compiling evidence shows the effectiveness of coastal and river ecosystems in mitigating flood risks and concurring damages (Barbier et al., 2008; Gedan et al., 2011; Arkema et al., 2013). Ecological engineering gives a central role to these ecosystems and their services in coastal management planning by attempting to preserve ecosystem services not just for their own sake, but also as a basis for extended services in the form of adaptive coastal defense and all concurring additional benefits (Cheong et al., 2013). It does not leave coastal development to natural evolution, but aims to adjust human intervention in order to maximize nature's contribution to coastal safety. Innovative approaches for flood risk mitigation that include ecosystems, their services and natural processes fit perfectly within the adaptive delta management strategy.

Experiences with adaptive management of sandy coastlines by sand nourishment could be used as a template for adaptive management of estuarine and muddy coastal systems. In theory, these systems can be adaptively managed using ecological engineering approaches, but there is little experience in doing this in practice. The 2012 Louisiana Coastal Master Plan of Louisiana represents a move in this direction. It proposes a large-scale effort towards cost-effective and sustainable management of estuarine systems to provide for coastal ecosystems and well as flood safety for local populations (Peyronnin et al., 2013). In coastal Louisiana establishing a healthy wetland system becomes an integral part of the coastal defense system (Barbier et al., 2013; Cobell et al., 2013). However, the area of wetland that can be conserved and restored depends on sediment availability. Estimates of available sediment quantities in future decades are based on present sediment budgets and can provide the basis for the targets and goals of the coastal management strategy. However, there is great uncertainty regarding the future supply of sediments from the Mississippi River, and the targets will only be met using a clear monitoring and management strategy, for which the Dutch sandy coast may serve as a good example.

Nowadays, many delta areas in the world face important decisions on how to reduce local flood risk. Here, the choice between

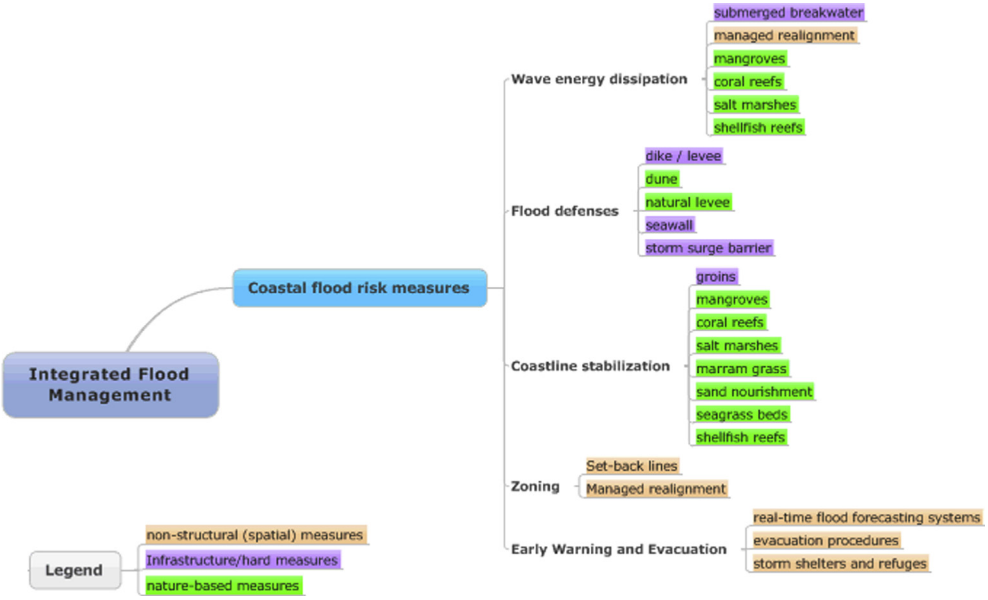

Fig. 3. Overview of non-structural, infrastructural and nature-based measures and their functions for coastal safety in an integrated flood risk management framework.

large-scale damming and alternatives still needs to be made. For example in the Mekong delta in Vietnam the closure of several largest of its nine estuaries is considered an option to increase coastal safety and reduce salinity intrusion (Käkönen, 2008). The consequences for the delta dynamics as a whole have not yet been studied, but will be significant. Alternatives to large-scale damming in this area would be to focus on reducing vulnerability by enhancing and supporting the adaptive ways of living with the floods that people in this delta have already adopted and to support small-scale flood protection as well as new flood-resilient urban designs (Le et al., 2007). Examples of living with floods in the Mekong delta are constituted by alternating between rice and shrimp farming, growing rice that is suited to the local flood regime and having floating markets and flood-proof houses (Käkönen, 2008). Another example is constituted by Jakarta (Indonesia) where around 14 million people are seriously threatened by both coastal and fluvial flooding (Brinkman and Hartman, 2009). To reduce risk on coastal flooding, damming of a large part of Jakarta bay is suggested (http://www.dutchwatersector.com/news-events/news/8608-new-garuda-shaped-master-plan-gives-jakarta-new-perspective-on-coastal-city.html). Combinations of this large-scale damming project with mangrove restoration are being explored, illustrating the rising popularity of more nature-based approaches. However, in the end infrastructure measures will only partially solve the frequent flooding problems of the city. The main challenge remains to revert from deep groundwater exploitation that is causing the cities' rapid subsidence (Abidin et al., 2001; Brinkman and Hartman, 2009). Further, in the Hudson River estuary (USA), damming is considered a measure to reduce flood risk after hurricane Sandy that caused large losses in New York and New Jersey. Here both green and gray alternatives to increase flood safety are seriously considered and weighed (http://www.wri.org/blog/rebuilding-cities-after-sandy-3-keys-climate-resilience).

5. Discussion and conclusions

The decision to build the Dutch Deltaworks was made in the 1950s: a time when there was hardly any recognition of potential ecological effects of engineering works and just after a terrible flood disaster. In the seventies awareness was rising that ecosystem services and values would be altered after closure of the Oosterschelde resulting in the decision to construct a semi-permeable storm surge barrier. Currently, we are even more aware of adverse effects that are generated when damming bays and estuaries. These effects reach further than only consequences for natural processes and loss of ecosystem services. Smits et al. (2006) made a strong case for the increasing risk that comes with our current diking and damming practices. Higher levees create a false sense of safety, thereby attracting more economic activity, whereas failure of levees at higher water levels results in more damage and fatalities. We feel that increasing knowledge and understanding of natural coastal processes, including bio-physical feedbacks, should enable us to redirect efforts in coastal defense from massive, energy-intensive and ecologically unfavorable static solutions towards intelligent, flexible and self-adjusting concepts of working with natural processes.

Large catastrophes, such as recent hurricane Sandy that hit New York, may act as drivers of change, including large-scale ecosystem-based solutions. The 1953 flood drove the implementation of the Deltaworks, and hurricane Katrina stimulated the development of the 2012 Coastal Master Plan in Louisiana. In this way tragic disasters, contrary to gradual and slow trends, such as sea level rise, climate change and subsidence, seem to generate momentum for innovative approaches and paradigms shifts. Given the human tendency to settle for conventional and 'proven' solutions (Filatova et al., 2011), the main challenge lies in mainstreaming ecosystem-based flood defense solutions in engineering and coastal management practices. In our opinion this can only be done if ecosystem-based designs are considered engineering approaches and consequently, are tested and developed in a similar manner. Where western engineers previously exported their knowledge on building large structures and dams, they should become confident to export ecosystem-based solutions. This implies that ecosystem-based solutions need to be tested according to engineering standards for probability of failure. Although adaptive delta management accompanied by innovative approaches that integrate coastal safety with ecosystem services is gaining popularity, it is not yet common practice to include adaptive pathways, a system-based view and ecosystem knowledge into coastal management projects. The challenge lies in implementing adaptive management and ecosystem-based alternatives for flood risk mitigation in the daily practice of engineers and coastal planners, as in the end only a more adaptive form of management, which allows for monitoring and a learning-by-doing approach, will enable us to deal with the dynamic and more unpredictable nature of ecosystems and, thus, with a more dynamic and uncertain future.

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