van Staveren, M. F., and J. P. M. van Tatenhove. 2016. Hydraulic engineering in the social-ecological delta: understanding the interplay between social, ecological, and technological systems in the Dutch delta by means of "delta trajectories." *Ecology and Society* 21(1):8. http://dx.doi.org/10.5751/ES-08168-210108
Erratum: This paper was originally published with a date of 2015, the error was corrected on 18 January 2016.

Insight

Hydraulic engineering in the social-ecological delta: understanding the interplay between social, ecological, and technological systems in the Dutch delta by means of "delta trajectories."

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ABSTRACT. Several of the world's largest deltas have recently been conceptualized as social-ecological delta systems. Although such conceptualizations are valuable in emphasizing complex interaction between social actors and ecological processes in deltas, they do not go into specific dynamics that surround technological developments in the hydraulic domain. By drawing from concepts originating in socio-technical systems research, we stress the importance of technology, particularly the domain of hydraulic engineering, in shaping a delta's future. Based on two geographically distinct cases of flood management infrastructure in the Dutch delta, we demonstrate the influence of existing hydraulic works, in mutual interaction with social responses and environmental processes, on the development of the congregated delta system over time. The delta trajectory concept is introduced as a way to understand the interplay between social, ecological, and technological systems in deltas. We discuss options to realign unsustainable pathways with more desirable ones. Adaptive delta management presents a policy environment where these messages may be picked up.

Key Words: *adaptive delta management; delta trajectory; flood management; hydraulic engineering; path dependency; social-ecological systems; technological lock-in*

INTRODUCTION

Deltas are among the most resource rich and environmentally dynamic ecosystems on earth (Millennium Ecosystem Assessment 2005). They are said to provide delta services (Lund et al. 2007) ranging from fertile soil and various natural resources to a geography that allows for easy settlement, transportation, and navigation. Delta inhabitants have for centuries attempted to manage such services for human betterment: to draw from or enhance positive services on the one hand, while trying to control or reduce perceived negative services on the other. Dealing with a delta's water resources (and, strongly related, erosion and sedimentation processes) is an exemplary domain of both sides of the coin: Irrigation systems are built to further improve distribution of limited water resources for the benefit of agricultural production, and flood management infrastructure is constructed to deal with high water levels in rivers or coastal areas. Hydraulic works have thereby significantly impacted environmental processes in deltas (Syvitski et al. 2009). Considering general socioeconomic trends, growing pressure on space, and climate change consequences in deltaic environments, dealing with water and floods will be one of the most dominant issues for delta managers in the decades to come (Syvitski 2008, Van der Most et al. 2009). In turn, hydraulic infrastructure will continue to play a central role in shaping future human-environment interactions in deltas.

Within the broader field of human-environment studies, social-ecological systems (SES) theory is frequently used to study interactions between human actors and environmental processes. From this perspective, several of the largest of the world's deltas have recently been conceptualized as social-ecological delta systems (delta-SES; Renaud et al. 2013); similar ideas also have been used at the level of large river basins, most of which include deltas (Cumming 2011). Although studies inspired by delta-SES argue that human-induced hydraulic interventions often negatively influence environmental processes in deltas, they do not go into details of how such technological dynamics in the hydraulic domain came about, and how they continue to steer delta futures.

Therefore, we were interested in further exploring how these dynamics, in particular the role of hydraulic engineering works, influencing and being influenced by social-ecological interactions in delta systems, affect the development pathway of the composite delta system. To do so we drew from socio-technical systems research. This simultaneously responds to earlier firm calls for intensified dialogue and exchange between SES research and socio-technological systems studies (Smith and Stirling 2010). Insights from socio-technical systems research contributes to continued debate regarding the place of technology and technological processes in relation to SES conceptualizations (Smith and Stirling 2010).

The article introduces the concept of delta trajectories, with the objective to enrich SES-style analyses of deltas with ideas about technological development. Presented as an analytical tool, delta trajectories may be used to assess and understand the evolution of a delta-SES over time under the influence of mutually interacting social, ecological, and technological systems. We argue that the concept is useful in understanding how past hydraulic interventions are still profoundly shaping the present-day delta "state," as well as outline, in an extrapolative fashion, possible future delta-SES pathways. This is particularly relevant when it comes to discussing delta futures or long-term delta planning, which is sometimes done by means of SES perspectives but which does not take into account the in-depth conceptual lessons that socio-technical system research offers. We support our observations by discussing a number of contemporary flood management interventions materializing in several of the world's deltas; we also present options to realign identified unsustainable

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pathways with more sustainable ones, or to avoid unsustainable paths in the first place.

TECHNOLOGY IN HUMAN-ENVIRONMENT CONCEPTUALIZATIONS

Human-environment studies frequently adopt system views to understand the complex and intricately linked dynamics of actors, environmental processes, and physical networks, or respective systems (Gerrits and Marks 2008, Glaser et al. 2008, Harden 2012). Among these are SES theory (Berkes et al. 2000, 2002), complex adaptive systems perspectives (Rammel et al. 2007, Dammers et al. 2013), and coevolutionary ideas about systems development (Norgaard 1994, Norgaard et al. 2009). Despite differences and variations in analytical emphasis, the approaches have in common that they stress dynamic interaction between social and ecological (sub)systems, and nonlinearity of system development over time.

Using an SES perspective primarily centers around notions of mutual interaction and coevolution of the social and ecological (Berkes et al. 2000, 2002, Gallopín 2006, Norgaard et al. 2009). A coupled SES is conceptualized as moving over time through a trajectory of states, conditioned by various endogenous and exogenous processes including technologies (Smith and Stirling 2010, based on Walker et al. 2006). Analytically, SES perspectives may be used as frameworks to assess how interactions between the social and the ecological take shape, and how the system under review evolves as a whole as an outcome of these interactions (Berkes et al. 2000, 2002, Enfors 2013). Concepts such as resilience and adaptability express systemic states or capacities for change (Walker et al. 2006, Folke et al. 2010), whereas "rigidity traps" express persistent, inflexible system states (Gunderson et al. 2015).

The SES approach proved to be useful to study the impact of human interventions on ecosystems, resulting in recommendations to improve environmental policy and governance arrangements, and to formulate concrete management options (Anderies et al. 2004, Folke et al. 2005, Lebel et al. 2006, Domptail et al. 2013). At the same time, Halliday and Glaser (2011) argue that the approach will benefit from further conceptual exploration, refinement, and operationalizing frameworks.

Delta-SES

Recently, several of the world's largest deltas, such as the Mekong delta (Garschagen 2010), the Sacramento-San Joaquin delta (Norgaard et al. 2009), the Dutch delta (Pel et al. 2014) and the Nile delta (Redeker and Kantoush 2014), have been conceptualized and studied as complex delta-SES. Using these frameworks is primarily driven by the different kinds of complexity encountered when dealing with water-related challenges in delta areas (Pel et al. 2014).

Both general and delta-specific SES studies have in common that they tend to criticize the aggravating human impacts on the delta ecosystem in the form of urbanization, reduction of natural area and ecosystem dynamics, and indirectly, climate change effects. Technology or infrastructure is thereby assessed in a dichotomous way. Flood protection infrastructures, such as high embankments, prevent flooding but also impact the ecosystem dynamics in which they are constructed. Scholars have argued that some deltas may be classified as Anthropocene-delta-SES, in which human hydraulic engineering has completely altered the initial Holocene-delta-SES beyond recognition and resulted in irrevocable impacts (Renaud et al. 2013). As formulated by Syvitski and Saito (2007:261), "...Human engineering is now a major influence on the growth and evolution of many deltas, through control of the flow path of distributary channels, and mitigation of the seasonal flood wave with concomitant change in the delivery of sediment load." Although we concur with general observations that hydraulic engineering is profoundly impacting deltas, much more is to be said about how such interventions materialize and continue to affect delta futures, in other words, are persistent in delta systems over time.

Into technology: hydraulical engineering systems in deltas

Insights from socio-technical systems research can contribute to continued debate regarding the place of technology and technological processes within SES theory (Kemp and Rotmans 2005, Young et al. 2006, Smith and Stirling 2010). Despite the different thematic interests, conceptual frameworks, and general objectives of socio-technical systems research, both fields of study find each other in addressing complex and dynamic interactions in systems, while proposing forms of governance for sustainability (Smith and Stirling 2010, Rijke et al. 2013) or managed transitions (Fischer-Kowalski and Rotmans 2009). From the broad domain of socio-technical systems research, we have a prime interest in the subfield of large technological systems (LTS) research and associated conceptual vocabulary, because those perspectives are applicable to the examples of large-scale hydraulic engineering that will be discussed later on.

The LTS field emphasizes the rigidity and long-term persistence of hard infrastructure over time by means of the mutually related concepts of path dependency and technological lock-in. In the literature, path dependency and technological lock-in are often used interchangeably, but a distinction can be made between them. Path dependency emphasizes future development of a system, whereas technological lock-in emphasizes a certain system state. The central idea of both is that technology and technological systems follow development paths that are specific, persistent, and relatively difficult to step away from (Nelson and Winter 1982, Perkins 2003). Following Wynne (in Feenberg, 2010: x), "...Complex and usually distributed but highly coordinated modern technologies, once established, lay down both material and imaginative pathways and constraints that themselves effectively delimit what may be seen as possible future developments."

The explicit aim of LTS research is to study the development of LTS embedded in their wider social and environmental context (Hughes 1983, 1987), such as electricity networks or railways. In a narrative, case study–oriented research style (Van der Vleuten 2013), a conceptual vocabulary has developed that explains the emergence, expansion, and general development of technological artifacts and their composite systems. From this perspective, technology researchers have shown an interest in studying the historic evolution and contemporary manifestation of hydraulic engineering systems using LTS or strongly related perspectives (Bijker 2002, Kaijser 2002, Van der Vleuten and Disco 2004), explaining contemporary unsustainable system states or technological pathways in deltas (Wesselink et al. 2007, Gerrits and Marks 2008, Syvitski et al. 2009, Sze et al. 2009).

From here on, when referring to a technological system, we specifically mean a hydraulic engineered system. A broadly defined hydraulic engineered system may comprise canals (irrigation, drainage, or navigation), sluices, locks, pumps, small-scale hydraulic works, dams, coastal or river embankments (also called dikes or levees in different parts of the world), or storm surge barriers. We focus empirically and analytically on the latter two.

Pathways to the future: delta trajectories

To better analyze how environmental, social, and technological systems interact in deltas, we introduce the delta trajectory concept. We define the concept as an analytical tool, intended to understand and assess the dynamic coevolution and interplay of environmental dynamics, social processes, and hydraulic infrastructure in delta-SES over time. It departs from social-ecological conceptualizations of deltas, emphasizing complexity, coevolutionary change, and nonlinearity in systems development, while incorporating insights from the domain of socio-technical systems research about the development of technological systems. Insights resulting from delta trajectory analyses are useful when discussing the future of the delta system under scrutiny, if centered around underlying challenges regarding water and flood management. With the delta trajectory concept, it is on the one hand possible to analyze the way past hydraulic engineering has affected and will affect delta futures, while on the other hand this concept provides scope to the development of sustainable pathways.

Complexity issues surface instantaneously when trying to get hold of the delta system under scrutiny. Considering that water, floods, erosion, and sedimentation processes all originate in or are influenced by drivers outside the imaginary or formally delineated delta, and also materialize differently day by day, it is practically impossible to define geophysical or ecosystemic delta boundaries. Therefore, national borders or institutional jurisdiction do not correspond with the geophysical delta, invoking political-ecological tensions when it comes to delta governance. Advantages and disadvantages of attempting to define system boundaries are provided in studies done by others (Alessa et al. 2009, Halliday and Glaser 2011). Here we argue that a too narrow delineation ("delta blinkering") of a delta system comes with risks. When sea currents or upstream rivers supplying sediment are not considered to be within a delta's boundaries, these sedimentation processes may be left out and not assessed for their capacities in raising a delta's land surface. Narrow views may likewise disregard political realities when it comes to governance arrangements, policy processes, and social participation in hydraulic decision making or re-engineering in international delta regions (cf., Bijker 2007, Huitema and Meijerink 2010).

The delta trajectory concept underscores the materiality and persistence of engineered works in driving the collective delta-SES trajectory. These works may start relatively small, tending to expand spatially over time, or take form in relatively large engineered objects such as coastal dams. Assuming that these structures perform in terms of preventing floods, hydraulic choices are often maintained by building on prevalent and proven conceptual approaches (Lach et al. 2005, Garrelts and Lange 2011). In addition to this socio-institutional dimension, the sunken costs of expensive technology make it economically more efficient to continue in the line of the established pathway (for example, by heightening or reinforcing existing embankments in response to floods), compared with fundamentally different strategies, such as river widening or embankment relocation (Ingram and Fraser 2006, Garrelts and Lange 2011, Bubeck et al. 2013).

This is, however, not to say that a certain pathway is set in stone forever. A profound change of course in flood management strategy can materialize, but this would require great economic efforts and substantial change in policy, or as some argue from a somewhat fatalistic perspective, an occasional major flood event to initiate such drastic change (Geels and Schot 2007, Huitema and Meijerink 2010). We look here at the capacities of social actors, notably policy makers and river managers, but also at other professional domains and social groups that have increasingly involved themselves with hydraulic decision making to proactively either maintain an inherited technological path or to pursue an alternative trajectory. A case in point is the growing influence of social actors, ecologists, and hydraulic engineers favoring ecosystem-based approaches to water management during what has been labeled the ecological turn in Dutch water management (Disco 2002, Saeijs 2008). This has laid a basis for contemporary ecoengineering, or building with nature-inspired thinking (Waterman 2008, Van Slobbe et al. 2013).

Managed change in flood management strategies commonly takes shape as a gradual transformation or incremental change to a prevalent approach instead of a radical shift (Huitema and Meijerink 2010). Policy change can be driven by policy entrepreneurs, individuals maneuvering between dominant policy approaches and personal objectives to bring in paradigmatic change (Huitema and Meijerink 2010). Similarly, physical adjustments to infrastructure or changes in management operations of the engineered works may materialize in the form of technological add-ons, thereby offering some room to maneuver from relatively strong development paths (Ingram and Fraser 2006, Geels and Schot 2007).

The delta trajectory concept is inspired by river basin trajectories (Molle 2003, Molle and Wester 2009) and "dynamic adaptive policy pathways" (Haasnoot 2013). River basin trajectories challenge linear thinking by arguing that there is no specific, preset direction or path for how river basins develop, both technologically and institutionally, over time (Molle 2003). The dynamic adaptive policy pathways approach provides a framework to help assessing the "expiry date" of certain policy actions, providing indications as to whether path dependencies and lock-in situations may be encountered, and which management options are available to shift strategies (Haasnoot 2013). On a different note, it has been argued that small-scale water system innovations have the capacity to open up new development trajectories (Enfors 2013). Although these approaches mention the role of technology in shaping dynamics with and between social actors and environmental processes in deltas, they do not further explain how and why such dynamics are taking shape. This will be discussed in the second half of the article.

METHODOLOGY

To illustrate how delta trajectories develop over time as the result of the interplay of environmental dynamics, social drivers, and hydraulic system development, we selected two cases of hydraulic engineering in the Dutch delta: the Oosterschelde storm surge barrier as an example of path dependency and the delta's river embankment network as an exemplary case of lock-in in delta trajectories. These cases illustrate in a detailed, empirical way how complex interactions give shape to a particular development trajectory. The analyses of the cases is based on the theoretical-conceptual lessons outlined above to scrutinize complex delta developments. The analyses function as examples for similar investigations in other deltas or delta regions, where hydraulic infrastructure and social-ecological processes interact.

Characteristic for the Dutch delta[1] is low-lying land formed by the rivers Rhine, Meuse and Scheldt, in tidal interaction with the North Sea. Centuries of water flows, erosion, sedimentation, vegetation growth, and human-induced modification by means of hydraulic engineering works are giving shape to a hybrid water-landscape. Drawing from insights from the Dutch delta is also legitimate because there is a growing interest in approaching the Dutch delta as a complex SES (Pel et al. 2014), because of the interest in hydraulic engineering from a socio-technical systems perspective (Bijker 2002, Kaijser 2002, TeBrake 2002, Van der Vleuten and Disco 2004) and because plans are being drawn up that address the challenges of dealing with long-term delta dynamics (Delta Programme 2015; see also http://english.deltacommissaris.nl/). We depart from these examples because the hydraulic structures on which the accredited Dutch success in dealing with water-related challenges are based display characteristics of technological lock-in and path dependency that only rarely are acknowledged or critically reflected on.

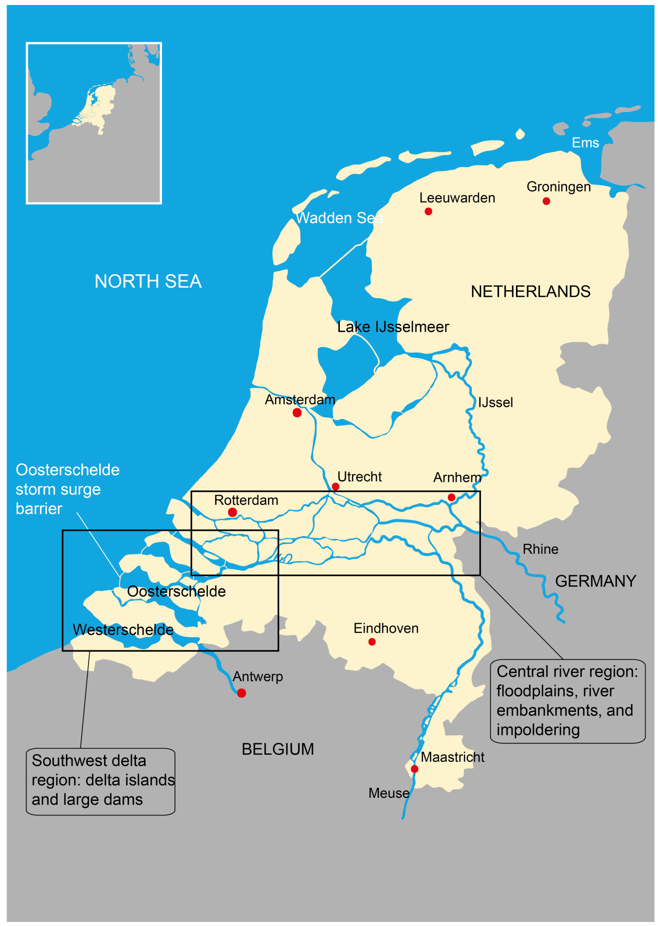
In this paper we place the empirical insights (primary data based on interviews, and secondary and referenced data based on literature) regarding historic developments in hydraulic engineering in the Netherlands in the light of contemporary debates about long-term, adaptive delta and flood management plans involving these structures. See Figure 1 for a map giving the locations of the structures.

DELTA TRAJECTORIES: EXAMPLES FROM THE DUTCH DELTA

Oosterschelde storm surge barrier: pivotal in delta decisions and initiating path dependency

After a devastating flood in the southwest delta of the Netherlands in 1953, plans for large-scale hydraulic works closing off most of the delta estuaries resurfaced. The so-called Delta Plan was presented as the project of the century: an icon of Dutch flood management-to-be and exhibiting full control over the forces of nature. The plan dated back to the 1940s but needed an actual flood disaster before it was taken up by governmental policy makers. It foresaw closing off the estuaries in the southwest delta by means of dams, each several kilometers long. Illustrative of a political dimension in hydraulic delta engineering (see also Bijker 2007) was that only the Westerschelde, connecting the Port of Antwerp to the North Sea, was exempted from being closed off. Dams in the other estuaries would substantially shorten the coastline; therefore, investments to reinforce and heighten hundreds of kilometers of more inland estuarine embankments could be dropped. As a consequence, however, the closures would halt tidal movement in the delta estuaries, forming new delta lakes containing water of a mixed quality and foreseen to slowly shift from saline tidal water to fresh water entering the lakes from upstream rivers (Van Veen 1962, Bijker 2002).

Fig. 1. The Netherlands, located in Northwest Europe. Source: Martijn van Staveren. For additional images and background on the Oosterschelde storm surge barrier and Dutch river embankments, see http://www.martijnvanstaveren.blogspot.nl/2016/01/background-info-oosterschelde-storm.html and http://www.martijnvanstaveren.blogspot.nl/2016/01/background-info-embankments-in.html, respectively.



The 9-km-wide Oosterschelde estuary presented the biggest engineering challenge. It was therefore planned to be the final closure, enabling the incorporation of lessons learned from preceding closures. When construction works of the Oosterschelde dam took off in the 1970s, the negative environmental impacts of those earlier closures boldly came to the fore: Instead of an expected transition from tidal saline estuaries to fresh water lakes, water quality in the new delta lakes quickly deteriorated. The Rhine river supplying water from upstream was at the time severely polluted, and marine ecosystems were quickly affected. Social pressure from concerned groups, but also growing professional doubts about environmental impacts of such large-scale engineering, were instrumental in the decision to step away from the plan to fully close off the Oosterschelde estuary. After years of social protests, compromising politics gave civil engineers leeway to pick up the idea and undertake the professional challenge of designing a storm surge barrier. In contrast with a fully closed dam, the designed storm surge barrier consisted of 62 sluice gates that are usually open to allow tidal movement and that can be closed individually in times of high water in the North Sea. The redesigned storm surge barrier would provide unprecedented flood protection to the region, while taking ecosystem dynamics into account (Bijker 2002).

The structure was presented as the masterpiece of Dutch hydraulic engineering, and at the time it promised to provide full flood protection for 200 years. This framing enabled acceptance of the project budget, which more than doubled to about 2.5 billion euros. The storm surge barrier fulfils its task when it comes to flood protection: Since its completion in 1986 the barrier has been closed more than 20 times to resist storm surges, most recently on October 21, 2014 (see http://en.wikipedia.org/wiki/Oosterscheldekering). However, it came with several environmental feedbacks. Although the barrier allows the majority of tidal inflow and outflow of water in the estuary, the reduction in volume is still substantial, which causes rapid erosion and disappearance of mud flats and tidal creeks in the Oosterschelde's interior. This causes the estuary bed to even out and at some locations undermines the foundations of embankments, making their underwater slope steeper. These second-order effects are met with additional engineering activities: Extensive sand supplementation is now done at strategic locations inside the estuary and broader delta, trying to compensate for the erosion losses of the mud flats. Within the context of the Building with Nature Programme, ecoengineering is brought forward as an approach to balance ecological dynamics and hydraulic engineering in the southwest delta, e.g., by using oyster reefs to stabilize eroding mud flats (De Vriend and van Koningsveld 2012). These interventions are presented as hydraulic innovations (Rijkswaterstaat 2008).

Cautious suggestions by the Delta Commission in 2008 to critically evaluate the barrier's functioning and future, hinting at potential removal, were heavily criticized. Other calls to deconstruct the barrier, notably on the part of environmental protection and conservation organizations, also rocked the boat, leading to responses stating that it is out of the question that the storm surge barrier would be removed prematurely. Long-term water and flood management strategies being drawn up for the southwest delta repeat the latter position, considering the option of dam removal unrealistic. In sum, such strategies pivotally revolve around the enduring presence of the barrier in the delta, which is foreseen for another 150 years, underscoring the robustness and long-term rigidity of this hydraulic structure (Delta Committee 2008, Rijkswaterstaat 2008, Deelprogramma Zuidwestelijke Delta 2014).

River embankments and impoldering: initiating a technological lock-in

Hydraulic engineering used to provide protection from river floods and options to locally manage water includes river embankments, the practice of impoldering (reclaiming land by means of circular embankments, and small hydraulic works to manage water in their interior) in river floodplains or wetlands, and various types of small-scale engineered works, such as canals, dams, sluices, and gates. A large network of river dikes, established and expanding since the 13th century predominantly in the centrally located region of the Netherlands, significantly decreased both the frequency and magnitude of river floods. Agricultural production could intensify (also because of better water management in protected lands), spurring socioeconomic development behind the embankments. At the same time, however, water drainage, digging for peat to be dried and used as fuel, and soil compacting caused land subsidence in protected or newly reclaimed lands (Kaijser 2002, TeBrake 2002, Van de Ven 2004, Van der Vleuten and Disco 2004).

The engineered constructions themselves impacted the hydromorphological regime within the rivers as well as the delta estuary. Embankments not only withheld flood waters, but also halted the seasonal deposition of sediments, clay, and silt on floodplains. Instead, sediment matter settled on, and silted up, the river beds, which increased water levels. In response to these issues, repetitive cycles of raising or strengthening embankments followed; in some areas of the Netherlands embankments are 8 m in height compared with the mean level of the land, holding back meters of water. This moved the Dutch delta toward a technological lock-in of ever-increasing embankment levels. Questions were raised about how long this can go on, both in technological and socioeconomic terms (Wesselink 2007, Gerrits and Marks 2008).

Over the centuries discussions arose occasionally, especially after near flood events that showed the relative vulnerability of "living low" behind high embankments, about whether the traditional approach of river embankments for flood prevention was still the right path to follow, or whether a more spatially oriented approach to dealing with floods (based on diversions, temporary water storage, or embankment relocations) should be pursued (Van Heezik 2008). This debate was most recently and vigorously held after near floods in the mid-1990s, butit did not tip the balance to one strategy in particular. The Room for the River Programme (2005-2015) that was subsequently formulated strongly advocated for the spatial flood management paradigm, but it was also preceded by a fast-track, large-scale embankment reinforcement program (Warner et al. 2013). Within the context of the program several river stretches have been widened or "depoldered" with the aim of combining water safety and nature restoration at the expense of agriculture. Such spatial solutions require huge investments, especially when compared with strengthening existing embankments. A recent program updating long-term flood management strategies in the Dutch delta stressed that investment in strengthening existing embankments was more cost-effective than, for example, spatial measures that would require buying out of farmers and acquiring land rights (Deelprogramma Rivierengebied 2014). The program introduced new flood protection norms that require several hundred kilometers of embankments to be strengthened and/or raised before 2050 (Deelprogramma Rivierengebied 2014). At the same time, proposals to slowly move away from the river embankment protection strategy and look for options that are deemed to address technological lock-in have received lots of criticism, both professionally and from broader society (Enserink 2004, Warner 2008). On an individual basis, projects in which removal or lowering of embankments is incorporated (see http://www.waterdunen.com/ and http://www.perkpolder.nl/) also met fierce protests from social actors defending the dikes (Warner 2008, Van Staveren et al. 2014).

Analysis and discussion: realigning unsustainable delta pathways

The above accounts show that the interaction between social, ecological, and technological subsystems are complex and influence each other mutually. Regarding the coevolution of subsystems, we primarily observed that environmental processes and technological developments have become strongly intertwined in the form of the Building with Nature and Room for the River programs.

Moreover, they have shown how in the Dutch social-ecological delta, decisions made in the distant past have initiated technological trajectories based on large-scale flood prevention schemes. Issues associated with technological lock-in and path dependency materialized, which are regionally specific depending on particular environmental processes or social drivers. Environmental consequences of technological lock-in and path dependency usually are addressed by policy makers and hydraulic engineers as second-order problems and are counteracted by new sequences of hydraulic engineering: raising embankments to deal with higher flood risks as a consequence of higher water levels in the rivers and subsiding polders, and sand supplementation to compensate for tidal flat erosion following the construction of the Oosterschelde storm surge barrier. Nevertheless, considering long-term impacts of dams and dikes, scholars have argued that the Dutch delta finds itself in unsustainable conditions in the long run, with slowly subsiding polders on the one hand and rising sea levels on the other (Gerrits and Marks 2008), while environmental dynamics in the southwest delta are under increasing pressure.

Delta-SES that run the risk of moving toward an unsustainable or undesirable system state may benefit from conceptual ideas and practical interventions that can reorient an inherited technological pathway. We chose to further explore this primarily from the perspective of ecological engineering. Coastal realignment, as an example of ecoengineering, has been brought forward as an approach to bring social and technological dynamics in tune with the options, or limitations, of coastal environmental processes (Pethick 2002, French 2006). It steps away from a sole focus on rigid flood defense structures and aims for a balance between hard and ecosystem-based measures (Pethick 2002, French 2006). This often involves managed retreat at locations where hard coastal protection is no longer justifiable, given the socioeconomic conditions in the area at hand. On similar terms, ecoengineering approaches take a different stance toward environmental processes, positioning themselves as reconciling hydraulic engineering with different gradations in the incorporation of ecosystem dynamics in design and operation of hydraulic works (De Vriend and van Koningsveld 2012), using terminology of ecotechnical system building (Van der Vleuten 2013, p.220), ecological engineering (Borsje et al. 2011), or building with nature (Waterman 2008, Korbee and van Tatenhove 2013, Van Slobbe et al. 2013).

When discussing realignment of a delta trajectory, timescales are important. Adopting long-term timescales may help to be reflexive about the unintended consequences (Tenner 1997) of hydraulic engineering. On relatively short- and medium-term timescales, hydraulic engineering works provide protection from extensive floods, thereby facilitating socioeconomic development. When seen over much longer timescales, however, the negative impacts of such repetitive interventions also materialize: Flood prevention inhibits the accretion of land in polders because of prevention of sedimentation, and polders start to subside. In environmentally relatively stable deltas such as those in the Netherlands, these processes materialize only very slowly, especially in contrast to, e.g., the Bangladesh delta, which is home to much more dramatic water and sedimentation processes.

Realignment in the Dutch delta

In the Dutch delta, realigning flood protection with long-term coastal environmental processes is the central tenet of the Sand Engine project (http://www.dezandmotor.nl/en/). North Sea currents slowly erode an artificially constructed sand island, dispersing its particles along the coast. This compensates for erosion in sections along the coast just north of the project site, which would otherwise require large scale-sand supplementation (Janssen et al. 2015). Similar plans have been proposed for the southwest delta region (Grontmij 2012). Several ecosystem-based hydraulic measures, e.g., constructing oyster reefs to stabilize eroding mud flats, have been proposed to address second-order erosion problems following the construction of the Oosterschelde storm surge barrier (Rijkswaterstaat 2008).

Realignment of unsustainable trajectories in the riverine region may likewise be addressed by ecosystem-based interventions, although this in practice results in different types of projects. River widening and depoldering take place at various locations in the Netherlands, which involve partial removal or lowering of river embankments. This restores flood dynamics in widened floodplains. Although depoldering, controlled flooding, and restored sedimentation processes in theory offer a way to break out of a technological lock-in (compensating for soil subsidence by increasing land height), it is not self-evident that this is pursued in practice. When sedimentation takes place in reconnected floodplains during floods, these new layers of soil are removed because the sedimentation would hamper the discharge capacity of the depoldered area (Van Staveren et al. 2014). In other large world deltas, however, despite differences in social-ecological drivers, temporarily restoring flood dynamics and capturing sediments in polders to increase land height are practiced: See Cox et al. (2006) and Maris et al. (2007) for parts of the Westerschelde located in Belgium, Bates and Lund (2013) for the Sacramento-San Joaquin delta in the United States, and Nowreen et al. (2014) for polders in the southwest delta of Bangladesh.

Realigning trajectories with adaptive delta management

Ideas about realigning trajectories are implicitly pursued by adaptive policies. Confronted by complex challenges taking place at the intersection of environmental dynamics, technological developments, and social processes, delta managers are turning to adaptive policies that can easily be adjusted over time when necessary (Walker et al. 2001, Clark 2002, Voß and Bornemann 2011, Becker et al. 2015). This rationale has been the foundation of adaptive delta management (Stratelligence 2012), which has been developed within the context of the Dutch Delta Programme [2] (Delta Programme 2015). Central to adaptive delta management is thinking along potential socioeconomic development scenarios for which certain policy responses can be formulated, the use of adaptation pathways to deal with climate change, and tipping points assessing the effectiveness of policy actions (Haasnoot 2013, Marchand and Ludwig 2014). As observed earlier, these approaches have set long-term timescales for which the delta trajectory concept might be of additional use, emphasizing historical aspects in delta planning and calling for realignment of unsustainable pathways.

CONCLUSION

Several of the world's deltas have recently been conceptualized and studied as complex social-ecological delta systems, or delta-SES. This does justice to the dynamic nature of deltas, in terms of both environmental processes and social structures, which are capricious and difficult to delineate. Conceptualizations inspired by Delta-SES stress the importance of hydraulic engineering in shaping system states and system pathways, but apart from criticizing its environmental impacts, have been less explicit in explaining how specific dynamics surrounding technological developments in deltas take place.

Responding to calls for an intensified exchange of insights and ideas between the social-ecological and socio-technical systems research domains (cf., Smith and Stirling 2010), we have explored dynamics in the hydraulic domain via the concepts of path dependency and technological lock-in. This has laid the basis for the delta trajectory concept, which is put forward as an analytical tool to understand the historic evolution and congregated outcome of systemic interplay between the social, environmental, and hydraulic systems in deltas over time. By means of the delta trajectory concept, hydraulic interventions may be assessed in relation to the complex delta setting in which they are constructed. By doing so, the delta trajectory concept calls for specific attention to the influence of hydraulic choices in the past on the historic, present, and future delta states, which reinforces the notion that hydraulic history matters (cf., Kaijser 2004). In reinforcing interaction with social and ecological processes, hydraulic engineering acts as a strong driver of a development pathway of the social-ecological delta.

We have used illustrative cases to describe two delta trajectories centered around large hydraulic works in the Dutch delta. The river embankment network and a large storm surge barrier provide high flood protection standards, facilitating socioeconomic development. They also came with unintended or unforeseen consequence such as soil subsidence, which has led some scholars to argue that the Dutch delta finds itself in unsustainable conditions in the long run (Wesselink 2007, Gerrits and Marks 2008).

The delta trajectory concept shows that technological interventions done in the past profoundly shape the direction in which deltas develop. The challenge for delta managers is, therefore, not to pinpoint the present and start from there in designing future policies and delta interventions, but to depart in their work from the "hydraulic heritage," its enduring consequences, and options for improvement and adaptation over time. Within the context of adaptive delta management policies, delta managers are confronted by the general challenge to tune hydraulic interventions with long-term sustainable delta pathways.

Ecologically informed or ecosystem-based forms of hydraulic engineering can be used for gradual, region-specific reorientations based on ecotechnological add-ons. This does justice to the physical rigidity of infrastructure, to past investments involved, and to interventions depending on environmental processes. A more thorough understanding of technological development in the hydraulic domain, in relation to social drivers and environmental delta dynamics, will contribute to formulating sustainable social-ecological delta futures.

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[1]In the light of the earlier discussion on delta boundaries, the "Dutchness" of the delta should be nuanced because the majority of water and sedimentation inflow in the delta comes from upstream countries, while Belgium (using the Westerschelde for the Port of Antwerp's shipping movements) is an important stakeholder when it comes to hydraulic engineering choices in the southwest delta region of the Netherlands.
[2]This national program was launched in 2011 with the objective of developing adaptive policies in socioeconomic and climate-related domains, resulting in practical challenges in the field of flood protection and fresh water supply in the Dutch delta (Delta Programme 2015). The final program report has been made available in English. See also http://english.deltacommissaris.nl/.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/8168

Acknowledgments:

The research for this article was funded by NWO, the Dutch Organization for Scientific Research, under grant number W.01.65.339.00. We wish to thank Dr. Jeroen F. Warner for participating in brainstorming sessions about the content of this article, two anonymous reviewers for their helpful and constructive comments, and attendees at a presentation on the topic at the Stockholm Environmental Institute (September 2015) for their valuable contributions.

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