The replacement of hydraulic structures in light of tipping points
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ABSTRACT
In many delta areas hydraulic structures are key elements in water management strategies for fresh water supply and flood risk management. Adaptation of delta areas to changing climatological and societal conditions will be in pace with the renovation and replacement of these hydraulic structures. Since hydraulic structures are prone to deterioration, their performance diminishes over time. Changes in society, the economy, and the physical environment can also alter the functionality of structures, or have an impact on their performance. Although faced with deterioration and exogenous changes, timing of replacement is essential because replacing too early leads to insufficient use of invested capital, while replacing too late leads to loss of societal benefits. This article explores the timing of replacement using adaptation tipping points. We indicate three drivers – deterioration, biophysical change, and socio-economic change – that determine the moment in time when replacement becomes necessary. Moreover, we conclude that for determining the moment of replacement, at the very least, the objectives, maintenance and operations of hydraulic structures need to be taken into account. This exploration is illustrated with the task of replacing seven hydraulic structures in the River Meuse.

Key words | adaptation, decision-making, infrastructure, uncertainty, water management

INTRODUCTION
Hydraulic structures such as weirs, dams, sluices, and barrages have an important role in water management strategies regarding fresh water supply and flood risk management. In current water management strategies not only these structures themselves, but also the way they are operated and maintained are critical elements. As elements in water management strategies, hydraulic structures provide different functions for society and are capital intensive (Hijdra et al. 2014). In time, hydraulic structures deteriorate or their functionality becomes obsolete, demanding decisions about renovation or replacement of such structures (Kallen et al. 2015).

In this paper, we discuss the task of replacement of hydraulic structures, which revolves around questions regarding whether or not to replace a hydraulic structure, when to replace it, with what type of structure to replace it (the same or with a different functionality), and where to replace the structure (on the same or on a different location). We focus primarily on the timing of replacement. Adequate timing is essential, because replacing too early may lead to insufficient use of invested capital, while replacing or renovating too late may lead to loss of societal benefits. To grasp the task of replacement, we explore the support of the adaptation tipping point method for decision-making in light of long-term changes of biophysical and socio-economic conditions.

Adaptation tipping points are defined by Kwadijk et al. (2010, p. 731) as ‘points where the magnitude of change due to climate change, or sea-level rise, is such that the current strategy will no longer be able to meet the objectives’. This definition differs from alternative definitions of tip or tipping points in social sciences (Grodzins 1957; Beshers 1967; Nuttall 2012), project management (Taylor & Ford 2008), and climate research (Lenton et al. 2008; Russil &
Nyssa 2009). These authors describe a tipping point as a moment in time when some kind of threshold is crossed and a system changes towards a new stable equilibrium. The definition given by Kwadijk et al. (2010) is interesting for two reasons. First, they add adaptation to the tipping point idea to determine the timing of a shift between a current and a new water management strategy. Second, they link adaptation tipping points to a water management strategy and the objectives to be met by such a strategy. Thus, the adaptation tipping point indicates that a strategy is no longer adequate to reach its objectives.

In this article, we focus on the usability of the adaptation tipping point method for the determination of the moment of replacement of a hydraulic structure. First, we explore the relation between a management strategy and the functionality and performance of structures. Second, we explore the drivers that influence the performance and the functionality of hydraulic structures. Third, we use the River Meuse in the south-eastern part of the Netherlands as a case to illustrate the interplay between functionality and performance, and the drivers that change both. The River Meuse was canalized in the 19th century for shipping purposes, comprising mainly the transportation of coal to the western part of the Netherlands. To make this transport possible seven combinations of sluices and weirs were built almost a century ago. While their performance is already decreasing, the type and moment of replacing these structures is not yet clear. We explore the replacement of these seven structures by using the adaptation tipping point method.

THE ROLE OF HYDRAULIC STRUCTURES IN A WATER MANAGEMENT STRATEGY

Hydraulic structures are often part of water management strategies such as those described by Kwadijk et al. (2010). In the definition of adaptation tipping points by Kwadijk et al. the phrase ‘current management strategy to meet the objectives’ has an important role, as well as ‘the magnitude of change’ of climatic conditions. Hydraulic structures have to meet the objectives and have to deal with this magnitude of change.

From a design perspective, hydraulic structures are developed for a function with specific goals or objectives in mind. An objective is, for example, to ‘supply’ for an expected demand of vessel passages, or for a pre-specified discharge. Such objectives are translated into functional requirements for a structure, which constitute the functionality of either a structure or a set of structures. Functionality can be defined as ‘what a structure should be able to do’, and gives a normative description for a hydraulic structure based on a set of objectives.

Functionality influences the performance of a structure, and the performance affects the functionality via possible alteration of one or more of the objectives. There are two sides to the performance of a structure. The first is the demand for use, which can change over time. In case of decreasing demand the performance will be lower than the optimal functionality, i.e., it is underused. When the demand for the use of a structure increases, demand can rise above the initial envisaged objectives. As such, functionality will start to fall short. The initial functionality of a structure often has an upper limit like a maximum amount of vessel passages or maximum discharge. The second side of the performance of a structure is the condition of the structure. To keep the performance in line with the desired functionality and to prevent deterioration of the structure, maintenance and operations have to be on an adequate level. When there is a lack of maintenance, or when operations are not well executed, the performance will diminish. Whether this is a problem depends on the user’s demands on a structure. If a structure is not used, it does not have to be ‘functional’. Thus, performance can be defined as ‘what a structure really does’.

The mutual dependency of objectives, functionality and performance shows that ‘not meeting the objectives’ for hydraulic structures can’t be answered easily. Determining or identifying the adaptation tipping point of a water management strategy is difficult since, via performance and functionality, hydraulic structures are influenced by, among others, changed normative ideas about a structure, changing demand, inadequate operations, or overdue maintenance. The adaptation tipping point can be identified based on different exogenous drivers, but a tipping point can also be delayed by changing operations and maintenance. We will describe the relation between performance,
functionality, and the water management strategy for hydraulic structures in more detail in the next three sections to indicate drivers for possible adaptation tipping points.

**Performance and technical lifetime**

The performance over time can be described by the lifecycle, or lifetime of the structure (Farran & Zayed 2009; Frangopol 2011; Frangopol et al. 2012). Deterioration determines the technical lifetime of a structure, which over time is inevitable. Deterioration is driven by two factors: environmental stressors and human use. Environmental stressors such as climate, acidity, discharge, and algal growth affect processes of corrosion, biological fouling, and concrete cancer. Human use affecting the technical lifetime of structures includes traffic (such as shipping, trains, cars or lorries, depending on the structure), movement of mobile parts of the structure, the use of water as a cooling product, and deposition of effluents. The rate of deterioration is affected by the intensity of the traffic, possible accidents, waves from shipping, the wearing of movable sections of the structure, and chemical or thermal pollution of the water.

Deterioration is influenced by multiple factors at once. The set of factors can change over the course of time, thereby altering the technical lifetime of a structure. A complicating aspect to determining the technical lifetime is that a structure is not one entity. For example, the technical lifetime of the structure’s construction is shorter than that of its foundation due to exposure to waves and water. Based on the technical lifetime, at least four different sections of a hydraulic structure can be distinguished. In decreasing order of their technical lifetime, these sections are: the foundations of the structure; the structure itself; movable elements; and the electronic steering system.

Deterioration makes active prevention, maintenance, renovation or (partial) replacement within an existing water management strategy necessary to maintain overall performance of a structure. Examples of active prevention include the placement of sacrificial anodes on metal parts to divert rust (Schramuk & Klopfer 2005) and the application of coatings to reduce concrete cancer and to strengthen the structure’s resistance against corrosion and biological fouling (Niblett 2004). Renovation and partial replacement include the upgrade of electronics, upgrading parts of the concrete structure, replacing movable parts (such as adding new sluice-doors, or valves that can be opened at higher speed), or retrofitting the structure (Ang 2011). By maintenance, renovation, and (partial) replacement, structures are kept fit for purpose.

Deterioration is an important driver for possible adaptation tipping points regarding the performance of a structure. Next to deterioration, biophysical change is also a driver for tipping points by influencing both the speed of deterioration and the performance directly. Biophysical change includes changes in water quantity (for example due to altered rainfall patterns in the watershed) and in water quality (for example due to accumulation of chemical pollutants or nutrients due to droughts).

**Functionality of structures**

Next to technical lifetime, hydraulic structures have a specific functionality, defined as: ‘What the structure should be able to do’. Functionality can, among others, be based on the socio-economic role of a structure, its geographic location, its role in the larger water system for among others the transport of water, ice or sediment, and the relation to other hydraulic structures within a water system. Functionality is determined by societal and political choices regarding the objectives of a structure. The technical design and dimensions of a structure facilitate the objectives, but also fixate the use with a specific functionality for pre-specified objectives. These pre-specified or design objectives often have upper and lower limits (maximum amount of vessel passages, minimum, and maximum discharge) to cope with expected variability, and which include safety margins to deal with uncertainty. The objectives can be formulated in very specific or in general terms, for one structure, a set of structures, or for a water management strategy based on structures.

In many cases, structures are designed and constructed for more than one objective. Large hydraulic structures are primarily used to regulate the main water system (for example, the main river tributary) for flood prevention, fresh water supply, and shipping. But there are also direct and indirect links between the water system and land use in the adjacent areas. These links include water quality, groundwater levels, and availability of irrigation water.
These links are determined by the use of water in the regional environment, or influence the usability of the land. The desired use and usability influence the functionality of a structure. For example, the production of fruit crops, as a high revenue form of agriculture, requires a specific groundwater level and water quality, which both can be defined in an objective. Regional and local politics, and the related decision-making processes, are important in determining the objectives of hydraulic structures. In the political arena, stakeholders can discuss and negotiate objectives, influenced by socio-economic trends. In this way, functionality is challenged by changing objectives based on socio-economic trends and political desires, a third driver for a possible adaptation tipping point.

**Water management strategy**

We contend that performance and functionality of hydraulic structures are important in water management strategies. The performance and functionality of the structure are affected by three different exogenous drivers: deterioration of a structure, biophysical change, and socio-economic change. These drivers change the deterioration rate, alter the performance, or change the objectives set in a political arena, each making the current functionality obsolete (Figure 1) and creating possible adaptation tipping points.

For example, climate change can lead to a change in discharge, affecting performance, or to changes in the local biophysical conditions, affecting the technical lifetime of structures (Stewart et al. 2011). Socio-economic change can affect the functionality of structures, for instance an alteration of local land use leads (via the political arena) to a change in objectives and thereby in functionality. The influence exerted by these exogenous drivers over the technical lifetime and functionality, indicate at least three possible adaptation tipping points for hydraulic structure-based management strategies. In determining which driver leads to the adaptation tipping point, the interrelation between the main drivers of change should be taken into account. An example of such an interrelationship is the dependency of the regional water system on the main water system to supply water in dry periods and to accommodate drainage water in wet periods. This dependency not only changes due to climate change, but also due to socio-economic change and political choices in the regional system, affecting water use and management.

![Figure 1](https://iwaponline.com/jwcc/article-pdf/6/4/683/600635/jwc0060683.pdf)

Figure 1 | Schematic overview of functionality and performance of a structure, related to the key ingredients of a hydraulic structure-based water management strategy.
Summary

There are three different drivers which determine the moment of replacement of hydraulic structures (or changes in Kwadijk et al. (2011) their definition of adaptation tipping points): (1) the deterioration of the structure, affecting the performance; (2) biophysical change, altering trends in discharge, water quality, and upstream management, thereby affecting the performance and the speed of deterioration; and (3) socio-economic change, affecting the intensity of actual use and affecting the demanded functionality via altered objectives in the political arena.

Each of these three drivers can lead to possible adaptation tipping points, whereof just one will become reality if not avoided. Therefore, these three different drivers, and related uncertainty, should be factored into the decision-making about the type, extent, and location of a replacement. Determining or identifying adaptation tipping points can be helpful in deciding about the replacement of hydraulic structures. We will illustrate the drivers and the interplay between the key concepts relevant for the replacement of hydraulic structures for the River Meuse case.

TIPPING POINTS IN HYDRAULIC STRUCTURE-BASED WATER MANAGEMENT STRATEGIES: THE RIVER MEUSE

We explored three drivers of change which need to be considered in determining tipping points for a water management strategy based on hydraulic structures. By exploring the task of replacement of seven hydraulic structures in the Dutch part of the River Meuse we illustrate the relevance of these drivers. This case is based on continuing work at Rijkswaterstaat, the executive body of the Dutch Ministry of Infrastructure and the Environment, and illustrates the complexity of decision-making about the replacement of these hydraulic structures.

Current management strategy in the River Meuse

In the southern part of the River Meuse (in the provinces of Limburg and Brabant), seven weirs were built in the early 20th century (see Figure 2 for exact locations). During this period, coal was excavated in the south-eastern Netherlands and transported by barge to the industrialised west of the country. The seven weirs were built to canalise the River Meuse in order to facilitate this transportation of coal. Shipping still continues, and land use also currently depends on the weirs. Important land uses in the Meuse Valley are agriculture and extraction of gravel and sand. Also, the region’s ecological value and its attractive, alternating landscape depend on the water system.

The seven weirs in the River Meuse are among the oldest hydraulic structures in the Netherlands (Table 1; Figures 2 and 3) and their main function is to maintain a high water level for shipping in the river. Since the Meuse is a precipitation-based river, water levels can fluctuate enormously. Weirs and some parallel canals (the Zuid-Willemsvaart, Julianakanaal, and Lateraalkanaal) prevent obstruction of the shipping route, which is classified as Vb in the European (CEMT) classification scheme. This classification means that ships of 190 m length, 11.4 m width, and 3.5 m draught, can travel along the canals and river (ECMT 1992). To provide sufficient water depth and width of the waterways, a river discharge of at least 20 m³/s is necessary (Bruggemans et al. 2013).

Since the weirs in the River Meuse influence the discharge of water, they also influence fresh water supply for irrigation, management of nature areas, and recreation in the region. In particular, the weirs at Borgharen and Linne are important for fresh water supply during the incidence of drought. Moreover, the weirs enable managing the fluctuations in discharge and pressure of the water on the dykes along the River Meuse. The weir in Linne also functions as a hydroelectric power station and plans exist to replicate this in Borgharen. Most of the weirs are made suitable for the passage of fish by means of fish ladders.

Possible tipping point 1: end of technical lifetime

The determination of concrete cancer and corrosion is based on inspection of the constructive elements of the structure. The prediction is highly accurate and extrapolation to the future is possible, within some margins of statistical uncertainty (RWS 2011). If problems concerning the construction arise, either operation costs rise, or the
structure fails (Figure 4). If either of these occurs, the current water management strategy comes under pressure to be changed. To avoid an ‘adaptation tipping point’ at the moment construction problems arise, several solutions are possible, depending on the objectives and the current strategy. These solutions aim at extending the technical lifetime in order to maintain the current water management strategy. Options for water managers confronted with construction problems (and faced with a possible end of lifetime) include: doing nothing; only monitoring, leading to possible total failure; repairing or intensifying maintenance, resulting in damage being repaired, but constraints in lifetime and functionality remaining; large-scale maintenance which lengthens the lifetime, but functional constraints remain (buying time); implementing constraining measures for use of a structure, but this may limit the existing functionality; renovation by replacing parts of the structure, including repair, or refurbishment of parts; or replacement (or construction), so building a new structure (possibly on another location).

For the hydraulic structures in the Meuse, the rate of deterioration and lifetime projections are analysed and reported in an inventory of risks, the so-called RINK Meuse (RWS 2011). The hydraulic structures appear to face the end of their technical lifetime within 15–20 years (Table 1). However, as has been indicated above, technical
lifetime can be extended by maintenance, refurbishment, specific treatment, or replacement of parts of the structure.

Technical improvements might extend the lifetime of the structures in the Meuse for some years, but the final end of technical lifetime is projected for each structure in the first half of this century (Table 1). A choice between the different solutions could be based on the cost–benefit ratio of remaining functionality and costs of maintenance and operations. Furthermore, the RINK shows that the end of technical lifetime is not necessarily a fixed moment in time. The different solutions, presented here, offer the opportunity to ‘buy time’ and hence create flexibility to decide on full replacement of structures in accordance with possible new objectives.

Possible tipping point 2: change of biophysical conditions

As we have seen, biophysical conditions and changes in these conditions influence the moment of replacement of a hydraulic structure via its performance (deterioration) and via its functionality (Figure 1). Climate change affects the hydrological regime of the River Meuse and aspects of its biophysical conditions. Climate change scenarios are provided specifically for the Dutch context (Bruggemans et al. 2014). Between the different scenarios, the timing of a possible adaptation tipping point differs due to differences in structural change in low and high flows, and the moment when hydraulic change affects demanded water supply,

### Table 1 | Overview of the hydraulic structures in the Meuse

<table>
<thead>
<tr>
<th>Name of weir (type)</th>
<th>Founding year</th>
<th>Value of replacement in € million</th>
<th>End of technical lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grave (Valves on a bridge)</td>
<td>1926</td>
<td>€101</td>
<td>Owing to current maintenance until 2018, end of lifetime in 2030–2035.</td>
</tr>
<tr>
<td>Sambeek (Stoney/Poiree)</td>
<td>1925</td>
<td>Replacement costs on other location: €185–270</td>
<td>Recently valves, chains and protection of foundation were renovated (due to a calamity). End of lifetime in 2035–2040 with maintenance of moveable elements and electronic steering system.</td>
</tr>
<tr>
<td>Belfeld (Stoney/Poiree)</td>
<td>1924</td>
<td>€154</td>
<td>Owing to current maintenance until 2017, replacement in 2030–2035 (influenced by alkali-silica reaction (ASR) of the concrete).</td>
</tr>
<tr>
<td>Roermond (Stoney/Poiree)</td>
<td>1921</td>
<td>€154</td>
<td>Owing to current maintenance until 2017, end of lifetime in 2030–2035 (influenced by ASR).</td>
</tr>
<tr>
<td>Linne (Stoney/Poiree)</td>
<td>1925</td>
<td>€181</td>
<td>Owing to current maintenance until 2017, replacement in 2035–2040 (influenced by ASR).</td>
</tr>
<tr>
<td>Borgharen (Valve and flaps)</td>
<td>1928</td>
<td>€163</td>
<td>Owing to maintenance executed in 2009 and 2010, end of lifetime in 2025–2030 (influenced by ASR).</td>
</tr>
</tbody>
</table>

The order is upstream, so Lith is the top weir in Figure 2 (nearest to the sea) and Borgharen is the bottom weir, near the border with Belgium (RWS 2011).
Handling of ships, or flood risk such that they cannot be sustained. For discharge regimes in each of the scenarios, the moment of replacement can be determined and set out in time. This is done by linking functionality of a structure to a critical discharge level when the failure of the structure is rendered inevitable. For instance, Requille-Solar et al. (2015) determined critical levels for minimum water depth in the river Rhine, following discharge changes caused by climate change.

For the Meuse the average discharge in September (the season with the lowest discharge) is anticipated to change from 89 m$^3$/s in 2000 to somewhere between 30 and 94 m$^3$/s in 2100, depending on the climate scenarios (Bruggemans et al. 2015). In February (the season with highest discharge), the average discharge is expected to change from 480 m$^3$/s in 2000 to somewhere between 520 and 590 m$^3$/s in 2100, also depending on the scenario. Extremely low discharges are possible, between 10-18 m$^3$/s in 2050 and 6-18 m$^3$/s in 2100, compared to 18 m$^3$/s in 2000. The occurrence of less than 25 m$^3$/s for more than 50 days in a row may change from 1 in 300 years in 2000, to 1 in 20 years in 2050, or even 1 in 4 years in 2100. The maximum discharge exceeding 3,600 m$^3$/s currently has a probability of occurrence of 1 in 1250 years. This will increase in 2050 to between 1 in 1000 and 1 in 400 years, and in 2100 to between 1 in 400 and 1 in 100 years, also depending on the scenario (Bruggemans et al. 2015). The rise of the maximum discharge is expected to have a minimal influence on the end of the (technical) lifetime of the weirs. However, the change in the hydrological regime is important for determining the functionality for the coming century.

If, in the current situation, the discharge exceeds 1,500 m$^3$/s the weirs are not able to facilitate shipping any longer. A possible result of climate change is that this situation will occur more often, thus shipping on this stretch of the River Meuse could be disrupted more often (personal communication RWS employee). If incidence of drought increases, some of the weirs (Borgharen and Linne) might become more important to retain ground water levels. In the current situation, the fresh water supply in this region is mostly based on ground water extraction. Some small industries and energy companies (including the Claus power plant near Maasbracht and the Willem Alexander power plant near Buggenum) depend directly on water extraction from the river. In periods of prolonged drought, water use directly from the river, as well as ground water use, could be threatened.

**Possible tipping point 3: socio-economic conditions**

Socio-economic conditions drive the third possible tipping point. This driver influences the objectives set for a water
management strategy. Socio-economic change can alter the desirability of current objectives (from desirable to undesirable, or vice versa) and influence new objectives to be set in the political arena if replacement is at hand.

The development of shipping and the future utilisation of the Meuse is uncertain. Depending on the applied scenario, estimates for shipping tonnage by Rijkswaterstaat and the Province of Limburg indicate a change in Gross Register Tonnage (GRT) of 19.6 million GRT/year in 2005 to somewhere between 32.9 million GRT and 16.6 million GRT in 2040 (Limburg 2008). Meanwhile, local governments and stakeholders invest in water-bound functionality. Whether the region ultimately wants to profit more from the shipping sector, or from recreation and tourism in relation to the River Meuse, is a debate that has not yet been concluded. Decision-making about the replacement of the weirs is connected to this dispute, since the shipping industry in the region depends on the functionality of the weirs.

Besides the above-mentioned socio-economic scenarios, demographic scenarios indicate trends in population for the southern parts of the province of Limburg. The current projection for this region shows the largest decline in population compared to other regions in the Netherlands (Custers 2009). The population in the northern parts of the province is not yet declining, but projections indicate that population could start to decline in the near future. These demographic developments influence the potential for economic development of the region, and need to be considered in setting objectives for the structures.

In considering objectives for the structures, stakeholders at local, regional, and national level envisage the future of the river differently, creating a highly complex political situation with unpredictable outcomes (personal communication RWS employee). In the political arena, the improvement of shipping routes to allow bigger ships on the Meuse (an upgrade in the CEMT classification) is debated (Limburg 2008; RWS 2013). Replacement of the hydraulic structures with structures with the same functionality is questionable if bigger ships need to be allowed. Not upgrading the shipping routes could harm the development of local ports along the river.

A first stakeholder analysis showed that most regional and local interests support continuation of the current situation and, therefore, of ensuring the river’s suitability for professional (and recreational) shipping. Some interest was shown in exploring the possibilities for upgrading the shipping route. Apart from the current primary functionality of the weirs, new additional functionality is desired by local and regional stakeholders. Several local governments in the catchment area of the River Meuse would like to create facilities to cross the weirs by bike and on foot to stimulate recreation. Hydroelectric power stations are built on some of the weirs, and almost all of the structures have legal protection as national monuments because of the accredited historical and cultural value. In deciding about replacement these interests must be considered.

The situation is more complex if national and international stakes are included. The ‘upgrading option’ can harm interests on a national and international level. Instead of providing alternative options that could be beneficial for stakeholders in neighbouring provinces and countries, it constrains these options by limiting shipping in adjacent regions. This line of reasoning can also be extended towards the replacement of the structures. Alternative options, for example, directing the Vb shipping category via the province of Noord Brabant towards Belgium, could affect the functionality of the structures in the Meuse. This alternative might produce a higher economic benefit, compared to continuation of the current situation. Given the deterioration of the current weirs, in combination with climate change, the current situation will demand huge investments. Thus, extending the technical lifetime of the separate structures can give extra time to decide on a higher spatial level, where more stakes and uncertainties regarding the socio-economic dimension need to be taken into account. Meanwhile, it is unclear how the regional economy could profit from the River Meuse and what infrastructure is required for the future.

**Determining the tipping point for the River Meuse management strategy**

Further uncertainty is introduced due to the combination of the different drivers of adaptation tipping points. Combining insights in each of these drivers is essential to indicate the best moment and type of replacement. However, the chronological order of when the possible adaptation tipping points occur is inherently uncertain and almost impossible...
to determine since each of the drivers can alter the speed of the other drivers and each leads to a faltering strategy. Analysis can give some information for the different drivers and the interaction with the replacement of hydraulic structures.

For the Meuse structures, extension of lifetime by means of maintenance is currently executed, delaying the technical end of lifetime of the structures, which is now projected to start to occur in 15–25 years from now (RWS 2011). The delay provides the possibility to address the task of replacement and gain more insight into the three indicated drivers (deterioration, biophysical change, and socio-economic change) which have the potential to induce a tipping point for the water management strategy. In the coming years more insight can be gained into the effects of climate change on the variability in the Meuse’s discharge and in the effects of socio-economic aspects such as population decline and change in shipping loads on the objectives for the structures. These objectives affect the decision to either replace structures with the same functionality, with a different functionality, or not at all, and should be factored into the decision-making process.

**DISCUSSION: TIPPING POINTS, CURRENT MANAGEMENT STRATEGIES, AND OBJECTIVES**

This paper started with Kwadijk et al.’s (2010, p. 731) definition of tipping points: ‘Points where the magnitude of change due to climate change, or sea level rise is such that the current strategy will no longer be able to meet the objectives’. In this definition, three key aspects can be identified: ‘Impact of climate change’, ‘current management strategy’, and ‘objectives to be met’. The current management strategy was adopted as the unit of analysis with hydraulic structures and their interrelations as vital part of such a water management strategy.

The current water management system in the Netherlands depends heavily on regulating the water system with hydraulic structures to meet societal demands, such as inland shipping, water safety and fresh water supply. Hydraulic structure design, functionality and performance are based on political objectives and socio-economic demands on a national, regional, and local level. Based on performance and functionality of hydraulic structures, we tried to assess the use of the adaptation tipping point approach to determine the moment of replacement and looked into the possible contribution of the adaptation tipping point approach to deal with uncertain future developments.

The impact of climate change, one of the aspects in the definition provided by Kwadijk et al. (2010), affects not only the structures (and the used materials), but also the original performance and required functionality. Climate change affects river discharge and water demand of different sectors. The relation between a hydraulic structure and climate change is multifaceted, and as we have shown cannot just be based on the physical effects of climate change on the hydrological conditions. Only considering climate change for an adaptation tipping point can lead to inadequate replacement. Other drivers need to be taken into account in determining the moment of the adaptation tipping point, whereby interrelation between different drivers add complexity. Illustrated by the case of replacing hydraulic structures in the River Meuse, in the Netherlands, it can be concluded that there are at least three drivers of the occurrence of an adaptation tipping point: (1) deterioration of the structure(s); (2) biophysical change (including climate change) – (a) in the main water system (change in discharge regime) and (b) in the regional system (change in precipitation and discharge); and (3) socio-economic change – (a) affecting the main water system (change in shipping demands) and (b) affecting the regional system (change in water demand or land use).

Assessing the current water management strategy in light of the tipping point discussion, the above analysis shows that it is problematic to have a tipping point analysis that merely confronts the impact of climate change with a policy objective based on Kwadijk et al. (2010). Next to the drivers of change, an analysis must also take the management strategy (consisting of at least objectives, maintenance, and operations) into account. Otherwise, it remains an incomplete assessment that only includes the impact of climate change, or another single faceted change on the hydraulic structure.

The case of the River Meuse also shows the complexity of a tipping point analysis. In the Meuse, the deterioration of a structure, its maintenance and operation, the regional
political agenda, changes in land use and all types of biophysical change are at least as important for the assessment of adaptation tipping points as the biophysical impacts of climate change. Excluding or misunderstanding the importance and ambiguous character of the regional political agenda in analysing adaptation tipping points will lead to a failure of the analysis. Ignoring ambiguity about the future political agenda, and uncertainty in the rate of deterioration and land use change, conflicts with the purpose of adaptation tipping points, i.e., dealing with uncertainties. Therefore, it is proposed that tipping points must be more strongly connected to the regional political agenda to formulate realistic and useful recommendations for policymakers (see also Van den Brugge & Roosjen 2015). The regional community has to be involved in the decision-making process about the replacement of structures and the validity of water management strategies. This involvement can lead to a different decision about the type and timing of the replacement of hydraulic structures. This paper reflects just an initial exercise in order to show the need for adaptive approaches like adaptation tipping point assessments for deciding on the replacement of hydraulic structures and assessing the tenability of water management strategies.

CONCLUSION

Hydraulic structures safeguard the Netherlands from flooding, facilitate inland shipping on rivers and lakes and enable fresh water supply to many parts of the Netherlands. In rebuilding and reshaping the Dutch Delta, these structures form key elements in the main water management strategy. They are not only essential in the River Meuse, but in the whole of the Netherlands, and in many other places around the world. Climate change and other future changes affect the performance of water management strategies, which leads to a re-examination of current practices. Since future changes are surrounded with uncertainty, adaptive approaches are increasingly necessary (Haasnoot et al. 2013), however, these approaches should take into account regional agendas, national politics, biophysical, and socio-economic change, end of lifetime of current structures, and changing objectives. All these should inform decisions about the moment and type of replacement, which could be very different in timing or type if one of these aspects is left out.

One opportunity is to include a wider range of analysis methods available in civil engineering, regional governance and strategic planning. An example is the combination of end of lifetime analysis, stakeholder analysis, and consensus planning with adaptation tipping point assessment as shown in this article. End of lifetime analysis can be helpful to include the physical deterioration of structures, essential for water management strategies. Stakeholder analysis and collaborative planning approaches enable planners to increase consensus-based adaptive policy, connected to local agendas (Islam & Susskind 2012). Integrating these different types of analysis with adaptation tipping point analysis and pathway approaches (Kwadijk et al. 2010; Haasnoot et al. 2013) could provide a firm base for informing decision makers in light of the uncertain impacts of future change.

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