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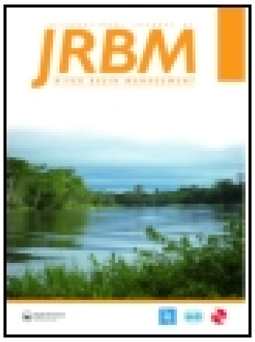

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RESEARCH PAPER

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# Assessment of the functional performance of lowland river systems subjected to climate change and large-scale morphological trends

K. S. Hiemstra[a], S. van Vuren[a,b], F. S. R. Vinke[a], R. E. Jorissen[a,b] and M. Kok[a,c]

[a]Department of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands; [b]Rijkswaterstaat, Ministry of Infrastructure and Water Management, the Hague, the Netherlands; [c]HKV consultants, Lelystad, the Netherlands

**ABSTRACT**
Worldwide, rivers provide important socio-economic and environmental functions and are essential to human well-being. The growing demand of user-functions and the change in river conditions due to large-scale morphology and climate change, increase the pressure on lowland river systems (e.g. Rhine, Meuse, Danube and Mississippi). To ensure a multi-functional river system, challenges related to uncertain exogenous trends should be tackled. This asks for an integrated approach that accounts for large-scale system behaviour rather than a sectorial approach. This paper proposes a framework that provides support to the river management decision-making process by assessing policy-options against uncertain exogenous processes based on the quantified performance of river functions. Hence, a case study of the Dutch Rhine was carried out, proposing a set of models to simulate river conditions and quantify the performance of the river functions navigation, nature and flood protection. The framework quantifies and monetized the impact of climate change and morphology on the user-functions in 2050. The application of the framework reveals a reduction of shipping efficiency, reduction of floodplain inundation and an increase in flood level. The monetization of river functions allowed an optimization of the policy-options, while dealing with uncertain processes as climate change and morphological changes. We demonstrated the merits of the assessment framework with a case study for the Dutch Rhine, as it provides useful quantitative information to support to decision-making in integrated river management.

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**KEYWORDS**
Climate change; river morphodynamics; integrated river management; river's functional performance

## 1. Introduction

### *1.1. Background*

Worldwide, rivers provide important socio-economic and environmental functions, which are essential to human well-being by provision of fresh water for drinking water, agriculture, industries and energy. The deeper channels of the river are used for inland shipping, while floodplains facilitate recreational areas. Furthermore, river ecosystems provide an important regulatory function by transporting sediments and nutrients, supporting biodiversity and regulating floods and droughts (Costanza et al., 1997; Gren et al., 1995). Hence, rivers play a central role to human civilization. Many of the lowland rivers are intensively utilized and therefore heavily trained by humans. To improve the utilization of the streams, hydro-morphological alterations have been carried out in many lowland river systems, including channel straightening, construction of dikes, dam regulation, construction of groynes and disconnection of the river from its floodplain. Indirectly, these alterations cause substantial changes in flow and sediment regimes. The response of channel morphology to engineering and regulation of alluvial streams has been assessed in a number of studies, and demonstrates remarkable large-scale morphological changes (Blom, 2016; Gregory, 1974; Williams & Wolman, 1984). These trends affect river functions by its impact on both flow conditions and stability of infrastructure (e.g. cables in subsoil, bridge piers and groynes). Furthermore, as a result of climate change extremer weather conditions (heavy rainfall and consistent periods of drought) will lead to larger dynamics in lowland river flows throughout the year, including larger inter-seasonal variability (e.g. Sperna Weiland et al., 2015). The changes in flow and sediment regime induced by climate change and river training works trigger longitudinal (long channel incision) and lateral morphological changes as the river seeks a new equilibrium situation (e.g. Blom & Arbos, 2019). Many lowland river systems are subjected to the aforementioned exogenous changes, as observed in Europe in the rivers Rhine and Danube (Blom, 2016; Klasz et al., 2013) and in the USA in the Mississippi River (Biedenharn et al., 2000). Goda et al. (2007) demonstrated the impact on navigation and (industrial) water supply in the Danube River. To facilitate the user-functions the river needs to suffice to certain river conditions. As the exogenous changes affect river conditions and user-functions demand increases, the discrepancies between functional performance and user-functions demand is enhanced.

### *1.2. Research objectives*

The impact of the – often highly uncertain – exogenous processes on the functioning of lowland rivers is not well understood and asks for a more detailed quantification. The implications of climate change on river functions have either been studied in qualitative way or quantified for only one function specific (e.g. Jonkeren et al., 2007; Middelkoop & Kwadijk, 2001). However, less attention is paid for (1) the role of uncertainty in driving variables and processes, (2)

**CONTACT** K. S. Hiemstra k.s.hiemstra@gmail.com

the impact of large-scale morphological trends, (3) the quantitative evaluation of the functional performance, and (4) the impact assessment of river management strategies in order to reduce functional performance losses or increase benefits. This paper aims to analyse the implication of multiple exogenous processes on the performance of multiple functions, and the connection with river management policy-options in an integrated approach. The objective of this research is to develop a framework that enables the quantitative assessment of the functional performance of a lowland river system subjected to uncertain exogenous processes, such as climate change and large-scale morphological trends. The impact assessment of policy-options can support river management decision-making process. The Netherlands is in the preparation phase of policy-making regarding the implications of the large-scale bed degradation and climate change. Hence, the potential of the framework is illustrated for the Dutch part of the river Rhine using a simplified model and climate and morphological scenarios 'to predict the future'.

## 2. Assessment framework description

### 2.1. Framework design

This paper presents an assessment framework, that enables the assessment of the performance of the river's functions, which supports today's river management decision-making process. The assessment framework (Figure 1) consist of two main blocks: (1) a numerical hydraulic model that describes river conditions incorporating uncertain exogenous processes and computes the hydraulic indicator and (2) a functional performance model that quantifies the river's functioning by performance indicators. Different scenarios are established that represent the uncertainty of physical processes, such as climate change and large-scale morphology. Application of the framework requires a case study specific elaboration of the framework, as the relevant processes, the river's functions and the policy landscape differ for different river systems. In other words, customization of the main blocks is required. For the purpose of illustration, the Waal, a sub-branch of the Dutch Rhine, is applied as a case study in this paper. Application of the framework enables the assessment of implications of relevant processes on the river's functional performance. In addition, it can also be used for the assessment and evaluation of policy-options or (sets of) river intervention measures to minimize the negative consequences of these trends. River intervention measures are meant to induce a certain hydrodynamic or morphological response in order to improve the functional performance. A feedback loop between the functional performance and river intervention measures enables the assessment of measures on the performance of the river system.

### 2.2. Numerical hydraulic model

The assessment of the functional performance requires a hydraulic indicator as input. A model is used to compute the hydraulic indicator (present and future state), which incorporates the uncertain processes climate change and large-scale morphology. Models describing flow conditions range from rather simple data-oriented models (e.g. empirical relations or rules of thumbs) to process-oriented models. In this study, we selected an one-dimensional hydrodynamic model, which allows pragmatic simulation of the climate and morphology scenarios and demonstrates the framework's potential without diversion into details and complex modelling issues. The hydrodynamic processes can be described via a set of mathematical equations based on physical conservation laws (Janssen et al., 1979). The model describes the river cross-section as a compound channel with a main channel with two adjacent symmetrical floodplains. The uniform flow conditions in a single channel are computed according to the Manning (1891) theory, which describes the balance between the forces of gravity and bottom friction. During flooding events, the floodplains contribute to the flow conveyance capacity and the total discharge is the sum of the discharges of all compartments. However, flow conditions vary in the floodplains due to an increased hydraulic roughness. To account for the different characteristics, the Divided Channel Method (DCM) proposes channel division through vertical lines (Huthoff et al., 2008). In that way, we neglect two-dimensional processes, such as lateral momentum exchange and asymmetry of the floodplains. As purely uniform flow conditions are fairly rare due to changes in the river profile geometry, a river generally flows non-uniform. The so-called backwater curve is described by an empirical fit to the theory of Bresse (1860), de Vriend et al. (2011).

### 2.3. Functional performance models

In this framework, performance indicators are defined to assess the river's functional performance, i.e. the degree a river system fulfils its functions to the demand of the users. A functional performance model translates a hydraulic indicator to function specific performance indicators (Figure 1). The assessment is limited to the river functions navigation, riverine ecology and flood protection. The hydraulic indicators water levels and water depths can be considered as common denominators to assess the functional performance for these functions. Besides a hydraulic indicator, functional performance models sometimes require socio-economic data to quantify the economic or societal impact. For various functions specific requirements are defined. These requirements are legal or policy rules formed by the government, the river management authority or other stakeholders to ensure the performance of specific river functions. This paper proposes a number of performance indicators for the considered functions.

- *Navigation*: Safe and efficient inland shipping requires a deep and wide navigation channel. In alluvial rivers the navigation channel dimensions are often maintained by means of dredging. Due to time limitations and/or the presence of cables, pipelines or 'hard' obstacles/structures in the river bed, dredging cannot always take place, which results in nautical bottlenecks (Blom, 2016). Due to a reduced navigable depth a ship's load factor is reduced (i.e. ratio between actual loading and total capacity). A ship's load factor follows from a function of the navigable depth, keel clearance, normative load capacity and a relation between load and draught. In case load factors of multiple vessels are reduced in periods of low water, transport cost per tonne rises. The societal impact or welfare loss due to this reduced navigable efficiency can be calculated by applying transport elasticities, which relates the

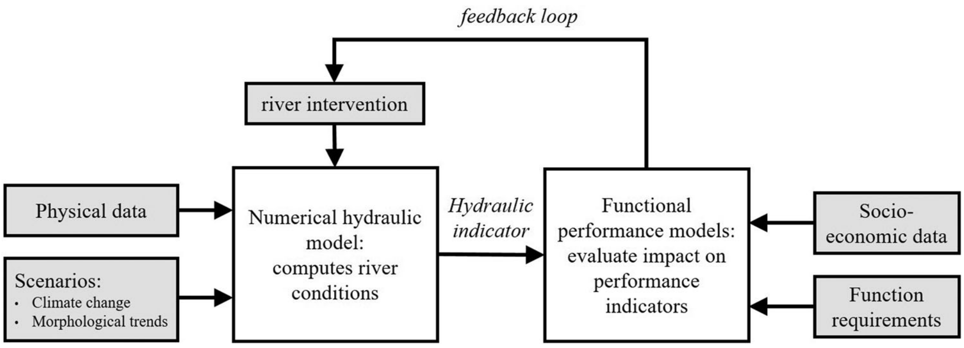

**Figure 1.** The assessment framework with required models and input (grey boxes) extended from Middelkoop and Kwadijk (2001).

relative change in costs to the relative change in transport volumes (Jonkeren et al., 2007).

- *Riverine ecosystem*: Sufficient inundation of the floodplains and river-floodplain interaction are key features of the ecological integrity of alluvial rivers (e.g. Bayley, 1995; Ward & Standford, 1995). Hence, performance indicators associated with these features are formulated to quantify the functional performance of the ecology. During inundation of floodplains and side channels nutrients, sediments and organisms are exchanged, which is crucial to the species-rich riverine ecosystem (Ward et al., 1999). Hence, inundation is considered to be a key element in assessing the riverine ecological function. The inundation frequency could be derived from water level statistics and the fixed inlet height of floodplains and side channels.
- *Flood protection*: Flood defences are common structures to provide flood protection at a certain safety standard to individuals and society. The design height of flood defences is often associated with a water level occurring during a design flood (Plate, 2002). This water level is referred to as design water level (DWL). The safety standards and thus the DWL follow from a risk assessment. The DWL forms an adequate performance indicator for flood protection.

Performance indicators are often unique for its function. Evaluation of river functions by separate performance indicators requires a value judgement by the river manager (i.e. relative importance of each indicator). A well-known method to structure decision-making and combine multiple criteria to an overall assessment, is a multi-criteria decision analysis (MCDA). In this method, the overall multi-attribute score is obtained through combining the scores for individual attributes. These kind of methods are increasingly used to support environmental management decision-making (Kiker et al., 2005). Another method to support decision-making is to evaluate the cost effectiveness of policy-options or river intervention measures. Various performance indicators can be monetized, which allows assessment of the economic societal impact by combing all costs and benefits in a cost–benefit analysis (CBA).

## 3. Case study

### 3.1. Study area

The Rhine is a large river in Western Europe rising in Switzerland as a snowmelt-fed mountain river and eventually flows as a rain- and snowmelt-fed lowland river in the North Sea. After the Rhine flows into the Netherlands, it almost directly bifurcates into different branches, viz. Niederrhein, Waal, Pannerdensch Canal, Lower-Rhine and IJssel (Figure 2). Over the course of centuries the Dutch have regulated the Rhine for inland navigation and flood management by large-scale river training works. The main channel is fixed by groynes, the floodplain separated from the channel by minor embankments and high dikes are acting as the primary flood defence to protect the hinterland. In this paper, we will assess the river functions navigation, ecology and flood protection in the upstream part of the Waal from Pannerdensche Kop (867 km) to Nijmegen (885 km).

Over the past hundred years the river bed of the upper Dutch Rhine branches degraded 1 to 1.5 m due to erosion. This incision is the effect of human interventions to the river system increasing the sediment transportation capacity, which triggers erosion (Sieben, 2009). During the last two decades, a continuation of the eroding trend of the main channel of the Waal of 1 up to 2 cm per year was observed, whereas the main channel of the Niederrhein became more or less stable (Blom, 2016). Unequal main channel incision induces a gradual redistribution of discharges over bifurcation points during both high and low flow conditions. Non-erodible structures in the river bed (e.g. bedrock layers or concrete sluice entrances) form nautical obstacles, as they stick out from the river bed. In addition to the incision process, a gradual siltation of the floodplains takes place. In case the bankfull discharge is exceeded, floodplains inundate and sediment is deposited, which elevates the floodplains. Due to the eroding process in the main channel and the accretion process in the floodplain, the inundation frequency of the floodplains will reduce, which results in dehydration of the floodplain and an increased disconnectivity between floodplain and river. The erosion of the main channel and accretion of the floodplains cause problems for nearly all river functions: depth restrictions for navigation, food safety problem induced by redistribution of the discharge, dehydration of ecological resources and agriculture, lowering ground water levels, problems related to fresh water supply, exposure of cable and pipelines, and stability problems of hydraulic structures (Deltares, 2015). The problems related to large-scale morphological trends are intensified by the impact of climate change. Sperna Weiland et al. (2015) analysed the implications of climate change on the Rhine's discharges, and their work reveals an increase in discharge in winter and spring and a decrease in discharge throughout the summer and fall, increasing the inter-annual variability compared to the current discharge variability throughout the year. Figure 3 shows a hydrograph of the period 1993–1998 showing discharge peaks during winter and spring.

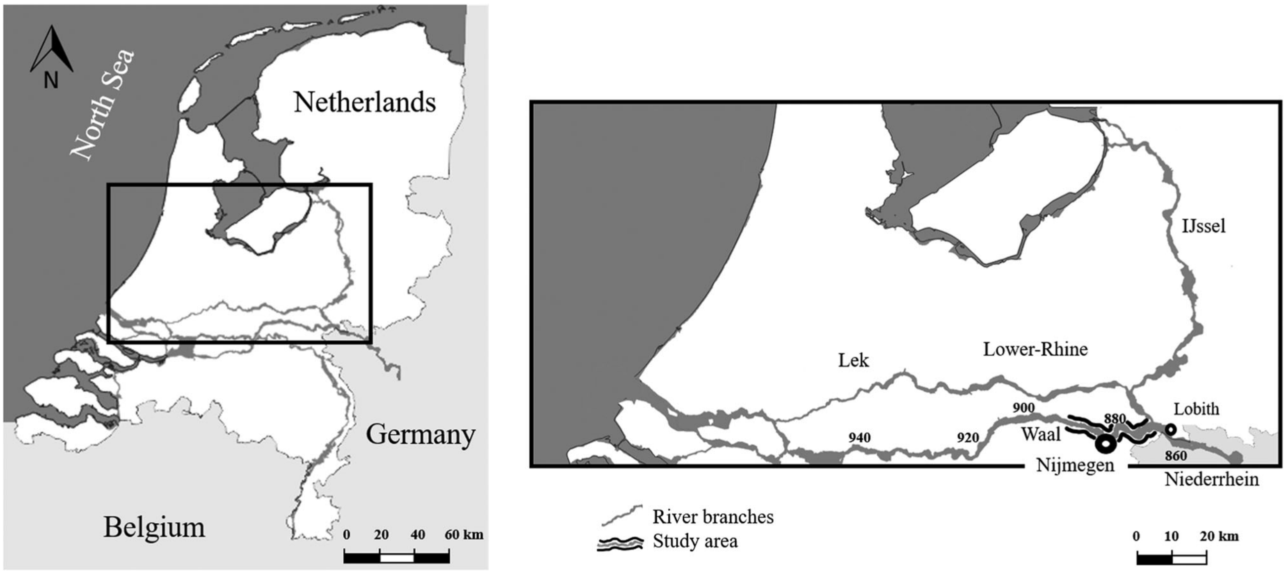

**Figure 2.** Map of the Rhine branches in the Netherlands (left) and the Waal study area with branch length indicated (right).

## 3.2. Modelling river Rhine: physical behaviour & functional performance

### 3.2.1. Physical behaviour

The physical behaviour of the Waal is described by an one-dimensional model consisting of one branch with two nodes. Two hydraulic boundary conditions are required: a discharge (hydrograph) at the upstream boundary and a rating curve (discharge-water level relationship) at the downstream boundary (Dodewaard, km 901). At the Pannerdensche Kop bifurcation, discharge is directed from the Niederrhein to the Waal following a fixed non-linear relation. By means of this non-linear relationship, the Niederrhein (Lobith) discharge is translated to the Waal discharge, which is imposed as upstream boundary at the Pannerdensche Kop (km 867). The Waal is a non-prismatic channel, as many variations in the river are noticed, such as variation in channel geometry, in floodplain height and width and in floodplain vegetation type. These variations are schematized in the model. The model has been calibrated by tuning the hydraulic roughness of the main channel for various discharge regimes to achieve an accuracy of approximately 10 cm between water level computations in relation to water level measurements. By simulating a 115-year discharge time series with daily records, representative daily water level and depth time series are obtained over a spatial grid size of 500 m for different projection years.

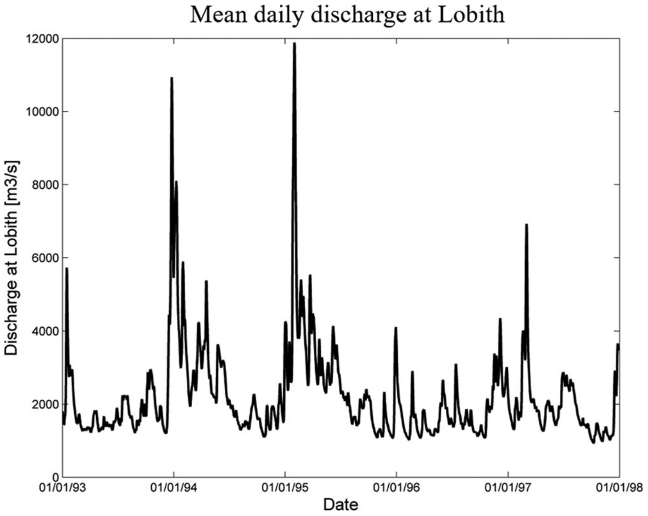

**Figure 3.** Hydrograph of the Rhine at Lobith over the period of 1993–1998.

### 3.2.2. Navigation

The Rhine provides access by inland waterway transport (IWT) to the European hinterland and fulfils an important role in the Dutch economy. During droughts periods, navigation encounters depth restrictions, which reduces the loading capacity of vessels (Jonkeren et al., 2007; Van Vuren, 2005). By maintenance dredging, the alluvial river bed is maintained to the required navigation channel dimensions, unlike at locations of fixed layers and other ‘hard’ bed structures. The spatial variation in bed degradation results in reducing navigable depths. Hence, the fixed layer Nijmegen (km 885) is predicted to be a future nautical bottleneck in the IWT trajectory Rotterdam-Duisburg (Blom, 2016; Sieben, 2009), called the Ruhrort market. Currently, Nijmegen is not always the least available depth in the Ruhrort market, but is considered by the shipping companies to be the nautical bottleneck due to (1) the fact that the impact of a ship grounding on a ‘hard’ layer is far more severe than hitting a sandy bed, (2) ships experience a sudden vertical displacement (commonly referred as squat) when entering the confined navigation channel at the fixed layer with a smaller depth than downstream (Lataire et al., 2012) and (3) shallow parts in sandy bed sections are dynamic and are dredged.

The navigation channel dimensions are related to Agreed Low Discharge (ALD) and the accompanying Agreed Low Water level (ALW), which follow from analysing the 95%-exceedance value of (representative) discharge time series. The required water depth at ALW is 2.80 m (CCNR, 2017), which is assessed by simulation of the ALD. A typical cargo ship transporting coals from Rotterdam to Duisburg has a draught of 4 m. If the navigable depth drops below 4 m, the loading capacity is reduced and transport costs per tonnes will rise. The load factor of a typical cargo ship can be computed with a physical relationship between loading capacity and draught.

The reduced loading capacity has a societal impact, as transportation costs rise. The societal impact is obtained by application of transport elasticities. Analysis of Jonkeren et al. (2011) revealed that the demand in the Kaub-related Rhine market (IWT trajectory Rotterdam-Kaub, which is 200 km upstream from Duisburg) is rather inelastic (i.e. the relative change in transport volumes is smaller than the relative change in price). A transport elasticity ($\varepsilon$) of $-0.6$ is also applied on the Ruhrort-related Rhine market. Jonkeren et al. (2007) defined the welfare loss as follows

$$\text{welfare loss} = (p_1 - p_0)q\left(\frac{\varepsilon(p_1 - p_0)}{2q}\right)$$

where $p_0$ is the normative transportation price (transportation price per tonne without depth restrictions), the actual transportation price ($p_1$) and the transport volume ($q$). In this approach, it is assumed that margins of each link in the chain remain unchanged and that the loss of welfare is finally paid for by the consumer (Lakshmanan et al., 2001). Based on a shipping simulation model BIVAS (Rijkswaterstaat, 2019), a relationship between the cost price of transportation and the navigable depth is derived:

$$\frac{p_1}{p_0} = 22.89e^{-1.47d} + 0.80e^{0.041d}$$

Now the computed depth time series are used to compare the daily transportation cost price to a normative transportation cost price. An annual transport volume of approximately 130 mln tonnes passes the fixed layer at Nijmegen (CBS, 2018). Part of this load will be transported to reaches with more critical depths than the depth at Nijmegen (e.g. beyond the Ruhrort market), which means that Nijmegen is no longer the nautical bottleneck. Based on analysis of Statistics Netherlands (CBS, 2017), it is estimated that 75% of the total transported load is depended on the navigable depth at Nijmegen.

#### 3.2.3. Riverine ecology

Various ecological rehabilitation programmes in the Rhine has been launched to improve the ecological quality (Van Dijk et al., 1995). However, ongoing processes as climate change and large-scale morphological processes can harm the riverine ecology along the Rhine. Erosion in the main channel in combination with siltation of the floodplain induce a disconnectivity between the main channel and floodplain. This in combination with the impact of climate change (i.e. longer periods of droughts and extremer low-flow conditions) induce dehydration of the floodplain area and a reduction of the main channel-floodplain interaction (floodplain inundation), and eventually ecological losses.

Within the study area, multiple important ecological elements are present, such as the side channel in the Klompenwaard (km 869). This man-made side channel is two-sided connected to the main channel during average river conditions (>1250 m$^3$/s at Lobith), while during low-flow conditions water may not enter into the upstream inlet. When water does not enter the inlet, there is no water flow through the side channel (Figure 4). The side channel is constructed with a design criteria of 300 days inflow per year. The inflow frequency is considered as a measure to assess the impact of system responses on ecology. To that end, the impact of climate change in combination with morphological trends on the inflow statistics of the side channel Klompenwaard is analysed. Once the inflow frequency drops below a critical point, ecological losses will occur. The quantification of the losses nor the monetization of the losses is not part of this research. Ecologists and economists did not yet agree on methods to monetize ecological value (Groot et al., 2002).

#### 3.2.4. Flood protection

Over the course of centuries communities settled along the banks of the Dutch Rhine, and started to protect themselves from the river floodings by construction of levees. These levees (called dikes) have gradually be reinforced. Recent flood events in 1993 and 1995 (Figure 3) initiated large-scale dike construction (Deltaplan Large Rivers) with risk-based approach. The flood defences of the considered Waal section offer protection against flooding to the Arnhem-Nijmegen metropolitan area. These flood defences are designed with an annual probability of flooding of less than 1/10,000. The design height of a flood defence for a certain safety standard is often associated with a design water level (DWL) occurring during a design flood with a probability of exceedance equal to the standard. It is expected that due to climate change the design discharge (i.e. discharge with a 10,000-year recurrence) will increase (Sperna Weiland et al., 2015). Van Vuren et al. (2005) showed that flood levels are also affected by morphology. As each part of the dike has a legally prescribed required flood protection level (Jorissen et al., 2016), an increased flood level requires a dike reinforcement or heightening. The linear costs related to these operations are estimated based on Dutch dike heightening index numbers (Eijgenraam, 2005).

### 3.3. Scenarios

Climate predictions are inherent uncertain, and are often given in scenarios (IPCC, 2007). Deltares and the Royal Netherlands Meteorological Institute (KNMI) developed representative discharge scenarios for the Rhine basin for the projections years 2050 and 2085 (Sperna Weiland et al., 2015). In this paper, we will evaluate the driest scenario $W_{\mathrm{H,dry}}$ (*dry2050*) and the wettest scenario $G_{\mathrm{L}}$ (*wet2050*) in the projection year 2050. Sperna Weiland et al. (2015) derived the design flood conditions of each climate change scenarios (discharge with a 10,000-year recurrence). Furthermore, the climate scenarios have been used to transform the historical 114-year daily discharge records at Lobith to daily discharge representing conditions conform the climate scenarios (Mens & Kramer, 2016). Figure 5 shows the daily discharge records of the year 2005 and the corresponding discharge records representing the same year including the impact of climate change. The Agreed Low Discharge (ALD) represents the Rhine discharge that is exceeded 95% of the time. In the reference case without climate change the ALD equals 1020 m$^3$/s. When considering climate change, the ALD in 2050 can be derived from the (adapted) discharge time series and is respectively 825 and 1102 m$^3$/s for *dry2050* and *wet2050*.

The bed degradation trends of the Rhine can be computed by a morphological model, and its uncertainty can be described by scenarios. In this research, we used different morphological scenarios. Due to the fact that the sediment transport capacity is larger than the sediment supply, it is

**Figure 4.** The side channel Klompenwaard during regular (left) and low-flow conditions (right). Due to low discharges the upstream inlet becomes dry and no inflow of the side channel takes place. Satellite images obtained from Netherlands Space Office.

expected that the channel incision proceeds in the near-future (Sieben, 2009), while the rate and spatial variability remain highly uncertain. When combining observed and simulated trends, a prediction of the trends over the longitudinal profile is performed (Sloff et al., 2014). This scenario will be referred to as *continuation incision* and is shown in Figure 5 with a projection of the river bed in 2050 and its state in 2018. However, two uncertain processes may cause a reduction in the degradation rates: (1) coarsening of the bed surface sediment; and (2) sea level rise that triggers an aggradation wave that migrates upstream (Blom & Arbos, 2019). The bed coarsening and effects of sea level rise can cause a decrease in, or even stop the channel bed incision. The Niederrhein (km 858–867) has stopped eroding over the past three decades, which seems to be related to the coarsening of the bed surface. Hence, another morphological scenario is assessed where the coarsening wave proceeds and the channel incision is stopped, namely *natural stabilization*. The morphological scenario is projected in the Rhine model by changing the width-averaged bed with the annual erosion rate following the trends (Figure 5).

The scenarios also impact the downstream boundary condition (stage relation) due to lowering water levels. This has been adapted based on the erosion trend near km 900. As channel incision in all Rhine branches will differ, this will most likely also impact the discharge distribution at the bifurcation point. However, it is assumed that the discharge distribution remains unchanged.

Along the Waal, the floodplains have elevated due to sediment deposition (Middelkoop, 2002). Based on a reconstruction of heavy metal profiles an average sedimentation rate of 5 mm per year for the floodplains of the Waal was found by Middelkoop (2002). This accretion trend is imposed uniformly on the floodplain bed level in the Rhine model.

## 4. Impact of processes on functional performance

### 4.1. Continuation main channel incision

In this section, the scenario of a fixed degradation of the main channel over time is assumed. Uncertainties regarding the bed level are neglected.

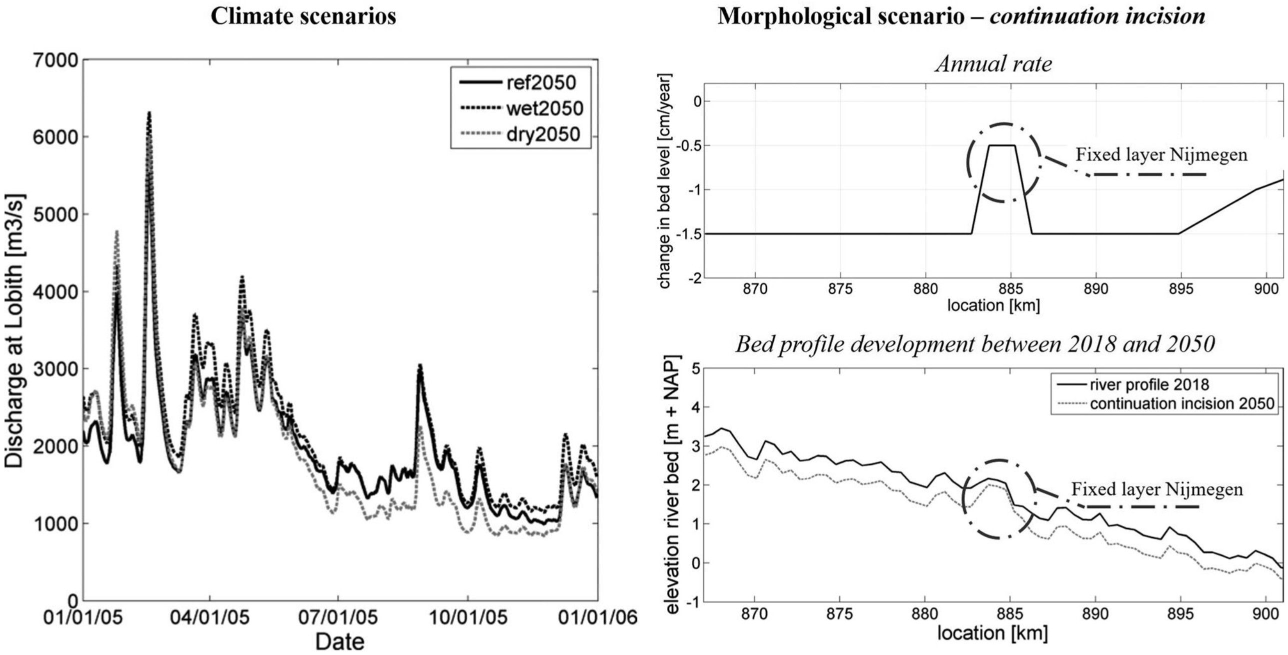

**Figure 5.** The adapted hydrograph of the year 2005 for the KNMI's14 climate scenarios (left) and the implications of the morphological scenario *continuation incision* (right) with the imposed annual bed level change and the projected river profile in 2050.

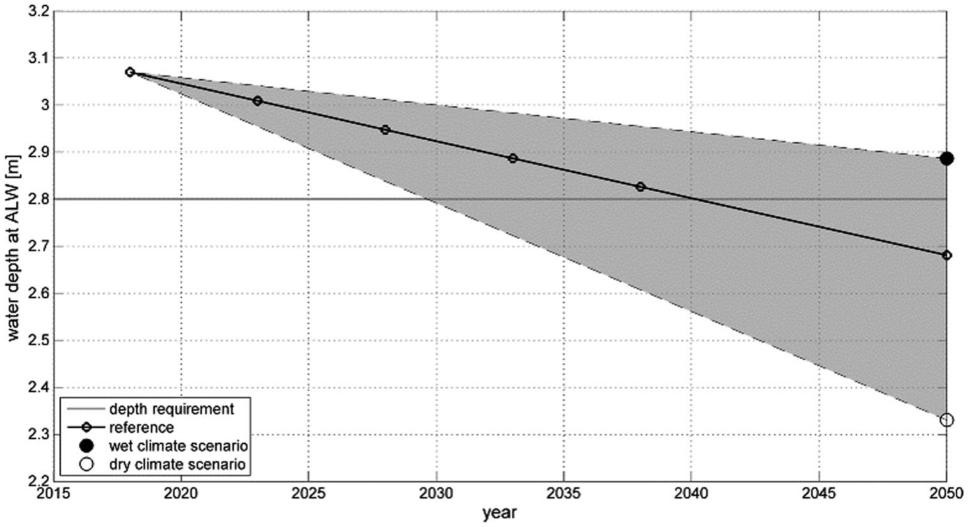

**Figure 6.** The development of water depth during ALD at the fixed layer of Nijmegen due to bed degradation that proceeds and the climate change scenarios.

### 4.1.1. Navigation

A Rhine model run is driven by the relevant ALDs per climate scenario, whereas in the meantime the morphological trends are imposed on the river bed. The combination of water level calculations in combination with bed level calculations gives information about the development of the water depth along the river during ALD conditions. The water depth at location Nijmegen turns out to be the most critical for shipping along the Waal stretch. Figure 6 shows the gradual change in water depth at Nijmegen during ALD conditions between 2018 and 2050 for both the situation without (solid line) and with climate change (dashed lines). It appears that for the situation without climate change, the navigation channel depth requirement in 2040 does not fulfil. Figure 6 shows that this can be already the case in 2030 for the dry climate scenario or even later than 2050 for the wet climate change scenario.

The trend of degradation of the navigation channel bed has a negative impact on the shipping efficiency of a cargo ship with reduced loading factors. Figure 7 shows the trend of the mean load factor of a typical Rhine cargo barge (type Europe 2–4 m) throughout the year annual. Due to wetter and dryer years, the statistical character of the fully loaded sailing time is analysed and presented in Figure 7, which shows a clear drop of the median from 260 to 155 days per year for *dry2050*. The impact on the total shipping efficiency due to depth restrictions is expressed by the annual welfare loss. According to our analysis, these extra costs are expected to range from €18 mln in 2018 to €42 mln, €81 mln and €28 mln for respectively *ref2050* (2050 without changing discharge statistics), *dry2050* and *wet2050*. This illustrates that morphological changes increase the welfare losses. The dry climate change scenario shows an increase of these welfare losses, whereas the wet climate change scenario show a diminution of the losses. The extra costs due to depth restrictions are part of the total estimated transportation costs over the Waal of €1140 mln per year. As a result of the trends at Nijmegen, the total transportation costs are expected to rise in 2050 with respectively 2% and 6% for *ref2050* and *dry2050*. In this case, only the impact of physical processes is considered, while in practice also economic growth, modal split

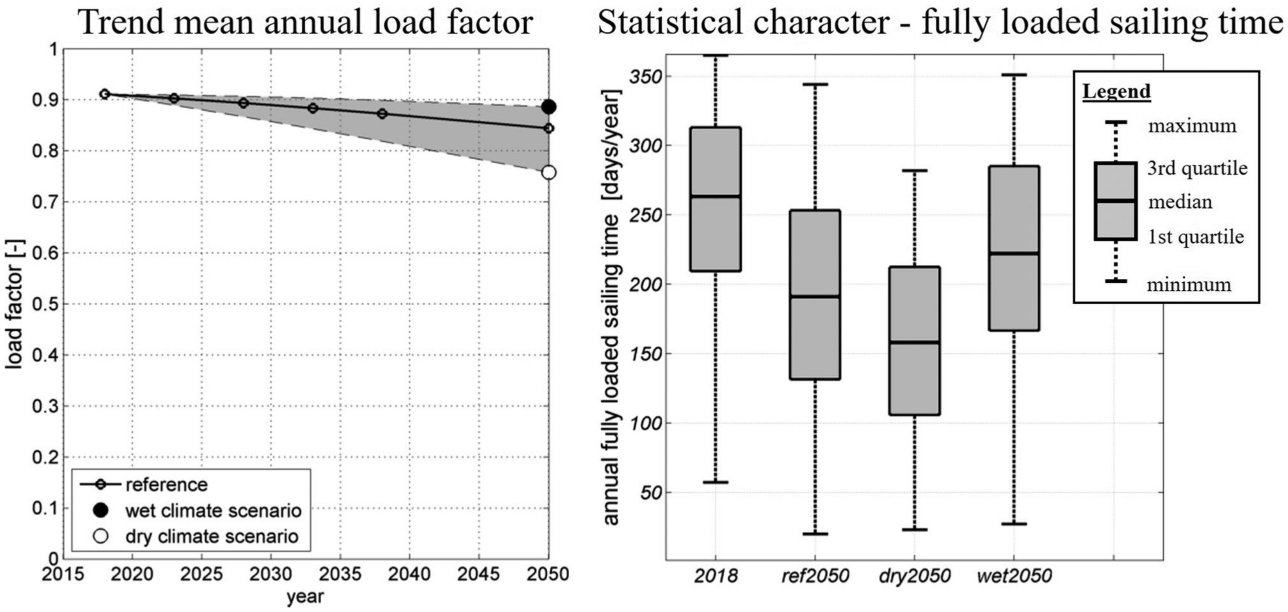

**Figure 7.** The load factor of a typical cargo ship as a result to depth restrictions at Nijmegen with the mean trend (left) and the statistical character of the fully loaded sailing time (right).

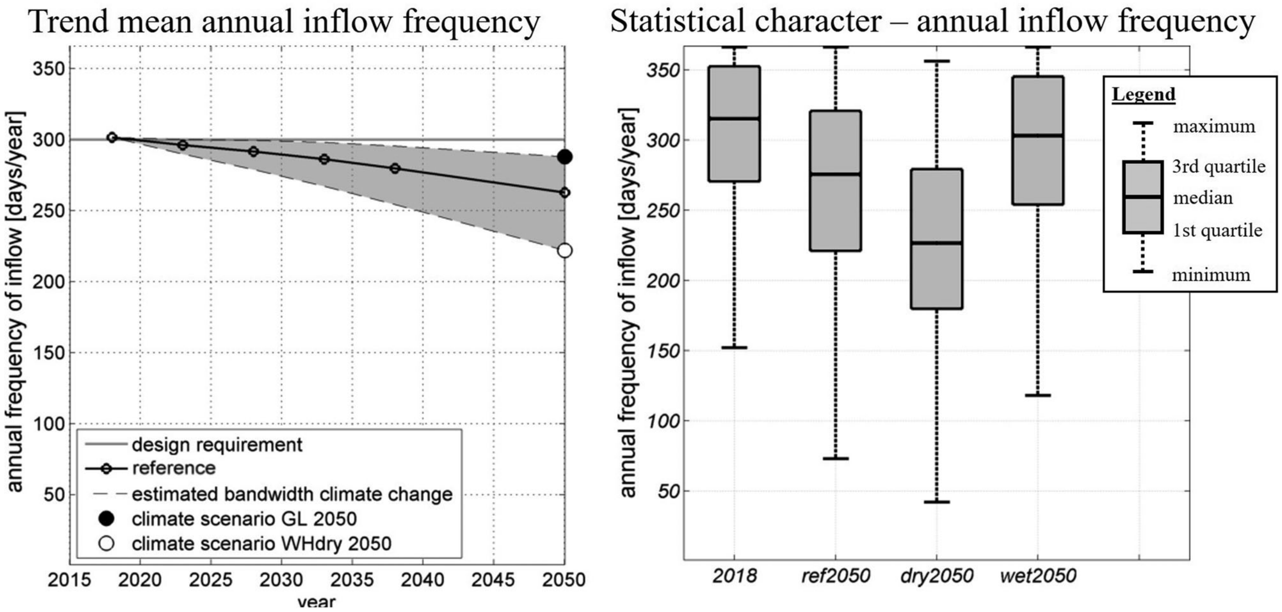

**Figure 8.** The development of inflow frequency of Klompenwaard with the mean trend (left) and the statistical character (right).

or other factors may impact the socio-economic data and the welfare loss.

### 4.1.2. Ecological impact

During low-flow conditions, water levels may not reach the height of the side channel's inlet, which results in no inflow of the side channel (Figure 4). The inundation frequency varies per year as an result of the discharge variation in the hydrograph. The statistical character of the annual inundation frequency follows from the simulation of the river state in 2018 and 2050 (Figure 8). The mean trend has been analysed from which can be concluded that the design criteria (inflow 300 days per year) will not be fulfilled in a few years from now (Figure 8). It seems reasonable to assume the ecosystem will be affected when the mean inflow frequency drops from 300 days per year in 2018 to 230 days per year in 2050 for climate scenario *dry2050*. Also the impact of dryer years becomes more severe, as is illustrated by the statistical character of multiple years (Figure 8). The consequences of the environmental change on the ecosystem (flora and fauna) is outside the scope of the present study.

### 4.1.3. Flood protection

So far we have shown that climate change and large-scale morphology impose considerable impact on functions restricted by low-flow conditions. The same processes also affect the flood conditions. Yet, the floodplain siltation did not impact navigation and ecology in this research, while during flood conditions the floodplains contribute to the discharge conveyance. Bed erosion processes induce a lowering of flood levels, whereas floodplain accretion induce an increase of flood levels. Climate change results in an increase in the design flood discharge implying an increase in design water levels (i.e. flood levels with a 10,000-year recurrence). We observed the combined effect of both morphological trends and climate change. The net impact of the opposing processes of the main channel incision and floodplain accretion is an decrease of the flood levels by 3 mm per year. When we do not consider climate change, the DWLs decrease approximately with 10–15 cm (see solid back line in Figure 9). This can be considered as a virtual economic benefit. Figure 9 shows also the impact of the two climate scenarios, showing that climate change dominates the impact of the morphological trends and results in a DWL increase of 28 up to 40 cm in 2050 depending on the location and climate scenario. An increased DWL requires dike heightening. As the stabilization of the river bed affects the flood levels in a larger area than the study area itself (i.e. backwater curve), we account for dike heightening costs over a length of 50 km in the Waal and Niederrhein (km 858–908). This results in an increase in the costs for dike heightening based on the climate scenarios between €62 and 70 mln.

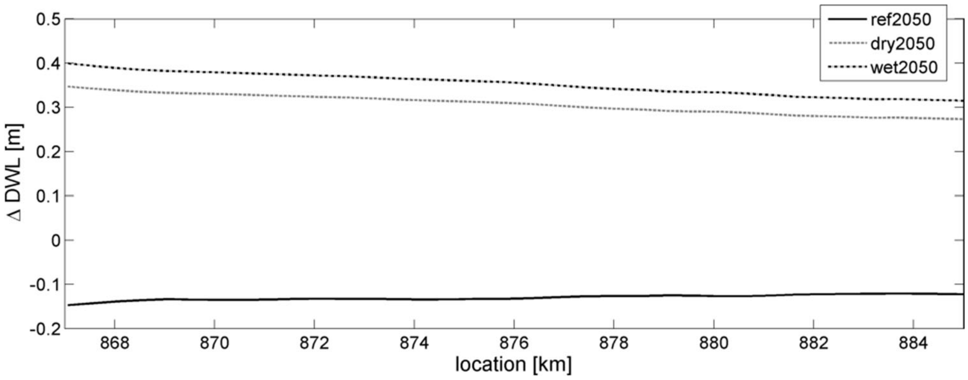

**Figure 9.** Spatial variation over the Waal section of ΔDWL (DWL 2050 – DWL 2018).

### 4.2. Natural stabilization of the river bed

In the previous results, we discussed a morphological scenario in which the bed degradation trends will proceed (*continuation incision*). As denoted in the case study description, the possibility exists that the main channel bed in the Waal is stabilized due to natural processes. The functional performance in the projected year 2050 is assessed for this morphological scenario in combination with climate change.

- The water depth during ALD at Nijmegen is computed 2.7 and 3.3 m in 2050 for respectively *dry2050* and *wet2050*. This means a relative increase in navigable depth (and shipping efficiency) compared to the morphological scenario *continuation incision* (Figure 7).
- The mean inundation frequency of the Klompenwaard in the projected year 2050 is computed 265 and 325 days per year for respectively *dry2050* and *wet2050*, which means more frequent inundation compared to the scenario that assumes *continuation incision*.
- The increase in DWL is 40–50 cm relative to 2018, which is an increase in DWL compared to the scenario that assumes *continuation incision* (Figure 9).

In comparison with the morphological scenario *continuation incision*, *natural stabilization* will improve shipping and riverine ecology as water levels and depths are increased during the low-flow season. Simultaneously, flood levels are increased, which results in higher flood protection costs.

## 5. Evaluation of policy-options

### 5.1. Sediment management strategies

The analysis of the morphological trends reveal remarkable losses in functional performance for navigation and ecology. These losses are reinforced by the dry climate scenario. A river manager has different sediment management strategies to limit the negative consequences of functional performance. Three policy-options with regard to the bed erosion are formulated:

(1) no interferences, allowing the continuation of the observed morphological processes,
(2) stabilization of the river bed position by not allowing continuation of the observed morphological trends,
(3) heightening of the river bed to restore the impact of morphological trends in the past.

A sediment nourishment can counteract erosion. It is also allows adaptive and tailor-made implementation, as the river manager can adapt nourishment volumes depending on the actual bed degradation. Moreover, a sediment nourishments is a nature-based solution, which allows continuation of natural processes (De Vriend et al., 2015; Van Wesenbeeck et al., 2014). To reduce bed erosion in the German Rhine, the German authorities have been applying sediment nourishments since 1978 (Frings et al., 2004).

### 5.2. Stabilization of the river bed by sediment nourishments

In this study, we assume a scenario with longitudinal channel erosion at a width averaged rate between 0 and 1.5 cm/year (Sloff et al., 2014) as shown in Figure 5. By means of this assumption, lateral variability in erosion rate across the channel is neglected and captured in a width-averaged value. The required nourishment volume to stabilize the river bed is determined by the linear relation between this rate, the main channel width and length of the considered river stretches. As river conditions in the study area are affected by morphological changes downstream (backwater effect) and near the bifurcation point (discharge distribution), these sections have to be stabilized as well and are estimated to require an annual volume of respectively 15,000 $m^3$ and 30,000 $m^3$. This boils down to an annual volume of 168,000 $m^3$. With index numbers the nourishment costs to stabilize the bed are estimated €2.2 mln per year. The impact of artificial stabilization of the river bed by means of sediment nourishments on the functional performance is the same as described for the morphological scenario *natural stabilization* in Section 4.2.

In this research, the river functions navigation and flood protection have been monetized, which results in an overall societal impact. A cost–benefit analysis (CBA) captures the combined functional performance of these two functions and is used to evaluate a sediment nourishment. The CBA we applied consists of the following elements:

(1) Nourishment costs
(2) Extra transport costs for navigation due to depth restrictions
(3) Dike heightening costs

The costs and benefits in the period 2018–2050 have to be discounted to its present value by means of a discount rate (assumed 3%). Figure 10 shows the contribution of each cost element for two policy-options *no interference* and *bed stabilization* by nourishing for the morphological scenario *continuation incision*. The shipping efficiency appears to have the largest contribution on the net present value following this method. It turns out to be cost effective to reduce depth restrictions by stabilization of the river bed by means of nourishments. In addition, stabilization of the river bed has a positive impact on the riverine ecology, which has not been monetized yet. There has not been accounted for a change in socio-economic conditions. In other words, only the impact of physical processes has been assessed.

### 5.3. Nourishment optimization

Besides stabilization of the river bed, a sediment nourishment can also elevate the river bed, which subsequently increases water levels and improves performance of navigation and ecology. There has been accounted for the costs related to the nourishment and the monetized functional performance costs of navigation and dike heightening. The costs of a sediment nourishment strategy depend on the magnitude of the large scale morphological changes. The larger the morphological changes, the larger effort to maintain a certain river bed position. The functional performance costs depend on the climate scenario given a certain river bed elevation scenario. Figure 11 presents the net present costs for a wet climate scenario of the two morphological scenarios. The morphological scenario *natural stabilization* requires no nourishment costs to stabilize the river bed (as this is the natural process),

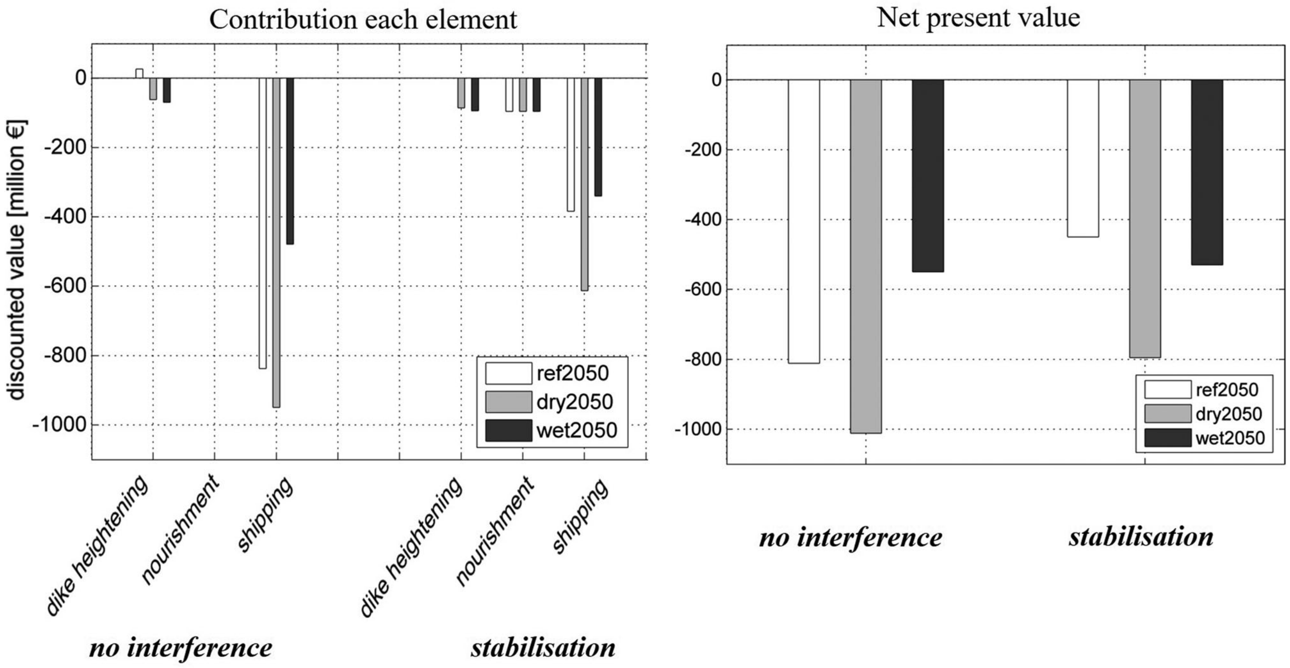

**Figure 10.** The discounted costs and benefits elements in period 2018–2050 (left) and net present value (right) of the policy-options *no interference* and *stabilization* for continuation of main channel incision.

but only require nourishment costs for elevation of the river bed. We assume that a relative elevation of the river bed in 2050, does not introduce new nautical bottlenecks at another location than Nijmegen and that this remains the most critical location with respect to the function navigation (navigable depth). Furthermore, we assume the bed degradation trend to proceed at the same rate.

Due to the economy of scales the nourishment price per cubic meter decreases with larger volumes (black rectangular markers), while the functional performance losses reduce as a functioning of heightening of the river bed (grey diamond markers). Concerning the wet climate scenario, this results in an optimum with the lowest net present costs around zero bed level change (rectangular markers). A similar analysis has been conducted for a dry climate scenario, which reveals that a much larger nourishment is cost effective. Based on this information, it is recommended to stabilize the river bed and to wait for more accurate climate change predictions. As denoted in the results, the riverine ecology also benefits from a higher bed level, which has not been monetized. This means that the benefits of an elevated river bed are in fact larger than presented in Figure 11. This may justify that a larger nourishment is more beneficial. Similar sensitivity analysis can be conducted by adapting discount rates, project periods, nourishment location and etcetera.

## 6. Applicability Dutch integrated river management programme

The Netherlands is preparing for a new integrated river management programme, that aims to ensure the Rhine's functions in the coming years. The programme's goal is to develop a strategy upon the negative consequences of the ongoing bed degradation. The summer and autumn of 2018 showed the consequences of both low-flow conditions and bed degradation over the last century in the Dutch Rhine.

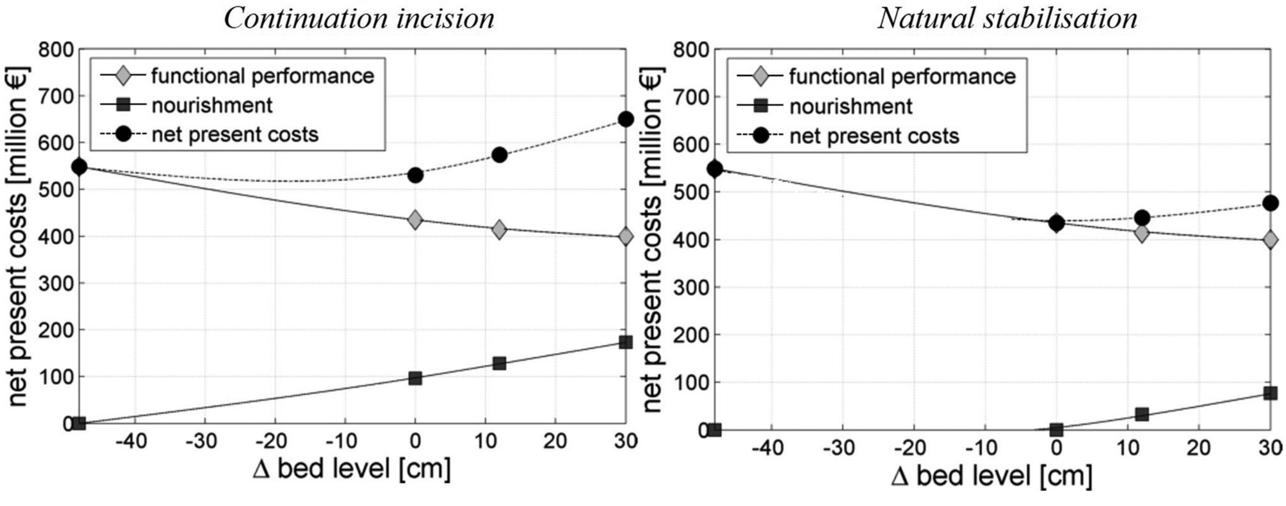

**Figure 11.** Sediment nourishment optimization for the wet climate scenario and two morphological scenarios. The net present costs (sum of nourishment and functional performance) as a function of the river bed in 2050. An optimum bed level has been found at Δ bed level zero (stabilization).

This resulted in record-breaking low water levels, extreme low navigation depth and subsequently nautical problems. The framework of this research, can provide support to decision-making of possible mitigation strategies. As demonstrated by the results of the functional performance in projection year 2050, the functions ecology, navigation may be under pressure, while flood protection requires dike heightening. The assessment of sediment management strategies reveals that the policy-option *no interference* is on the long term not cost effective. This shows a need for action.

Complex modelling tools are increasingly used to support decision-making, as these models deliver more accurate simulations than simple methods. However, the use of these complex models requires larger computation effort and costs, and results in diversion from the focus on integrated implications. Hence, the case study has been carried with simple modelling tools and a number of assumptions to show the potential of the framework itself. This research demonstrated the importance of an accurate prediction of the exogenous processes to the assessment of policy-options. Hence, we recommend to improve the input of the climate and large-scale morphological scenarios in the first place. These can provide quick useful insights in combination with simple modelling tools. Moreover, we recommend to enlarge the scope of the framework as follows:

(1) *Geographic*: In practice, the societal impact of a river cannot be projected on a small study area, but need be extended over a larger part of the river system.
(2) *Functional*: Other important functions need to be assessed and monetized (e.g. ecology, agriculture, industries, drinking water and recreation), as river serves more environmental and socio-economic functions.
(3) *Socio-economics*: To simulate realistic future scenarios, socio-economic scenarios have to be developed representing the future socio-economic state.

## 7. Conclusions

This paper reveals the negative impact of river morphology and climate change on user-functions. As we also expect an increase in demand of user-functions, the pressure on lowland river systems increases. This asks for smart integrated river management. Application of the framework (case study) demonstrates how various models can be linked to quantify river conditions and the functional performance. The model-chain consist of a simplified numerical hydraulic model and a number of assumptions to show the essential and potential of the framework itself. This method demonstrated the impact of policy-options on function specific performance indicators (e.g. inundation frequency side channel or load factor cargo ship), which requires a value judgement in decision-making. The societal impact quantified by monetized functional performance allows to express multiple function in the same denominator. The combination of both methods (value judgement and CBA analyses) can be used to support decision-making in policy-options. We demonstrated the merits of the assessment framework with a case study for the river Waal, showing the impact of different sediment nourishment strategies on functional performance of the Waal. The societal impact analysis allowed an optimization of the policy-options accounting for the uncertainty of both climate change and morphological changes. It appeared that the policy-option *no interference* is not cost effective in any morphological scenarios nor the climate scenarios.

As demonstrated in this paper, large-scale morphological trends and climate change has its implications on multiple functions, putting pressure on the multi-functionality of a lowland river system. Hence, integrated river management is required in which quantitative information is crucial to an assessment of different policy-options. This paper demonstrates a useful framework to support decision-making in integrated river management of lowland river systems subjected to uncertain exogenous processes.

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## Disclosure statement

No potential conflict of interest was reported by the author(s).

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