LOW-HANGING FRUITS IN LARGE-SCALE FLUVIAL LANDSCAPING MEASURES: TRADE-OFFS BETWEEN FLOOD HAZARD, COSTS, STAKEHOLDERS AND BIODIVERSITY

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Abstract. Adapting densely populated deltas to the combined impacts of climate change and socioeconomic developments presents a major challenge for their sustainable development in the 21st century. Decisions for the adaptations require an overview of cost and benefits and the number of stakeholders involved, which can be used in stakeholder discussions. Therefore, we investigated the balance between multi-faceted costs and benefits of common landscaping measures to compensate for changes in discharge and sea level rise on the basis of relevant, but inexhaustive, quantitative variables for physical, ecological and societal costs and benefits. We modelled the largest delta distributary of the Rhine River with adaptation scenarios driven by (1) the choice of seven measures, (2) the areas owned by the two largest stakeholders (LS) versus all stakeholders (AS), and (3) the ecological or hydraulic design principle. We evaluated measures by their efficiency in flood hazard reduction, potential biodiversity, number of stakeholders as a proxy to governance complexity, and measure implementation cost. We found that only floodplain lowering over the whole study area can offset the altered hydrodynamic boundary conditions; for all other measures, additional dike raising is required. LS areas comprise low hanging fruits for water level lowering due to the governance simplicity and hydraulic efficiency. Measures implemented in LS areas are 3 to 74 % more efficient than in AS areas. Clear trade-offs were revealed between evaluation parameters, but no single measure represented the optimal combination on all aspects. The multidimensional evaluation space provides a frame for the co-creation of adaptation paths for climate-proofing deltas.

1 Introduction

The World Economic Forum ranked extreme weather events, natural disasters and failure of climate-change mitigation and adaptation in the top five risks in terms of likelihood as well as in terms of impact (WEF, 2018). Between 1995 and 2015, floods made up 43 % of the global occurrences of disasters within the category of extreme weather events (Wahlstrom and Guha-Sapir, 2015). For the future, Alfieri et al. (2016) showed that the rising global temperatures will further increase the frequency and magnitudes of alluvial floods globally. In addition, coastal flood hazards are expected to increase to due sea level rise and changing storm wave and storm surge characteristics (Pardaens et al., 2011;de Winter and Ruessink, 2017) with high adaptation costs for coastal flood damage (Hinkel et al., 2014). Coastal deltas are particularly prone to flooding due to the possible coincidence of peak river discharges and storm surges. But even without a storm surge, the increased backwater effect due to higher sea levels affects water levels in delta distributaries during alluvial flood events. The ongoing urbanization in many deltas, combined with the associated land subsidence, further aggravates the potential flood hazard and limits the sustainability (Giosan et al., 2014;Tessler et al., 2015). Flood protection measures therefore need careful

integration in the spatial planning of transport infrastructure and cities with a temporal horizon 2100 and beyond. At the conceptual level, a strong point has been made for adaptation planning and nature-based solutions (Brown et al., 2014;Cheong et al., 2013), but the tools are missing to quickly apply these concepts at delta scale.

5   Measures for flood hazard reductions should also take nature restoration into account. Rivers and deltas potentially have a high biodiversity because of the periodic flooding (Tockner and Stanford, 2002;Ward et al., 1999). However, land use change and population growth degraded the biodiversity of floodplain habitats, especially in North America and Europe (Vorosmarty et al., 2010). River restoration efforts over the last three decades have tried to reverse degraded fluvial ecosystems (Bernhardt et al., 2005;Buijse et al., 2002), which was supported by the Clean Water Act in the US and the
10   Water Framework Directive in the EU (Hering et al., 2010). The combined efforts of projects with a joint objective of lowering the flood hazard and increasing biodiversity proved possible, although the biodiversity of protected and endangered species is still far below its potential (Straatsma et al., 2017).

River management has to combine varying objectives: flood safety is the primary goal in densely populated deltas and
15   navigation is often second. River restoration is increasingly aimed at in industrialized countries to improve the biodiversity. A key challenge for environmental management is the number and diversity of the actors and sectors involved in the decision process, because each has its own perceptions, interests and resources (Robinson et al., 2011). Differences are fueled by the short temporal horizon for political decisions and the long term effects of climate change, but also by the perceived necessity of landscaping measures to climate-proof the delta and societal resentment against large measures. Given
20   the multitude of objectives and options for spatial planning, the need for decision support systems (DSSs) has long been recognized. Ideally, a DSS provides rational input, which could remove emotional objectives against specific adaptations, but we recognize that the personal threat experience also strongly drives actions to limit the flood risk (Grothmann and Reusswig, 2006). Newman et al. (2017) reviewed 101 DSSs for natural hazards, of which 19 focused on fluvial flood risk. Two included studies in the Netherlands: Hübner et al. (2009) developed the "Nature-oriented flood damage prevention",
25   targeting regional water systems, whereas Schielen and Gijsbers (2003) created "DSS-large rivers", which was oriented towards national to continental-scale. Both DSSs required the manual implementation of landscaping measures in the accompanying Geographic Information System (GIS). To the best of our knowledge, none of the DSSs for fluvial flooding listed by Newman et al. (2017) contained an option for the automatic creation of measures at the spatial scale of the river reach. Coupling a DSS with automated measures could have additional value in the exploratory phase of planning new
30   measures to provide all stakeholders with the efficiency of measures with respect to flood hazard reduction, costs, and biodiversity.

The implementation of large-scale measures requires the alignment of governance at national, provincial and municipal level and the involvement, compensation, or expropriation of different land owners. Land owners and actors involved in river
35   management have diverse perspectives on, and incentives for, implementing river management measures based on socio-economic, cultural, and land-use characteristics (Rosenberg and Margerum, 2008;Verbrugge et al., 2017). New adaptation measures could therefore be implemented faster when fewer stakeholders are involved, provided they can agree about the type of measure. Therefore, it is necessary to understand land owner characteristics and their motivating factors to indicate the potential for implementing large-scale measures (Rosenberg and Margerum, 2008). Our objective was to quantify multi-
40   faceted trade-offs between landscaping measures to adapt a large delta distributary to sea level rise and increased river discharge while honouring ecological value and societal stakes. The decision between different possible interventions is often a delicate process. Scientists can help to support this process by transforming their data, models and tools into quantities that can be used to objectively evaluate the different interventions. Here we show an example of how using advanced DSSs, that include cost-estimates, as well as physical quantities and biological quantities, can help to move

towards an evidence-based and more optimal intervention. We assessed the ability of seventeen measures to compensate the effects of increased discharge and rising sea levels in the Waal River in the Netherlands. The measures were located in areas owned by the two largest stakeholders versus all stakeholders and parameterization was based on nature restoration principles, or maximizing flood conveyance capacity.

5 **2 Study area**

The study area is located in the Rhine delta (Fig. 1) in the Netherlands, and comprises the main channel and embanked floodplains of the Waal River. The Waal is the main distributary of the Rhine River and is affected by expected changes in peak discharge as well as sea level rise. The three main concerns here are flood risk in view of global change, navigability and ecosystem functioning. The study area spans an 85-km-long river reach with an average water surface gradient of 0.10

10 m/km. The total area of the embanked floodplains amounts to 132 km^2. Recent nature rehabilitation programs led to increased areas with herbaceous vegetation, shrubs and forest (Koopman et al., 2018) in an area dominated by meadows. The design discharge is now set to 16 000 (Q16), and 10165 m^{3}s^{-1} for the Rhine branches, and the Waal River, respectively. Q16 represents an average return period of 1250 years. Such a discharge is expected to give a 3.99 m water level above ordnance datum (+OD) at the downstream end of the study area. The main channel, 250 m wide, is fixed in place by groynes (spur

15 dikes) for navigation and prevention of ice dams. The groynes were partly lowered during the 'Room for the River' project (Van Stokkom et al., 2005). In 2017, the design discharge was combined with a risk-based approach that takes the potential damage and casualties within the protected areas into account (Van Alphen, 2016).

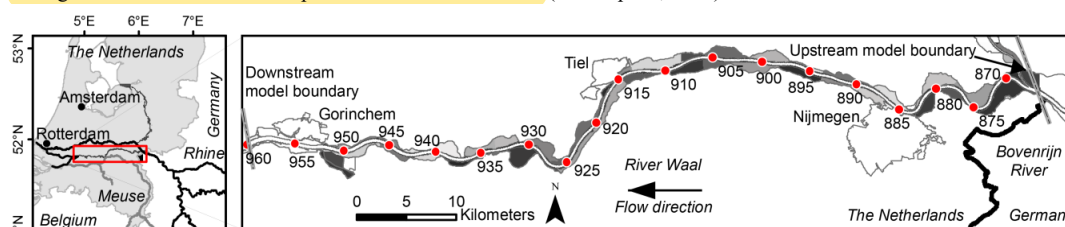



Figure 1 The River Waal, an 85 km long river reach between the Pannerden bifurcation near the Dutch-German border and
20 **Gorinchem, upstream of significant tidal influence. The center of the study area is located at 51º53'N and 5º37' E. The grey scale**
differences show the 94 individual floodplain sections.

Flood risk management involves a number of public and private stakeholders (Table 1). It traditionally focused on the construction and maintenance of embankments, but recently the link with sustainable spatial planning has gained attention (Jong and Brink, 2017). Governmental responsibilities are divided over four levels, i.e. national, provincial, regional (water

25 boards) and local (municipalities) (Fliervoet and van den Born, 2017;Jong and Brink, 2017). The two largest land owners are Public Works and Water Management (PWWM, Rijkswaterstaat in Dutch), which owns 2889 ha, mostly consisting of the main channel and groyne fields, and the State Forestry Service (SFS, Staatsbosbeheer in Dutch), which owns 2813 ha that are mostly situated in the floodplains (Table 1). PWWM is the national water authority and SFS is a national nature conservation organization, both are governmental organizations. The total number of owners is 1233 between the

30 embankments and 5512 within an additional 50 m buffer (Table 1) based on the cadastral database, which highlights the complexity of implementing area-wide measures.

Table 1 Characteristics of land owners involved in the maintenance of floodplains (based on Fliervoet and Van den Born (2017)). The remaining area is owned by foundations (66) and churches (20).

Stakeholder	Organizational aim and/or responsibility	Govern-mental	Total area (ha)	No. of owners[a]
Public Works and Water Management (PWWM)	Manage all activities in the floodplains that influence water quality and quantity (flood protection) on a national scale.	yes	2889	1
State Forestry Service (SFS)	National nature conservation.	yes	2813	1
Private land owners	Citizens, famers and other local business without a (private or limited) company.	no	1122	964 (4855)
Private and limited companies	Create additional shareholder value.	no	958	149 (319)
Sand, gravel, and clay mining industries	Making profit and generating a long-term perspective for the extraction of sand, gravel and clay from floodplains.	no	767	13 (15)
Water Board	Responsible for dikes and levees (flood protection).	yes	614	1 (1)
Province foundations 'Geldersch and Brabants landschap'	Provincial organisation aiming at the conservation of nature and cultural heritage.	no	405	2 (2)
Provincial government	Responsible authority for nature conservation goals, including the implementation of the European Natura 2000 objectives on the provincial scale.	yes	366	1 (1)
Municipalities	Responsible for local spatial planning: regional development through balancing economy, nature, recreation and flood protection.	yes	328	15 (17)

[a] number of owners between the main embankments per type of stakeholders (sum = 1233). In brackets the number of
5 owners is given between the embankments plus a 50 m buffer (sum = 5512).

The study area consists of 94 floodplain sections (Fig. 1) on the left river bank (south) and the right bank. The area per stakeholder type differs strongly over the sections (Fig. 2a) as well as the number of owners (Fig. 2b). For example, the section at river kilometer (rkm) 870 on river left (Fig 2; 870-l) is called the Millingerwaard. It has a total surface area of 721

10 ha including the main channel, is largely owned by the State Forestry Service (428 ha) and has a total of 17 different owners, of which 12 are private citizens. Section 885_l (city of Nijmegen) contained the largest number of owners in the embanked area: 633 in total.

3 Methods

The automated spatial planning and evaluation of measures required detailed input data (Table 2). Here, we describe the
15 modelling tools plus their input data and the choices made within the hydrodynamic and landscaping scenarios.

Table 2 Overview of input datasets used for intervention planning and evaluation.

Dataset	Derived data	Reference
Baseline	River geometry, trachytopes	(Scholten and Stout, 2014)
BAG-2015	Buildings locations and type	(BAG, 2016)
Cadastral map	Stakeholder type	www.kadaster.nl/-/eigendomskaart-eigenarenkaart
Soil pollution map	Areas of polluted soil	(Stienstra, 2011)
Top10vector	Road location, type and width	www.kadaster.nl/-/top10nl
Ecotope map 2012	Ecotopes, side channel location	(Scholten and Stout, 2013)

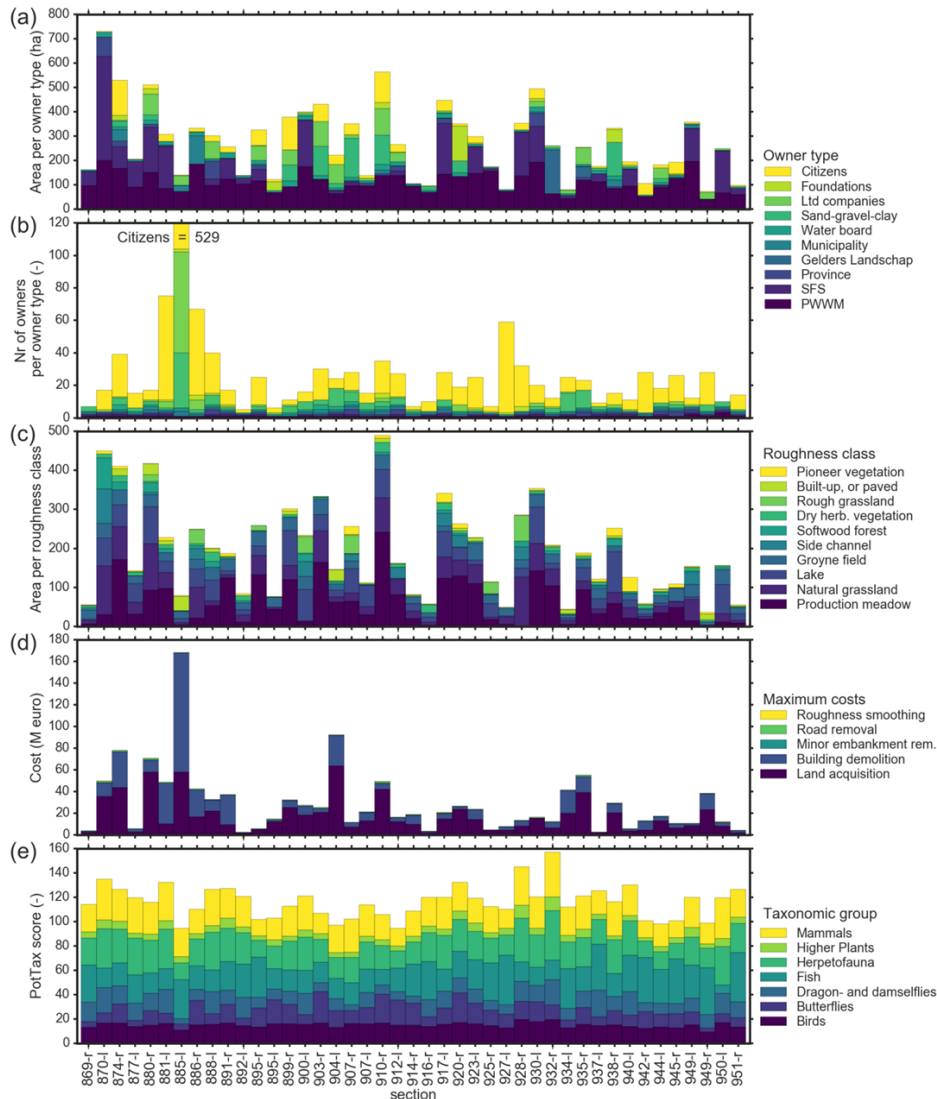



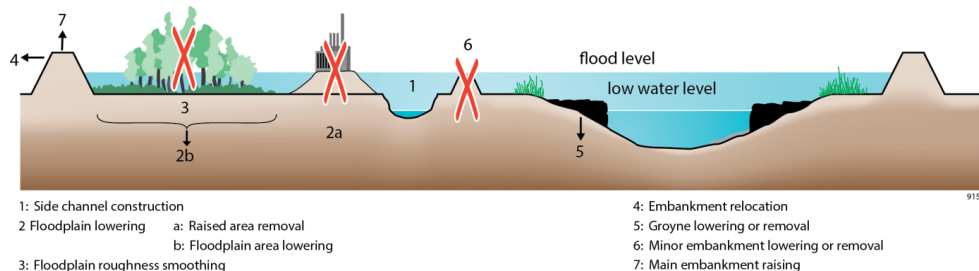
Fig. 2 Overview of attributes of floodplain sections (Fig. 1). The sections are labelled by the mean river kilometer, followed by the '-r' for river right and '-l' for river left: (a) surface area per type of owner, (b) number of owners per owner type, (c) surface area of the 10 dominant hydrodynamic roughness classes, (d) costs per item over the whole section, and (e) floodplain biodiversity scores per taxonomic group.

3.1 Modeling tools

3.1.1 RiverScape: positioning and parameterization of measures

In current river management practice, managers propose measures (interventions) in the embanked floodplains together with landscape architects, engineers, policy advisors and local stakeholders. Once the sketch of the intervention is clear, a GIS specialist translates the position of the measure and the parameterization in terms of land cover and terrain height into layers of spatial data, for example with HEC-GeoRAS (Ackerman, 2011), or Baseline (Scholten and Stout, 2014). Both steps are time consuming and, therefore, not suitable for rapid scenario development, which is often limited to a few scenarios (Nardini and Pavan, 2012). For this study, we used RiverScape, a software tool for the automatic positioning and parameterization of flood hazard reduction measures. A detailed description of the tool is given by Straatsma and Kleinhans (2018). In brief: given a set of raster layers describing the hydrodynamic conditions at design discharge, the geometry, and

the land cover this tool locates seven different types of measures (Fig. 3). The new bathymetry and the height of minor embankments and groynes are controlled by user-specified reference heights expressed as water levels at the river axis with a specific exceedance probability. The new land cover is given as an ecotope and roughness class. RiverScape was extended with a masking option to enable the application of the measures over arbitrary areas, in this case, the areas owned by specific

5 stakeholders. Each measure is defined by seven raster layers (area, bathymetry, ecotopes, trachytopes (roughness class), groyne height, minor embankment height, main embankment height), together with the user settings. The generation of landscape scenarios takes less than two minutes, which makes it a good option for scenario development, but it does not have the public support generated by stakeholder sessions.

10 **Fig. 3 Typical landscaping measures implemented in this paper (figure after (Middelkoop and Van Haselen 1999))**

3.1.2 Delft3D Flexible mesh: hydrodynamics

RiverScape was coupled to a calibrated 2D hydrodynamic model. We used Delft3D FlexibleMesh (DFM), the open source hydrodynamic model that is developed and maintained by Deltares (2016). The computational core of DFM solves the shallow water equations based on the finite-volume method on an unstructured grid (Kernkamp et al., 2011;UGRID, 2016).

15 The computational mesh of the study area consisted of 71 000 active cells between the main embankments. The DFM input files consisted of bathymetry, trachytopes, fixed weirs for groyne height and minor embankment height, thin dams for buildings and bridge pillars, and dry areas for embankment relocation. These files were updated with the RiverScape measure definition of each intervention following procedures described by Straatsma and Kleinhans (2018). The boundary conditions are specified by the upstream discharge and the downstream water level (Fig. 1). Only stationary discharges were

20 simulated.

3.1.3 BIOSAFE: potential biodiversity

We applied the BIOSAFE model (De Nooij et al., 2004;Lenders et al., 2001;Straatsma et al., 2017) to evaluate the measures on the potential biodiversity for protected and endangered species that are representative of the fluvial environment. The BIOSAFE conceptual model comprises a set of links between riverine species and legal and policy documents on the one

25 hand and links between species and ecotopes on the other hand. These two sets create a link between the legal domain and ecotopes via species. BIOSAFE calculates scores of potential biodiversity for seven taxonomic groups. The scores represent potential species presence based on habitat requirements, which were weighed by (1) the number of legal and policy documents, (2) the surface area of associated ecotopes, and that are normalized by the area under consideration enabling the comparison of the scores over floodplain sections with different sizes. In this study we calculated the *PotTax*, the potential

30 biodiversity of protected and endangered species for each of the taxonomic groups (higher plants, dragonflies plus damselflies, butterflies, fish, herpetofauna, birds, and mammals). *PotTax* values were summed up into a single *PotAll* score for all groups together. *PotTax* and *PotAll* scores were calculated for each floodplain section (Fig. 1; 3e) separately and averaged over the whole study area for each scenario. Figure 3e shows the *PotTax* scores for the reference situation.

3.1.4 Cost evaluation

River restoration projects are costly, but costs are often reported in aggregated form over the whole project (Bernhardt et al., 2005). Ayres et al. (2014) compiled the available evidence of the cost of river restoration and showed that the costs varied strongly for a single type of measure, but also that only a few of the cost estimates contained information on different cost

5 items. They proposed a cost typology, which distinguished non-recurring costs (planning, transaction, land acquisition, and other construction/investment costs) from recurring costs (annual maintenance and monitoring costs). In this study, we limited the scope to the non-recurring costs required for the implementation of the measures. The data for the cost appraisal (Appendix A; S. Prins, unpublished data) should be interpreted as indicative, as neither the building contractor nor the client that orders the intervention wants to share their valuation tables for fear of losing their position during negotiations.

10 The preprocessing for the cost evaluation consisted of the information extraction from several sources to obtain the spatial distribution of the cost items. The so-called cost maps were subsequently overlayed with the measure definition. We used (1) the BAG-2015 database, a cadastral database for building locations and building types, (2) Top10vector a vector-formatted geodatabase containing the roads location, type and width, (3) the ecotope map of 2012 for a simplified land, (4) the Baseline geodatabase for the position and length of groynes, minor and main embankments, and (5) the soil pollution map

15 (Table 2 and references therein) Polluted soil is expected only in the top 1 m of the soil (Middelkoop, 2002) from sediment deposition in the floodplains. The ecotope map was used for the cost of smoothing, and it also contained an attribute describing the river section, which was used to link with the cost of embankment relocation and dike raising. To calculate the cost, we determined the capital expenditures (CAPEX) for each measure. We are aware that additional operational expenditures (OPEX) increase the total cost over the lifetime of the measure and that different trade-offs could be found

20 depending on the temporal horizon, but this is out of the scope for this study. For each cost item, we mapped the mean over the study area in Euro per piece, or Euro per m^3. The standard deviation is around 15 % of the mean price per unit (Table S1). The spatial distribution of the costs of smoothing, road removal, minor embankment removal, building acquisition and demolition and land acquisition (Fig. 2d) indicate that the acquisition cost of land and buildings dominate overall cost of measures.

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The calculation of the cost per measure comprised the overlay of the cost maps with the measure definition. For side channel recreation and floodplain lowering, the unit costs of earthwork per cubic meter were added. The volume of earthwork depended on the measure settings and the existing topography. Postprocessing was required to correct for the use of data from different sources. For example, the ecotope map does not contain road information, but the cost for road removal

30 should be equal to zero for a smoothing measure. No land acquisition costs are assumed for roughness lowering.

3.1.5 Owner type and number of owners

We used the cadastral map (www.kadaster.nl/-/eigendomskaart-eigenarenkaart) to classify the owners into different classes of stakeholders (Fig. 2a, b). The name of the entitled person of each parcel was processed with a set of rules to classify them into 11 different stakeholder types listed in Table 1 plus foundations and the remaining class 'other', which consisted mainly

35 of parcels owned by churches. PWWM and SFS were easily classified as they consisted only of a single or a few entitled owners. On the contrary, sand, gravel and clay companies were extracted by their specific names, e.g. 'WIENERBERGER B.V.". The number of owners was determined by counting the number of individual owner within the area of the measure, or within each floodplain section (Fig. 2b) using vector overlay operations.

3.2 Scenario development

40 These modeling tools enabled the exploration of different future scenarios with respect to changing hydrodynamic boundary conditions and adaptation measures. We used three hydrodynamic scenarios for 17 sets of measures (Table 3). Trade-offs

between flood safety, implementation cost, potential biodiversity and number of stakeholders were assessed for each scenario by means of a scatter plot matrix (Fig. 10). Each panel in this matrix shows the most efficient combination of two variables as a line, which was extracted from the convex hull of the scattered points. No attempt was made to select a single optimal measure by means of minimizing an objective function, because such techniques require weighing factors for the four aspects and these are currently unknown. The weighing factors can also change quickly due to changing public opinions and political will.

3.2.1 Hydrodynamics

The hydrodynamic boundary conditions were given by the upstream river discharge and the downstream water level. The embankments have a flood protection standard for a flood (Q16) with a statistical return period of 1250 years (Silva et al., 2004). However, Q16 did not include the effects of climate change. The future design discharge of the river Rhine is uncertain. In policy documents, 18 000 m^3s^{-1} (Q18) is used as the likely maximum discharge for the year 2100 based on climate change and (emergency) measures taken in Germany (Deltaprogramma, 2017). This value was based on an extensive study, which combined a stochastic weather generator with a flood routing scheme (Hegnauer et al., 2014). We chose Q16 and Q18 as the upstream boundary conditions in the hydrodynamic model. Q18 translates to a discharge of 11 435 m^3s^{-1} for the river Waal. Sea level rise (dh) was implemented as a 1.8 m additional set up of the downstream water level (dh1.8) for 2100. This value has a 2.5 % probability (de Winter et al., 2017), and includes the possibility of Antarctic ice sheet collapse (DeConto and Pollard, 2016). With Q18 and dh1.8 a large part of possible future hydrodynamic conditions is covered. We ran DFM with three sets of boundary conditions, labeled as 'Q16_dh0.0', 'Q18_dh0.0', and 'Q18_dh1.8' for all measures. We compared the resulting water levels at the river axis for each measure with the modelled reference water levels of Q16_dh0.0 without any measure.

Table 3 Overview of 17 landscaping scenarios: Six measures, two locations based on stakeholders (all stakeholders and large estate owners), and two design principles (smooth and natural). All measures were evaluated for three sets of hydrodynamic boundary conditions (Q16_dh0.0, Q18_dh0.0, and Q18_dh1.8). The abbreviations are used in results figures.

Measure type	Stakeholders[a]	Design principle	Abbreviation
Roughness lowering	All	natural	Smoothing_AS_natural
Roughness lowering	All	smooth	Smoothing_AS_smooth
Roughness lowering	Large	natural	Smoothing_LS_natural
Roughness lowering	Large	smooth	Smoothing_LS_smooth
Sidechannel creation	All	natural	Sidechannel_AS_natural
Sidechannel creation	All	smooth	Sidechannel_AS_smooth
Sidechannel creation	Large	natural	Sidechannel_LS_natural
Sidechannel creation	Large	smooth	Sidechannel_LS_smooth
Floodplain lowering	All	natural	Lowering_AS_natural
Floodplain lowering	All	smooth	Lowering_AS_smooth
Floodplain lowering	Large	natural	Lowering_LS_natural
Floodplain lowering	Large	smooth	Lowering_LS_smooth
Minor embankment lowering	All	NA	Minemblowering_AS
Minor embankment lowering	Large	NA	Minemblowering_LS
Groyne lowering	All	NA	Groynelowering_AS
Groyne lowering	Large	NA	Groynelowering_LS
Dike raising	All	NA	Dikeraising_AS

[a] abbreviated to 'AS' for all stakeholders and to 'LS' for large stakeholders, i.e. Public Works Department and State Forestry Service.

3.2.2 Location: stakeholder involvement

The options for landscaping measures for flood safety and river restoration by far exceed the two options to change hydrodynamic boundary conditions. The multitude of possible scenarios is driven by the responsible authorities and the number of stakeholders, their land ownership, and their preferred land use and legal permissions. At the same time, the

5   perceived urgency to reduce the flood risk, the available budget and the political will also affect the choice for measures and the speed of implementation, although all stakeholders agree about flood safety as the number one priority. We simplified and summarized the stakeholders' preferences for specific measures based on their organizational objectives and responsibilities (Table 1) in order to derive a manageable set of scenarios for landscaping measures (Table 4). The stakeholders' preferences (Table 5) were based on table 1, literature (Fliervoet and van den Born, 2017;Fliervoet et al., 2013)

10   and expert judgement.

The directorate for Public Works and Water Management (PWWM) is the largest landowner (Table 1). They are the responsible authority for the flood protection objectives together with the water boards. Therefore, both are in favor of measures that improve the flood protection levels, especially on their own lands, such as roughness smoothing, floodplain lowering and groyne lowering (Table 5). Although, many side channels were constructed in the "Room for the River"

15   program to realize flood protection and nature objectives, the PWWM do not have a clear preference for side channels, because of high maintenance costs and increased sedimentation in the navigation channel (Van Vuren et al., 2015).

The State Forestry Service aims to develop more natural (unregulated) river systems by giving more room to natural erosion and sedimentation processes, in line with the vision of "self-regulating nature" (Stanford et al., 1996;Ward et al., 2001). This

20   vision became a source of information for the Dutch ecological rehabilitation programs of the Rhine branches and Meuse River (Buijs, 2009), and it addresses measures which create more dynamic floodplain environment, such as the construction of a side channel or lowering the floodplains (Table 5).

The provincial governments are responsibility for maintaining and developing nature in the floodplains since the

25   decentralization in 2014 from the Ministry of Economic Affairs. They plan and implement EU Natura 2000 objectives, based on the European legislation and they allocate subsidies for nature conservation. This may require changes in land use, which are in turn regulated by the municipalities. Although, the provinces are the nature authority, they are in favor of measures that have multiple objectives, such as constructing a side channel or lowering a floodplain. Both measures have the opportunity to reconcile the objectives of flood protection and restoring nature in the floodplains.

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The Water Boards are responsible for, and the owners of, the dikes and minor embankments. They prefer the following measures; minor embankment lowering and dike raising. Private land owners (especially farmers) and companies are often against measurements, such as minor embankment lowering and floodplain lowering, due to the increased flooding frequency of their land, which negatively affects their activities. The sand, gravel and clay mining industries are often in

35   favor of measurements, which lead to the excavation of soil in the floodplains. Finally, the province foundations ('Geldersch and Brabants Landchap') are aiming at the conservation of nature and cultural heritage, such as braid hedges or fortresses in the floodplains. These foundations perceive minor embankment lowering and floodplain lowering negatively, and roughness smoothing positively when a 'park-like' landscape is concerned (Fliervoet et al., 2013).

40

Table 4 Simplified stakeholder preferences for different measures.

Stakeholder type --> Meaure	Public Works and Water management	State Forestry Service	Private land owners	Company	Mining companies	Water Board	Province foundations	Provincial government	Munici-palities
Side channel construction	0	+	0	-	+[b]	0	0	+[a]	0
Roughness smoothing	+	-	+[c]	0	0	0	+[d]	0	0
Floodplain lowering	+	+	-[c]	-	+[b]	0	-	+[a]	0
Groyne lowering	+[e]	0	0	0	0	0	0	0	0
Minor embankment lowering	0	0	-	-	0	+[f]	-	0	0
Dike raising	0	0	0	0	+[b]	+[g]	0	0	0

Legend: + = in favor for implementing measure on own properties; 0 = no clear opinion or no mandate; - = against measure.
Notes: [a] in case flood safety and spatial quality are combined, e.g. in the 'Room for the River'-program, [b] extraction of sand, clay or gravel, [c] agricultural function, [d] to maintain cultural landscape, [e] responsible for groynes, [f] responsible for minor embankments, [g] responsible for and owner of the main embankment.

Stakeholder involvement and their land ownership determined the locations where the RiverScape measures were positioned. The first option for the location of measures was the combination of the large stakeholders (LS) that own large areas, being PWWM and SFS. They own 56 % of the whole study area together (Table 1), and 31 % of the groyne field plus floodplain area. They agree with floodplain lowering as a possible measure, disagree with roughness smoothing, and do not disagree with the other measures (Table 5). SFS opposes roughness smoothing, because it opposes their vision of "self-regulating nature", except when it is performed within the context of cyclic floodplain rejuvenation. Given the large area owned by these two stakeholders only, they can relatively easily implement the different measures on their own property even though they pursue different ultimate objectives. The second option was that the measures could be implemented at the properties of all stakeholders (AS). This means that all 1233 stakeholders would need to endorse the measure, or be compensated. Given the different objectives of the stakeholders, this can only be realized after a major disaster in times of a perceived high urgency. Although, this is not the current state in the Netherlands, we still include it, because of the changing hydrodynamic boundary conditions over time. This gave two location scenarios: LS and AS.

3.2.3 Measure type and design principle

Six adaptation measures were implemented in the groyne field and the existing floodplains (Fig. 3); measures in the main channel and the areas protected by the main embankments were not considered. The design principle of the measure affected the choices made within RiverScape with respect to the new land cover and the cross sectional shape of new side channels. The first option, labeled as 'smooth', was to optimize the conveyance capacity of the floodplain, whereas the second option, labeled as 'natural', included ecological qualities as favored by SFS and the provincial government. No difference between smooth and natural designs were implemented for minor embankment lowering, groyne lowering and dike raising, because the land use is assumed to remain identical.

We parameterized the measures in RiverScape (Straatsma and Kleinhans, 2018) with the following settings. Firstly, roughness lowering (smoothing) was applied over 100 % of the location (LS, or AS) and resulted in production meadow (ecotope UG-2 and trachytope 1201) for the smooth scenario and natural grassland (ecotope UG-1, and trachytope 1202) in the natural scenario. Production meadow has a slightly lower roughness than natural grassland, with Chézy coefficients of 38 and 35 $m^{\frac{1}{2}}s^{-1}$ at 3 m water depth, respectively (Van Velzen et al., 2003). However, the potential biodiversity of natural

grassland is twice as high. Secondly, floodplain lowering led to excavation of the terrain to the local height that is inundated 50 days per year for both the natural and the smooth option. Production meadow was assigned to the measure area in the smooth option and natural grassland in the natural option, similar to roughness lowering. Thirdly, natural and smooth side channels differed in their cross sectional shape and depth. Both were connected to the main channel only at the downstream

5 end. We choose a width of 75 m, a depth of 2.5 m and lateral slopes of 1 to 3 for smooth side channels. Natural side channels were parameterized with a 50 width, a 1 m depth and lateral slopes of 1 to 7. Ecotopes for deep and shallow side channel were assigned, which translates into the same trachytope. Finally, minor embankments and groynes were lowered to the water level exceeded 50 and 150 days per year, respectively. The main embankment was raised with 1 m over the whole study area.

10 ## 4 Results

In order to substantiate the trade-offs, we will first describe individual components to gain detailed understanding. The hydrodynamic evaluation is given most attention, because flood safety represents top priority for all stakeholders.

4.1 Measure positioning and hydrodynamic effects

The measures were positioned in the areas owned by PWWM and SFS (Fig. 4), or over the whole area. The fraction

15 ownership varied strongly between the floodplain sections. The main channel and the groyne field are completely owned by the PWWM, whereas SFS owns the majority of specific floodplains sections, such as around 900-l and 928-r.
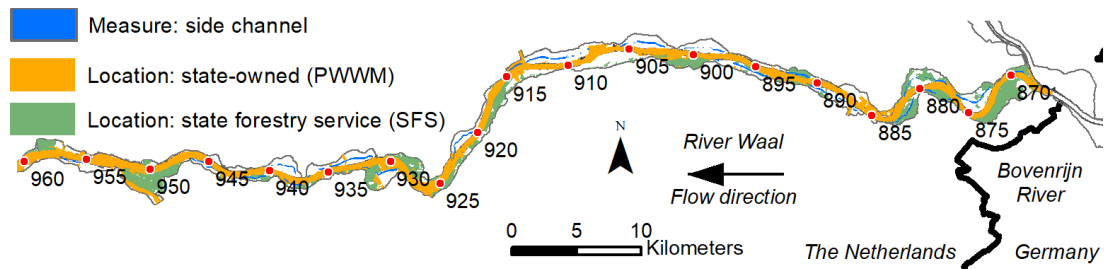
Figure 4 Location of the two largest stakeholder, the state (Public Works and Water Management) and the State Forestry Service
20 **(SFS). The other public and private stakeholders own the remaining areas in white.** The location of the side channels represents the smooth option for the whole area (AS). Water flows right to left.

The different hydrodynamic boundary conditions (Fig. 5a, b) led to spatial variation in the water levels. Q18_dh0.0 gives a 0.33 m increase in water levels at the downstream boundary, which increased rapidly in the upstream direction to a maximum of 0.76 m at rkm 880. Conversely, the Q18_dh1.8 scenario gave the highest water level increase downstream:

25 2.12 m. In the upstream direction, the differences decline due to the reduced impact of the backwater effect further upstream, with a minimum increase of 0.76 m at rkm 868, the model boundary on the upstream end.
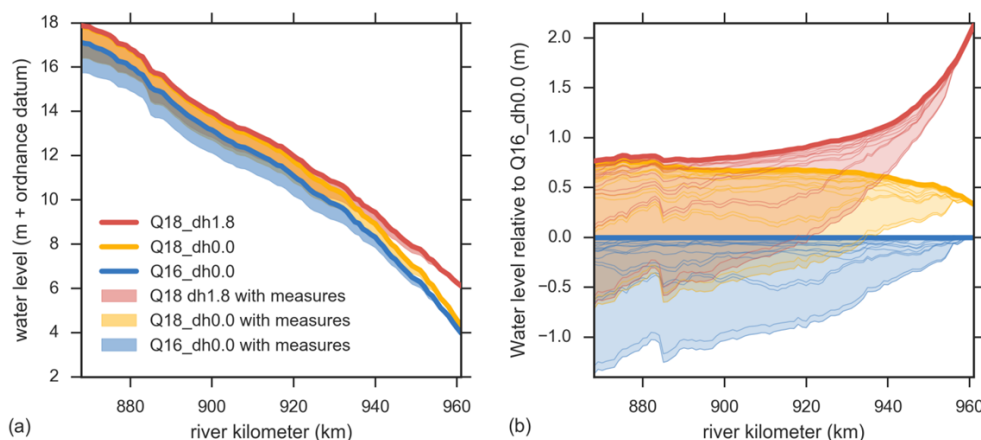
Figure 5 (a) Absolute water level for the three hydrodynamic sets of boundary conditions (solid lines) and the effects of the implemented measures for Q16_dh0.0 and Q18_dh1.8 in the shaded areas. (b) Changes in water level relative to the reference situation, Q16_dh0.0 without measures. The thick lines represent the relative changes without any measures; the thin lines represent the 16 different measures for each set of boundary conditions. Water flows left to right.

The effects of the measures differed strongly between the type of measure, and the location (Fig. 6, left column). We compared the simulated water level with the reference situation (Q16_dh0.0, without measures) for all hydrodynamic and landscaping scenarios to see to what extent the measures can lower the flood hazard, or mitigate the changing hydrodynamic conditions. Groyne lowering mainly affected the upstream area, with a maximum lowering of 0.06 m. Minor embankment lowering gave a maximum lowering of 0.07 and 0.11 m for large stakeholders (LS) and all stakeholders (AS), respectively. Roughness lowering was more effective with a maximum of 0.21 m for AS_smooth, a minimum of 0.09 m for LS_natural. LS_smooth and AS_natural both reach 0.14 m water level lowering. The largest effects and the largest differences between the measure parameterizations were observed for side channels and floodplain lowering. Side channels showed a sequence of backwater curves from the individual measures with a maximum lowering of 0.38 m for AS_smooth and 0.34 m for AS_natural (Fig. 6) in the upper part of the Waal, which is due to the combined effects of all channels and the higher water surface slope. Side channels at the LS locations were 42 % less effective. Floodplain lowering gave the maximum water level reductions, which ranged between 0.62 m for lowering_LS_natural and 1.37 m for lowering_AS_smooth.

The effects of the measures proved independent of the hydrodynamic conditions. This can be observed in Fig. 6 by comparing the water level differences with each hydrodynamic scenario without any measures, i.e. y=0 in the left column and the grey lines in the middle and right column. For each of the three hydrodynamic boundary conditions, we calculated the mean water level at the river axis for the situation with measures and compared that against the reference situation without measures. The water level changes from the measures under different hydrodynamic conditions correlated very strongly, with all values in the correlation matrix exceeding 0.999.

The measure efficiency in compensating the changing hydrodynamic conditions (Fig. 6 middle and right columns) showed that only floodplain lowering was able to compensate enough. Lowering was more efficient upstream, with the zero crossing at rkm 933 and 920 for AS_smooth in Q18_dh0.0 and Q18_dh1.8, respectively (Fig 6). The other measures did not lower the water levels enough to maintain flood safety without additional embankment raising. All measures were more efficient in water level lowering in the upper reach (Fig. 7). On average, the lowering was 2.2 times larger in the upper reach compared to the lower reach, ranging from 1.1 times for smoothing_AS_natural to 4.4 times for minemblowering_LS. The overview of water level lowering over the upper and the lower reach (Fig. 7) showed that floodplain lowering at the locations of all stakeholders could compensate for the additional discharge (Q18_dh0.0), but for Q18_dh1.8 also this option fails in the lower reach.
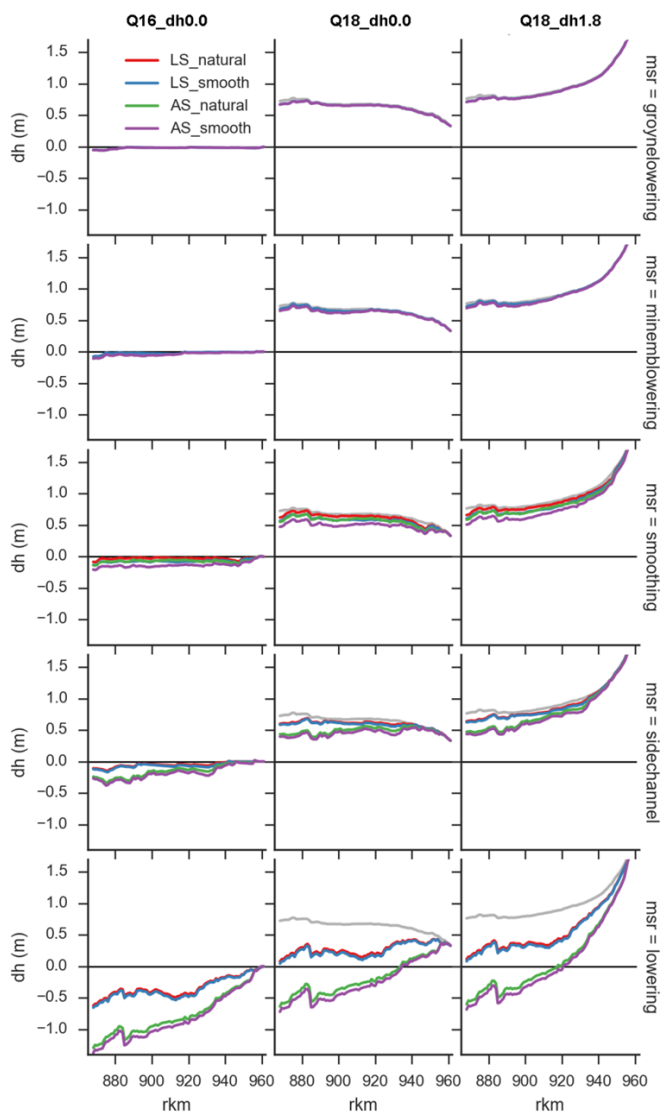
Figure 6 Facet plot of water level changes (dh) at the river axis relative to the reference situation (Q16_dh0.0). The water levels of Q18_dh0.0 and Q18_dh1.8 are shown as grey lines. Water flows left to right. Measure (msr) type is indicated on the right. The grey lines in the middle and right column represent the effects of boundary conditions only.
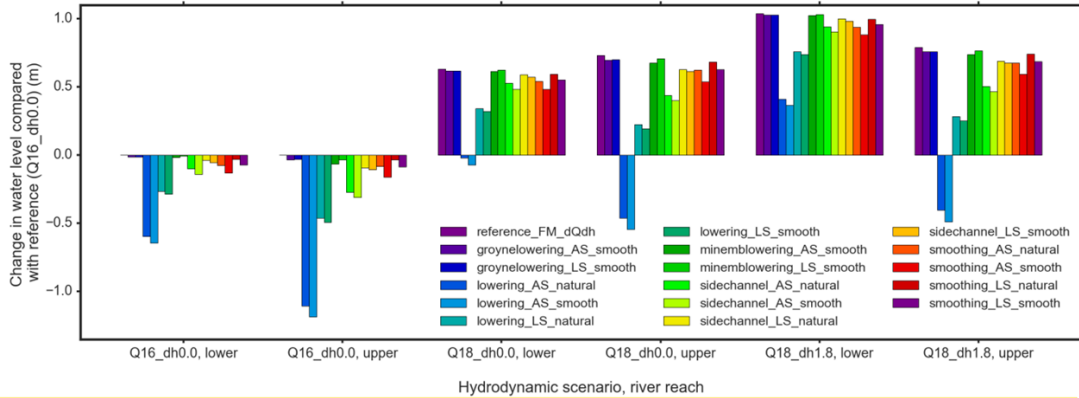
Figure 7 Mean differences with the reference situation (Q16_dh0.0) in peak water level in the lower reach (rkm 919 to 945) and the upper reach (rkm 868 to 894).

4.2 Effects on potential biodiversity and implementation costs

The overall changes in *PotAll* varied strongly between the scenarios and between the floodplain sections (Fig. 8). Floodplain smoothing gave the largest positive and negative differences, with the positive changes related to the natural scenario and negative changes to the smooth scenario. The largest positive changes represent floodplain sections that largely consisted of agricultural fields and production meadows, which were converted to natural grass land (e.g. 895-l and 912-l in Figs. 1, 8). Conversely, the smooth scenario led to the largest decline in *PotAll*, due to the conversion of ecologically valuable ecotopes to production meadow. Most notable is 932-r, which has a *PotAll* value of 157 in the reference situation and 94 and 107 after the implementation of smoothing_AS_smooth and lowering_AS_smooth, respectively. The effects of side channels on *PotAll* scores were positive, independent of scenario. However the differences were smaller compared to floodplain lowering and roughness smoothing (Fig. 8) due to the smaller spatial extent of the side channels.
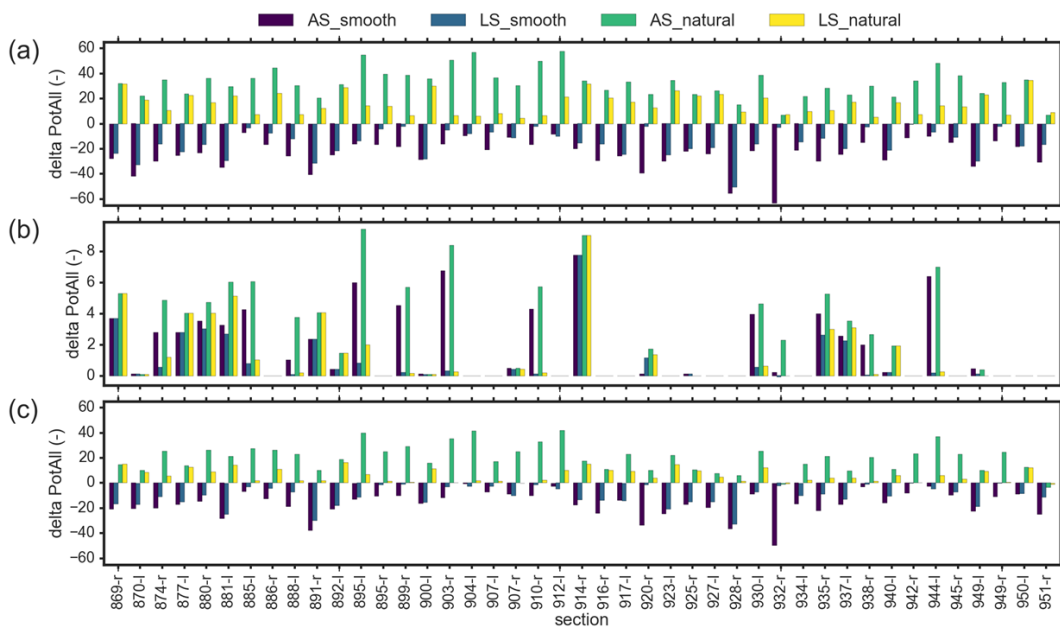
Figure 8 Changes in *PotAll*-scores per floodplain section for three measure types: (a) smoothing (roughness lowering), (b) side channels, (c) floodplain lowering. Note the different vertical scale in (b).
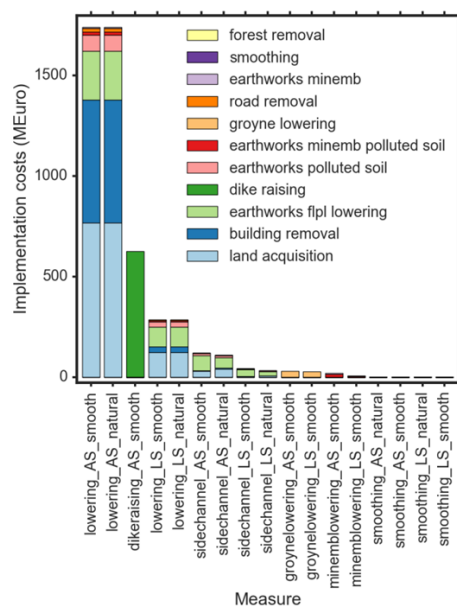
Figure 9 Comparison of costs between scenarios.

The implementation costs varied strongly between the measures ranging from €1.7 billion for lowering_AS to €2 million for floodplain smoothing (Fig. 9). The largest costs are inferred by the acquisition of buildings and land, and the costs of forest

5   removal and mowing for floodplain smoothing are very low. The costs of raising the dikes represent a 1 m increase in dike height. The fraction of the costs for building removal is 9 % for the LS case and 35 % for the AS case, indicating that the LS stakeholders have relatively few built-up areas.

4.4 Trade-offs of climate adaptation measures

10   The combination of the water level lowering, changes in *PotAll*, the implementation costs, and the number of stakeholders involved provided insight in the trade-offs of the different scenarios (Fig. 10). Water level lowering was averaged over the entire river reach, *PotAll* scores were averaged over all floodplain sections, and total costs are presented. The total number of individual stakeholders involved was calculated over the measure area. The lower left corner of each panel (Fig. 10) represents utopia, the optimal combination of the two criteria, and the wide grey line represents their optimum trade-off.

15   Note that the *PotAll*-axes were reversed to visualize utopia in the lower left corner. Dike raising by 1 m was visualized as a water level lowering of 1 m for visualization purposes.

We considered a low number of stakeholders favorable for fast implementation of a measure. The number of stakeholders involved in measures has an optimum in water level lowering for dike raising (n=948), lowering_LS, and sidechannels_LS

20   (both n=2) (Fig. 10a). Smoothing_AS_natural is closest to dystopia with 1200 stakeholders and only a small reduction in water level, which highlights the problems of managing the floodplain roughness. However, legislation exists that makes roughness lowering obligatory in areas with high conveyance capacity.

The trade-offs between *PotAll* and water level lowering consisted of dike raising, lowering_AS_natural, and smoothing_AS_natural (Fig. 10b). The mean reference value of *PotAll* is 114 as represented by dike raising and 'reference'.

25   All measures above this reference line (*PotAll*=114) have a lower *PotAll* score (note the reversed axis) and a decreased potential biodiversity. The natural and smooth scenarios for floodplain lowering and smoothing and show up as paired points above and below the reference line with a similar water level lowering.

Cost-effectiveness measures in terms of water level lowering consisted of dike raising and smoothing_AS_smooth (Fig. 10c), which are the two traditional methods of flood risk prevention in the Netherlands. Floodplain lowering_LS touches the grey optimum line and keeps an intermediate position. Lowering_AS is almost three times more expensive than dike raising

5 and does not lower the water levels much in the lower reaches (Fig. 6).

Improving the *PotAll* scores wa easiest in terms of number of stakeholders with smoothing_LS_natural, which followed by smoothing_AS_natural, even though 1200 stakeholders were involved (Fig. 10d). The reference situation is also on the optimum line, because zero stakeholders were involved. These measures also represent the cheapest way to increase *PotAll*

10 values (Fig. 10f). The selection of the reference situation on the optimum line indicates that the ecological value can still be lowered as well as is the case for the smooth scenarios for floodplain lowering and roughness smoothing.

The optimum in the number of stakeholders against total costs is represented by groyne lowering, minor embankment lowering and smoothing at the LS-locations. These points are not obvious in the plot (Fig. 10e); they only show up after magnification of the lower left corner. The reference situation only is ignored, because it does not represent a measure.
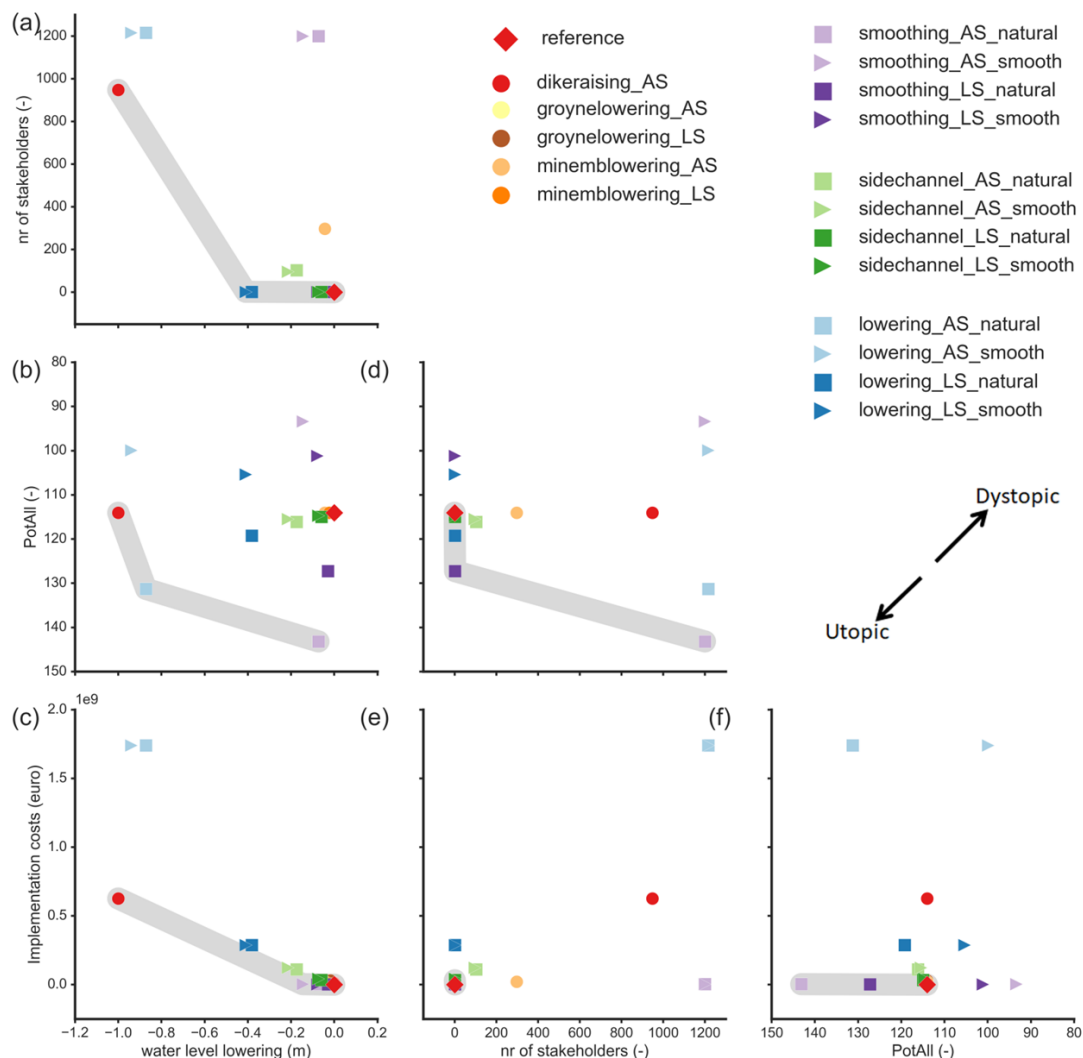
Figure 10 Scatterplot matrix of the main criteria for intervention planning. The grey areas indicate the optimum combination of criteria for each panel. Similar colors represent one type of measure and shading represents the difference in location. The two design principles are visualized with a rectangle for natural and a triangle for smooth. The diamond represents the reference situation.

5 Discussion

The flood safety structures and the land use in the delta are driven and constrained by three main needs: flood safety, socioeconomics and ecology as protected by national and European law. In this paper, we evaluated 17 landscaping measures to adapt a large delta distributary to increased flood hazards from sea level rise and increased river discharge: only floodplain lowering over the entire sufficed without additional raising of the embankments. The management of these adaptations is driven by public opinion and associated political will. Historic events that affected changes were the 1993 and 1995 floods, which caused evacuation of 250 000 people (Van Stokkom et al., 2005), but also reports on ecological degradation drove changes in land use (De Bruin et al., 1987).

Our methodology suits the early stages of the planning process as it provides an overview of possible interventions to adapt to climate change and the associated capital expenditures, and the hydrodynamic and ecologic effects. Additional assessments have to be carried out after this initial stage, which include operational expenditures, morphological changes in the navigation channel, compensation of land owners that have increase inundation of their land due to the removal of minor

5   embankments. We also assumed that all measures are implemented instantaneously, whereas the timing could be made dependent on the recorded speed of sea level rise to optimize the measures under uncertainty and avoid unnecessary costs (Postek et al., 2018). Compared to other DSSs targeted at intervention planning (Hübner et al., 2009;Schielen and Gijsbers, 2003), we added the option for automatic positioning and parameterization of measures over arbitrary areas, costs and the number of stakeholder. Our modular structure in Python simplifies adding other evaluation criteria.

An alternative to the owner-specific areas of measure locations could be ecological, or financial considerations. Ecological optimization would involve ranking the ecotopes according to their potential biodiversity. High-ranking ecotopes should be left untouched whereas ecotopes with a low potential biodiversity are suitable candidates for river restoration measures. Additional weighing of the ranking could be the hydrodynamic roughness, or specific taxonomic groups. Likewise, the

15   locations with high economic value could be left untouched to lower the costs of implementation. All these choices would have to be made as part of management, policy and politics and here we opt for the more straightforward evaluation criteria.

We showed that flood safety can only be maintained by raising the dikes by one meter, or excavating the floodplains over the entire area as long as only measures inside the embanked floodplains are considered. Large scale embankment relocation can

20   also lower water levels by a meter (Straatsma and Kleinhans, 2018). None of these options are politically accepted at the moment, given the recent completion of the so-called 'Room for the River'-program. This program aimed at increasing the design discharge from 15 000 to 16 000 m^{3}s^{-1} and now river managers focus on efficient maintenance of the floodplains (Fliervoet and van den Born, 2017). However, given the large uncertainties in sea level change and river discharge, the focus may quickly change. For example, floodplain excavation is considered too expensive for the moment, due to the sediment

25   deposits polluted with heavy metals from the 20th century (Middelkoop, 2000) and lack of sediment storage options. At the same time, soil subsidence due to compaction and peat oxidation require large volumes of sediment, and previous smaller excavation measures positively affected biodiversity (Straatsma et al., 2017;Vliegenthart and Van der Zee, 2018).

The limited capacity within the floodplain area to lower the flood hazard points to the need to create more space for the river

30   and robust measures. Robust measures create additional conveyance capacity without embankment raising, which is not counted on in hazard assessment. Embankment raising is cheap, but the higher flooding speed in case of a dike breach increases the risk (Van Stokkom et al., 2005). Robust measures would allow for vegetation succession and the associated benefits of biodiversity increase and the attenuation of wind-driven waves. By comparison, vegetation succession gave a maximum increase in simulated water levels of 0.7 m for the river IJssel (Makaske et al., 2011). Robust measures would also

35   lower the costs of monitoring, because of the additional discharge capacity.

We assumed that the 1.8 m sea level rise translated into a 1.8 m rise of the downstream boundary condition and ignored the long-term morphological changes. Under natural conditions, the bathymetry would follow the rising sea level, but the Rhine delta has a reduced sediment supply due to the storage in upstream reservoirs for hydropower, which led to erosion of the

40   main channel over the last decades (Frings et al., 2009). For the future, Sloff et al. (2014) predicted a main channel erosion of 0.25 m in the lower reach and 0.4 m sedimentation in the middle reach of the Waal, based on a 2D morphological study spanning the period 2015 to 2055. Their results and the uncertainty in long term morphological modelling justify our assumption.

The owner-specific areas for measures served as a proxy for the complexity of implementation in terms of governance, because more owners means longer implementation times. It created insight in the possible contributions of the stakeholders for large scale interventions. Reality is more complex with contrasting laws and regulations and limited cooperation between stakeholders. Robinson et al. (2011) highlighted "the substantial financial and human resource investment required to

5   generate and translate available science to inform policy-level decision making." Our results are useful for developing an integrated river basin management plan, because we provided large scale boundaries for decision making at a large scale. The results can help to argument in favor of establishing multi-stakeholder platforms, such as river basin organizations, collaborative watershed partnerships, Stewardship council (in Dutch Waardschap) and 'collaborative superagencies' (Fliervoet and van den Born, 2017;Jaspers, 2003;Pratt Miles, 2013;Verbrugge et al., 2017). With such collaborative

10   structures, the major problem of fragmentation in terms of the number of land owners (Table 1, Fig. 10) could potentially be overcome.

6 Conclusions

Adapting large and densely populated deltas to changing hydrodynamic conditions is a daunting task, especially since the need for river restoration and socioeconomic drivers prevent a single-objective solution. Careful spatial planning with

15   stakeholder involvement should benefit from integrated assessment of possible alternatives. We presented an automated method for the implementation and evaluation of landscaping measures, and we developed 17 scenarios based on the type of measure, the number of stakeholders involved, and ecological design principles. We found that (1) the traditional measures of flood hazard reduction in the Netherland, dike raising and roughness lowering, represent the most cost-effective solutions, (2) the choice for production meadow, or natural grassland had a small effect on simulated water levels (less than 0.08 m

20   difference) but a major effect on the potential biodiversity (-12 to +25 % compared to the reference), (3) the two largest stakeholders could effectively lower flood levels: they own 31 % of the groyne field plus floodplain, but the water level lowering from measures in these locations accounted for 34 to 54 % of the lowering due to measures in the whole study area., and (4) only floodplain lowering over the whole area can compensate for the changing discharge and sea level rise at the costs of 1.74 billion euro and 1200 stakeholders.

25

We determined the trade-offs between landscaping measures with respect to flood hazard, costs, biodiversity and number of stakeholders. No single measure ranked highest on all attributes, underlining the wickedness of the problem. Our approach contrasts with the detailed analyses carried out the daily practice of river management, which normally consider a single floodplain section as a project area and is influenced by individual stakeholders. Our setup enables fast exploration of

30   pathways at the scale of a whole river reach with standardized cost estimates and state of the art assessments of potential biodiversity. We showed the extent to which the two largest stakeholders can alter the river system on their own property. The method can be transported to other regions, such as the Elbe, Mississippi and Mekong Rivers, and upscaled to the entire delta to support sustainable land use planning. However, subsequent detailed analyses are required before the measures are carried out in practice, which should assess morphological changes, recurring costs, timing of measures, and vegetation

35   succession. These aspects could also extend this DSS. The benefit of our approach lies in the large scale of the measures, and the multiple criteria used in the evaluation, which enables higher-quality and more transparent planning with long time horizons. It also shows the future challenges and normative choices that need to be made.

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Appendix A

Non-recurring costs of measure implementation in unit prices. The unit prices represent the 2015 price level and exclude VAT and indirect costs for engineering, design, and unexpected costs.

Category	Cost item	Price per unit	Price standard deviation	Unit
Real estate	**Acquisition**			
	Agricultural area	6.7	0.8	€/m²
	Nature areas	1.2	0.2	€/m²
	Water areas	0.8	0.1	€/m²
	Builtup areas	190	50	€/m²
	Individual house	500	120	k€/pc
	Farms	900	220	k€/pc
	Business	1400	330	k€/pc
	Demolition			
	Individual house	20	3	k€/pc
	Farm	40	6	k€/pc
	Business	120	20	k€/pc
Earthworks	**Floodplain lowering**			
	Storage at 25 km	7.2	1	€/m³
	Additional cost of polluted soil	10.2	3.4	€/m³
	Earthworks floodplain lowering, local usage	3.1	0.8	€/m³
	Side channel			
	Storage at 25 km	8.1	1.2	€/m³
	Additional cost of polluted soil	10.2	3.4	€/m³
	Earthworks floodplain lowering, local usage	3.1	0.8	€/m³
	Minor embankment			
	Storage at 25 km	6.9	1	€/m³
	Additional cost of polluted soil	10.2	3.4	€/m³
	Earthworks floodplain lowering, local usage	1.9	0.5	€/m³
Roads and bridges	**Removal**			
	Bike lane removal, incl. dumping/recycling	14	1	€/m²
	Road removal, incl. dumping/recycling	27	3	€/m²
	Bike lane construction (width < 2m)	28	3	€/m²
	Road construction (width < 7m)	50	10	€/m²
Roughness smoothing	**Removal**			
	Grass mowing and removal	540	170	€/ha
	Herbaceous vegetation mowing and removal	810	270	€/ha
	Forest clearing and removal	1330	440	€/ha
Groynes	**Lowering and conversion**			
	Groyne lowering	650	170	€/m
	Conversion to longitudinal training dam	1900	390	€/m