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Flood hazard reduction from automatically applied landscaping measures in RiverScape, a Python package coupled to a two-dimensional flow model

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A B S T R A C T

River managers of alluvial rivers often need to reconcile conflicting objectives, but stakeholder processes are prone to subjectivity, time consuming and therefore limited in scope. Here we present RiverScape, a modeling tool for numerical creation, positioning and implementation of seven common flood hazard reduction measures at any intensity in a 2D hydrodynamic model for a river with embanked floodplains. It evaluates the measures for (1) hydrodynamic effects with the 2D flow model Delft3D Flexible Mesh, and (2) the required landscaping work expressed as the displaced volume of material. The most effective flood hazard reduction in terms of transported material is vegetation roughness smoothing, followed by main embankment raising, groyne lowering, minor embankment lowering, side channel construction, floodplain lowering and relocating the main embankment. Implementation of this tool may speed up decision making considerably. Applications elsewhere could weigh in adverse downstream effects, degradation of the ecology and overly expensive choices.

1. Introduction

Flood risk reduction ranked high on the political agenda over the last two decades, which is warranted given the high and increasing societal cost of flooding, the anticipated ongoing climate change, and economic developments in fluvial and deltaic areas (Hirabayashi et al., 2013). Here, flood risk is defined as the inundation probability times the inundation effect. The European Flood Directive (European Commission, 2007) states that it is feasible and desirable to reduce the risk of adverse consequences associated with floods, and obliges member states to create flood hazard and risk maps, and a flood risk management plan for the implementation. Flood risk management can be summarized by (1) strategy, i.e. protection against floods, living with floods, and retreat to flood-safe areas, and (2) timing of the action relative to the flood event, i.e. pre-flood preparedness, operational flood management and post-flood response (Kundzewicz and Takeuchi, 1999). Consequently, river managers are confronted with large challenges in the planning of measures in and around floodplains of embanked alluvial rivers, not only due to the number of stakeholders involved, but also due to the long lasting effect on the landscape, economic development and riparian ecosystems (Pinter, 2005).

Flood hazard management at the river basin scale consists of storing water in the headwater of the basin, retaining water instream in the middle parts and discharging the water in the downstream reaches (Hooijer et al., 2004). This is because the propagation of a flood wave, or flood wave celerity, increases with the flow velocity of the water and with the fraction of the discharge conveyed by the main channel (Jansen et al., 1979). For example, the narrowing of the floodplains by embankments and decreasing the flow resistance of the floodplain vegetation increases the flood wave celerity, which adversely affects the flood hazard downstream (Clilverd et al., 2016). Here we present a flexible tool for quantifying effects and effectiveness of common measures to lower the flood risk with the aim to support stakeholder discussions with evidence-based facts and figures. We develop and apply the tool to a specific case of a lowland deltaic floodplain at the downstream end of the river Rhine, which is a medium-sized river draining part of North-West Europe.

Typical measures at the scale of a floodplain section (Fig. 1) have in common that they increase the water storage, and the conveyance capacity during floods. Two types of measures are considered

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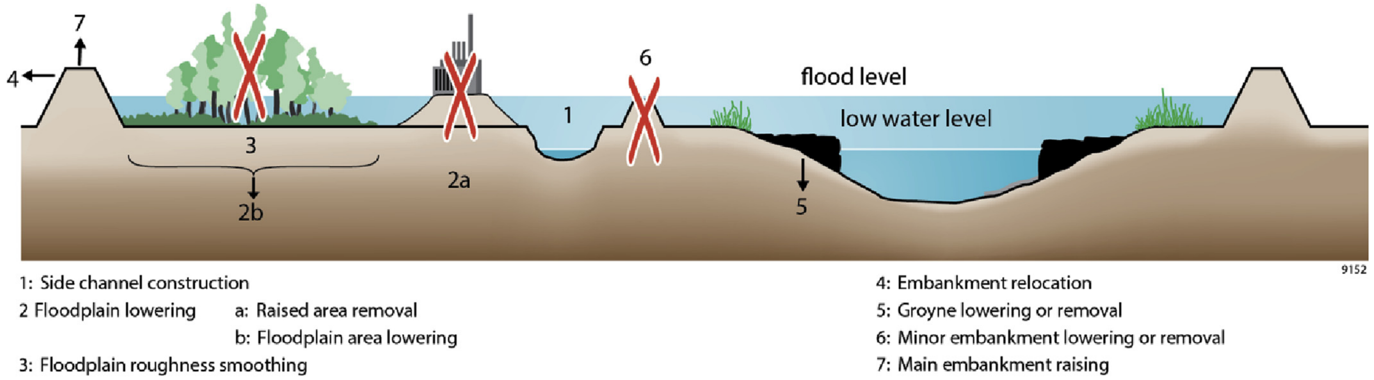

Fig. 1. Typical landscaping measures implemented in this paper (figure after (Middelkoop and Van Haselen, 1999)).

here to lower the flood hazard, more specifically, the probability of flooding the embanked areas. The first type lowers the flood stage during peak discharges (measure type 1 to 6, Fig. 1) by creating more space for the river within the embankments. The second type comprises raising the main embankment, which enables higher water levels. The flood hazard reductions of these measures have been reported previously (Baptist et al., 2004; Remo et al., 2012), and are routinely evaluated in operational river management. The typical workflow comprises a geodatabase with spatial information that is converted to input data for a hydrodynamic model. Experts, together with stakeholders, choose what measure will be implemented, and manual adjustments are made to the geodatabase and the derived hydrodynamic model. Expert judgment drives this process, which is limited by the amount of manual work required to update the hydrodynamic model with a realistic bathymetry and land cover at the spatial extent of the measure. These processes can take years for simple measures, and more than a decade for complicated projects due to the complex and iterative nature of joint decision making. Decision support systems (DSS) for these long term planning projects in the preparedness phase are scarce, contrary to DSSs for operational flood management.

The options for flood hazard management for the lower reaches of the River Rhine in the Netherlands (Silva et al., 2004) were modelled for individual measures, and the water level lowering at the river axis were made available in a graphical user interface (WL|Delft-Hydraulics, 2008). Interactive planning of some measures was possible using geospatial software (Van der Werff ten Bosch, 2009). Application at the river-reach scale with realistic measures, however, is tedious and impractical, showing a need for automated procedures to generate these measures in larger areas. Measures can be applied with different gradations and spatial extents, to which we will refer to as ‘intensities of application’. The units of this intensity vary, e.g. small and large side channels, or relocation of embankments over short or large distances. Nonetheless, each measure lowers the flood hazard and their implementation requires material displacement. Our main objectives were to (1) develop a tool to automatically position and parameterize seven flood hazard reduction measures and (2) evaluate these measures on hydrodynamic effects plus the required volume of displaced material. These aims are limited to the physical domain; evaluation on costs was outside the scope of this study, even though it is closely related to transported material. We developed the RiverScape package in Python and applied it to the main distributary of the River Rhine. The results are followed by discussion of the applicability to other alluvial rivers and future perspectives to incorporate values other than material displacement.

2. Materials and methods

We developed RiverScape, a Python package, which uses map algebra functions from PCRaster (Schmitz et al., 2013). RiverScape can position and parameterize landscaping measures and update the input data for the two-dimensional (2D) flow model Delft3D Flexible Mesh (DFM), which is also open source. It requires input on hydrodynamic boundary conditions, a geodatabase with layers of river attributes, and settings to determine the intensity of application for each measure (Fig. 2). Once the measures are known, we updated the 2D flow model's input in order to determine the flood hazard reduction and the flow velocities. Here, we present the methods implemented.

2.1. Study area and available data

The case study area is located in the Rhine delta, which consists of three distributaries: the Rivers Waal, Nederrijn and IJssel. We selected the River Waal, which is the main distributary of the River Rhine in the Netherlands (Fig. 3). The three main concerns here are flood risk in view of global change, navigability and ecosystem functioning. The study area spans an 94-km-long river reach with an average water surface gradient of 0.10 m/km. The total area of the embanked floodplains amounts to 132 km^2. The main channel is around 250 m wide and fixed by groynes. The cross-sectional width between the primary embankments varies between 0.5 and 2.6 km. Meadows dominate the land cover, but recent nature rehabilitation programs led to increased areas with herbaceous vegetation, shrubs and forest. The design discharge for the River Waal is now set to 10,165 m^3s^{-1}, which has 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 functions as the primary shipping route between the port of Rotterdam and major industrial areas in Germany. The main channel position is fixed in place by groynes, which were partly lowered during the ‘Room for the River’ project (Van Stokkom et al., 2005). In the future, the design discharge will be combined with a risk-based approach that takes the potential damage and casualties within the protected areas into account (Van Alphen, 2016).

The spatial data describing the major rivers in The Netherlands are stored in an ArcGIS file geodatabase according to the *Baseline* data protocol, version 5 (Scholten and Stout, 2013). This protocol, specific for the Netherlands, describes the layers in the geodatabase and specifies the required attributes for each of the layers in terms of names, and properties. *Baseline* schematizations include layers with (1) land cover as a polygon layer of ecotopes (landscape-