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Ylla Arbos, Claudia; Blom, Astrid; Schielen, Ralph M.J.

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Rivers in an uncertain future

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University of Twente	telephone:	+31 53 489 35 46
P.O. 217	e-mail:	secretariat-mfs-et@utwente.nl
7500 AE Enschede	www:	https://www.utwente.nl
The Netherlands		

Contact NCR

dr. ir. K.D. Berends (programme Secretary)	telephone:	+31 6 21 28 74 61
Netherlands Centre for River Studies	e-mail:	secretary@ncr-web.org
c/o Deltares	www:	https://www.ncr-web.org
P.O. 177		
2600 MH Delft		
The Netherlands		

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Scenarios for Controls of River Response to Climate Change in the Lower Rhine River

Clàudia Ylla Arbós[a,*], Astrid Blom[a], Ralph M.J. Schielen[a,b]

[a]*Delft University of Technology, Department of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, PO Box 5048, 2600 GA Delft, the Netherlands*

[b]*Ministry of Infrastructure and Water Management - DG Rijkswaterstaat, Utrecht, the Netherlands*

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Introduction

The majority of the world's large rivers are heavily engineered. In such heavily engineered rivers, channel response (i.e., changes in bed elevation, channel slope, and bed surface grain size) is predominantly determined by human intervention [e.g., Surian and Rinaldi (2003); Ylla Arbós et al. (2020)]. The relative influence of climate on channel response may, however, increase in the upcoming decades, as climate change alters the river controls. Specifically, climate change affects (1) the characteristics of the flow rate, through changes in precipitation patterns; (2) the downstream base level, through sea level rise, or lake base level drop; and (3) the sediment flux, due to changes in water discharge.

It is increasingly necessary to anticipate future channel response to climate-related changes in the river controls. This can be done using numerical models, by changing their boundary conditions. A required step is determining climate change scenarios for the river controls and translating them into suitable boundary conditions for numerical models, taking into account different sources of uncertainty.

Here we consider the Lower Rhine River, from Bonn (Germany) to Gorinchem (Netherlands). We discuss the projected changes of the hydrodynamic river controls over the 21st century, and how they can be transformed into suitable boundary conditions for a schematized model.

Changes in water discharge

Several studies have attempted to predict water discharge in the Rhine basin until 2100 using a model chain [e.g., Gorgen (2010); Hegnauer (2017)]. First, the different emission scenarios or representative concentration pathways (RCP's) defined by IPCC are used as input to climate models. The output is then used to obtain future precipitation time series. Finally, the precipitation time series are input to a hydrological model that transforms daily precipitation into daily river discharge. Numerous models and techniques are used in this process, and the results are sensitive to these choices, in particular to that of the climate model (Gorgen, 2010; Hegnauer, 2017). In general terms, the different studies predict similar future trends in water discharge along the Rhine basin (Hegnauer, 2017). In upstream, snowmelt-dominated locations (e.g., Basel), higher temperatures lead to earlier snowmelt, which slightly shifts the annual discharge peak to earlier in the year, the magnitude of the peak not changing significantly. In the downstream, rainfall-controlled tributaries (e.g. Trier, Raunheim), higher peak flow rates and lower base flow rates are expected, without shifts in the timing of the peaks. In the Lower Rhine River, a combined behavior is expected, with a rainfall-peak in the winter, a smaller snowmelt-peak in summer, and higher peak flow rates and lower base flow rates. At Bonn, the winter mean monthly discharge may increase 15-50%, while summer mean monthly discharge may decrease 0-40% (Gorgen, 2010; Hegnauer, 2017).

A river tends to equilibrium channel characteristics, eventually attained if the controls do not change, or do so at low rates (Blom et al., 2017). The equilibrium bed profile can be decomposed in a mean bed profile, and fluctuations about it. The mean bed profile depends on the combination magnitude-frequency of flow events (the flow duration curve), while the order of flow events determines the fluctuations (Arkesteijn et al., 2019). Channel response is inseparable from discharge variability, and more information on discharge variability than mean monthly discharge is needed as an upstream flow boundary condition.

Gorgen (2010) provides an ensemble of synthetic daily discharge time series covering the period 1951-2100, and Hegnauer (2017) provides 50-year synthetic daily discharge time series representative of the period 1951-2006, 2050, and 2085. We propose to use these data to create create simplified hydrographs, which sufficiently preserve discharge variability, while ensuring that the only difference between sce-

*Corresponding author

Email address: c.yllaarbos@tudelft.nl (Clàudia Ylla Arbós)

URL: www.tudelft.nl (Clàudia Ylla Arbós)

narios is the climate signal, facilitating comparison between scenarios. A base-case, cycled 10-year hydrograph with similar statistical properties as the long-term historic time series, can be modified for each climate scenario, such that the future hydrographs have the same statistical properties as the synthetic hydrographs provided by Gorgen (2010); Hegnauer (2017), but keep the the order of flow events unchanged. From the synthetic hydrographs, the probability density function of water discharge for each scenario S_i can be obtained, providing the discharge associated to a certain probability of occurrence p, that is, $Q_{S_i}(p)$ (Figure 1a). The same exercise can be done with the base-case hydrograph, so as to obtain $Q_0(p)$. Each flow event in the base-case hydrograph can then be related to a probability of occurrence p, and further multiplied by the factor $F_{S_i}(p)$=$Q_{S_i}(p)/Q_0(p)$ (Figure 1b). The effect of the hydrograph cycled period can then be assessed. Further research is needed to validate this method.

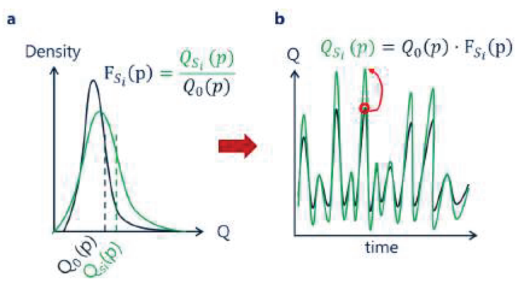

Figure 1: (a) Statistics of water discharge in the base case, and scenario S_i; (b) simplified hydrograph in the base case and in scenario S_i.

Changes in sea level

Climate scenarios foresee an increase of sea level between 0.2 and 3 m by the end of the century (Haasnoot et al., 2018). In all scenarios, sea level rise accelerates with time (up to 7 cm/a) when compared to the current rates of 0.2 cm/a. The increase in sea level has to be translated into the corresponding increase of water surface elevation at Gorinchem, the downstream boundary of our domain of interest. As an indication, an increase of sea level of 3 m at Hoek van Holland, would result into a water level increase of 2.75 m at Gorinchem, considering a water discharge of 2200 m^3/s, and based on hydrodynamic computations only (Haasnoot et al., 2018).

An increase in base level is expected to trigger a morphodynamic response towards a new equilibrium state, which consists of an increase of bed level equal to the total rise of sea level. Due to the sand deficit in the Lower Rhine-Meuse Delta (Cox et al., 2020), bed level cannot keep pace with sea level rise. Further analysis will provide insight on how the water level at Gorinchem will be affected by sea level rise.

Discussion and conclusions

Climate change affects the boundary conditions of the Lower Rhine River, which may affect future channel response. We have discussed foreseen changes in the hydrodynamic river controls. In addition, scenarios for changes in the sediment flux are required, based on changes in the hydrograph, and land-use changes. The high degree of uncertainty related to climate projections calls for a statistical or a scenario approach.

Changes in future intervention policy may have a greater effect on channel response than climate change. Modeling of channel response must consider intervention scenarios. A comparison between climate-triggered response and intervention-triggred response will shed light on the relative importance of natural versus human controls on channel response.

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