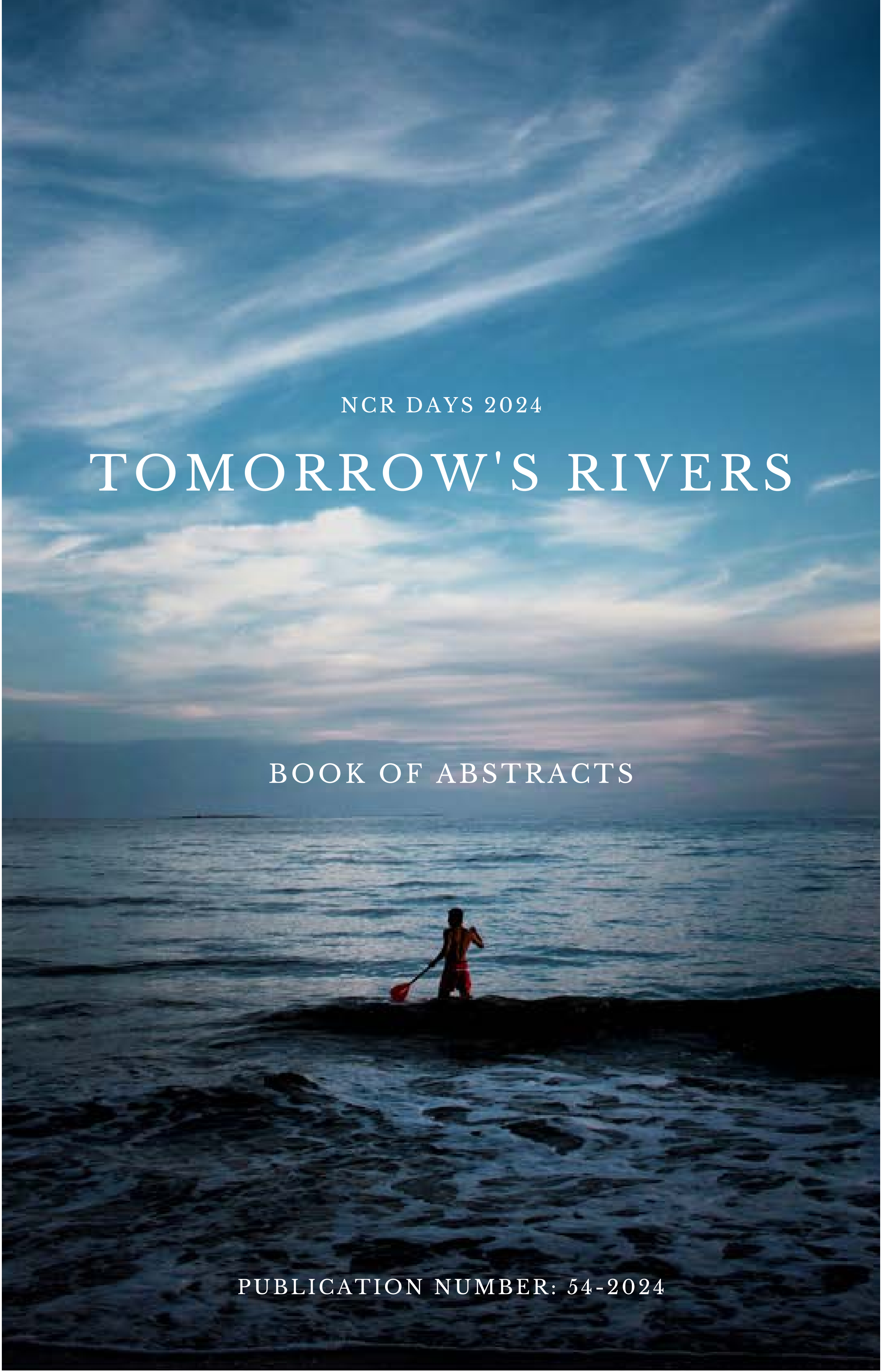

NCR DAYS 2024

TOMORROW'S RIVERS

BOOK OF ABSTRACTS

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NCR DAYS 2024

Tomorrow's Rivers

Niesten, I, Tahsin, N, van Grootheest, D., Barneveld, H., Waldschläger, K. and Hoitink, T.

Organising partner:

Sponsored by:

Conference venue
Wageningen University and research
Gaia (Building number 101)
Droevendaalsesteeg 3
Gebouw 101
6708 PB Wageningen
The Netherlands

telephone: +31 31 748 17 00
e-mail: ncrdays2024@wur.nl
www: https://ood.wur.nl/building/gaia/

Contact NCR
dr. ir. K.D. Berends (Programme Secretary)
Netherlands Centre for River Studies
c/o Deltares
Boussinesqweg 1, 2629 HV Delft
P.O. Box 177, 2600 MH Delft
The Netherlands

telephone: +31 6 21 28 74 61
e-mail: secretary@ncr-web.org
www: http://www.ncr-web.org

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Preface

Welcome to the 25th edition of the NCR Days, the annual meeting of the Netherlands Centre for River studies (NCR). This year, the NCR Days are hosted by Wageningen University and Research, and has the theme Tomorrow's Rivers. The theme is inspired by the project Rivers2Morrow, which is a central NCR project where all partners participate. NCR partners are united to prepare for the effects of land use and climate change on the river landscape, which requires the joint effort of scientists, engineers, and practitioners.

Four of the six session topics this year can be considered traditional: river restoration and nature-based solutions, short- and longterm morphdynamics, modelling and monitoring, and integrated river management. Then we have the topic 'transport of sediment and plastics', which welcomes contributions from the growing research community focusing on micro and macro plastics. Finally, we have contributions on the physics of estuaries, where we stretch the NCR focus area towards the coast. We hope the new topics in NCR are here to stay.

We have found four keynote speakers to be willing and able to envision Tomorrow's Rivers from various perspectives. Ir. Tim van Hattum from Wageningen Environmental Research will set out his keynote around the central question: "How can decision- and policy-makers inspire and be inspired to lead the transformation towards a nature-based future?" Prof. Frans Klein from Deltares and TU Delft dispraises an over simplified engineering perspective on river management, and calls for a geo-ecosystem perspective on river management in which hydraulic, morphological and ecological feedbacks are addressed. Dr. Anne van Loon from VU Amsterdam offers a plea for a socio-hydrological approach to managing the river system, which is needed to cope with extremes. The NCR Days will be closed by Dr. Alessandra Crosato from IHE Delft, who will summarize the main factors governing river morphology, and explore how rivers may adapt to climate change.

As a local organizing committee, we are happy that our meeting will be fully in person. We thank the NCR Program Secretary Anna van den Hoek and Koen Berends for their support during preparations. The NCR Days are financially supported by the Netherlands Organization for Scientific Research (NWO).

We wish you a very pleasant stay in Wageningen!

Iris Niesten, Nazwa Tahsin, Derk van Grootheest, Hermjan Barneveld, Kryss Waldschläger and Ton Hoitink

Wageningen, February 2024

Conference details

Organising partner

Organizing partner of the 2022 edition of the NCR Days is Wageningen University and Research (WUR).

Venues

The conference venue is Gaia, one of the oldest buildings on the Wageningen campus. The building name 'Gaia' was named after the mythical Greek goddess of the earth, and is home to the Environmental Sciences group of Wageningen University and Research. For 105 years, Wageningen University and Research has been working on solutions to the major problems of the time. Since the establishment of the Rijks Hoogere Land-, Tuin- en Boschbouwschool in 1918, scientists and students have committed themselves to securing sufficient food for everyone. Now, 105 years later, Wageningen University and Research focuses on shaping a sustainable future, with research and education on climate, biodiversity, land use and circularity. This lustrum year, various activities and publications are all about the theme 'Shaping Sustainable Futures', which links closely to the theme of this year's NCR Days: 'Tomorrows rivers'.

Local organising committee (LOC)

The LOC consists of the following members: Iris Niesten, Ton Hoitink, Kryss Waldschläger, Hermjan Barneveld, Derk van Grootheest and Nazwa Tahsin.

Program

Day 1

	Day 1 - Wednesday 28 February 2024	
	08:45 - 09:15	Registration, welcome & coffee
	09:15 - 09:25	**Opening of the 26th edition of the NCR days**
	09:25 - 10:05	**Tim van Hattum | Keynote Lecture**
	10:05 - 10:20	**Poster pitches**
	10:20 - 10:50	Poster session 1
Session 1	**River restoration and nature-based solutions**	
	10:50 - 11:50	**Haydar Hussin** *GIS web application for sustainable dike reinforcement solutions using nearby floodplains* **Amber Spriggs** *Evaluating the impact of Room for the River flood management measures on vegetation health and diversity in the Netherlands via optical remote sensing* **Anouk Boon** *Hydrodynamic modelling of habitat availability in the Common Meuse* **Jelle Dercksen** *Flow-induced fragmentation and mixing of eDNA for river biodiversity assessment*
	11:50 - 13:20	Lunch & Lab Tour
	13:20 - 14:00	**Frans Klijn | Keynote Lecture**
Session 2	**Short- and long-term river morphodynamics**	
	14:00 - 15:00	**Niguse Abebe Hagos** *Exploring anthropogenic impacts on channel morphodynamics (Methodology)* **Hermjan Barneveld** *A Sediment Budget for the Dutch part of the Meuse River* **Claudia Ylla Arbos**

		Mitigation of Channel Bed Erosion through Floodplain Lowering and Nourishments **Judith Zomer** *The morphodynamics of multiscale dunes in the Waal River*
	15:00 - 15:30	Poster Session
Session 3	**Transport of sediment and plastic**	
	15:30 - 16:30	**Frans Buschman** *A source-to-sea approach to evaluate policy measures that aim to reduce macroplastic transport in Dutch rivers* **Jana Cox** *Exploring the mechanisms that govern the spatial and temporal trends of suspended sediment in the Rhine basin* **Jiaqi Liu** *Approaches reproducing suspended sediment transport through vegetation* **Antonio Magherini** *Accumulation of floating particles at hydraulic structures*
	16:30	Drinks & Bites*
	16:30-18:30	**NCR Board Meeting**
	18:30 - ?	Conference Dinner & Pubquiz by YNCR

Posters Day 1	
Jasper Candel	*Roman-aged counterpoint deposition in the Waal River near Nijmegen*
Patit Chotemankongsin	*Nature-based solutions for flood and drought protection: Comparison between Thailand and Western Europe*
Daan Eldering	*Sorting out sediments: trends in the 2021 flood deposition of the Meuse, Rur and Geul*
Kshitiz Gautam	*Flow partitioning between branches of the Karnali river in Nepal*
Derk Grootheest, van	*Towards understanding the physics of biofouled microplastics transport in rivers*
Lieke Haastrecht, van	*Morphological development of the Vecht river due to changes in the weir policy*
Rahel Hauk	*Plastic transport dynamics revealed through flood induced buttertub spill*
Eki Liptiay	*A Field Study on Groyne Field Nourishments*

Marthe Oldenhof	*Understanding the long-term dynamics of scour holes in lowland rivers*
Ferdinand Pendula	*Gelderse Poort: A nature-based solution for conservation and flood protection*
Paolo Scussolini	*Can we attribute river flood events?*
Menno Straatsma	*Superposition of large interventions and succession*

Day 2

	Day 2 - Thursday 29 February 2024	
	08:30 - 09:00	Registration, welcome & coffee
Session 4	**Integrated river management**	
	09:00 - 10:00	**Jantsje van Loon** *Room for small rivers* **Roel Velner** *Update of the Dutch Major Rivers Policy (Bgr)* **Evelien van Eijsbergen** *Long-term development of lowland rivers Rivers2Morrow - a research program* **Yvo Snoek** *ResiRiver - Mainstreaming and Upscaling Nature Based Solutions in North West European Rivers*
	10:00 - 10:40	**Anne van Loon | Keynote Lecture**
	10:40 - 11:00	Poster Pitches
	11:00 - 11:30	Poster session
Session 5	**Physics of estuaries**	
	11:30 - 12:30	**Robert-Jan den Haan** *Using an idealized network model as the physical module for a salt intrusion serious game* **Sem Geerts** *Estuarine sand dunes as a nature-based solution against salt intrusion* **Iris Niesten** *Asymmetric mixing as a driver of residual sediment transport in an estuarine channel* **Eise Nota**

		Experimental assessment of topographic forcing in sandy estuaries
	12:30 - 14:00	Lunch + Lab Tour
Session 6	**Modelling and monitoring**	
	14:00 - 15:00	**Parisa Khorsandi** *Improving mesh set-up to increase accuracy of discharge capacity representation for water level prediction* **Leon Besseling** *Fast computation of dike breach growth and outflow* **Victor Chavarrias** *Challenges in numerical modelling of bifurcations* **Robert Groenewege** *Rapid simulation and assessment of the Derna (Libya) dam failures*
	15:00 - 15:30	Poster session
	15:30 - 16:10	**Alessandra Crosato | Keynote Lecture**
	16:10 - 16:30	Ton Hoitink | Closing remarks
	16:30	Drinks and awards

Posters Day 2	
Hermjan Barneveld	*Accuracy of Numerical Morphological Models based on Simplified Hydrodynamics*
Kifayath Chowdhury	*Developing a Model to Study the Climate Change Impact on River Bifurcations in Engineered Rivers*
Joshua Climo	*Investigating drivers of the ecological functioning of the Common Meuse*
Temma Fujii	*Reevaluation of the Japanese traditional river training structure "Seigyu"*
Nabil Khorchani	*Hydrodynamic modelling of Wadi flash flood in arid regions*
Luuk Laar, van	*Short-term bed level predictions for the Waal River: a machine learning approach*
Anna Loboda	*The influence of vegetation occurrence on water levels*
Paran Pourteimouri	*Developing an integrated assessment model for salt intrusion mitigation measures in delta systems*
Eleonora Saccon	*Do we really have the right tree in our freshwater floodplain forests?*

Job Thijssen	*The effects of river re-meandering on flood extent and inundation depth in the Geul river catchment*
Mo Wannasin	*How accurately can we model estuarine salt intrusion in the Rhine-Meuse Delta?*
Niels Welsch	*Action perspectives on climate extremes in the Dutch river system: system-level impacts and mitigation strategies*

KEYNOTE SPEAKERS

Healthy rivers at the heart of a nature-based future for The Netherlands and Europe in 2120

Tim van Hattum[a*]
[a] Wageningen University & Research, Wageningen Environmental Research, *P.O. Box 47, 6700AA, Wageningen, the Netherlands*

Keywords — nature-based solutions, climate adaptation, long-term visions

Introduction

Climate change and biodiversity loss are the most important global crises of our time, and will be for future generations. Both challenges are already causing social, ecological and economic disruptions around the world.[i] Failing to act will increase human vulnerability, inequality, poverty, food insecurity, involuntary displacement and political instability and conflict. However, it is not too late to act. If society as a whole turns insights into committed action, we still can turn the tide.

A healthy biosphere should be at the core of achieving a sustainable, resilient and liveable future for all as visualised by the SDG Wedding cake.

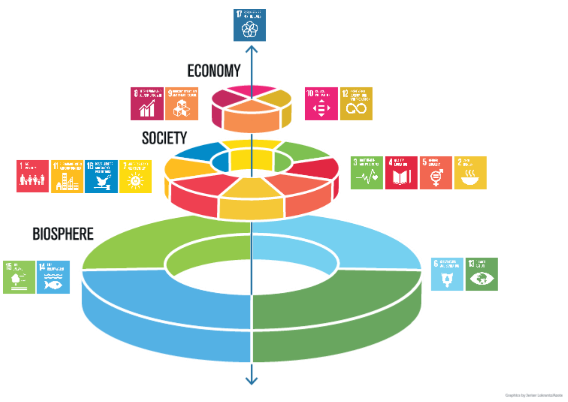


Figure 1 Wedding Cake illustrates the interconnectedness and importance of social, economic and ecological systems to achieving the SDG's (Source: Stockholm Resilience Centre)

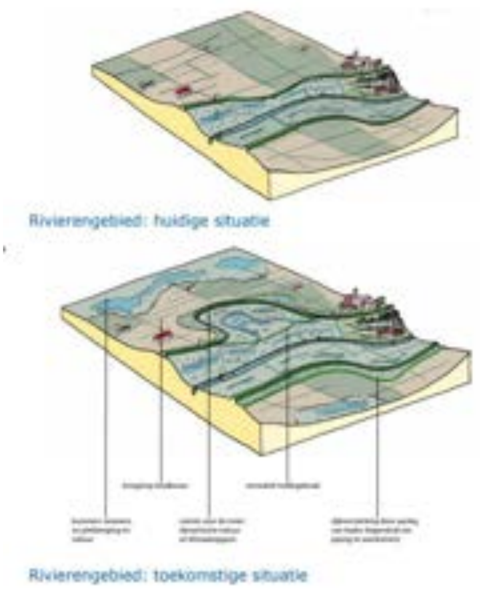
Nature-based Solutions (NBS) play a vital role in achieving a healthy biosphere and have the potential to address multiple global sustainable development challenges simultaneously. The European Commission defines nature-based solutions as: "Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions". Scientific evidence supports NBS as promising climate solutions that contribute to climate mitigation, climate adaption and biodiversity conservation. Additionally, NBS offer significant societal benefits, ranging from environmental and socio-economic improvements to well-being and health. Many NBS have demonstrated cost-effectiveness, resilience and adaptability, making them suitable for large-scale combined implementation. Despite the growing awareness and evidence for the potential benefits of NBS globally, including in Europe, actual implementation of NBS and financial support lag behind.[ii]

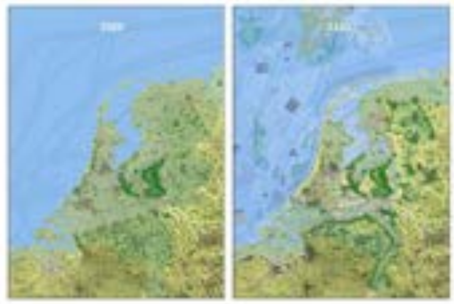
Achieving sustainability and building resilience under climate change requires transformative and multi-scale visions, which stimulate coherent thinking and action towards profoundly different future scenarios. Long-term visions are important tools for guiding long-term change on the way to increased sustainability, aiding in the reconciliation of diverse societies. However, they remain insufficiently employed within scientific and policy discussions.[iii] This presents a serious obstacle as we require widespread engagement and commitment from society to in order to tackle these major crises. Everybody must be actively involved. This leads us to a crucial question: how can decision- and policy-makers at European, national and regional landscape levels inspire and be inspired to lead the transformation towards a nature-based future?

We firmly believe that imagining nature-positive futures can be a powerful inspirational tool to bridge the gap between urgency, awareness and required actions. Generating shared European visions at various scales, could provide inspiration and an overarching direction while engaging diverse audiences and raising environmental awareness and stewardship.[iv] These narratives should offer room for imagining more desirable collective futures and provide actionable pathways to achieve them.[v]

Imagining nature-based futures

In 2019 Wageningen University & Research developed an integrated long term vision for a nature-based future for The Netherlands in 2120.[vi] The Netherlands faces major challenges: the energy transition, transition towards a sustainable food system, nature restoration, urbanisation and climate adaptation. Major changes are needed to cope with rising sea levels, increasing floods risk by extreme weather events, an increasing demand for food production and a need to reduce greenhouse gas emissions. It is inevitable that the Netherlands will look very different in a hundred years. An integrated long term vision for the future of The Netherlands is required for short term decision making. WUR experts aimed to highlight the importance of a healthy biosphere for the future of The Netherlands by visualising a nature-based future for their country. Healthy waters and NBS were at the heart of this vision, which was presented as a new map of the Netherlands with more room for healthy waters and nature, with regenerative agriculture, green cities, renewable energy and a circular bio-based economy that results in a genuinely nature-inclusive and sustainable society.





The science-based narrative generated significant attention in the Dutch media and this vision has been discussed and further developed with and by many stakeholders such as ministries, provincial authorities, water authorities, municipalities, NGOs and businesses. It empowered and inspired many regions to further develop this vision together with local stakeholders leading to concrete actions supported by substantial government funding. In the context of the alarming news about climate and biodiversity, this vision NL2120 created a sense of hope for the future. It inspired policy-makers and citizens and helped to create awareness for the importance of restoring nature and nature-based solutions as an essential part of a liveable future.

It also raised the question about whether we also can imagine a nature-based future for Europe? In September 2023 Wageningen University & Research presented a nature-based vision for Europe in 2120, again with a central role for healthy waters and soils and resilient landscapes.[vii] This vision for a nature-based future for Europe was co-designed by an international community of students and researchers at Wageningen University & Research. Not as blueprint or to predict the future, but to inspire and instigate further discussion about the future we desire and how to make this journey together. It could be seen as a first step towards a Europe-wide process of co-designing nature-based futures in European regions, while at the same time accelerating local and regional actions.

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[iv] Lubker et al. (2023). Imagining sustainable futures for the high seas by combining the power of computation and narrative. Nature Ocean Sustainability, Vol. 2, 2023
[v] Guardian (2023). Why we need new stories on climate. Article
[vi] Baptist & Hattum et al. (2019). A nature-based future for The Netherland in 2120
[vii] Hattum et al. (2023). Imagining a nature-based future for Europe in 2120. Nature-based solutions at the heart of a visionary and landscape-based approach for accelerating the transition to a climate resilient and nature-positive future. Mansholt lecture. Wageningen University & Research.

Towards a robust and well-functioning Rhine River system that can sustainably provide its geo-ecosystem services

Frans Klijn[a,b]
[a]*Deltares, P.O. Box 177, NL 2600 MH Delft*
[b]*Delft University of Technology, department TPM, Jaffalaan 5, NL 2628 BX Delft*

Keywords — Robustness, Discharge capacity, Transformation

The context

The policy programme Integrated River Management (IRM) aims to anticipate climate change and to redress the negative consequences of earlier river engineering interventions. Its objective is to first and foremost ensure a well-functioning river system that can provide its essential ‘public’ geo-ecosystem services: safe discharge of floods, reliable freshwater supply, reliable waterways to the hinterland, and good conditions for aquatic and terrestrial ecosystems in the floodplains and beyond. Challenges, however, relate to the changing discharge regime resulting from climate change, and to the conflicting requirements of the various river functions and values. These pose real dilemmas about when to act, how to act, which function or value to support and which one to curb.

A geo-ecosystem perspective

The reflection on the current state of our rivers (Klijn et al., 2022) revealed a number of worrying developments, partly caused by earlier engineering interventions and due to neglected feedback mechanisms, which now make things hard to control. Examples are the unequal scouring of the river bed in the upstream stretches of the various Rhine branches, the sedimentation on the floodplains, and the well-known ‘levee effect’ that at the same time makes society more vulnerable to flooding and limits the possibilities to enlarge the discharge capacity of the river by realigning embankments. Understanding these feedbacks requires a systems approach, and the recognition of their nature – hydraulic, morphological and ecological – calls for a geo-ecosystem perspective, instead of a over-simplified engineering perspective.

Climate change and its consequences for the Rhine’s discharge regime

Every few years KNMI and Deltares translate the new IPCC climate scenarios into discharge scenarios for the rivers. The KNMI’23 scenarios have so-far only been translated into mean and low discharges, so for exterme high discharges we need to fall back on the KNMI’14 scenarios (Sperna Weiland et al., 2015). These revealed that floods will occur more frequently and that the Rhine River’s extreme discharge may increase with about 10-15% by 2100.

Safely discharging this extra discharge is one of the key challenges for IRM, which is complicated even further by the fact that this discharge can be distributed over three river branches and may have to be temporarily stored for some time when the sea level is already higher and discharge to the sea is hampered by prolonged northwesterly winds. The Expertise Network Flood Security (ENW) therefore recommended to investigate various discharge distributions, as this ultimately determines which portion of the extra discharge each Rhine Branch must be able to safely discharge in the future.

Reasons to reconsider the discharge distribution

Firstly, not every Rhine branch is equally long. And a longer route means less inclination, slower flow and higher flood levels.

Secondly, not each branch can be equally easily enlarged: the Nederrijn-Lek is narrow, crosses deep lowland peat areas and has hardly any floodplains in the most western stretches. This was reason for the government to decide to not further load this branch into the future after having increased the discharge capacity to 16.000 m^3s^{-1} by making Room-for-the-River.

By looking at the behaviour of the water levels in the three branches at various discharges, we also ascertained that the Waal branch is kind of ‘hyperventilating’, whereas the IJssel branch breathes quietly (Klijn et al., 2019). Reason is that we squeeze a relatively large proportion of the discharge through the Waal. This ‘breathing behaviour‘ made us hypothesize that it could be a good metric to express a river’s robustness: (absence of) sensitivity to uncertainties and/or increasing discharges.

And related to this, it was established that this distribution can only be delivered by strong control of the distribution at the junctions by maintaining artificial bottlenecks (Fig. 1), which is reflected by the different water level slopes of the branches at the junctions (Fig. 2). Whereas, according to Kleinhans et al. (2013), the natural tendency of the river would be an avulsion.

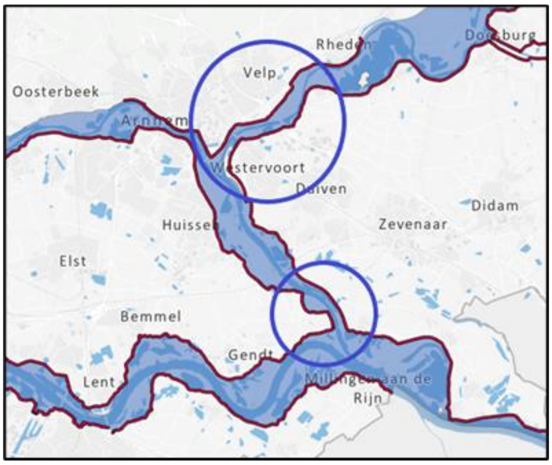

Figure 1. The artificial bottlenecks needed to ensure that the discharge distribution of the three Rhine branches at 16.000 m^3s^{-1} meets the requirements of the policy decision

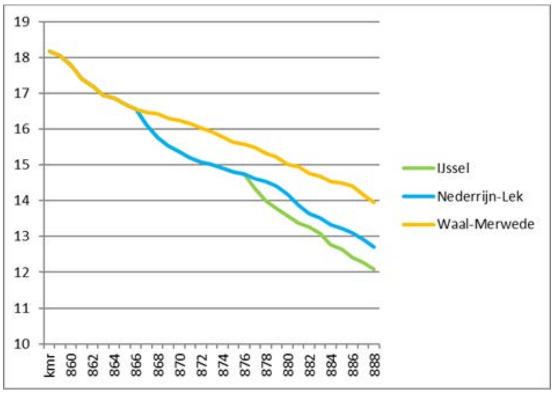

Figure 2. Slope of the water level in the three Rhine branches at the junctions at 16.250 m^3/s^{-1}, reflecting the bottlenecks

Postponing a policy decision about by which route to sluice the increase in extreme Rhine River discharges towards the sea requires that space must be earmarked for possible future interventions (e.g. by so-called Barro reservations) along each Rhine branch. That would impede further spatial development. Therefore, the ministry has now commissioned a policy analysis into the desired flood discharge distribution for the far future, because of the path-dependency of decisions to be made. '*Better narrow down the spatial options to further explore sooner than later*'.

Criteria to consider and past proposals

Criteria for this policy analysis encompasses, among other things, the flood vulnerability of the protected areas along the branches, the respective storage capacity of the IJsselmeer and Rhine-Meuse estuary, and the possibilities to increase the discharge capacity by means that would also benefit other policy objectives, such as biodiversity (Klijn et al, 2002).

* Corresponding author
frans.klijn@deltares.nl

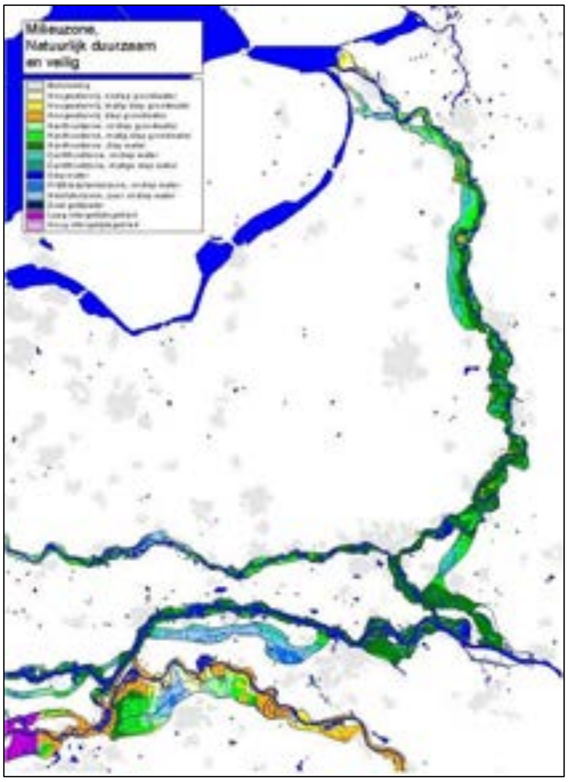

Figure 3. A proposal to enhance the discharge capacity of both Waal and IJssel that benefits typical river ecosystems and their diversity at the national scale (Klijn et al., 2002)

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Managing river extremes in connected hydro-social systems

Anne F. van Loon[a]
[a]*Institute for environmental studies (IVM), Vrije Universiteit Amsterdam*

Keywords — Hydrological extremes, droughts

Rivers flows are the result of a myriad of hydrological and anthropogenic processes. To predict and manage future river flows, we need to understand the interacting hydro-social processes. In this presentation, I will share a socio-hydrological view on river systems and specifically focus on extremes, e.g. streamflow droughts. During dry periods, water inflows from upstream (mountain snow and glaciers) and underground (groundwater) are crucial. In recent studies, we investigated the contribution of snow and ice to downstream flows during drought and found that snowmelt droughts are increasing in frequency and the compensating effect of glaciers downstream is limited. We also found a strong effect of human influences such as groundwater abstraction and reservoir operation, despite active river management (e.g. environmental flow requirements). Nature-based solutions and small-scale technical interventions could potentially compensate for the decrease in water storage due to glacier / snowmelt and water abstraction, but care is needed in designing these in a holistic way and taking into account the unintended consequences during wet periods. In the presentation, I will discuss how future river management could become more prospective.

Figure 1: Low water levels at the Waal near Nijmegen. Photo © Ronald Puma.

* Corresponding author
Email address: anne.van.loon@vu.nl

On the factors governing river morphology with a look on how rivers adapt to climate

Alessandra Crosato[a,b]
[a]IHE Delft Institute for Water Education, Department of Water Resources and Ecosystems, Westvest 7, 2611 AX Delft, the Netherlands
[b]Delft University of Technology, Dept. of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Stevinweg 1, 2628 CN Delft, the Netherlands

Keywords — River morphology, channel width, adaptation to climate

Introduction

River morphology can be described at different scales: at the basin scale we distinguish the river network; at the reach scale the planform, the slope and average features, such as the width and bankfull water depth; at the cross-section scale the transverse variations of river bed topography; and at smaller scales we observe bedforms and sediment grains. What are the factors that influence the river mophology at the different scales? Does climate govern these factors and if climate changes, how does the river react?
This review addresses these important questions, focusing at the reach and cross-section scales. Important knowledge gaps are related to the channel width formation, a key factor for river morphology. Several predictors based on field data relate the equilibrium width to bankfull discharge, sediment size, vegetation and bank resistance. However, it is not clear if the river width also depends on the conditions at the start of the morphological process. An example are rivers that adapt their morphology after their water and sediment discharge regimes have been altered by an external factor, such as a dam of a change in climate. Does the morphology of these rivers depend also on their previous width?

Theoretical background

Assuming morphodynamic equilibrium, the combination of water and sediment balances, momentum equation for water, and a sediment transport law allows deriving slope and average water depth of river reaches as a function of discharge Q_W, sediment transport rate Q_S, sediment size D_{50}, hydraulic roughness C (Chézy), and channel width B (Jansen et al., 1979). Applying Engelund and Hansen's (1967) formula (sand-bed rivers), the equilibrium slope i is given by:

$$i = K\left(\frac{1}{Q_W}\right)\left(\frac{Q_S^3 D_{50}^3 B^2}{C}\right)^{1/5} \qquad (1)$$

where coefficient K depends on gravity and the mass densities of water and sediment.

The value of longitudinal slope is often used to predict the channel planform, i.e. meandering (smaller than a threshold value), braiding or in between. Several empirical formulas have been derived based on field data (e.g. Leopold and Wolman, 1957). A physics-based approach considers the number of bars in the channel cross-section. Re-writing the formula of Crosato and Mosselman (2009), and assuming that central bars form the limit between meandering and braiding, it is possible to derive a threshold slope i_{cr}, in a way similar to other predictors:

$$i_{cr} = 11.75\left(\frac{h}{B}\right)^2\left(\frac{u}{\sqrt{gh}}\right)\left(\frac{C}{\sqrt{g}}\right)\sqrt{\Delta\frac{D_{50}}{h}} \qquad (2)$$

with h = water depth, u = flow velocity, g = acceleration due to gravity and Δ = relative sediment mass density under water. This relation extends Parker's (1976) predictor, who derived i_{cr} as a function of width-to-depth ratio and Froude number. Both approaches highlight the role of width-to-depth ratio and thus of the channel width, assumed known. Their application needs to be coupled to a width predictor, but existing ones perform poorly. Width predictors relate to bankfull conditions and have the general form:

$$B = f(Q_{W,}D_{50}) \qquad (3)$$

According to Parker et al. (2007) for sand-bed rivers the bankfull width increases if the discharge increases and decreases if sediment size increases.

Factors influencing the channel width

Riparian vegetation plays an important role in bank erosion and accretion. Its growth on river floodplains and emerging bars is able to reduce the river braiding degree and width (e.g. Crosato and Samir-Saleh, 2011). However, unvegetated bank material resistance has similar, even stronger, effects on river width (Fig. 1).

Figure 1. Channel development from straight in the laboratory with two different sediments: uniform sand (top) and poorly sorted sand behaving as cohesive at the flume scale (down).

In sand-bed rivers with vegetated floodplains, vegetation density strongly impacts the channel width (Fig. 2), whereas discharge rather affects the water depth (Crosato et al. 2022).

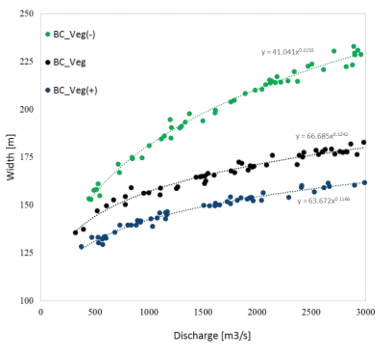

Figure 2. 2D Delft3D reproduction of Pilcomayo River. Channel width as a function of discharge and floodplain vegetation density (Grissetti-Vázquez, 2019).

Paudel et al. (2022) show that the final width of gravel bed rivers without floodplain vegetation hardly depends on initial channel width. It rather depends on boundary conditions, especially sediment input. During the transition period, however, the width is most of the time very different from the final one. With densely vegetated floodplains and a fixed amount of sediment input, instead, Munir et al. (2023) found a dependency on initial width. Possibly, for these systems the transition period is much longer than for rivers with unvegetated floodplains. In all other cases, different initial geometries lead to final widths having the same order of magnitude. The results of these studies only partly support the use of empirical formulas derived from natural rivers supposed in equilibrium, considering that with vegetated floodplains the transition period might be very long. Finally, Vargas-Luna et al. (2019) and Naito and Parker (2020) show that the formative discharge should not be derived from bankfull geometry, as it is rather a frequent flood.

* Corresponding author
Email address: a.crosato@un-ihe.org (A.Crosato)

Role of climate

Climate governs the river discharge regime, sediment input and riparian vegetation. Climate change has thus a strong influence on river morphology.

If the climate becomes warmer and wetter, we can expect higher discharges and vegetation density with less sediment input, and the river to become narrower, deeper with gentler slope and less bars, and a more sinuous planform.

If the climate becomes warmer but drier, we can expect lower discharge and vegetation density with higher sediment input, and the river to become wider, shallower, and steeper, with more bars and increased braiding degree.

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SESSION ONE

RIVER RESTORATION AND NATURE-BASED SOLUTIONS

GIS web application for sustainable dike reinforcement solutions using nearby floodplains

Haydar Hussin[a*], Thijs van Hofslot[a], Luke van Hout[a], Jan den Daas[b], Mathijs Bos[c], Maria Barciela Rial[b]
[a]*Van Hall Larenstein University of Applied Sciences, Larensteinselaan 26-A, 6882 CT Velp*
[b]*HAN University of Applied Sciences, Ruitenberglaan 26, 6826 CC Arnhem*
[c]*Waterschap Rivierenland, De Blomboogerd 1, 4003 BX Tiel*

Keywords — Dike reinforcement, soil, floodplain, GIS

Introduction

By the year 2050, it is projected that approximately 1,500 kilometres of dikes in the Netherlands will require reinforcement (Rijkswaterstaat, 2023). Regular maintenance and strengthening activities are conducted in river areas to ensure freshwater supply, navigability, nature development, recreation, raw material extraction, and most importantly, water safety. Climate change is predicted to intensify weather phenomena, leading to more extreme events (IPCC, 2021). For instance, in December 2021, a significant amount of precipitation was recorded in the border region of the Netherlands, Belgium, and Germany. This event resulted in the unfortunate loss of 238 lives and caused approximately 38 billion euros in damages, with 1.8 billion euros attributed to the region of Limburg (NOS, 2021). Such intense periods of precipitation are expected to increase the peak discharge in rivers, potentially leading to more frequent dike breaches or river discharges if appropriate measures are not implemented (Dutch Water Authority, 2022).

Considering the substantial impact of human activities on the climate, it is crucial to adopt more sustainable practices in these works. The benefits of such practices include reduced CO2 emissions, minimized environmental nuisance, lesser impact on the landscape, and cost savings. Currently, land owned by the area is seldom utilized for dike strengthening. However, water boards are showing a preference for more circular and sustainable methods.

Currently, dike reinforcement in the Netherlands frequently utilizes non-local soil. To promote sustainability, there is a need for increased use of local land and improved collaboration among water boards for soil management. The water boards and other stakeholders require digital GIS platforms to map available land and dike projects, enabling automatic cost and emission calculations related to dike reinforcements.

The objective of this work is to develop an accessible, user-friendly application within the ArcGIS online environment that enables water boards to indicate land availability and excavation locations in and near the floodplains (Fig. 1) to reinforce dike sectors along the rivers. The application aims to utilize this data to identify the most sustainable and cost-effective soil movement strategies by linking extraction locations, land demand and transport routes to the dikes. This research is part of RAAK-publiek project Rivierwerken (Project nr.: RAAK.PUB09.018).

Figure 1. Previous development work conducted in the Heesseltsche Floodplain (River Waal), part of the study area within the research project.

Approach

Several waterboards and stakeholders, including Waterschap Rivierenland and Rijkswaterstaat were interviewed to determine the required datasets needed and to understand which outputs and visualizations are important to the possible end-users of the GIS platform. The location of available soil types and clay for reinforcement were an issue. Also locations for dike safety zonation and nature reserves were important factors to consider.

The datasets used were of three types: (1) the soil and subsurface layers; (2) location of the dikes needing to be reinforced and (3) geo-spatial information layers needed to determine the zones and areas to be excavated.

The GeoTOP 3D subsurface model was used (Endrizzi et al., 2014). This model shows the subsurface of the Netherlands up to a maximum of 50 meters below NAP in blocks of 100 x 100 x 0.5 meters. Each block provides information about the layer structure, soil type (sand, gravel, clay or peat) and lithological classes (Fig. 2).

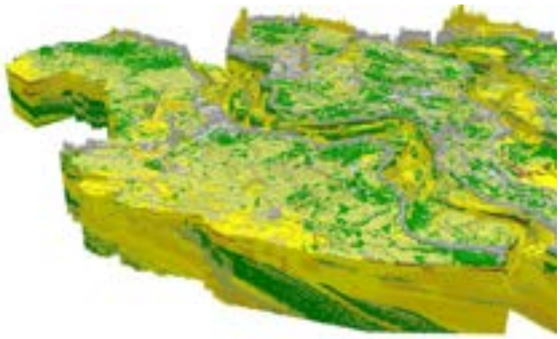

Figure 2. Example of the 3D GeoTOP subsurface Voxel model

The numerous floodplains were retrieved from the water boards and further adjusted according to latest GIS and remote sensing datasets. The excluded zones taken into consideration were nature reserves, residential areas, infrastructure and transport networks, cultural and archaeological sites among other important factors. Certain buffers up to 50 meters were excluded from these areas. The dike sectors were prioritized and mapped using the STBI stability testing criteria. Only the dikes classed 3 and above were considered to be reinforced with at least 20 m^3 per meter dike sector.

The site suitability of the foreland floodplains to be excavated was conducted in GIS. River groynes (kribben) were also included in this analysis and the dike safety zones were calculated in the forelands (floodplains) based on the risk of piping (Rijkswaterstaat, 2021). The Geotop model was then downscaled to 1 m resolution to calculate the soil type for each 0.5 m section below the surface down to a depth of 4 m. This resulted in 8 depth sections per square meter within the floodplain polygon locations (Fig 3) including the volume (m^3) of clay and other soil types.

Figure 3. One of the proposed areas of excavation within the floodplain of the River Waal showing the clay deposits from the surface to a depth of 0.5 m.

The resulting GIS web application developed highlights each floodplain areas with statistics on depth and volume information. The areas are further linked by a nearest routing network analysis to the closest dike sector needing to be reinforced based on its priority classification (Fig. 4).

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Figure 4. A first prototype of an ArcGIS Online web application linking soil excavation sites with dike sectors in the River Waal

* Corresponding author
Email address: haydar.hussin@hvhl.nl

Evaluating the impact of Room for the River flood management measures on vegetation health and diversity in the Netherlands via optical remote sensing

Amber Spriggs[a*], Erik Mosselman[ab], Ralph Schielen[ac], Laura Stancanelli[a]

[a] *Delft University of Technology, Department of River, Ports, and Dredging Engineering, Faculty of Hydraulic Engineering, Stevinweg 1, 2628 CN Delft, The Netherlands*

[b] *Deltares, P.O. Box 177 2600 MH Delft, The Netherlands*

[c] *Ministry of Infrastructure and Water Management (Rijkswaterstaat), P.O. Box 2232, 3500 GE Utrecht, The Netherlands*

Keywords — River restoration, remote sensing, GIS, biodiversity, Normalized Difference Vegetation Index (NDVI), vegetation classification

Introduction

Recent policy initiatives in Europe emphasize a movement towards nature-based solutions in flood management; however, a quantitative relationship between specific flood management measures and indicators of ecological health and biodiversity is difficult to establish (Penning et al., 2023). In the Netherlands, several studies have been conducted on floodplain vegetation monitoring; however, these studies are primarily focused on monitoring changes to hydraulic roughness for flood risk assessment (Harezlak et al., 2020; Penning & van de Vries, 2020). These works provide an opportunity to expand upon existing research to explicitly connect river management practices with indicators of floodplain biodiversity change in the Netherlands.

In this study, we utilize publicly available geospatial data to identify changes in land use, vegetation classification and spectral indicators of vegetation health at restoration sites associated with the Room for the River (RftR) program in the Netherlands. Completed in 2018, RftR involved over 30 river management projects constructed to reduce flood risk by lowering peak water levels (Mosselman, 2022).

Our objective is to quantify the impact of ecologically focused RftR projects on habitat heterogeneity and river connectivity in the surrounding floodplains.

Study Area

To first establish a methodology for quantifying the connection between Room for the River measures and changes to ecological health, we examined a case study site of the Noordwaard depoldering project near the Biesbosch National Park.

Completed in 2015, the depoldering of the Noordwaard is one of the largest Room for the River projects and resulted in a significant transition from agricultural to natural land-uses.

Figure 1. Depoldered area, Noordwaard near Werkendam, the Netherlands.

Methodology

To quantify the relationship between these land-use changes and floodplain ecological health, we:

1. Utilized the LGN (Landelijk Grondgebruiksbestand Nederland) datasets, a raster database with a resolution of 25 m (5 m resolution for LGN 2018 – 2022), to identify areas in the Noordwaard and its surroundings that have transitioned from agricultural to natural land-use classifications between 1995 and 2018.
2. Identified land-use changes within the areas labelled as "changed to natural" throughout the entire series of LGN datasets, to quantify incremental trends in vegetation heterogeneity.
3. Utilized satellite multispectral imagery from Landsat-8 with less

* Corresponding author
Email address: a.m.s.spriggs@tudelft.nl (Amber Spriggs)

than 20% cloud cover during the growing seasons of 2013 through 2022, cropped to the extent of the “changed to natural” areas. With this imagery, we calculated the Normalized Difference Vegetation Index (NDVI), which has correlation to photosynthetic activity and biomass (Suir and Sasser, 2019).

Preliminary Results

Between LGN3 (based on 1995 satellite and aerial imagery) and LGN 2018 (based on 2018 satellite and aerial imagery), we observed a transition from agricultural to natural land-use classifications within the study area, as shown in the dark green (“changed to natural”) areas of Figure 2. Areas newly classified as inundated with water in LGN 2018 (as compared with LGN3) are shown in the dark blue (“changed to water”) areas of Figure 2.

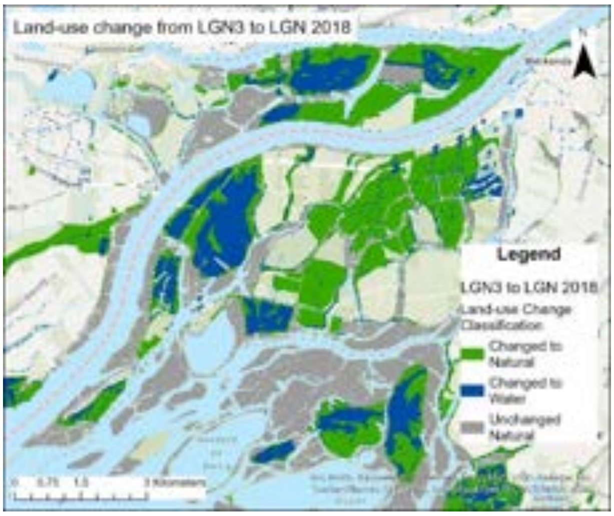

Figure 2. Land-use change at the Noordwaard depoldering project site and surrounding area, from LGN3 (1995) to LGN2018 (2018).

Within the areas designated here as “changed to natural”, we observed a general trend towards increased heterogeneity of the LGN classifications over time. For the averaged growing-season NDVI values from 2013 through 2022, we observed increased stability in NDVI fluctuations over time, with increased NDVI concentrated in the areas immediately surrounding the areas designated as “changed to water”. This underscores the importance of the vicinity of water for the natural terrestrial areas. Further analysis will incorporate more detailed information on management practices in the Noordwaard area, to validate the connection between these observations and construction of the depoldering project.

Future Work

Moving forward, we will expand this methodology to other RftR sites, connecting these changes with floodplain ecological health more broadly throughout the Netherlands.

We will utilize an application of graph theory, where different RftR project sites are considered as nodes, to compare impacts of different RftR projects on vegetation diversity changes, and to evaluate connectivity throughout the entire system.

Establishing remote-sensing based evaluation metrics to connect floodplain management practices and biodiversity changes can help inform more ecology-focused floodplain management practices and enhance site selection for future applications of RftR-type flood management programs in the Netherlands and abroad.

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Hydrodynamic modelling of habitat availability in the Common Meuse

Anouk Boon[1*], Callum Blacow[1], Maarten G. Kleinhans[1] and Menno W. Straatsma[1]
[1] Utrecht University, Department of Physical Geography, Faculty of Geosciences, PO BOX 80125. 3508 TC, Utrecht, the Netherlands

Keywords — Morphodynamics, Fluvial ecology, Habitat availability

Introduction

Macrofauna in gravel bed rivers live in a morphologically dynamic environment that is challenging, especially when human influence worsens the living conditions (Salmaso et al., 2021). The Common Meuse is one of the most natural rivers in the Netherlands, but also heavily engineered to maintain the border, water quality and flood safety. Standards for aquatic biodiversity set for the European 'Natura 2000' protected natural areas are not met. The hypothesised cause is the lack of available suitable habitat, due to strong armouring of the river bed, bank protection, colmation and hydropeaking (Salmaso, 2021). To come to biodiversity enhancing morphological management measures, we need insight into the habitat availability in the Common Meuse. We aimed to calculate (1) suitable habitat areas of five macrofauna target species with respect to flow velocity and water depth and (2) the grain mobilisation over the 2019 growing season.

Methods

We used the Delft3D Flexible Mesh model with the j19 schematisation between the upstream weir at Borgharen and the downstream weir at Linne. A model run was performed for the months June and July, which form the growing season of the targeted macrofauna. During this period, frequent hydropeaking occurred (see Fig. 1).

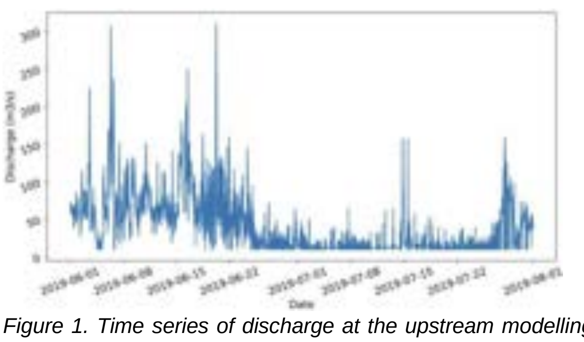

Figure 1. Time series of discharge at the upstream modelling boundary, the weir at Borgharen (The Netherlands).

Postprocessing of the model output was done using the Xugrid package in Python. We selected five species that are representative for either occurring or targeted macrofauna species in the Common Meuse reach (Caenis Luctuosa, Chironomus Riparius, Ephemera Danica, Hydropsyche Contubernalis and Nemoura Avicularis). Suitable and unsuitable areas were calculated based on the species' tolerance for water depth and flow velocity, as defined by the Werkgroep Ecologisch Waterbeheer (2019) (see Table 1). These variables can be integrated by considering the lowest value of the two by applying Liebig's Law of the minimum (Gorban et al., 2010). The analysis is done for both a relatively high (around 300 $m^3 s^{-1}$) and a low (around 20 $m^3 s^{-1}$) summer discharge.

Table 1. Habitat preferences of five macrofauna species for flow velocity and water depth (CL=Caenis Luctuosa, CR=Chironomus Riparius, ED=Ephemera Danica, HC=Hydropsyche contubernalis and NA=Nemoura Avicularis) (Werkgroep Ecologisch Waterbeheer, 2019). Scores of categories sum to 10 for every species.

Species	Flow velocity preference ($m s^{-1}$)				
	0.01-0.05	0.05-0.10	0.11-0.15	0.16-0.25	> 25
CL	3	3	2	1	1
CR	8	2	0	0	0
ED	0	1	2	3	4
HC	0	0	1	3	6
NA	1	2.7	2.7	1.8	1.8
Species	Water depth preference (m)				
	0.01-0.05	0.05-0.5	0.5-5	5-10	> 10
CL	1.4	3.3	0	5.3	0
CR	5	5	0	0	0
ED	0	10	0	0	0
HC	0	3.8	6.2	0	0
NA	10	0	0	0	0

Grain mobilisation was calculated based on the Shields number and the modelled shear stress as described in Eq. (1):

$$D = \frac{\tau}{\rho_s - \rho_w} * g * \theta_s \qquad (1)$$

where D = grain mobilisation size, τ = shear stress, ρ_s = density of sediment (2650 kg m^{-3}), ρ_w = density of water (1000 kg m^{-3}), g = gravitational force (9.81 m s^{-2}) and θ_s = 0.03.

Results

The flow velocities (Fig. 2) of the 5^{th} and 95^{th} percentiles were 0.014 and 1 m s^{-1}, respectively. The full range of defined preference classes is thus covered (see Table 1). For the water depth, the 5^{th} and 95^{th} percentile values lie at 0.26 and 25.9 m. With this, the shallowest class of water depth is missed. The median grainsize of 32 mm could be mobilised in a small part (0.33 km^2) of the modelled area during the higher discharge conditions.

The calculated suitable areas are displayed in Fig. 3. For most species, more habitat with suitable flow velocities became available during the higher discharge conditions. The water depth was more limiting for the amount of available living area than the flow velocity for four out of five species. No suitable habitat was found for the Nemoura Avicularis based on the water depth. The largest amount of suitable area was available for the Hydropsyche Contubernalis.

Figure 2. Excerpt of the model domain with flow velocities during low discharge conditions (around 20 m^3 s^{-1}).

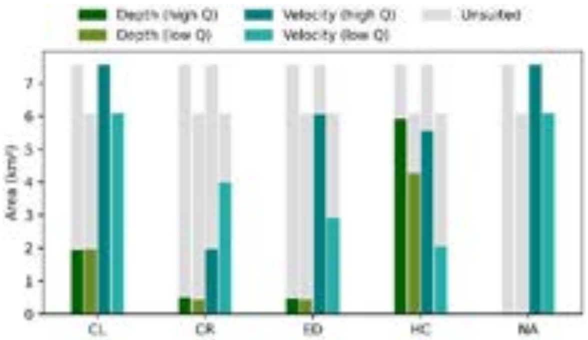

Figure 3. Sum of the areas with suitable ecological conditions based on either water depth or flow velocity for five selected species (CL=Caenis Luctuosa, CR=Chironomus Riparius, ED=Ephemera Danica, HC=Hydropsyche Contubernalis and NA=Nemoura Avicularis). Dark colors depict the higher discharge conditions (around 300 m s^{-1}), light colors the lower discharge conditions (around 20 m s^{-1}).

Discussion

Habitat was not abundantly available for all targeted macrofauna species in the Common Meuse during the modelled growing season. Shallow flowing areas are highly ecologically relevant, but only available to a limited extent. The amount of habitat influenced by morphological change due to grain mobilisation is small, and therefore expected to have little effect on the macrofauna during the growing season.

An analysis of the entire hydrological year could give an overview of habitat availability during every phase of the life cycle of the macrofauna. The modelling outputs and estimated grain mobilisation can be made more robust by using new grain size data, that was recently sampled and analysed. We will furthermore improve the analysis on the effect of hydropeaking by collaborating with ecologists on the knowledge gap regarding coping strategies of macrofauna to increased discharges.

Variables additional to the water depth and flow velocity, like shear stress, could have an important effect on macrofauna (Lorenz & Wolter, 2019). The next steps comprise the combination of effects of the different variables to come to a realistic estimate of habitat availability. To this aim, we will undertake lab experiments with macrofauna in a flume and combine field measurements of macrofauna occurrence with the model output.

Conclusion

Areas of suitable habitat based on water depth and flow velocity were calculated for five indicative macrofauna species for both a relatively high and a low discharge. The amount of available habitat varied by species. It was found that shallow flowing areas were missing, which excluded one of the species. The water depth was often found to be more limiting than the flow velocity. To add other relevant variables and understand their integrated effect on the macrofauna, research consisting of detailed lab/field work is needed. Understanding the governing variables may help identify morphological management measures that enhance biodiversity in the Common Meuse.

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Flow-induced fragmentation and mixing of eDNA for river biodiversity assessment

Jelle A. Dercksen[a*], Laura Maria Stancanelli[a], Krijn B. Trimbos[b], Astrid Blom[a]
[a] Delft University of Technology, Dept. of Hydraulic Engineering, Stevinweg 1, 2628 CN, Delft, the Netherlands
[b]Leiden University, Institute of Environmental Sciences, P.O. Box 9518, 2300 RA, Leiden, the Netherlands

Keywords — environmental DNA, biomonitoring, fragmentation

Introduction

River restoration is an established method for the rehabilitation of river ecosystems in order to combat the current declines of freshwater biodiversity (Wohl et al., 2005; WWF, 2022). The urgency of restoration is recognized internationally, as the IUCN has proclaimed 2021-2030 to be the 'Decade on Ecosystem Restoration' (Cooke et al., 2022). So far only few restoration projects have been evaluated based on monitoring data (England et al., 2021), and there is a need for monitoring techniques to assess restoration practices.
The analysis of environmental DNA (eDNA) has gained popularity in the last decades, as it allows for rapid standardized biomonitoring across the tree of life, requires a reduced dependence on taxonomic expertise for species identification, and it is cheaper than traditional monitoring methods. Depending on the organism, eDNA is shed by its host in forms such as mucous, shed skin cells, and faeces. After release, eDNA is exposed to a wide spectrum of environmental variables that may impact its state, transport capacity, fate, and the subsequent inference made by the practitioner (Barnes and Turner, 2016). Our objective is to study how eDNA quantities are affected by flow and sediment transport in river ecosystems.

Methods

A set of laboratory eDNA concentration experiments was performed inside an annular flume (depth = 19.7 cm; Ø = 3.7 m) under different flow conditions (Fig. 1). The flume was filled with a mixture of potable water and effluent culturing water of wildtype *Danio rerio* (zebrafish) to introduce eDNA, which was subsequently rotated to induce a constant flow velocity. Each experimental run lasted for 168 hours, and was repeated for four rotation velocities. The flume was cleaned with bleach, and subsequently rinsed with potable water before each experimental run in

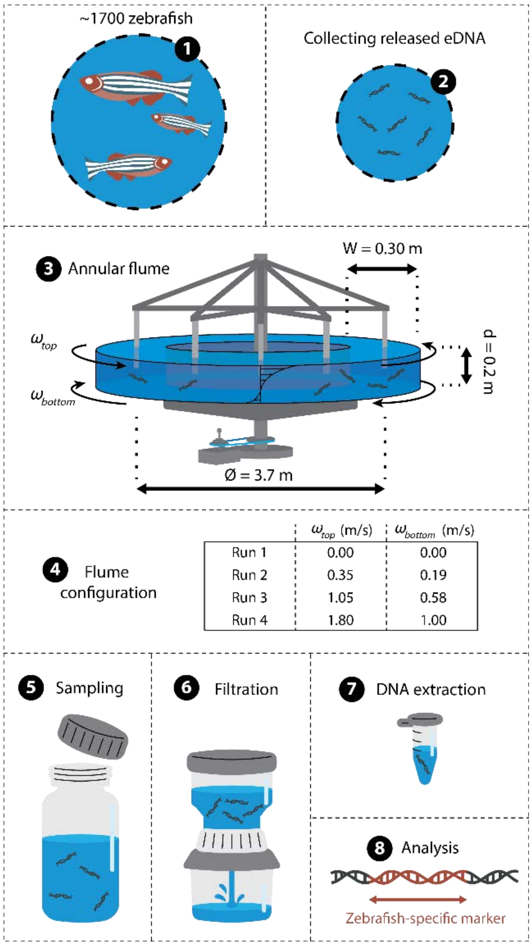

Figure 1. Schematized workflow followed through the set of laboratory experiments.

order to remove trace amounts of zebrafish DNA. Prior to the addition of eDNA, vertical flow velocity profiles were measured inside the tank using a Nortek Vectrino ADV. Sampling and filtration equipment, and worksurfaces used during the sampling procedure were cleaned with bleach, ethanol, and demineralized water. Water samples were collected at multiple time points in triplo during each experimental run. 300 ml of each water sample was immediately filtered on site (pore size = 1.2 µm). Filters were stored at -80 °C awaiting extraction to avoid sample decay. Samples were extracted using the DNA/RNA Mini Prep Plus Kit (Zymo Research, Irvine, CA),

* Corresponding author
Email address: j.a.dercksen@tudelft.nl (J.A. Dercksen)

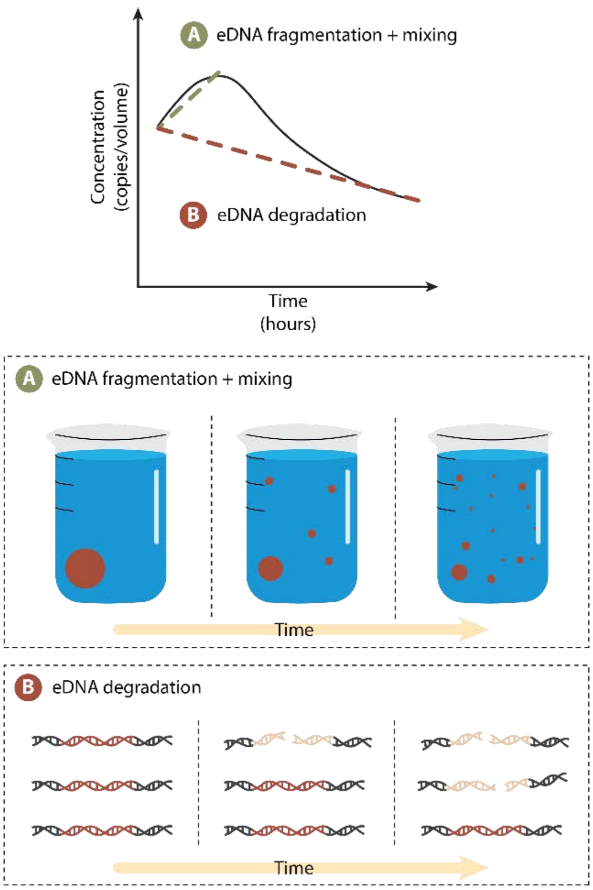

Figure 2. Schematized eDNA concentration over time, and the suggested mechanisms steering the trend.

following the extraction protocol as described in Marshall et al. (2021). eDNA concentrations were quantified in duplo by measuring copy numbers of a 73 base pair fragment on the cytochrome *c* oxidase I (COI) gene using a primer-probe assay designed by Zhao et al. (2021) and the QX200 Droplet Digital PCR (ddPCR) platform (Bio-Rad, Hercules, CA).

Results & discussion

Across all trials, the chosen COI marker consistently remained detectable throughout the entire experiment, with eDNA degradation rates notably lower than those typically observed in eDNA time-series data. In the absence of indicators of contamination, we attribute these low degradation rates to a combination of factors. Firstly, eDNA degradation rates increase exponentially with increasing fragment size (Jo, 2023). The selected DNA sequence of 73 base pairs is relatively short, with low degradation rates as a result. Secondly, the filters selected for eDNA larger than 1.2 µm. As a result, smaller-sized 'free' extracellular DNA particles, associated with high degradation rates, were discarded.
The low eDNA degradation rates allowed us to distinguish between two mechanisms that affect detectable eDNA quantities (Fig. 2): (A) particle fragmentation followed by mixing, and (B) eDNA degradation. We attribute the fragmentation-mixing mechanism to turbulent flow structures, which result in smaller, and more evenly abundant eDNA particles in the experimental volume, increasing the probability of eDNA detection. The impact of the fragmentation-mixing mechanism increased with flow rate, resulting in an initial increase of detectable eDNA quantity during an experiment. The second mechanism, eDNA degradation, resulted in a steady decrease of the total detectable quantity of eDNA over the course of the experiments.
Our data and the described mechanisms are in line with field data published by Wood (2021) and Van Driessche (2023), which took note of fragmentation and mixing phases. In the case of the field experiment of Van Driessche (2023) a consistent peak in the detected eDNA concentrations downstream of a source population of fish was partly attributed to the aforementioned mechanisms.

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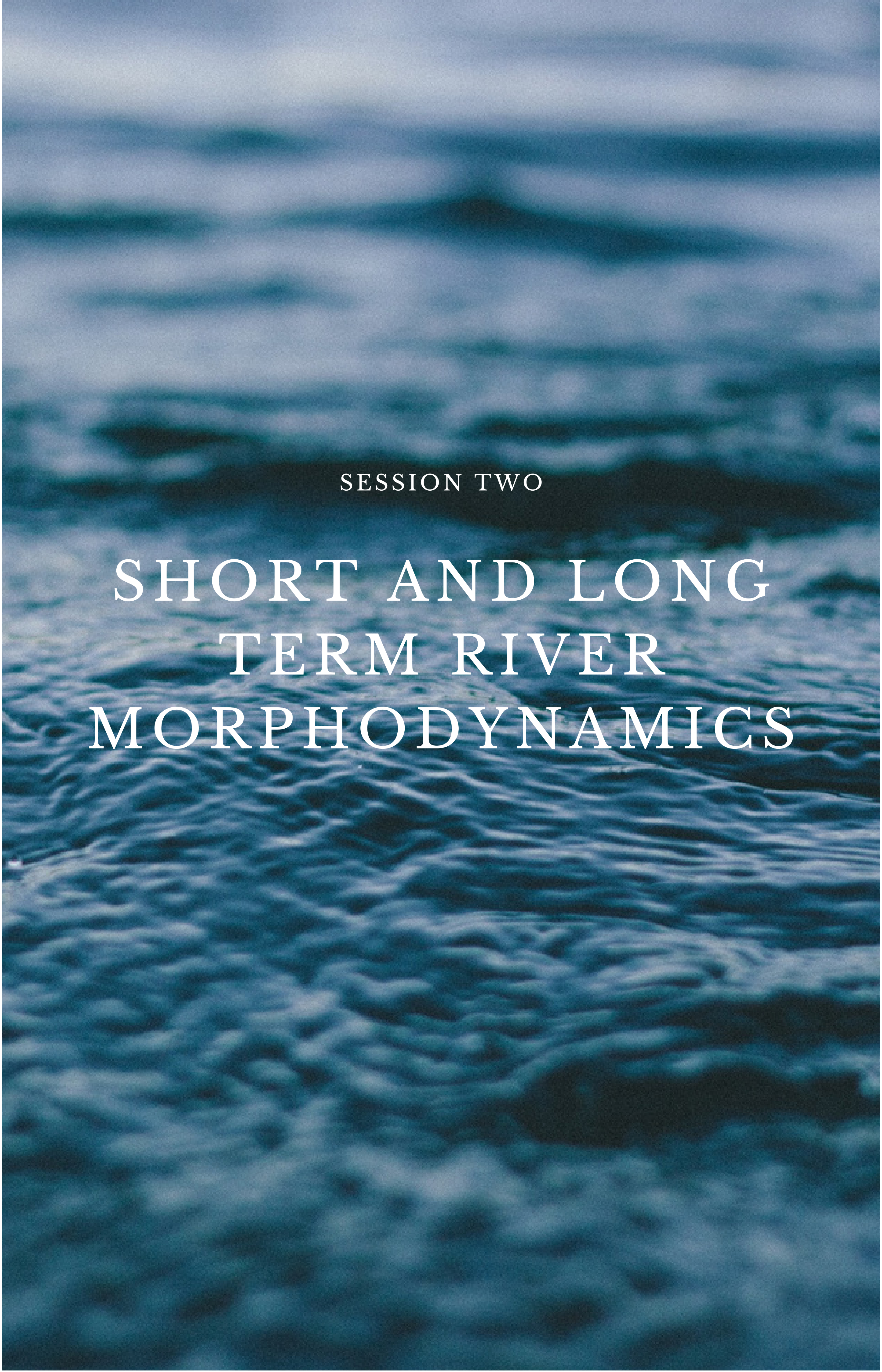

SESSION TWO

SHORT AND LONG TERM RIVER MORPHODYNAMICS

Exploring anthropogenic impacts on channel morphodynamics (Methodology)

Niguse Abebe[1,4*], Jantiene Baartman[2], Joris Eekhout[3], Berhane Grum[4], Bart Vermeulen[1], Joris de Vente[3], Carolina Boix-Fayos[3], Ton Hoitink[1]
[1]Hydrology and Environmental Hydraulics Group, Wageningen University, Wageningen, The Netherlands.
[2]Soil Physics and Land Management group, Wageningen University, Wageningen, The Netherlands.
[3]Soil and Water Conservation Department, CEBAS-CSIC, Murcia, Spain
[4]School of Civil Engineering, Mekelle University, Mekelle, Ethiopia

Keyword: Check dams, Reforestation, CAESAR-Lisflood

Introduction

The anthropogenic barriers that affect river channel morphology are construction of dams, check dams, channelization, gravel and sandmining, reforestation/deforestation (Fryirs 2013; Boix-Fayos et al., 2007; Abbasi et al., 2019). In the Rogativa catchment (SE Spain), there was human intervention in constructing check dams and reforestation in the 1970s, consequently, there is occasional channel incision and channel narrowing due to vegetation encroachment (Boix-Fayos et al., 2007; 2008; Eekhout et al., 2020; 2024; Abebe et al., 2023). Therefore, it important to study channel geomorphic response to check dams and vegetation using a numerical modelling (e.g., CAESAR-Lisflood). The objective of this study is to investigate how discharge, sediment dynamics and channel morphology develops and changes with changing conditions (e.g., land use change and with/out check dams). Changing conditions in the catchment changes the flow regime and sediment dynamics leads to evolution of channel morphology. We hypothesize extreme flow events may serve as critical indictors, progressive riparian vegetation encroachment leads to channel narrowing and incision, and the alluvial wedges behind check dams can lead to local aggradation and widening of the channel.

Material and Methods

CAESAR-Lisflood, a 2-D geomorphological model is employed to achieve the objective and evaluate the outlined hypotheses tailored to the scenarios. In ungauged catchments (e.g., Rogativa), it is possible to run the CAESAR-Lisflood at 'catchment mode' to generate flow from rainfall at the river outlet to use as input for the 'reach mode' simulation (Milan, D., 2022; Poeppl et al., 2019; Walsh et al., 2020). Run the model for the periods in 1956 (without check dams and no forest) and 2016 (landfilled check dams and reforestation) to understand the impact of the reforestation and check dams on the channel morphological changes over time. Main input data are the 5m resolution DEM of drainage and bedrock depth resampled to a coarser resolution of 20m using bilinear interpolation, hourly precipitation data downloaded from a meteorological station at about 10 km from Rogativa for the period 2006-2021 (http://siam.imida.es/), and land use factors (m value used by TOPMODEL) for 'catchment mode', valley floor DEM of 2m resolution and discharge for 'reach mode', grain size distribution (classes up to 9) for both modes (Fig. 1). Model parameters such as 'm' value and Manning's n will be calibrated and validated based on measured discharge events in 2016/2017. The size of the catchment and reach to be include in the analysis is determined based on the number of cells to maintain model stability and run time speed of the model. The input DEM is hydrologically conditioned (sinks and pits removed) using TauDEM tool and fill using the Arc hydro tool. The main stream channel in 1956 and 2016 and the landfilled check locations in 2016 (Fig. 2&3), were digitized from the orthophoto of 25cm resolution (http://www.ign.es/wms/pnoa-historico), georeferenced and aligned with the streamline generated from 2m resolution DEM.

Expected output

The output includes a time series of DEMs reflecting topographic changes at a specified time interval, erosion/ deposition levels, hydraulic variables (flow rates, velocity, flow depth) for each time at river outlet and selected reach sections.

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Email: niguseabebe.hagos@wur.nl

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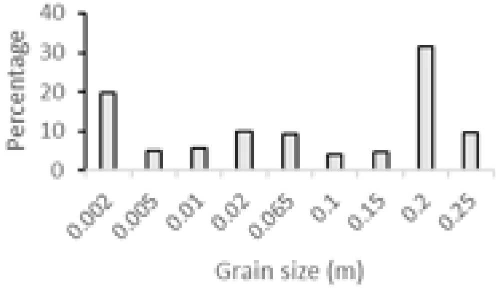

Figure 1. Grainsize distribution

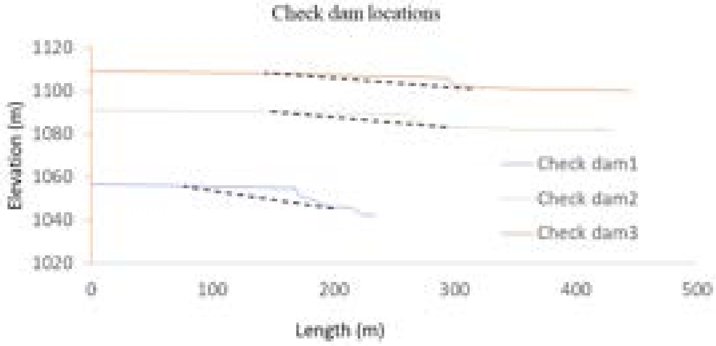

Figure 2. Landscape change induced by check dams along the streamline (shown by broken line)

Figure 3. Channel landforms in 1956 (a), 2016 (b), overlapped (c) and one of the check dams in the main channel (d)

A Sediment Budget for the Dutch part of the Meuse River

H.J. Barneveld[a,b], R.M. Frings[c] and A.J.F. Hoitink[a]

[a] *Wageningen University and Research, Hydrology and Quantitative Water Management Group, Department of Environmental Sciences, Wageningen, the Netherlands, hermjan.barneveld@wur.nl, ton.hoitink@wur.nlfull*
[b] *HKV, Lelystad, the Netherlands, barneveld@hkv.nl*
[c] *Rijkswaterstaat Zuid-Nederland, Maastricht, the Netherlands, roy.frings@rws.nl*

Keywords — Sediment budget, Floods, River Management

Introduction

Knowledge about the sediment budgets in rivers may help in assessing the morphological impacts of interventions and changes, and to improve river management (Frings and Ten Brinke, 2018; Habersack et al., 2013). The objective of this study is to assess the sediment budget for gravel and sand in the Dutch part of the Meuse River, and to compare annual estimates of sediment budget components to erosion and sedimentation volumes observed during the extreme flood of July 2021.

The Meuse River flows from France, through Belgium and the Netherlands to the North Sea, and is highly engineered. Over the last 200 years, levees were built, the riverbed was narrowed and deepened, multiple barrages and sluices have been constructed and bends were cut off. Only short stretches of the river are free flowing. In the last 25 years, river widening measures (Meuse Program, Van Looy and Kurstjens, 2022), maintenance dredging and removal of bank protection were the main factors controlling the morphological changes in this supply-limited river. Information on bed level changes, erosion of new natural banks, aggradation on floodplains, an inventory of human sediment extraction and feeding, and a hypothesis for negligible sediment load from upstream, are key components in the first sediment budget of annual fluxes of sand and gravel for the Dutch Meuse River.

Method

Input, output and storage terms determine the sediment budget (Figure 1). We collected and analyzed data on the bed development of the main river and floodplains as well as data on sediment mining and dredging. The riverbed was measured with single beam and multibeam echo soundings (before and after 2000, respectively). Since 2007, the riverbed is monitored annually. In addition to the data quantifying geometrical changes, a database has been constructed with all sediment management measures since 1995, such as dredging and implementation of river widening works. For the erosion of natural riverbanks and the erosion and sedimentation on the floodplains, laser altimetry data acquired for the actual elevation model of the Netherlands (AHN1 to AHN4: data collected in the periods 1996-2001, 2011-2012, 2015-2018 and 2020-2021 respectively) are used to assess volumes of change per period.

Figure 1. Representation of a channel sediment budget in a human-controlled river system, showing different sediment inputs (I),outputs (O) and the storage term (ΔS). Source: Frings et al. (2019).

With information on the subsoil composition, we translate these values to average annual erosion volumes of sand and gravel.

For the July 2021 flood event we analysed the bed level changes in the main channel during the flood from the multibeam data set, deposition on the floodplains collected by field work and laser altimetry and echo soundings in several lake areas.

Results

Analyses of bed level changes and dredging in the period 2010-2020 show, that the volumes extracted from the riverbed as part of the Meuse Program (Maaswerken) and for maintenance of the navigation channel, were more than 5 times higher than the sediment load in the Meuse during this 10 year period (Figure 2).
We further show that the long-term average annual sediment loads per river reach since 1995 are limited compared to the volumes of sand and gravel mobilized during the 5 day flood period in 2021. The massive riverbed and riverbank erosion, especially in the Common Meuse during a few days of extreme

discharges, produced sediment loads equivalent to those of multiple average hydrological years. The contribution of floodplain deposits to the sediment budget during such high floods shows to be significant.

Other (less important) terms of the sediment budget will be added at a later stage.

Conclusion

As little sand and gravel enters the Dutch Meuse River, the river is supply limited and incising. For a sustainable river system net extraction of sand and gravel from the main riverbed should be terminated, sediment management strategies should be designed, and future morphological impacts of plans should be assessed.

Acknowledgments

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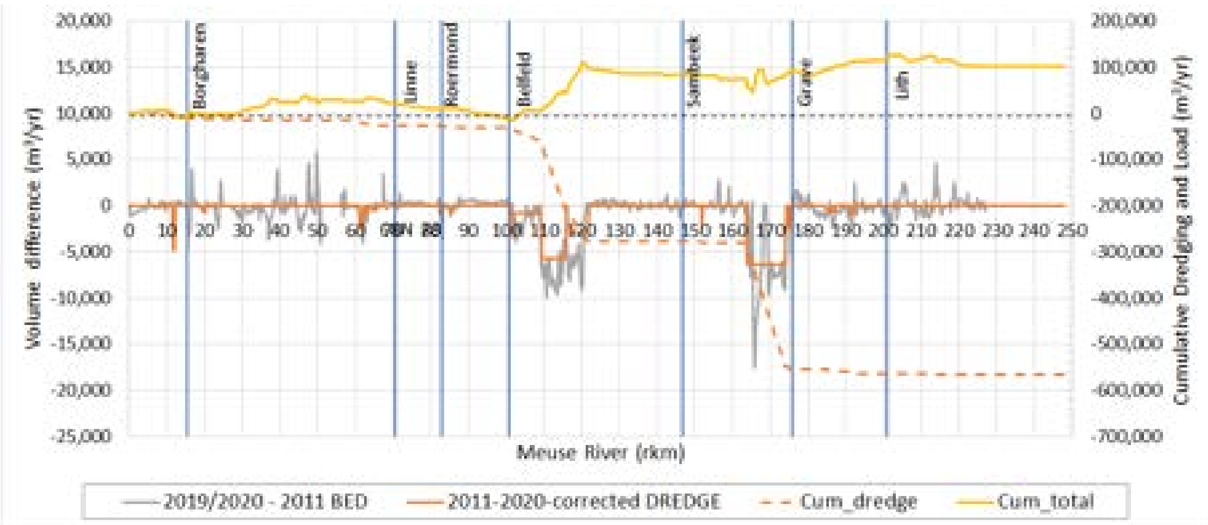

Figure 2. Annual volumes of bed level change (grey line) in the main channel and sediment extraction in that channel (orange line), for the period 2011-2020. The 7 barrages are indicated with blue vertical lines. Large dredging activities for maintenance of the navigation channel at Venlo (km 101-109), river bed deepening section Sambeek (km 109-122) and river bed deepening section Grave (km 164-174) are clearly visible. The yellow line shows the cumulative summation of these two budget terms on the right y-axis, starting with zero input at the upstream boundary (hypothesis of zero sediment load through Lixhe barrage at the border). The downstream cumulative load of approximately 100,000 m^3/yr is less than 20% of the total dredged volume of sand and gravel (orange dotted line).

* Corresponding author
Email address: hermjan.barneveld@wur.nl (Hermjan Barneveld)

Mitigation of Channel Bed Erosion through Floodplain Lowering and Nourishments

Claudia Ylla Arbos[a], Ralph M.J. Schielen[a,b], Saskia van Vuren[b], Yvo Snoek[b], Astrid Blom[a*]
[a]*Faculty of Civil Engineering and Geosciences, Delft University of Technology, the Netherlands*
[b]*DG Rijkswaterstaat, Ministry of Infrastructure and Water Management, Utrecht, The Netherlands*

Keywords — channel bed erosion, erosion mitigation, nourishments, numerical modelling

Introduction

Channel adjustment in engineered rivers is often associated with channel bed incision (e.g., Chowdhury et al., 2023, Czapiga et al., 2022a, 2022b, Ylla Arbós et al., 2021). Channel bed incision reduces the stability of in-river structures, exposes river-crossing cables and pipelines, and the spatial variability of channel bed incision due to less erodible reaches creates shipping bottlenecks.

Various measures have been implemented to cope with these issues. They range from sediment nourishments to erosion control structures (e.g., Habersack and Piégay, 2007).

Our objective is to assess the potential of floodplain lowering and sediment nourishments in mitigating large-scale channel bed incision in engineered rivers affected by climate change, considering a spatial scale of hundreds of kilometres. Our domain of interest is the Rhine River between Bonn, Germany, to Gorinchem, Netherlands. This reach has been extensively channelized during the 18th-20th centuries for improved navigation and flood protection (e.g., Ylla Arbós et al., 2021).

Methods

We apply the schematized one-dimensional numerical model set up and calibrated by Ylla Arbós et al. (2023). The model uses the steady solution to the shallow water equations for describing the flow and the active layer model describing the conservation of grain size classes in a surface layer. We use a sediment transport relation that includes a threshold of motion and accounts for hiding effects. The model includes five grain size classes, which range from fine sand to coarse gravel, and have characteristic grain sizes of 0.5 to 40 mm.

The model initial state represents the current (non-graded) river conditions and is built on measured data of the period 1990-2020. Cross-sectional and bed surface grain size data are smoothed strongly such that the model focusses on large-scale trends and is incapable of replicating local effects.

Boundary conditions include a repeated 20-year hydrograph based on historical data (1967-1986 whose statistics best match those of the long-term series 1951-2006), sediment fluxes for the 5 five grain size classes (based on Frings et al., 2014), and a downstream boundary condition that accounts for a sea level rise at rates representing the centreline of the KNMI (2015) projections. Climate change is accounted for in the boundary conditions through two scenario combinations:

(1) moderate climate change
    water discharge following GL scenario (KNMI, 2015) and sea level following lower end of RCP 4.5 scenario (IPCC, 2013)
(2) high-end climate change
    water discharge following WH scenario (KNMI, 2015) and sea level following upper end of RCP 8.5 scenario (IPCC, 2013)

The conversion of climate scenarios to model boundary conditions follows Ylla Arbós et al. (2023).

Sediment nourishment measures are schematized as an abrupt rise in bed level, which is repeated every five years. Each nourishment consists of 370,000 m^3 of sediment equivalent to about 70,000 m^3/a, covering the full channel width. Sediment is only nourished in the upper and middle Waal, as the other river reaches do not suffer from pronounced incision. We consider four nourishment schemes (point-source nourishments, where the total volume is dumped over a single 3 km long reach, 10-km- and 20-km-spaced nourishments, and fully-spread nourishments, where the total volume is evenly distributed.

We consider nourishment volumes of 70,000, 150,000 and 200,000 m^3/a to investigate the effect of the nourishment volume.

Floodplain lowering is schematized by modifying the model cross sections such that all points corresponding to the floodplains are lowered by 0.5, 1, and 1.5 m.

Results and Conclusions

Our runs indicate that sediment nourishments have more potential to reduce channel bed incision than floodplain lowering. In our runs, floodplain lowering over a long reach is not able to halt channel bed incision by 2050 (Fig. 1). In runs with spatially alternating floodplain lowering (with short reaches in between without lowered floodplains) erosion is reduced more effectively, yet leading to significant spatial variation in bed level.

Sediment nourishments are more effective, yet halting of erosion requires the addition of order 200,000 m^3 of sediment annually (Fig. 2) and leads to an increase of the bed level in the downstream reach (that is already aggradational).

Considering climate change, our runs show that nourishment schemes with reasonable nourishment volumes (70,000 m^3/a) lead to more than 1 m of incision by 2050.

Effect of nourishments largely depends on parameters (grain size, spreading, nourished volume and frequency). Coarser nourishments are more effective at mitigating channel bed incision, although they require spatial spreading, which is associated with larger operational constraints. For finer nourishments the spatial spreading is less important, but they require a larger volume for equal efficacy.

Climate change enhances incision and not accounting for it in future intervention design may make measures ineffective.

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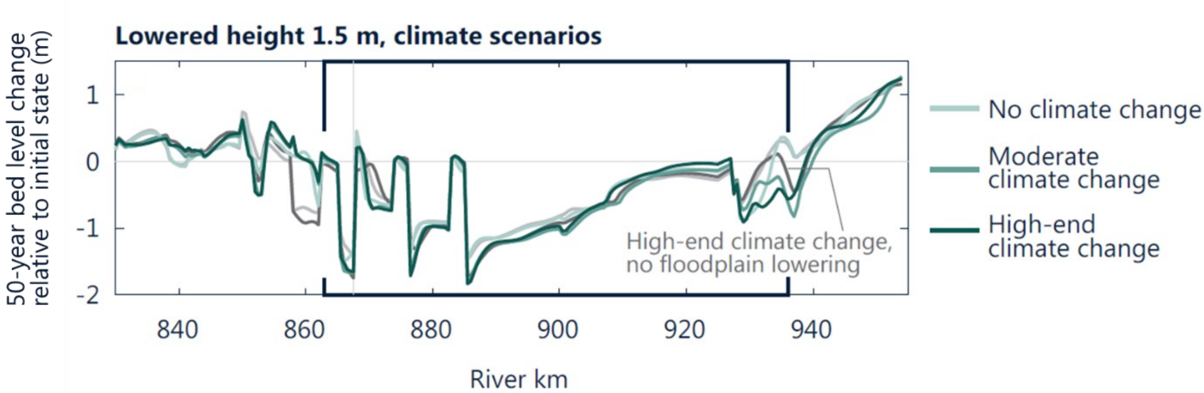

Figure 1: Predicted 2050 bed level profile for a reference case (gray) without floodplain lowering and high end climate change compared to three cases of 1.5 m floodplain lowering over Bovenrijn-Waal for three climate change scenarios (no, moderate and high).

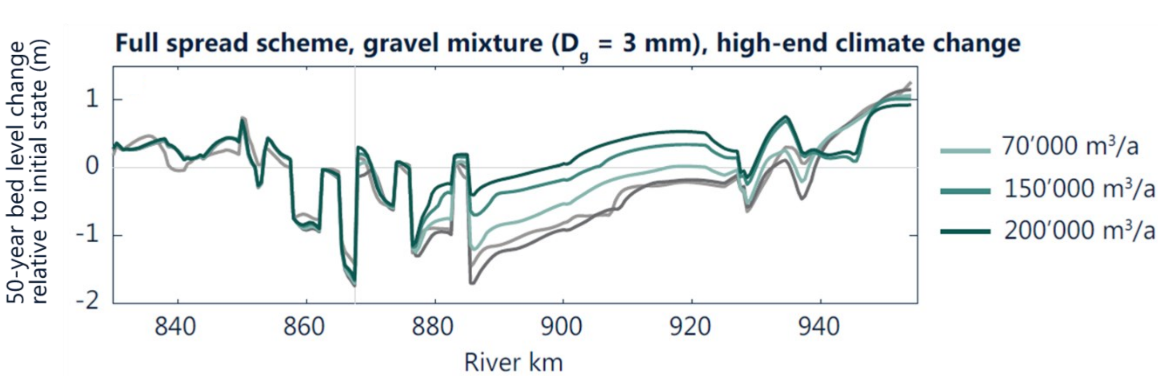

Figure 2: Predicted 2050 bed level profile for two reference cases without nourishments (light gray without climate change and dark gray for high end climate change) compared to three cases of fully spread nourishments (grain size distribution similar to the average one of the upper Waal) of different volume (70,000, 150,000 and 200,000 m^3/a) for the high end climate change.

The morphodynamics of multiscale dunes in the Waal River

J.Y. Zomer[a,*], A.J.F. Hoitink[a]

[a] *Hydrology and Environmental Hydraulics Group, Department of Environmental Sciences, Wageningen University & Research, Wageningen, Netherlands*

Keywords — River Dunes, Dune Tracking

Introduction

A secondary scale of dunes, superimposed on larger, primary dunes, has been observed in fluvial systems worldwide, among which the Dutch Waal River (*Zomer et al.*, 2021). This notwithstanding, very little is known about the morphological behavior and characteristics of secondary bedforms. Also, it has remained unclear how these smaller-scale bedforms affect the sediment transport dynamics in a fluvial system, and if and how dune tracking can be applied for the quantification of bedload sediment transport.

In this contribution, a first aim is to better characterize and understand how two dune scales coexist in fluvial systems and how both scales adapt over time and space, considering their interdependence. This was done based on a large biweekly multibeam echo sounding (MBES) dataset from the river Waal.

A second aim is to better understand the interaction between the two dune scales whilst migrating downstream, and the implications for the downstream transport of sediments and applicability of dune tracking. This is investigated based on a series of field measurements in the Waal, near Tiel.

Methods

The biweekly MBES data were analyzed using the tool developed by *Zomer et al.* (2022), which allows to isolate multiple dune scales from a bed elevation series. Bed grain size data was also available, indicating a strong lateral variation in grain size, offering unique conditions to study the effect of grain size on dune morphology.

During the field campaigns, the river bed was repeatedly scanned, enabling tracking of both secondary and primary dunes over time. In addition, ADCP measurements were collected, as well as river bed samples and water samples.

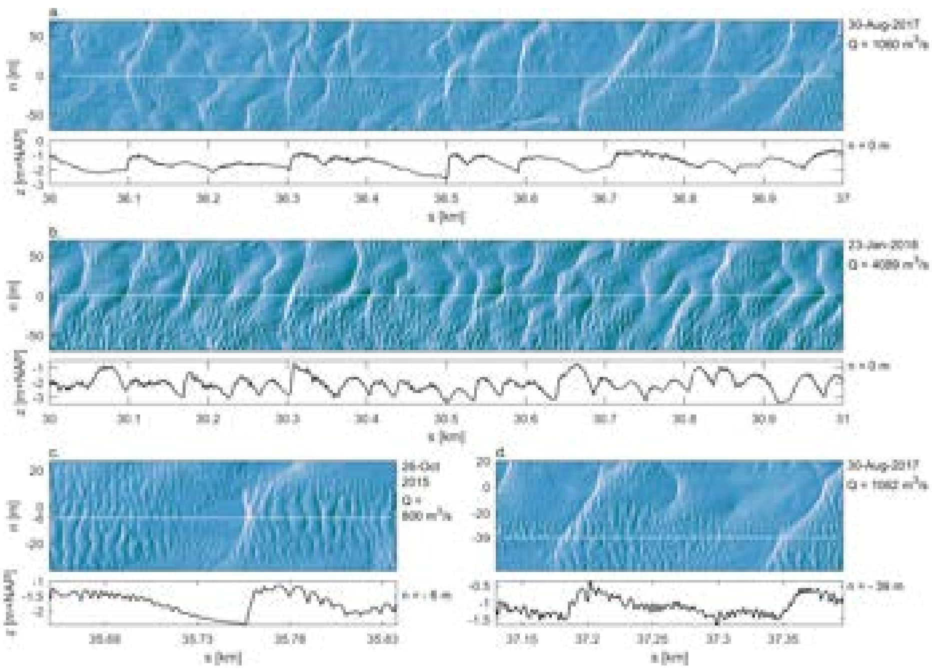

Figure 1: Examples of the bed morphology, indicating the coexistence of primary and secondary dunes in the Waal river. The bathymetry is visualized using hillshade. Below each bathymetric map, a bed elevation profile from that map is shown. Reprinted from Zomer et al. (2023)

*Corresponding author
Email address: `judith.zomer@wur.nl` (J.Y. Zomer)
URL: `www.wur.nl` (J.Y. Zomer)

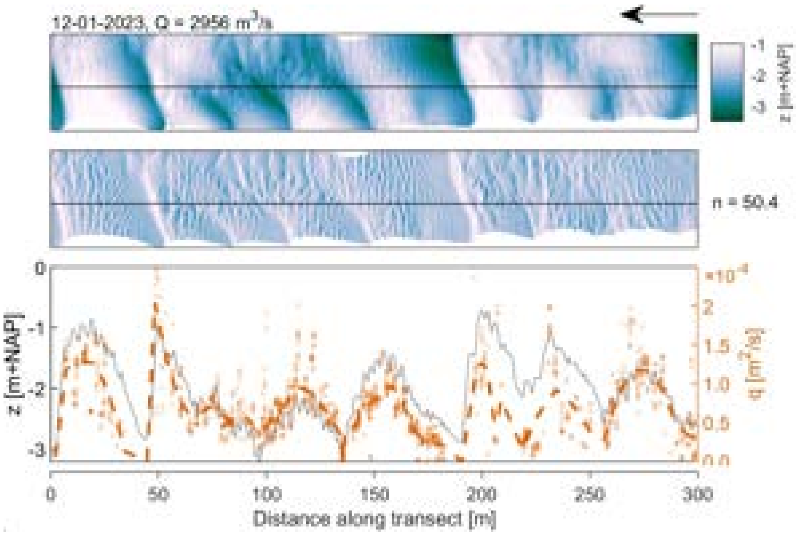

Figure 2: An example bed elevation profile. Top panel: Bed morphology. Central panel: Bathymetry visualized with hillshade. Bottem panel: BEP (left y-axis) and sediment transport rates based on secondary dune tracking. The individual data points have been smoothed through LOESS. Adopted from Zomer et al. (2024)

Results

The main findings for the first objective were (*Zomer et al.*, 2023):

1. The secondary scale is ubiquitous across time and space, and not limited to specific flow or transport conditions.
2. Primary dunes lengthen during low flows, whereas secondary dune height, lee slope angle, and length correlate with discharge. Secondary dune size and migration strongly depend on the primary dune lee slope angle and height.
3. Secondary dunes can migrate over the lee slope of low-angled primary dunes.
4. In the Waal, a lateral variation in bed grain size, attributed to shipping, strongly affects dune morphology. Primary dunes are lower and less often present in the southern lane, where grain sizes are smaller. Here, secondary bedforms are more developed. At peak discharge, secondary bedforms even become the dominant scale, whereas primary dunes entirely disappear but are re-established during lower flows.

To address the second objective we looked at the sediment transport linked to secondary dune migration over several dunes. Results show that transport increases of the host dune stoss, eroding the host dune stoss, and transport decreases over the lee, indication deposition at the host dune lee side. This indicates that secondary dunes control migration of the host dune, both when they persist over the host dune and when they disintegrate at the lee side (*Zomer et al.*, 2024). There are implications for the applicability of dune tracking. Application of dune tracking to primary dune migration, which is usually done, can lead to significant underestimation of bedload transport when secondary dunes are superimposed.

Acknowledgements

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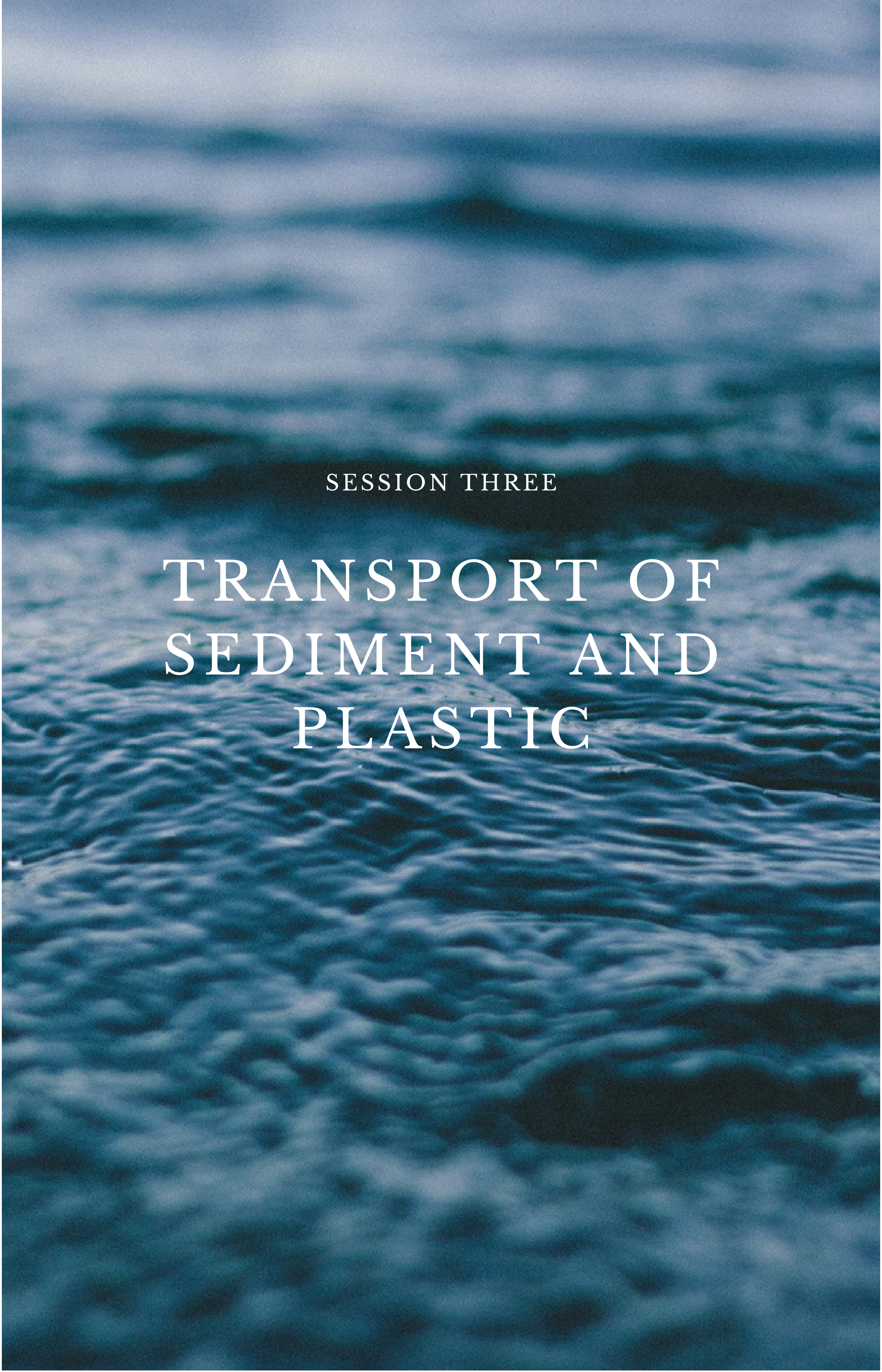

SESSION THREE

TRANSPORT OF SEDIMENT AND PLASTIC

A source-to-sea approach to evaluate policy measures that aim to reduce macroplastic transport in Dutch rivers

Frans A. Buschman, Joana M. Veiga, Fatimah Sulu-Gambari, Lora Buckman, Arjen Markus, Marieke Eleveld, Antonio M. Rodenas, Petra Krystek, Thaiënne van Dijk, Arjan Wijdeveld, Tineke Troost, Hilde Passier[a]
[a] *Deltares, Delft and Utrecht, the Netherlands*

Keywords — Plastic pollution, monitoring, integrated modelling

Introduction

Plastic litter is now well-established as an environmental pollutant both on land and in the water. Rivers are recognized to be key transport pathways and may also act as sinks (Van Emmerik et al., 2022). Plastic items vary in size, shape, chemical composition and density. The large variation contributes to variability in the transport of a particular litter object, as it is carried from its source point to its ultimate and possibly marine destination. In mass, macroplastics (5 mm and larger) represent the dominant component of river plastic pollution. Fragmentation of macroplastics is an important source of microplastics, which are associated with environmental impact and risks to human and animal health (Prata et al., 2021).

Monitoring of macroplastic pollution in the Netherlands includes standardized beach and riverbank observations. Within the Netherlands, Lobelle et al. (2023) estimated that between 8-843 tonnes of plastic waste end up on riverbanks and 14-27 tonnes are deposited on beaches annually. Since no regular observations are available for lakes, large estuaries and canals, these environments were not included. Occasional sampling in the water column (Vriend et al., 2023) and visual counting from bridges (Van Emmerik et al., 2023) show the wide spatial variation of macroplastics concentration and composition and how the concentration generally relates to river discharge.

Challenge to evaluate effect of policies

Several European policies directly address marine litter or its sources, including: (1) the European Marine Strategy Framework Directive (MSFD) that is evaluated every 5 years, (2) the EU Directive on Single-Use Plastics (SUP), which targets some of the most commonly found plastic items on beaches (including plastic bottles and cutlery), (3) the Waste Framework Directive, (4) the Packaging Directive, and (5) the Plastic Bags Directive. An important and legally binding agreement is currently being prepared by the United Nations and is expected to address the full lifecycle of plastic.

However, it is challenging to evaluate the effect of a policy measure on plastic pollution in either rivers or the sea from observations alone, for several reasons: (1) a quantitative baseline is needed and determining such a baseline requires observations over a sufficiently long period to capture the wide variability in occurrence and distribution in space and time (e.g. low to high river discharge) (2) the monitoring techniques and standardization of analysis are still under development, (3) policies are often formulated in a way that is not easily translated into monitoring requirements, and (4) such an evaluation will likely show the combined effect of measures instead of a single one.

Source-to-sea approach

We state that in order to evaluate the effect of a policy measure on plastic pollution in rivers and the sea, it is necessary to take a holistic approach: the source-to-sea approach (Figure 1). The source-to-sea approach encompasses all pathways of plastic pollution, from its generation (leakage into the environment from a particular source), its transport in rivers and channels, to its ultimate destination, which may be the sea. We argue that looking at aquatic pollution alone does not generate the necessary information to assess the need and impact of preventive measures, which must be taken at the source. As such, interlinking the domains of plastic production, usage of plastics and waste management with environmental modelling is central in this approach.

For a successful application, it is key to make use of the best available data as input and for validation. Figure 1 illustrates the three key elements of the source-to-sea approach, namely estimate the sources, determine the transport along pathways as a result of the hydrology and evaluate the impact of the plastic litter.

An illustrative example of such an integrated approach is described by Veiga *et al*. (2023), who estimated a national baseline for Indonesia

* Corresponding author
Email address: frans.buschman@deltares.nl (Frans Buschman)

of plastic transport into the sea from land-based sources and from transport via rivers. Through an integrated modelling approach realistic time series of plastic transport into the sea were obtained, based on material flow analysis for estimations of exposed mismanaged plastics and based on actual rainfall. The value of such an approach is that it pinpoints the locations and specific waste handling practices that contribute the most to marine plastic pollution.

Therefore, we propose this source-to-sea integrated modelling approach for the Netherlands as well. With a nation-wide integrated model, scenarios of applying different (single) policy measures can be evaluated. This can be beneficial when considering which measures are most effective. Furthermore, this approach can be used to interpret the scarce observations and may also be used to select locations where capture devices are expected to be most effective.

Roadmap for Dutch rivers

Since the integrated model is now only partly set up for the Netherlands, we identify four steps with which to complete it: (1) estimation of sources to land and water, also using overflow results of the existing National Water Model (NWM), using simulated emissions for several macroplastics categories within the Netherlands, and inflow via rivers from abroad from large-scale numerical models, (2) calculation of transport in rivers and their main connecting channels, including the processes advection, sedimentation & resuspension, retention, (3) verification of the integrated model results by comparing per category with observations (e.g. using available data from sampling and visual counting from bridges) and (4) reduction of a source and calculate its effect with respect to the baseline.

To estimate retention of macroplastics in the estuarine part of the nation-wide transport model, results of a 3D particle tracking model can be used. Macroplastics that are transported from upstream into the estuary but are not transported to the sea are likely to be retained in the estuary.

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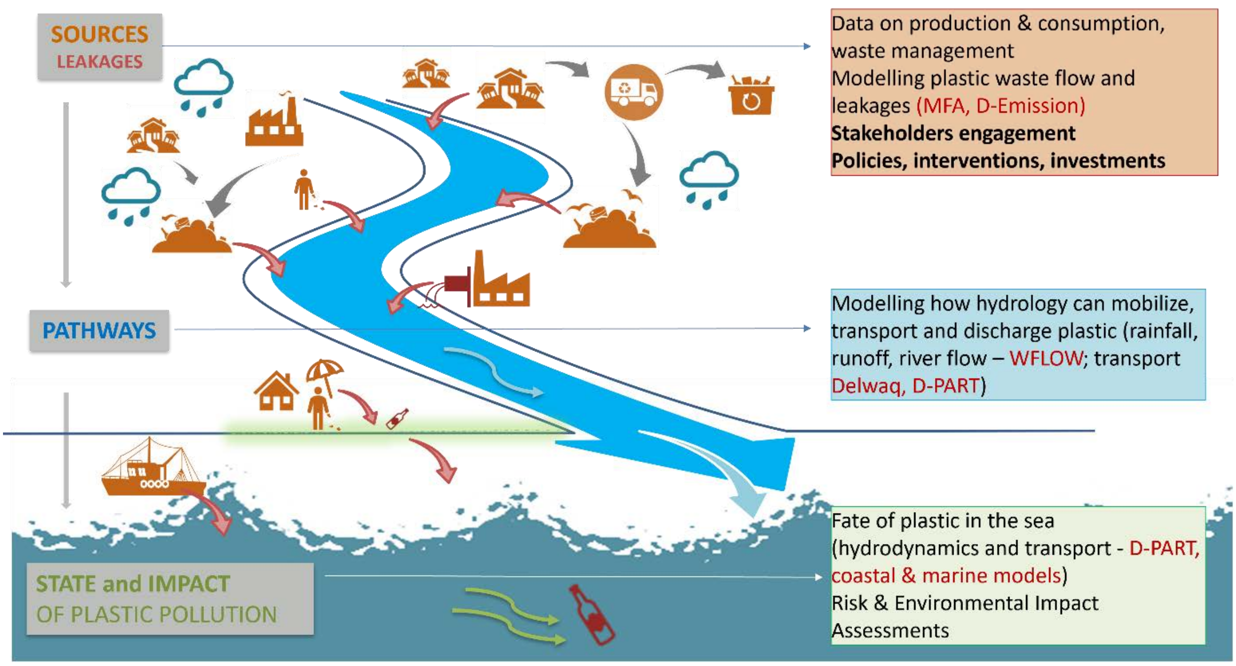

Figure 1. Conceptual framework of the source-to-sea approach for the Netherlands, with on the right integrated model components.

Exploring the mechanisms that govern the spatial and temporal trends of suspended sediment in the Rhine basin

Jana R. Cox[a]*, Tatjana Edler[b], Marcel van der Perk[a], Hans Middelkoop[a]
[a] Utrecht University, Department of Physical Geography, Faculty of Geosciences, PO Box 80125, 3508 TC Utrecht, The Netherlands.
[b] Deltares, Boussinesqweg 1, 2629 HV, Delft, the Netherlands

Keywords — rivers, suspended sediment, channel erosion

Introduction

The Rhine-Meuse delta has been experiencing a negative sediment budget for several decades causing damage to morphology and infrastructure. This is partly due to the declining fluvial sediment supply at the delta apex (Lobith). Lobith has recorded a declining suspended sediment flux since the 1950s. To understand the cause of this decline, we systematically investigate the spatial and temporal patterns of suspended sediment in the Rhine and its major tributaries (Aare, Main, Mosel and Neckar).

Assessing suspended sediment fluxes

Suspended sediment concentrations (SSC) and discharge (Q) data were gathered for 26 stations in the basin from 1997-2014 (see Figure 1). To account for varying frequency of data sampling, the rating curve method was applied to predict daily SSC. For each station and year, a power-law rating curve with a scale-break was fitted using a 5-year moving average window. Using the predicted daily SSC, annual suspended sediment loads (SSL) and discharge-weighted suspended sediment (SSC-dw) were calculated.

A spatial trend in the temporal trend

Most stations in the central and downstream parts of the river basin show a declining suspended sediment trend over time. However, more interestingly, there is a clear spatial trend in these temporal trends: the decline in SSC becomes more severe in a downstream direction. This is particularly the case for the Main, Mosel tributaries and in the main stem of the Rhine in Germany. In contrast, stations in the Alpine and Upper Rhine show a positive or neutral change in SSC during the study period. In the impounded section of the Rhine, there is a negligible change in SSC and SSL. Thus, the free-flowing part of the Rhine is where the important changes for the declining delta supply are occurring. In this free-flowing section, the SSC decline becomes more severe moving towards the delta apex, despite the confluences with three major tributaries which contribute additional sediment.

Causes of the declining SSC

Globally, the causes of declining fluvial sediment fluxes can typically be explained by the construction of dams or sediment management activities. However, in the Rhine basin, such endeavours took place before the decline at Lobith is observed, and most of these activities take place in the impounded section, in which no substantial change has been observed in recent decades. There has been a slight decline in SSC and SSL in the Main basin, however this cannot fully explain the scale of decline in the lower Rhine. To further explore the possible mechanisms and causes of the declining SSC trends, we investigated the relation of the SSC-dw and SSL with channel bed incision rates using bed level data. We hypothesise that part of the SSL of the Rhine is derived from the channel bed and that changing channel bed incision rates lead to changes in suspended sediment supply from the river bed. Comparison of channel bed incision data for the lower Rhine from Ylla-Arbós et al. (2021) with the SSL trends at Lobith confirms a concurrent decline in both SSL and channel bed incision rates.

The incision of the Rhine occurred in response to channel straightening and narrowing activities in the 20th century. However, as proved by Ylla-Arbós et al. (2021), the incision has slowed down in recent decades as the bed is stabilizing due to both sediment management activities to combat incision and also due to bed armouring. Thus the current 'low' sediment supply at Lobith is likely to persist in coming decades. This also indicates that the response time of both bed level incision and resulting sediment budgets to human interventions can be relevant not only at a decadal timescale but can also persist for several centuries after the activities occur. It also indicates that future fluvial sediment supply is more likely to be

* Corresponding author
Email address: j.r.cox@uu.nl (Jana Cox)
URL: janacox.com (Jana Cox)

governed by anthropogenic changes in the lower Rhine than by climate change.

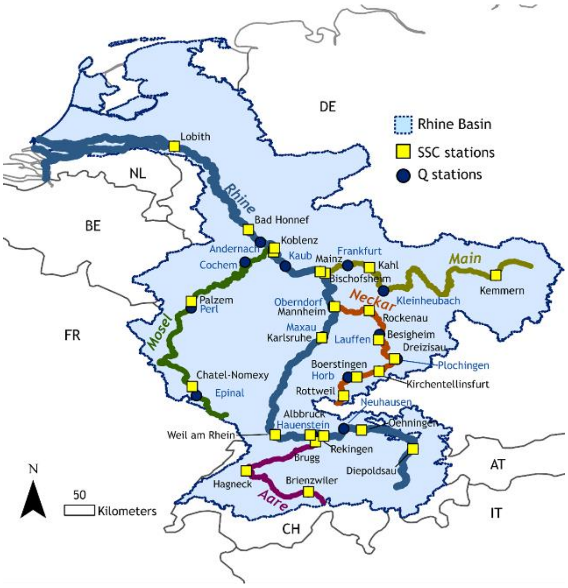

Figure 1. Locations of discharge (Q) and suspended sediment concentration (SSC) measuring stations.

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Approaches reproducing suspended sediment transport through vegetation

Jiaqi Liu[a,b*], Francesco Bregoli[b], Alessandra Crosato[a,b], Giulio Calvani[c]
[a]*Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands;*
[b]*Department of Water Resources and Ecosystems, IHE Delft Institute for Water Education, Delft, the Netherlands*
[c]*Platform of Hydraulic Constructions (PL-LCH), IIC, School of Architecture, Civil and Environmental Engineering, EPFL, Lausanne, Switzerland*

Keywords — suspended sediment transport, vegetated flow, Delft 3D

Introduction

Working as natural filter, well-designed vegetation schemes have been widely applied to improve the quality of water (Aiona, 2013; Stefanakis, 2015). Proper design, however, requires appropriate physics-based modelling of their filtering capacity. Several theoretical models predicting sediment transport in vegetated flow have been proposed: Baptist (2005); Yang and Nepf (2018); Wu et. al. (2021); Tseng and Tinoco (2021); Yagci and Strom (2022); Wang et. al. (2023). Some of them have been implemented in numerical tools (e.g. Caponi et al., 2022; Li et al., 2022) and in particular in Delft 3D (Deltares, 2014). However, they have been mostly designed and verified based on bedload processes, and their performance for suspended load should be further investigated.

This work compares different approaches on their ability to reproduce the effects of vegetation on suspended solids concentration in two-dimensional models built in Delft3D. The work focuses on emerging vegetation, represented as rigid cylinders, and sediment deposition. Comparisons are based on the ability to reproduce flume experiments available in the literature by analysing both flow field and sediment deposition results.

Methodology

Sharpe's (2003) experiments, selected as test cases, were conducted in a straight 20 m long and 0.38 m wide laboratory flume. Woody rigid cylinders were used to represent reed stems with staggered patterns having three different densities. The flow discharge was kept constant during the tests and relatively-steady flow conditions were obtained by adjusting the downstream weir. Sediment with D_{50} = 0.17 mm was constantly fed as a line source at the middle of the flume. Selected tests were reproduced in 2DH models built in Delft3D. The flow was calculated as shallow water Navier-Stokes equations and suspended sediment transport by means of Advection-Diffusion equations with source and sink terms. Three approaches were applied to include the effects of vegetation: Baptist's (2005), representing vegetation as extra flow resistance; the Drag Force approach, which in 2D regards vegetation as an extra drag force in the momentum equations; and the Single Stem approach, distinguishing each stem in the numerical model.

Different experimental tests were considered for calibration and validation of the models. Comparisons between were based on the results of validation. The unvegetated models were calibrated based on bed roughness coefficient. Hydrodynamic calibration of vegetated flow was based on drag coefficient C_D for the Baptist and Drag Force approaches, and on horizontal eddy viscosity for the Single Stem approach. Morphodynamical calibration was based on longitudinal sediment deposition by tuning the settling velocity.

Results

The results of calibration for the flow field are shown in Tab.1.

Table 1 Calibrated parameters for vegetation modelling approaches

Calibrated parameter	Vegetated modelling approach		
	Baptist	**Drag Force**	**Single Stem**
Bottom Manning coefficient ($s/m^{1/3}$)	0.021	0.021	0.021
Drag coefficient	1.15	1.35	-
Horizontal viscosity (m^2/s)	1	1	0.00008

The results of validation are shown in Tab.2. All three approaches reproduce the flow field well with calibrated parameters. Differently from the other two, the Single Stem approach can reproduce the local flow field around the rigid stems, shown in Fig.1.

* Corresponding author
Email address: j.liu@un-ihe.org (Jiaqi Liu)

Table 2 RRMSE for the flow field validation

Case	RRMSE		
	Baptist	Single Stem	Drag Force
1	5.6%	0.6%	0.8%
2	0.0031%	1.0%	0.2%
3	0.26%	0.1%	0.1%

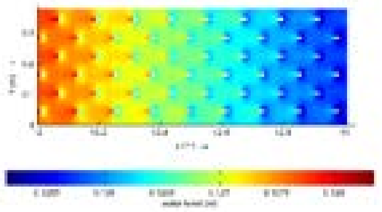

Figure 1 Water level distribution in the 12-13 m section. Results of the Single Stem approach.

For the sediment transport, the calibrated settling velocity is 10 mm/s. However, validation results show that all three approaches performed not so well in reproducing the longitudinal profile of sediment deposition (Fig. 2). The simulated deposition remains the same also with different vegetation density, which is different from experimental observations.

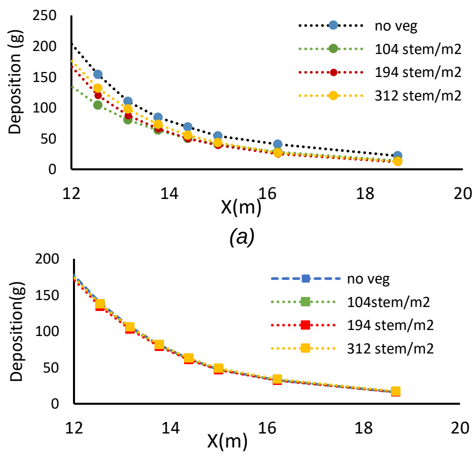

Figure 2 Longitudinal profile of sediment deposition (a) experimental results (b)computed with Drag Force approach

Baptist and Drag Force approaches result in uniform profiles of transverse sediment deposition. The Single Stem approach shows an asymmetry caused by the computational grid (Fig.3).

Conclusions

All three considered approaches perform well in reproducing the flow field inside the vegetated area. The Single Stem approach reproduce also the local flow field around rigid stems. All three approaches can't reproduce the observed changes of longitudinal sediment deposition with vegetation density. The reason may due to neglectying the effect of turbulence generated by the stems, which should be further studied in the future.

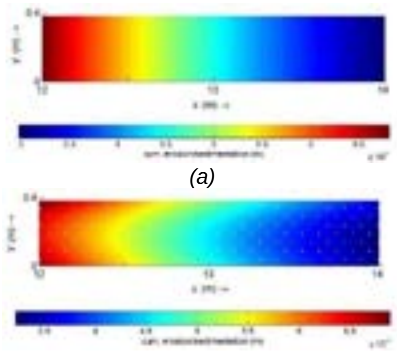

Figure 3 Sediment deposition distribution of the(a)Drag Force and Baptist approach (b) Single Stem approach

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Accumulation of floating particles at hydraulic structures

Antonio Magherini [a,*], Chit Yan Toe[a], Laura M. Stancanelli[a], Davide Wüthrich[a], Wim S.J. Uijttewaal[a]
[a] *Delft University of Technology, Department of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, 2600 GA, Delft, the Netherlands*

Keywords — Plastic accumulation, hydraulic structures, carpet instability and erosion

Introduction

Plastic pollution is a threat for all ecosystems due to its effects on people, animals, and environment (*Mai et al.*, 2020). Rivers are estimated to transport around 0.5 millions tons of plastic per year (*Strokal et al.*, 2023). When plastic enters a river system, it is transported downstream towards the sea but it is also likely to accumulate at specific cross sections and locations, including hydraulic structures (*Al-Zawaidah et al.*, 2021), eventually increasing the risk of floods.
Gates, locks, weirs, and bridges are commonly present in rivers and canals and have several functions, including water level regulation, flood safety, and inland water shipping. These can also be found in water treatment plants, hydropower stations as well as debris/plastic collection systems (*Honingh et al.*, 2020). Riverine plastic accumulation is also known to cause geomorphic changes (*Al-Zawaidah et al.*, 2021).
In-depth knowledge on how plastic particles accumulate upstream of hydraulic structures is therefore crucial to understand the processes that affect plastic transport, its influence on the safety and functionality of hydraulic structures and their effects on the hydro- and morphodynamic conditions of the flow (*Yan Toe et al.*, 2022).
In this research experiments were performed using simplified plastic particles to analyse the processes that lead to the instability of accumulated particles upstream of a simple gate.

Rise Velocity

As we are dealing with floating particles, their characteristics are reflected in the rise velocity and need to be determined first. Initial experiment determined the rise velocity of single plastic particles in a 2 m tall water column. The particle with diameter $d_p = 6$ mm and density $\rho = 904$ kg/m^3 was released from the bottom of the column with almost no initial velocity ($u_{s,0} \simeq 0$ m/s).

The rise velocity was computed as

$$u_s = \frac{l}{\Delta t} \tag{1}$$

where l is the distance between two marks on the water column and Δt is the time interval in which the particle passed between the two marks (Fig. 1). This time interval was extracted from videos recorded with a frame rate of 25 frames/second.

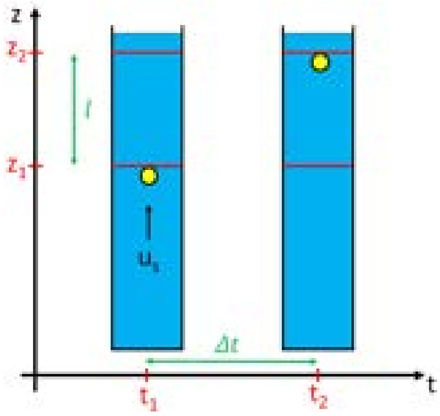

Figure 1: Sketch of setup used during the rise velocity experiment. The image is not to scale.

The experiment was repeated nineteen times. Fig. 2 shows the experimental data, which compares well with a CDF assuming a normal distribution for the rise velocity.

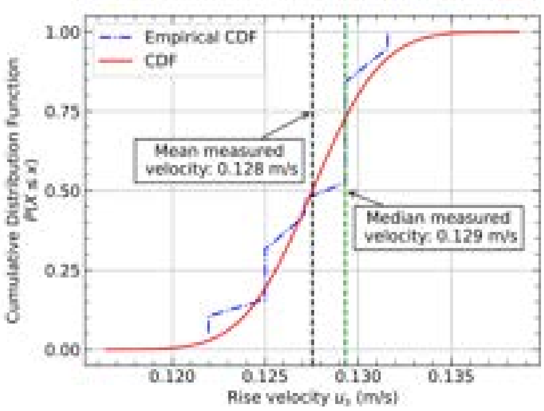

Figure 2: CDF of the measured rise velocity. The black and green lines represent the mean and median velocity.

At the end of the tests, the mean measured rising velocity was $\overline{u}_s = 0.128$ m/s, the median

*Corresponding author
Email address: antonio.magherini@gmail.com (Antonio Magherini)

was $u_{s,median} = 0.129$ m/s and the standard deviation was $\sigma_{u_s} = 0.003$ m/s. From rise velocity and drag coefficient formulas included in *Yang et al.* (2015) and *Kuizenga et al.* (2022), the expected rising velocity was slightly larger than the measured ones, between 0.131 and 0.144 m/s, with a median value of 0.134 m/s.

Carpet instabilities

This experiment determined the flow velocity for which the particles were no longer stable in the carpet. For that, a carpet of the same particles (Fig. 3) was placed upstream of a 0.06 m deep gate, allowing for a 0.10 m clearance, installed in a 14 m long and 0.40 m wide flume. The discharge was increased by steps until instabilities were observed.
The following regimes were identified:

- **Stability Region**: This is defined by a set of hydraulic conditions ($\overline{U}$, d_w), carpet length (λ), and particles characteristics (u_s, d_p), ensuring stability for the particles.
- **Squeezing**: This phenomenon occurred when a particle within the carpet, positioned at a minimum distance of 5 cm upstream of the gate, was pushed down by neighboring particles and completely submerged.
- **Erosion**: This took place when a particle on the upstream section of the carpet underwent a horizontal downstream displacement, causing it to be located in a second carpet layer below the initial one.

Figure 3: Configuration of the particle carpet setup.

Experiments were performed two times for multiple carpet lengths $\lambda = 0.30, 0.45, 0.60, 0.67, 0.75$ and 0.90 m. Despite some scatter, a linear relation seems to exist between carpet length and velocity at which both processes occur. The resulting coefficients of determination R^2 seem to confirm this relation. Erosion is always observed to occur for larger velocities than squeezing (Fig. 4). For $\lambda/d_p \leq 40$, where the two regression lines seem to meet, the carpet is too short to distinguish erosion from squeezing.

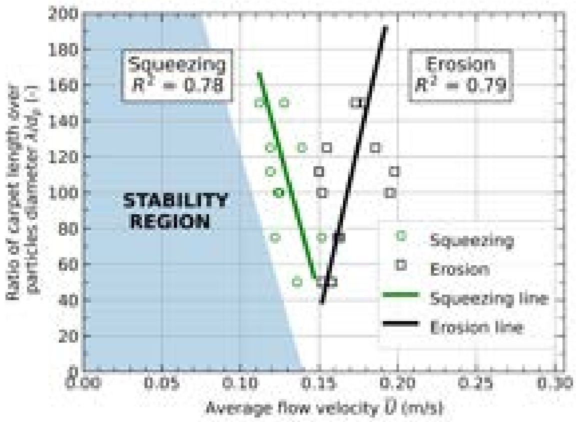

Figure 4: Stability region (blue light area on the left). Circles and squares are the observed values, while lines are the regressions of the observations.

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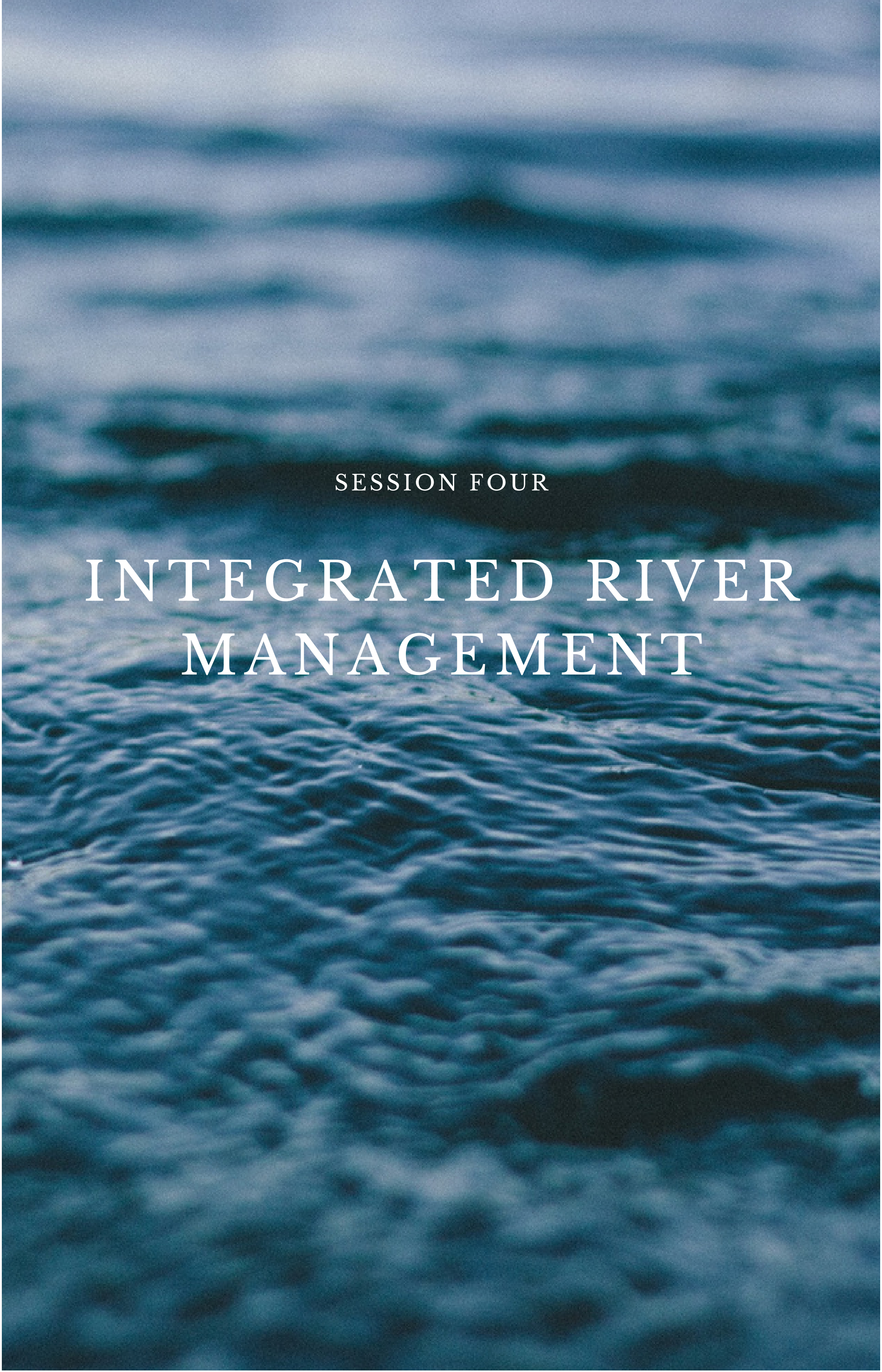

SESSION FOUR

INTEGRATED RIVER MANAGEMENT

Room for small rivers

Jantsje M. van Loon-Steensma[a,b*], Dan Assendorp[a], Bram van Leeuwen[a], Haydar Hussin[a], Gert-Jan van der Veen[a]

[a]*Van Hall Larenstein University of Applied Sciences (Velp, the Netherlands)*

[b]*Wageningen University and Research (Wageningen, the Netherlands)*

Keywords — Climate Adaptation, Nature-based Solutions

Introduction

The Netherlands has a long and established tradition of water management and flood protection that resulted in intensive use of drained and dike-protected areas (Ritzema and Van Loon-Steensma, 2018). The extreme events of 1993 and 1995 made clear that we may have over-managed our major rivers and that they need more space in view of future water safety. Since 2006, the government has actually created extra space for extreme amounts of river water within the 'Room for the River' program by widening and/or deepening the floodplains and creating side channels or spillway areas. This often simultaneously offers space for restoration or creation of various riverine habitats and for recreation along the major rivers.

Although since the 1970s several projects along small rivers and watercourses aim to restore their nature and landscape values (Stańczuk-Gałwiaczek et al. 2018) and to improve their water quality, there has not been much attention for the role of small rivers and watercourses in climate adaptation and mitigation. Recent weather extremes, however, underline that climate change also poses serious challenges for smaller rivers and watercourses. Local extreme precipitation can lead to flooding of such smaller rivers in both rural and urban areas resulting in nuisance and economic damage. Furthermore, small rivers and watercourses play an important role in the freshwater supply for agriculture and are pivotal for biodiversity, nature and landscape values in the rural area. Therefore, it is important to strengthen their natural adaptation potential and to optimize their capacity to store water during extreme precipitation and to overcome dry periods.

In addition, smaller rivers and watercourses are often directly connected to major rivers, lakes or estuaries, and could offer interesting additional or sequential nature-based flood protection options (Vogelsang et al. 2023).

We explore (in collaboration with local stakeholders) the potential of nature-based management of small rivers for climate adaptation: solutions for too much or too little water. 'Room for Small Rivers' from a climate perspective, with co-benefits for nature and biodiversity, sustainable agricultural use, a valuable landscape, and improvement of water quality.

Approach

We started with mapping (restoration) projects along three small rivers that were executed during the last decades (Fig. 1): Lauwers river (which originates in a lowland peat area and drains in former Wadden Sea estuary Lake Lauwers), Overijsselse Vecht (which originates in Germany and drains in Lake IJssel) and Linge river (which is entirely located in the Dutch riverine area).

Figure 1. Overview of projects in rivers Lauwers, Overijsselse Vecht and Linge

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Update of the Dutch Major Rivers Policy Guideline (Bgr)

(Roel Valkman[a], Louis Broersma[b], Hennie Roorda[c], Jeroen Doornekamp[d], Koen van Bezu[a], Rebecca Geurts[b], Martijn Steenstra[b], Roel Velner[b])
[a]*TwynstraGudde Postbus 907 3800 AX Amersfoort, Nederland*
[b]*Sweco Nederland BV Postbus 203, 3730 AE De Bilt, Nederland*
[c]*Ministerie van Infrastructuur en Waterstaat Postbus 20901 2500 EX Den Haag, Nederland*
[d]*Rijkswaterstaat Postbus 2232 3500 GE Utrecht, Nederland*

Keywords — National river policies, legal instruments, river management, climate adaptation, governance

Reason and purpose of the research

The Dutch Major Rivers Policy Guideline (in Dutch: Beleidslijn grote rivieren, in short: Bgr) is the legal instrument with which Rijkswaterstaat assesses third-party initiatives in the Dutch riverbed. This assessment involves a balance between, on the one hand, making spatial planning possible to a certain extent, and on the other hand, the protection of sufficient conveyance and storage capacity and the prevention of spatial developments that are harmful to the functioning of the river. In November 2022, the Minister of Infrastructure and Water Management (IenW) sent a letter (min IenW, 2022) to the Dutch Parliament containing: principles and structuring choices to make water and soil guiding principles in spatial planning. One of these structuring choices is 'no new buildings in the floodplains'. Following this letter, the ministry of IenW has updated the purpose of the Bgr in a more future-oriented manner: 'The new aim of the Bgr is to better manage spatial developments in the riverbed so that there is sufficient storage and conveyance capacity available for the river in the upcoming 100 to 150 years, the conveyance and storage capacity is increased where possible and significant damage caused by high water to objects or activities in the riverbed is prevented'.

Scope of the new Bgr and the report

An advisory report (TG/Sweco, 2023) on the necessary update of the Bgr, to the new purpose, has been released in the summer of 2023. The following principles, concerning the Bgr, were used in the advisory report:

• The function of the Bgr remains unchanged. The Bgr remains a legal instrument for assessing initiatives in the riverbed and does not become an instrument to actively create extra storage or conveyance capacity in the river system.

• The new purpose of the Bgr is also about preventing significant damage to objects and/or activities in the riverbed. However, it remains the case that initiators in the riverbed are themselves liable for damage and are responsible for taking measures to protect themselves against potential harm.

• A number of important decisions about the river system will be made in the coming years, for example in the context of the Integrated River Management (IRM) program and the Delta Decisions, expected in 2026. It is therefore expected that a new update of the Bgr will be required after 2026.

Method

To determine which adjustments to the Bgr are necessary, the current Bgr has been tested against: 1) Letter to Parliament on guiding principles Water and Soil, 2) autonomous developments in the river system, 3) policy developments and 4) lessons from current Bgr implementation practice. This assessment took place by means of a document study, interviews, case studies and working sessions with those involved. The research was carried out under the supervision of a committee with a broad representation of relevant stakeholders.

Findings

The assessment revealed the following points of attention when updating the Bgr. [1] The letter to Parliament states that no new buildings are permitted in the floodplains that fall under the Bgr legislation. The aim here is: whatever can be built behind an existing dike *must* be built behind the dike, not in the floodplains. This course is more cautious than the current Bgr, which, under certain conditions, offers room for building in the floodplains of the river. The Dutch government strives for a rapid legal anchoring of this new course in the Bgr. [2] Global warming causes sea levels to rise and higher peak discharges in rivers. The sea level rise has a backwater effect and will therefore also influence high water levels further inland. Studies with a forecast period up to 2050 and 2085 predict an increase in peak discharges of 10-15% in the Meuse and 10-20% in the Rhine.

* Corresponding author
Email address: roel.velner@sweco.nl (Roel Velner)
URL: www.sweco.nl or www.twynstragudde.nl

There are no finished studies with a time horizon of 100 or 150 years, but it is not unthinkable that peak discharges will increase further. These peak discharges will have to be dealt with in a river system that has evolved over the past centuries and has been given less and less space. As an illustration: since 1850, the space in the Rhine branches has been halved, mainly by construction of dykes. Research in the IRM program (Programma IRM, 2023) shows that for the tasks up to 2050, the currently available space in the floodplains for some river sections is insufficient. Whether the space in the current Barro reservations is sufficient, remains to be seen and is not clear at the moment. It is the subject of policy research for the purpose of tightening the IRM policy decisions in 2026. [3] Regarding policy developments: in the IRM program, the national government and stakeholders in different regions are working on an integrated vision on the Dutch rivers and floodplains. In the program new policy is developed to maintain and increase conveyance capacity. However, at the time of writing the report, this policy was not sufficiently worked out to translate into the updated Bgr and also aimed at the medium term (2050), while the new Bgr has a scope into the next 100 or 150 years. The recalibration of IRM 2026 identifies valuable areas for future river widening. That same year the revised Delta Decisions are also expected, based on the new KNMI climate scenarios (2023). In the Flood Protection Program (HWBP), water managers ensure that the primary flood defenses are updated to meet new standards ultimately by 2050. Since 2017, the standards for water safety *outside* the floodplains have been based on a flood risk approach. This involves looking at the probability of an event *and* its consequences in terms of victims and damage. This new approach for areas outside the floodplains contains opportunities for customization to the area within the floodplains of the Dutch rivers, because not only the probability of a flood can be influenced, but also the possible consequences. Possibly a flood risk approach can also be used to determine and assess risks in the riverbed. The Environmental Act (in Dutch: Omgevingswet) will come into effect on January 1, 2024. It is not yet completely clear how the Bgr policy rules for licensing will be incorporated in the Environmental Act. [4] Points of attention from the Bgr current implementation practice include dealing with acquired rights based on old permits, dealing with the temporary nature of some permits and limited enforcement afterwards, the stacked effect of small developments, and the complexity of the requirement that initiatives in the riverbed must ‘on balance' involve a lowering of high water levels (Article 6 in the current Bgr). In current Bgr implementation practice a coherent and more future-oriented assessment of initiatives is missed.

Proposals for adjustments to the Bgr

Based on the findings, it is proposed to adjust the Bgr on a number of points. These proposals for adjustment of the Bgr can be summarized as a provisional reduction of room for initiatives in the riverbed. With regard to new buildings the adjustments exercise restraint regardless of the location of the buildings in the riverbed. In addition, with regard to existing buildings, it is proposed to still offer development opportunities for the benefit of quality, liveability and vitality in the riverbed. The proposed adjustments are:

- Do not change the current boundaries of the spatial scope of the Bgr (for the time being).
- Implement one regime for the whole riverbed in which new non-river-related buildings are not permitted (instead of the multiple regimes in the current Bgr).
- Abolition of the policy rule that approves of activities that ‘on balance provide more space'. Because these extra activities can harm future possibilities to adapt the river system.
- Maintain rules for demolition and replacement of existing buildings and the rule on ‘ten percent expansion of existing buildings’.
- Avoid stacked effects of clusters of small initiatives that are individually small, but can have a relevant accumulated effect on the river.

Recommendations

The following recommendations are about what else is needed, in the long term, in addition to the above adjustments to the Bgr to maintain sufficient space for the river.

- Determine what space the river needs in the long term and determine valuable areas that need extra protection inside the floodplains.
- Draw up a development vision for the riverbed together with the regional area partners.
- Investigate the influence of the expected sea level rise on existing buildings in the floodplains.
- Investigate the integration of Bgr into the Environmental Act (in Dutch: Omgevingswet).
- Investigate the possibility of renewing old permits that are overly large.

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Long-term development of lowland rivers
Rivers2Morrow - a research program

Evelien van Eijsbergen[a] , Ralph M.J. Schielen [a]
[a] *Rijkswaterstaat, Ministry of Infrastructure and Water Management, P.O. Box 2232, 3500 GE, Utrecht, The Netherlands*

Keywords — Long-term trends, river morphology, river policy

Introduction

The National Delta program comprises a number of research lines that focus on the various water systems in the Netherlands. One of those research lines has been given the name Rivers2Morrow, and deals with rivers. Within this research program, work is being done to increase the system knowledge of lowland rivers with respect to hydraulics and morphology, as well as ecology and governance. The program focuses on developments that take place on a long temporal time scale until 2100, and sometime beyond). The results of this research can add to substantiate policy decisions and make the management and maintenance of rivers more effective and efficient. The research focuses on the effects of climate change, such as increased discharge, a changing discharge regime, sea level rise, and large-scale human interventions.

Policy themes

Rivers2Morrow focusses on policy questions concerning flood protection, navigability, freshwater supply and nature and water quality. R2M is in the centre of this complex interplay.

Figure 1. Policy themes of Rivers2Morrow.

Research themes

The eight PhD research topics within this program focus on: the supply of fine sediment from the Rhine basin, the stability of river bifurcations in the Rhine, the effects of climate change and sea level rise on bed level elevation of the Rhine Branches and the morphology of the Rhine-Meuse estuary, improved quantification of sediment transport, the dynamics of bed forms, sediment dynamics in the Rhine-Meuse estuary, and the sediment budget of the Meuse.

Within Rivers2Morrow 2.0 three new PhD studies will start in 2023 on sediment dynamics of groyne field beaches and a combined study on the ecological and morphological characteristics of the Common Meuse.

The research program also aims to improve morphological models to support various policy and maintenance decisions.
A synthesis report (Ten Brinke, 2020) present the research focus and questions from policy and management for all eight research themes in more detail, and illustrates this with informative infographics.

Organisation

The program is funded by the Ministry of Public Works and Watermanagement and Rijkswaterstaat. The universities of Twente, Wageningen, Utrecht, Delft and Nijmegen conduct the studies. The research will also make frequent use of the knowledge available at Deltares and specialized engineering firms.
Each researcher has his/her own supervision team consisting of expert users, varying from the government, engineering firm or regional stakeholder.

Results

Rivers2Morrow 1.0 has started in 2018 and will run until 2024. The first researches are finalised in 2023. River2Morrow 2.0 has started in 2023 and will run until 2029.
The studies contributes to the following programmes:

- Integrated River Management
- Knowledge Program Sea Level Rise
- Programmatic Approach to Large Water Systems

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ResiRiver - Mainstreaming and Upscaling Nature Based Solutions in North West European Rivers

Stanford Wilson[a*], Nils Rem[a], Ralph M.J. Schielen[a,b], and Yvo Snoek[a]
[a] *DG Rijkswaterstaat, Ministry of Infrastructure and Water Management, Utrecht, The Netherlands*
[b] *Faculty of Civil Engineering and Geosciences, Delft University of Technology, the Netherlands*

Keywords — Nature based solutions, assessment frameworks, international cooperation

Introduction

River managers today are faced with the challenge of adapting to climate change while also having to sustainably secure all important functions in a healthy river system for society. Nature-based Solutions (NbS) have proven themselves effective across a multitude of contexts; providing integrative approaches for river restoration, conservation and sustainable management, ensuring both climate change adaptation and contribute to climate change mitigation and biodiversity recovery for generations to come. NbS are multi-faceted and more importantly, they are effective when it comes to addressing complex societal challenges (e.g. reducing flood risk, increasing natural values and biodiversity, ecosystem services and human well-being), as they provide a novel, integrative and coherent approach. Despite the significant and rapidly growing base of scientific evidence regarding the effectiveness of NbS in riverine systems management, the actual uptake and application of NbS on a larger (EU) scale is still in its early phase. From where we stand today, a major barrier to the wider uptake and application of NbS in riverine systems remains (a) our limited experience in scaling solutions beyond their local contexts (so called 'Upscaling'), and (b) make Nbs as a standard work practice within water management organisations throughout North-West Europe (so called 'Mainstreaming'). Also, our lack of standardised methods for quantitative assessment and monitoring of ecosystem services and benefits related to NbS hinders replication and application at a wider scale.

The INTERREG ResiRiver Project

The Interreg North West Europe project ResiRiver (Creating Resilient River Systems by Mainstreaming and Upscaling Nature-based Solutions, see https://resiriver.nweurope.eu/) is a close partnership between local, regional and national water management authorities, municipalities, Ngo's in stakeholder engagement and universities from France, Germany, Ireland, Belgium and the Netherlands. ResiRiver aims to overcome the challenges related to the limited application of NbS by bridging the gap between practice, science, society and policy. This is done in three work packages (WP's, see also Figure 1). In WP1, we consider the individual pilots that vary in terms of geographical location in river systems and are subdivided into two broad groups; i) physical pilots and ii) study pilots and concentrate on enablers that lead to successful implementation of NbS, and on barriers that prevent that (Moons et al 2021). The first thing to do is to apply the IUCN Standard for Nature based Solutions (IUCN 2020, Berg 2022) to assess the current state of the pilots. In WP2, we will focus on training methods and training material, where we use the experience from the pilot studies as well as insights from previous projects. The training material is aimed at contributing to a firm base with respect to supporting NbS at the various levels (implementation, but also planning and policy) in the river management organizations that are part of the ResiRiver project. In WP3, we develop strategies, action-plans and guidelines that build upon existing material, to assess the pilot studies and quantify the NbS-co-benefits in those initiatives. This also results in writing policy-briefs at regional, national and European level, to influence policy on those different levels.

The project has had its kick-off last year (2023) and is currently working towards its overarching objective through several "large scale – learning by doing NbS pilots" in NWE rivers.

First Results

At this stage, ResiRiver's primary activities include: the development and execution of IUCN baseline assessment studies for all pilots; the design and improvement of specific NbS-technologies and the advancement of suitable frameworks schemes that serve to evaluate and monitor the effectiveness of proposed measures. Another important project-element, is the creation of hands-on training schemes and materials, based on the knowledge and experience gained from these pilots; which serve to support and inform not only the project partners, but also the river management community as a whole. Finally, in order to facilitate the mainstreaming and

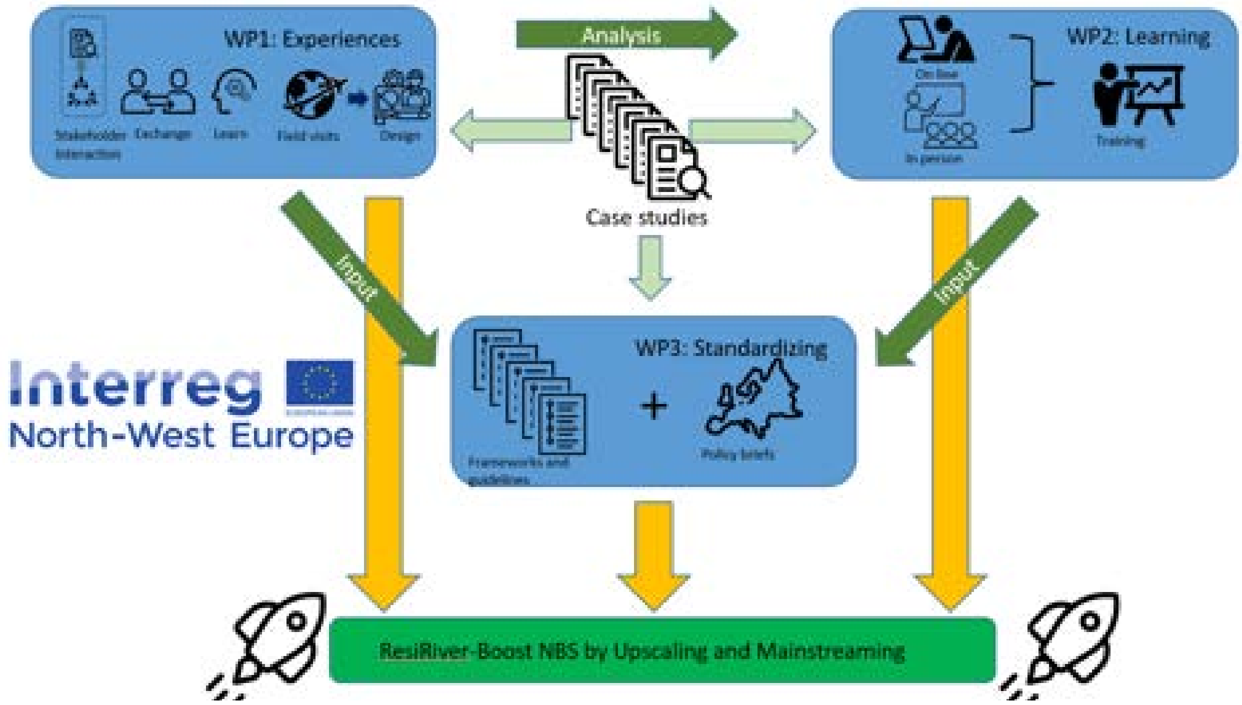

Figure 1: Graphical summary of ResiRiver, with the three WP's and the overall goal: Upscaling and Mainstreaming Nature based Solutions.

upscaling of NbS beyond local contexts in the future, ResiRiver aims to continually work on the improvement of existing frameworks and guidelines for NbS through experimentation and critical analysis. It's our ambition that our insights will be imbedded at relevant policy- levels and fields by actively contributing to the development of local, national and EU-based policy papers and guidelines. This may play a pivotal role in making NbS a standard measure for river restoration.

Next steps

Currently, we are making progress in assessing NbS activities at the 9 pilot locations of ResiRiver, using the IUCN self-assessment (IUCN 2020). This exposes certain shortcomings in the Standard, and we are developing initial ideas for extension of the Standard.
We are also developing preliminary ideas on how to effectively build a knowledge and training schemes to achieve mainstreaming and upscaling of NbS in riverine systems. Here, we make use of the concepts of Technical Readiness Level and Societal Readiness level, applied to the pilots, and use this to determine whether we need a societal pull or a technological push in order to help to make the next step in the application of NbS.
Lastly, we are using the scientific partners and associated partners in the project to set up a Science Team that takes up the scientific challenge to develop new concepts for mainstreaming and upscaling, based on the experiences in the pilots and the discussions in the various WP's. The newly developed concepts will be tested scientifically and published in journals, such that the knowledge is stored and can be used by the NbS-community.

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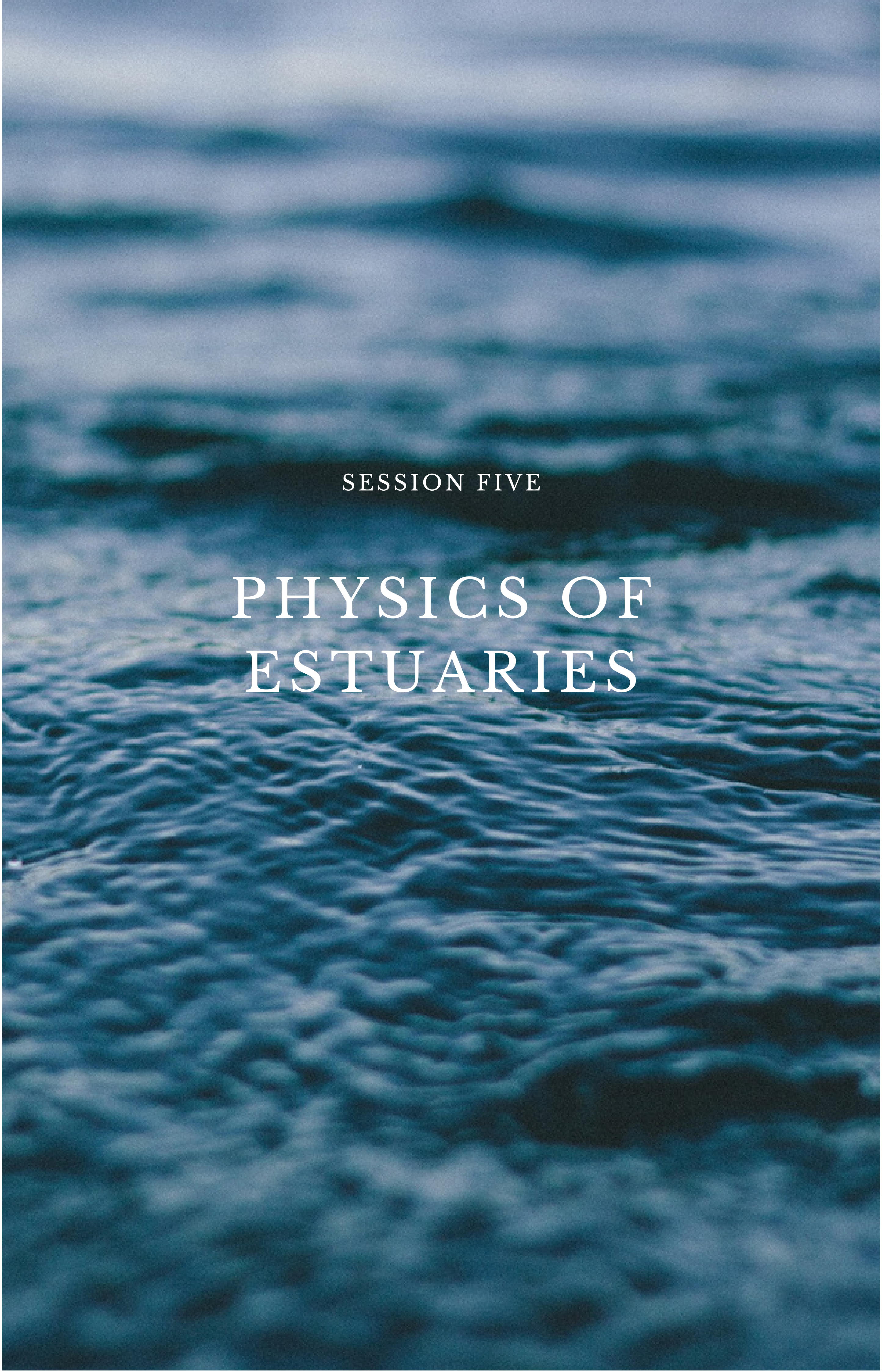

SESSION FIVE

PHYSICS OF ESTUARIES

Using an idealized network model as the physical module for a salt intrusion serious game

Robert-Jan den Haan[a*], Bouke Biemond[b], Fedor Baart[c,d]
[a] *University of Twente, Department of Design, Production and Management, Faculty of Engineering Technology, P.O. Box 217, 7500 AE, Enschede, the Netherlands*
[b] *Utrecht University, Department of Physics, Institute for Marine and Atmospheric research Utrecht, Utrecht, the Netherlands*
[c] *Deltares, River Department, Delft, Boussinesqweg 1, 2629 HV, Delft, the Netherlands*
[d] *Delft University of Technology, Section Ports and Waterways, P.O. Box 5058, 2600 GB, Delft, the Netherlands*

Keywords — Idealized modelling, Serious game, Salt intrusion, Climate change

Introduction

Salt intrusion is a growing problem in many deltas around the world. During periods with low river discharges, salinity upstream in a delta increases and affects freshwater availability, ecology, and other delta functions. For example, in the Rhine-Meuse estuary (the Netherlands), brackish water can reach drinking water intakes about 40 km from the estuary mouth during droughts. Salt intrusion is likely to become more severe in the context of climate change, as a result of sea level rise and a lower river discharge during droughts.

The challenges with salt intrusion for the Netherlands are addressed in the Salti Solutions research program. Within this program the Delta Management Game offers an interactive environment where policy-making stakeholders can experience salt intrusion management and experiment with adaptation and mitigation strategies in the Rhine-Meuse estuary. As a serious game, the goal is for players to *"learn by taking actions and by experiencing their effects through feedback mechanisms that are deliberately built into and around the game"* (Mayer, 2009, p. 825).

A particular design challenge for serious games is simplifying the environmental system and sufficiently representing the relevant physics, while offering exploratory and experimentation through (near-)instant, interactive feedback. The physical module for salt intrusion in the Delta Management Game should be able to deal with, among others, changes in bathymetry (e.g. depth or width of waterways, adding a sill) of the estuary in the game, while offering relatively quick feedback.

* Corresponding author (Robert-Jan den Haan)
Email address: r.j.denhaan@utwenter.nl
URL: https://people.utwente.nl/r.j.denhaan

Here, we addressed this challenge by developing a game demonstrator as a proof of concept, which uses the idealized network model of the Rhine-Meuse estuary and simplifies the estuary geometry to a regular grid.

Idealized network model

The physical module in the serious game is an idealized network model, which builds forth on the work of Biemond et al. (2023). This model solves the dominant physical balances for flow and salinity in an estuarine channel network. For the Rhine-Meuse estuary, 21 channels and 13 junctions are used.

Preliminary analysis has indicated that water levels, flow and salinity in the Rhine-Meuse estuary can to a satisfactory level be reproduced by the model. The runtime of the model is in the order of one second for a day simulation time, which meets the requirement of near-instant feedback required for the serious game. Moreover, the model setup allows for adjustments to geometry and forcing conditions.

Abstracting the Rhine-Meuse estuary

To use the idealized network model in the game, the physical system and its behaviour should be abstracted in such a way that it balances its playability with its representation of reality (Harteveld, 2011). For this, we looked to abstract the Rhine-Meuse estuary by transforming the relevant waterways captured in the network model to a regular grid. This way, players can apply adaptation or mitigation measures on different grid cells, while showing effects on the estuary system scale. To develop the demonstrator of the Delta Management Game, we extended the physical board used in The Virtual River Game (den Haan et al., 2020), which is a 143-cell hexagonal grid. We drew an equal number of polygons on a map of the Rhine-Meuse estuary to include the sea boundary at the Rotterdam Waterway, the Haringvliet, the river boundary to include the Hollandse IJssel, and downstream sections of the Lek, Waal and Meuse. We shaped the polygons in such a way that these aligned with either waterways or land and that each polygon shares the same neighbours of the hexagonal grid. This way, each polygon covering real-world coordinates has a corresponding hexagon in game-world coordinates. We subsequently mapped in which polygons the waterways in the network model are located and drew a corresponding network of waterways on the hexagonal grid. To do so, network junctions in specific polygons were positioned as midpoints of the corresponding hexagon. As a last step, we reprojected the real-world coordinates of the network model output locations of each waterway to the waterways drawn on the hexagonal grid. The result is an abstracted, grid-based representation of the Rhine-Meuse estuary, where chloride concentration output of the network model is transformed to game-world coordinates (Figure 1).

Integration

We present a proof of concept of the use of an idealized network model of the Rhine-Meuse estuary to include salt intrusion modelling in the Delta Management Game. The presented approach can be used with a different salt intrusion models and different grid layouts, making it suitable for game design and adaptable for finding the balance between the systems representation of reality and its playability.

Next steps

A next step in the development of the Delta Management Game is to evaluate the developed proof of concept with policy-making stakeholders. The evaluation goal is, among others, to determine a suitable grid layout that represents relevant estuary locations and offers in-game measures on these locations that adequately represent real-world policy options.

Another improvement is the inclusion of the recently released updated climate change scenarios and associated Rhine and Meuse discharge scenarios (Buitink et al., 2023), to include future climatic conditions in the game.

The proof of concept furthermore includes the working output interface between the model and game, visualizing chloride concentrations on the grid-based estuary. Further development of the grid as input to the network model is possible, e.g. that by changing the geometry of a grid cell the bathymetry of the corresponding waterway in the model is updated.

Finally, additional physical processes like storm surges can be added to the idealized network model.

Acknowledgements

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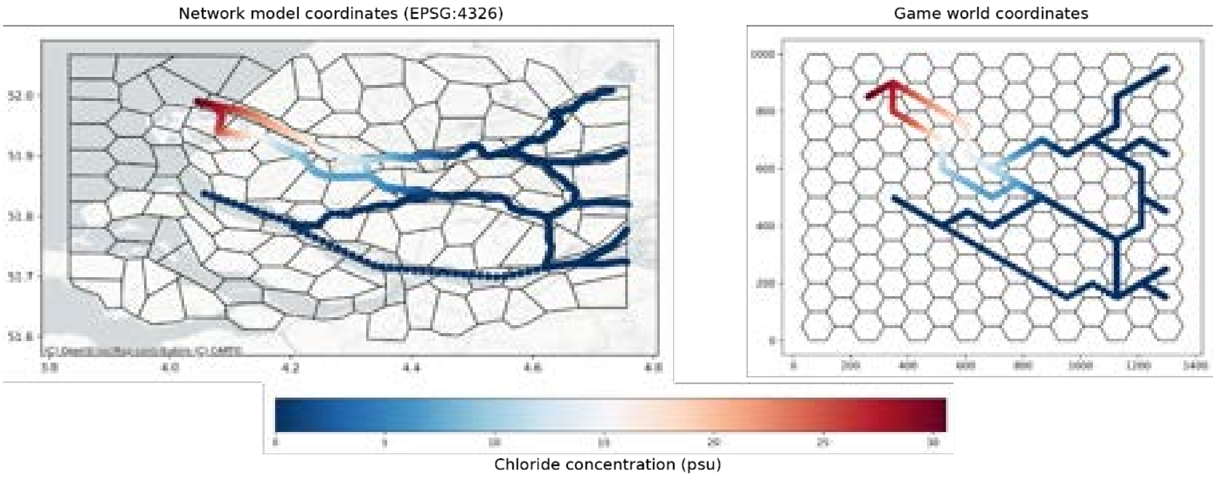

Figure 1. Chloride concentration values on one timestep at the Rhine-Meuse estuary network model output locations (left) and at their reprojected location on the hexagon grid-based game world (right).

Estuarine sand dunes as a nature-based solution against salt intrusion: an idealised morphostatic model approach

Sem J. Geerts[a,b,*], Wessel M. van der Sande[a], Suzanne J.M.H. Hulscher[a], Bernard J. Geurts[b], Pieter C. Roos[a]

[a] University of Twente, Department of Water Engineering and Management, Faculty of Engineering Technology, P.O. Box 217, 7500 AE, Enschede, the Netherlands

[b] University of Twente, Mathematics of Multiscale Modelling and Simulation (3MS), Faculty of Electrical Engineering, Mathematics and Computer Science, P.O. Box 217, 7500 AE, Enschede, the Netherlands

Keywords — Estuarine Sand Dunes, Salt Intrusion

Introduction

Saltwater intrusion in estuaries can pose a critical issue as it potentially leads to a shortage of fresh water. In turn, this can have significant implications for human activities such as industry, agriculture and drinking water extraction; also it can be unfavourable for environmental sustainability. The intensity of salt intrusion is influenced by various factors, of which freshwater river flushing and the amount of vertical transport are key predictors (*Geyer & MacCready*, 2014).

This study investigates the impact of estuarine sand dunes, bedforms with heights in the order of meters and lengths of tens to hundreds of meters (*Zorndt et al.*, 2011), on salt intrusion. Estuarine sand dunes potentially increase the net vertical flux, by an increase in turbulence, tide-averaged circulation cells and resonant internal waves, and, as such, likely reduce the salt intrusion length. We investigate the complex dynamics of estuarine salt transport and determine the potential of estuarine sand dunes as a nature-based solution against salt intrusion.

Methods

We investigate the influence of estuarine sand dunes on salt intrusion using an idealised morphostatic model with 2DV geometry. This enables us to specifically study the effect of vertical flow behaviour without possible interference from other estuarine processes. The model is designed to investigate estuarine systems that can be approximated as a single-channel estuary with relatively uniform geometry. In this study, model settings are based on the Rotterdam Waterway (RWW), the Netherlands, with a length of 50 km and mean depth of $h = 15$ m. Only the M2 tidal constituent with an elevation amplitude of 1 m is imposed as a seaward boundary condition. With an inflowing river velocity of 0.1 m/s, these settings are representative of summertime conditions in the RWW, when salt intrusion is most extreme.

Using this model, we focus on two dune configurations that are visualised in Fig. 1: we (a) vary the dune characteristics (such as dune height H_d, dune length λ_d and asymmetry) while keeping the mean water depth equal, and (b) vary the height of the dunes while keeping the navigable depth equal, which would be a situation in which dunes are artificially dredged. We seek a dynamic equilibrium of the system with the tide. We determine the influence of bathymetric changes on the salt intrusion length $\langle L_s \rangle$, which is defined as the tide-averaged distance from the seaward end where the maximum concentration over the water column equals 1 ppt.

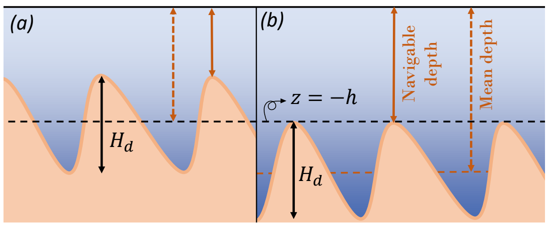

Figure 1: Schematisation of (a) sand dunes while keeping mean water depth equal and (b) ensuring a navigable depth for equal dune height H_d.

The model is implemented in Delft3D-FLOW, and the RANS equations model the flow and salt transport under the hydrostatic assumption. Turbulence is modelled by the k-ϵ model. We use 40 non-equidistant vertical layers and a horizontal grid cell width of 10 m. A numerical convergence study shows robust numerical convergence; a negligible accuracy improvement of the model output is achieved with subsequent grid refinement. Furthermore, the discretisation and model parameters effectively capture most of the flow, salt transport behaviour, and turbulent eddy diffusivity representative of field measurements of the RWW (*de Nijs et al.*, 2010).

*Corresponding author
Email address: s.j.geerts@utwente.nl (Sem J. Geerts)

Results

Across all model runs, the system stays partially mixed and the presence of estuarine sand dunes does not qualitatively change the horizontal transport mechanisms. The estuarine circulation and river flushing are the dominant transport processes, which is also the case for the RWW (*Dijkstra et al.*, 2022). We discuss the influence of both sand dune configurations as depicted in Fig. 1 separately.

(a) Firstly, an increase in dune height enhances vertical transport, bringing more saline water upwards through the water column, which reduces the salt intrusion length significantly, as shown in Fig. 2. Similarly, a decrease in dune length (not shown here) increases the dune slope and enhances the vertical exchange. However, the influence on the change in salt intrusion is not of the same order of magnitude for the dune lengths evaluated (50 m to 250 m). Dune asymmetry has a negligible influence on our model results, potentially a result of the hydrostatic assumption.

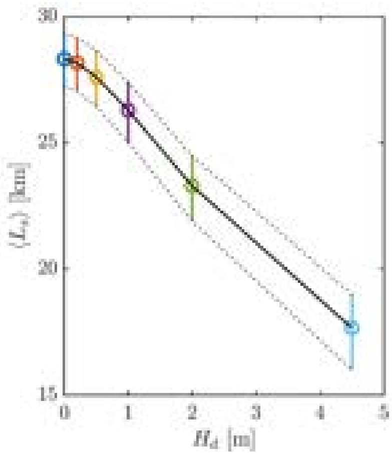

Figure 2: Influence of dune height H_d on the salt intrusion length $\langle L_s \rangle$ with dune length $\lambda_d = 100$ m for fixed mean water depth (Fig. 1(a)). Solid vertical lines indicate the excursion over the tide.

(b) Fig. 3 shows that small dredged dunes ($H_d < 1.2$ m) increase the salt intrusion. However, when dunes are dredged deep enough, sufficient advective vertical mixing is generated to counteract the adverse effects of channel deepening that is introduced.

A vertical salt flux decomposition on the model output shows that changes in dispersive transport, i.e. by turbulence and diffusion, are negligible for different sand dune configurations. In this hydrostatic model, sand dunes mainly change the subtidal vertical advective transport. Generally, the salt intrusion length is inversely proportional to the mean amount of vertical mixing throughout the region of stratification for all model runs, which, in turn, largely depends on the sand dune dimensions.

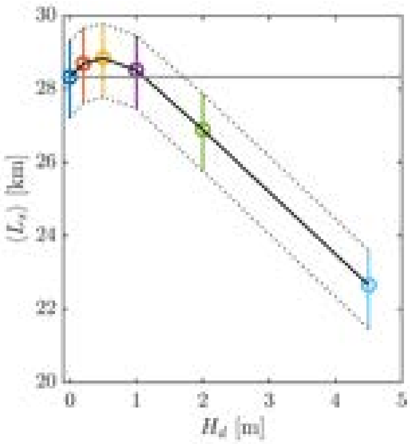

Figure 3: Influence of dune height H_d on the salt intrusion length $\langle L_s \rangle$ with dune length $\lambda_d = 100$ m while maintaining a navigable depth (Fig. 1(b)).

Conclusion

Dredging practices that increase the mean water depth and weaken vertical variations of the bed increase salt intrusion. An increase in sand dune steepness (H_d/λ_d) increases vertical advective mixing which reduces salt intrusion and can overcome the adverse effect of channel deepening. In this way, estuarine sand dunes can likely serve as a nature-based solution to mitigate salt intrusion without changing accessibility to seaports.

Acknowledgements

This work is part of the Perspectief Program SALTISolutions, which is financed by NWO Domain Applied and Engineering Sciences in collaboration with private and public partners.

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Asymmetric mixing as a driver of residual sediment transport in an estuarine channel

I. Niesten (Iris)[a,*], Y. Huismans[b], A.J.F. Hoitink[a]
[a]*Hydrology and Environmental hydraulics, Environmental Sciences Group, Wageningen University*
[b]*Applied Morphodynamics. Marine and coastal systems, Deltares*

Keywords — Sediment transport, Estuaries, Internal asymmetry

Introduction

The bed stability of an estuary is largely controlled by the net import or export of sediment, which is in turn controlled by multiple processes. Apart from the upstream riverine supply, the net sediment flux is largely controlled by tidal hydrodynamics and the associated sediment exchange with the sea. The main mechanisms leading to sediment import are well described by Burchard et al. (2018) and include gravitational circulation – characterized by a landward directed flow near the bed due to a longitudinal salinity gradient – and flood-dominant tidal asymmetry, characterized by a shorter flood duration with strong currents in flood direction. In general, flood dominancy favours sediment import, whereas ebb dominancy favours sediment export (Guo et al., 2014).

The prediction of residual sediment transport in estuaries is further complicated by variations in the vertical density structure. Simpson et al. (1990) describe how tidal straining leads to de-stratification during flood and increased stratification during ebb, resulting in a landward salt flux. Analogously for the sediment flux, Scully and Friedrichs (2003) attribute the landward sediment flux in the York River Estuary to vertical mixing being suppressed by a stable pycnocline formed during the ebb tide. During flood tide, sediment mixes higher in the vertical, resulting in a large landward transport capacity.

While descriptions of systems with flood-dominant mixing are abundant in literature, some estuaries show an opposite behaviour. In these cases, the flood tide stabilizes stratification, while the ebb tide destabilizes the water column, a phenomenon typically observed in strongly stratified systems. The impact of this ebb-dominant mixing in more stratified systems on the residual sediment flux however is less well studied. Our study aims to assess the impact of ebb-dominant mixing on residual sediment transport. This is crucial as ebb-dominant mixing may contribute to sediment export while a stronger gravitational circulation favours sediment import.

Methods

We set up a field campaign in the New Waterway, The Netherlands. We carried out two full 13-hour measuring campaigns: one covering a neap tidal cycle and one covering a spring tidal cycle. Continuous velocity and backscatter profile data were collected using a vessel-mounted ADCP over a longitudinal trajectory of 3 km. Two measuring locations were defined at the end points of the longitudinal trajectory. At both measuring locations, hourly casts were carried out collecting salinity, turbidity and sediment concentration data over depth. ADCP velocity data are analysed with the recently developed method of Jongbloed et al. (2023), which removes turbulence and noise with a physics-based approach and therefore

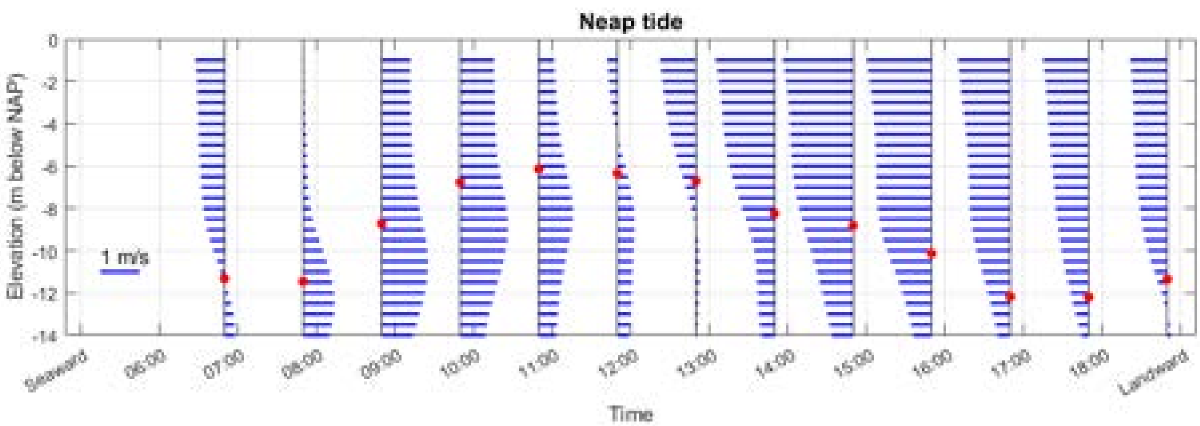

Figure 1: Hourly flow velocity profiles (neap tidal cycle only). Dots indicate the height of the pycnocline.

* Corresponding author
Email address: iris.niesten@wur.nl (I. Niesten)

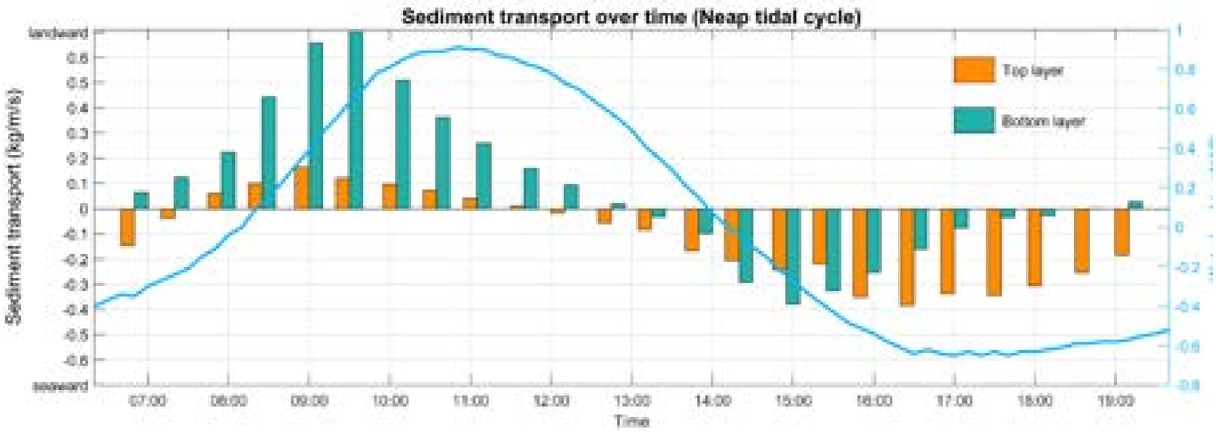

Figure 2: Transect-averaged sediment transport over time (neap tidal cycle only). While the maximum instantaneous transport rate is directed landward, the period of seaward transport is longer and suspended sediment is more evenly distributed over the top and bottom layer during ebb. For reference, the water level is plotted on the right y-axis.

allows for more accurate estimates of velocity gradients and shear.

Results

The collected data provide a clear overview of the tidal and sediment dynamics. Both the neap and spring tidal cycle are clearly flood dominant (Figure 1), with high near-bed flood currents and a long ebb period. During both tidal cycles, the pycnocline (height of the maximum vertical salinity gradient, separating the lower saline layer from the upper fresh water layer) is highest during flood while it lowers during ebb. During the flood phase of the neap tidal cycle, the density stratification is stable and suspended sediment is mostly confined in the saline layer below the pycnocline (Figure 2: 08:00 – 11:00). During the ebb phase, however, the pycnocline lowers and interacts with the bottom boundary layer, leading to a collapse of the salt-wedge structure, and sediment is mixed higher into the vertical (Figure 2: 14:00). The stratification during the spring tidal cycle shows a similar pattern, but the degree of mixing varies more strongly. Again, vertical exchange is at its minimum around high water. Around maximum ebb, bottom-induced turbulence increases which leads to a break-up of the salinity structure. The water column then remains well-mixed during the long period of low water slack and the start of flood.

During both tidal cycles, suspended sediment is mostly confined to the lower layer during flood, due to stable salinity stratification. Vertical mixing leads to a higher sediment transport height during ebb. Although the instantaneous maximum sediment flux in flood direction exceeds the flux in ebb direction (Figure 2), the period of ebb transport (7-8 hours) is much longer than the duration of the flood (5 hours). Both the tidal duration asymmetry and the mixing asymmetry favour sediment export in the New Waterway, resulting in a residual seaward sediment flux in the measured area and for the existing tidal and discharge conditions.

Discussion and conclusions

We found that the residual sediment flux in the New Waterway is directed seaward. This is in spite of its flood dominant tidal character and strong gravitational circulation. We infer internal asymmetry (ebb-dominant mixing) and the long duration of ebb are the main drivers of the seaward residual sediment flux. These results correspond to the findings of Scully and Friedrichs (2003), who found that flood-dominant mixing leads to a landward residual flux in the York River Estuary.

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Experimental assessment of topographic forcing in sandy estuaries

Eise W. Nota[a], Maarten G. Kleinhans[a]
[a]Utrecht University, Department of Physical Geography, Faculty of Geosciences, Princetonlaan 8a, 3584 CB, Utrecht, the Netherlands

Keywords — Estuary, morphology, topographic forcing

Introduction

Sandy estuaries commonly consist of dynamic braided channel networks, where fluvial and tidal currents are driving mechanisms for channel and sandbar migration. Ideally, sandy estuaries have planforms that that converge landwards exponentially, allowing for free shifting of sandbars and channels in the upstream and downstream directions (Leuven et al., 2018-a; 2018-b). However, many estuaries deviate from this ideal shape due to either geological confinements or human engineering for coastal protection or economic purposes of maintaining ports and shipping routes. Such natural or human made confinements can locally suppress the migration of sandbars and scour holes, resulting in topographic forcing of estuarine morphology. Topographic forcing has been studied for both rivers (e.g. Seminara, 2010; Schuurman et al., 2013) and estuaries (Leuven et al., 2018-a; 2018-b). For estuaries, it is still limitedly understood how morphological patterns are shaped by topographic forcing due to a lack of sufficient spatial and temporal data. This study aims to enhance the knowledge of topographic forcing in estuaries through scale experiments of sandy estuaries in the periodically tilting flume, the Metronome (Kleinhans et al., 2017).

Methods

The Metronome is a 20 by 3 m flume with a mobile sand bed and water depths up to a few centimetres. Using a tidal cycle period of 40 seconds, the Metronome imposes reversing shallow flow which results in self-formed channel-bar patterns. Earlier work showed that the dimensions of these patterns normalized by local width, scale the same as in natural estuaries. Further information on the functioning and scaling of the Metronome is addressed in Kleinhans et al. (2017).

We conducted several experiments of scaled sandy estuaries with various configurations of fixed banks of rough sandpaper and initial flat beds of mobile sand. We group our conducted experiments as follows (Fig. 1).

- Initial control run of a straight 54 cm wide channel without fixed banks.
- Initial condition of a straight 54 cm wide channel, where banks are fixed after 2000 cycles of natural bank development.
- Initial condition of a linearly converging planform from the seaside to the riverside with fixed banks and a sea outlet of 1.8 m wide.
- Initial condition of a linearly converging planform from the seaside to the riverside with fixed banks and a sea outlet of 3 m wide.

For each experiment, at least one repeat experiment was conducted under the same initial conditions. Moreover, several pilot runs were conducted with initial perturbations of various size applied to the flat bed to study whether they would affect the patterns of topographic forcing observed in the main experiments. All experiments were run until morphological development reached the flume's sea boundary, which is typically around 22,000 cycles for experiments with fixed banks.

For each tidal cycle, time-lapse imagery is collected by 7 overhead cameras, allowing for video imagery of morphological development and blue-dyed water. Moreover, after each run of around 500-1000 cycles, orthophoto imagery (Fig. 1) and Digital Elevation Models from a line laser scanner (horizontal accuracy of 3 mm) were acquired. Finally, Particle Image Velocimetry and water surface elevation measurements from 3 acoustic distance meters were conducted at specific moments for determining hydrodynamics.

Results and discussion

We observe the development of topographically forced channel scours and sandbars that also emerge in repeat experiments. This occurs mostly in the scenario with fixed banks of the naturally developed planform, but surprisingly also for the scenarios with the fixed linearly converging banks, where this is not expected due to a lack of alternating wider and narrower sections. Furthermore, all experiments show quasi-periodic formation and disappearance of sandbars and channels that are not topographically forced. For the configuration of fixed naturally formed banks, we observe a channel network which rapidly shifts between three stable states, suggesting that a mechanism of coupled oscillators may be involved in sections of the system morphodynamics. However, the periodicity of this quasi-cyclic behaviour varies substantially between repeat experiments, which implies complex system dynamics depending on initial conditions.

Conclusions

Fixed banks in laboratory estuaries cause patterns of topographic forcing that correspond between repeat experiments, even with linearly converging banks. The periodicity of observed quasi-cyclic behaviour of non-forced sandbars and channels is not repeatable, implying that there is a degree of chaos in the system. This provides challenges for numerical modelling and field observations of morphology in natural estuaries.

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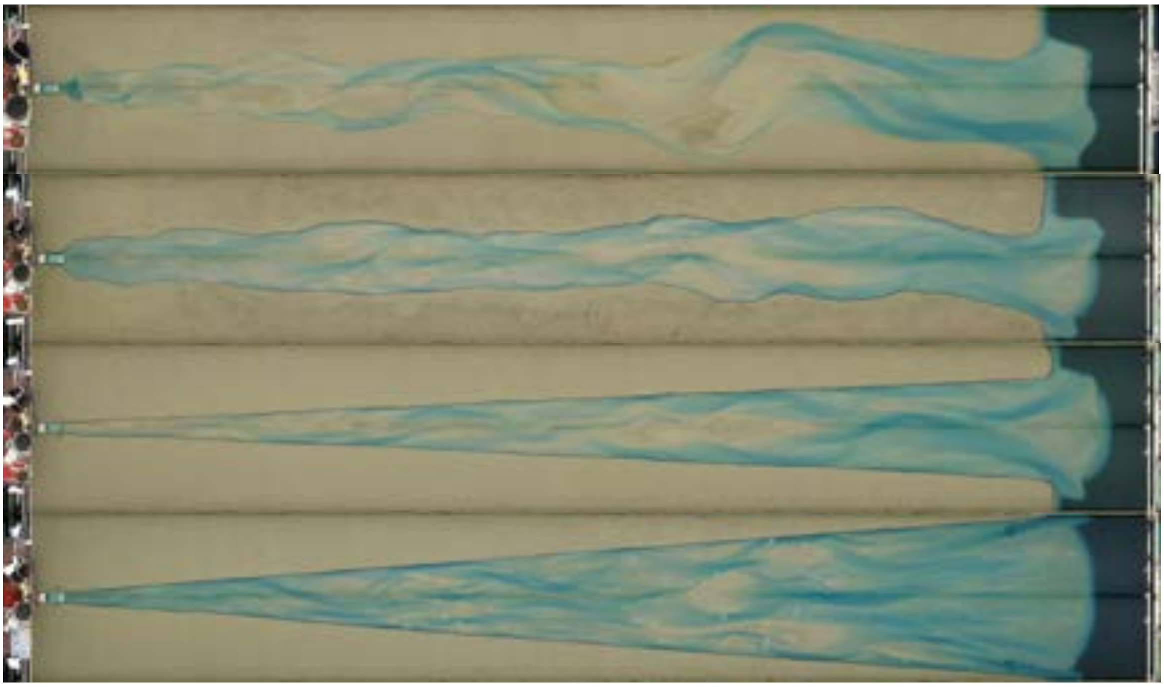
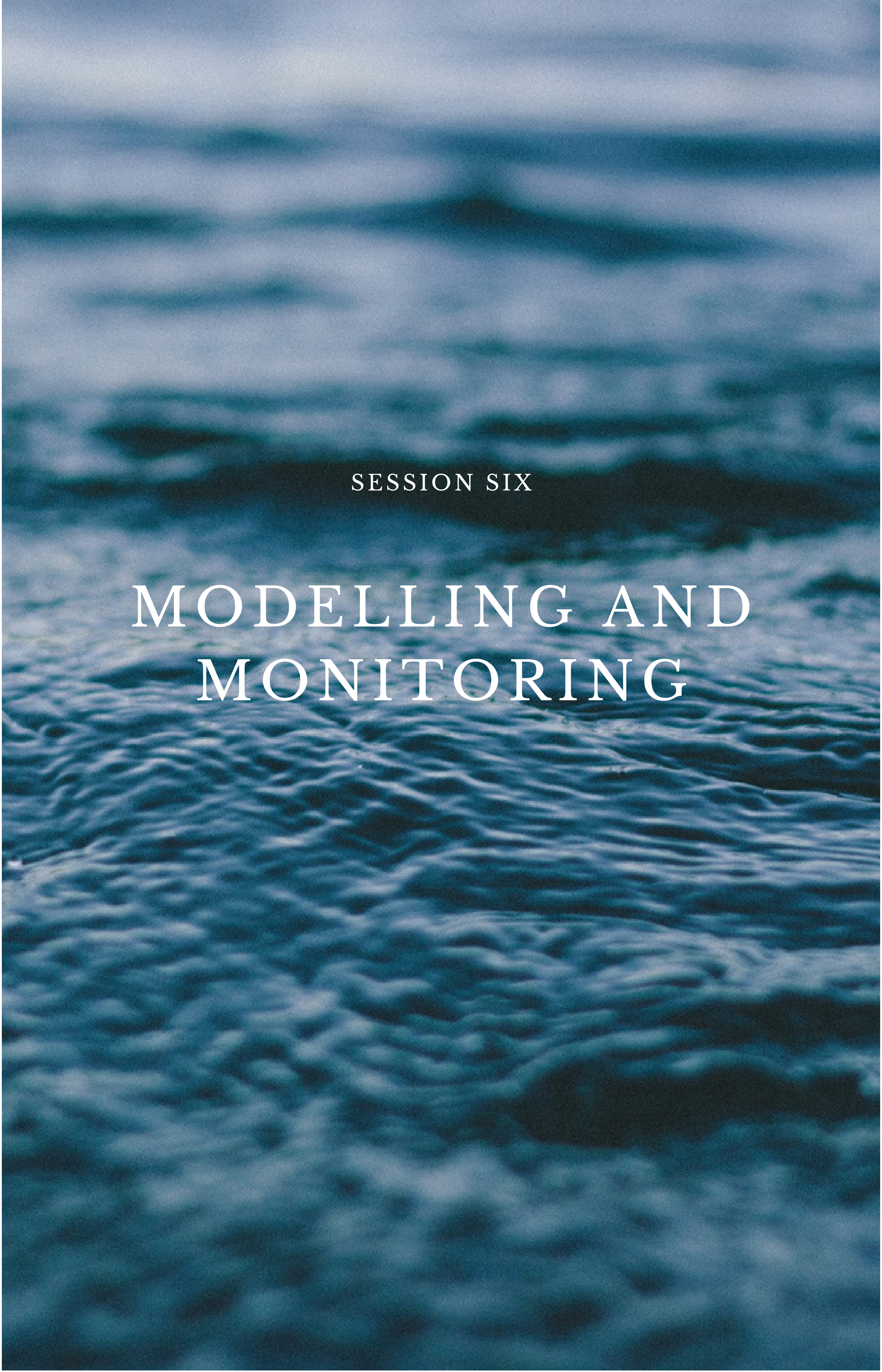


Figure 1. Orthophoto imagery of specific cycles of Metronome experiments displaying the different bank configurations of the experiments conducted in this study.



SESSION SIX

MODELLING AND MONITORING

Improving mesh set-up to increase accuracy of discharge capacity representation for water level prediction

Parisa Khorsandi Kuhanestani[a,*], Anouk Bomers[a], Martijn J. Booij[a], Jord J. Warmink[a], Suzanne J. M. H. Hulscher[a]

[a]*University of Twente, Department of Water Engineering and Management, Faculty of Engineering Technology, P.O. Box 217, 7500 AE, Enschede, the Netherlands*

Keywords — Hydraulic modelling, Mesh, resolution, Bathymetry, Numerical modelling

Introduction

Accurate prediction of river water levels is crucial for various environmental applications, including flood and drought prediction, as well as river management and infrastructure planning. Hydraulic modeling software, particularly 2D models, offers detailed simulations compared to 1D models (*Bomers et. al*, 2019). However, ensuring high accuracy in simulations remains challenging due to uncertainties in model inputs such as mesh set-up and bed roughness (*Warmink et al.*, 2011). The mesh set-up, encompassing cell size, shape, and node elevation allocation, significantly influences 2DH model accuracy (*Bilgili et al.*, 2023).

While a higher mesh resolution improves accuracy, it increases computational time and may not be efficient for large-scale rivers (*Bomers et. al*, 2019). This study aims to reduce mesh-related errors and enhance water level predictions in low-resolution mesh setups. An algorithm is developed to modify the mesh by adjusting the mesh nodes elevation to obtain a cross-section with an equal volume as the high-resolution one. Subsequently, hydraulic simulation of water levels is done to evaluate the performance of the modified low- resolution mesh.

Method

Material

As case study, the Waal River, a branch of the Rhine in the Netherlands is selected. Four hypothetical river with different cross-sectional structure types are used to isolate the impact of natural complexity on simulated water level. The four hypothetical rivers, three single cross-section rivers and a combined cross-section river are depicted in Figure 1.

Each of the single cross-section rivers is designed by replicating one of the Waal River cross-sections for 100 km to isolate boundary effects, creating a geometrically simple river. The selection is based on the graphical shape of the cross section to ensure representation of various cross-section complexities.

The combined Cross Section River is designed by gradually changing between the used cross sections in the previous step.

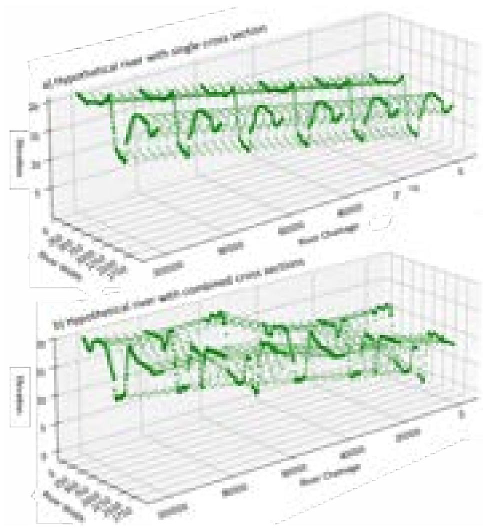


Figure 1: Hypothetical river with a) single cross section and b)combined cross section.

Mesh modification method

The mesh modification process developed a Python algorithm to ensure that the coarser mesh maintained the same flow volume as the high-resolution mesh representing the bathymetry measurements by altering the elevation of mesh nodes bellow each specific water level in all section.

Simulations

The hydraulic simulations aimed to evaluate the impact of the modified low-resolution mesh setup on simulated water levels compared to high-resolution and standard low-resolution meshes across varying discharge levels in hypothetical rivers. D-Flow-FM software (version 2021.03) was used for flow simulations, solving the 2DH shallow water equations. The hydraulic model considered river geometry,

*Corresponding author

Email address: `p.khorsandikuhanestani@utwente.nl` (Parisa Khorsandi Kuhanestani)

URL: `www.utwente.nl` (Parisa Khorsandi Kuhanestani)

cross-sectional profiles, bathymetry, and mesh setup. Hypothetical river stretches were used, employing three mesh setups: high-resolution (10 m x 10 m), low-resolution, and modified low-resolution (both 40 m x 40 m, commonly used for the Waal River in existing literature). In total, 84 simulations were conducted, considering seven different discharge levels from low to high levels. This comprehensive approach aimed to assess the modified mesh performance under various conditions.

Results

In Figure 2, water levels for four hypothetical rivers are shown at the model's equilibrium state, and averaging along the river in parts without influence of the boundary conditions. The assumption is that high-resolution mesh-simulated water levels align with real-world observations. Overall, the results indicate favorable performance of the modified low-resolution mesh set-up, with water levels closely resembling high-resolution simulations, especially in single cross-section rivers. The water level improvement which could be related to decrease in differences with high resolution mesh set-up results, varied for each river with the specific bathymetry, influenced by the bathymetry of the rivers. For the combined river, which incorporates all cross sections, the improvements were smaller than for each single cross section river, but still demonstrated improvement.

Conclusion

In conclusion, the implementation of a modification algorithm significantly improved the accuracy of volume predictions, leading to enhanced water level simulations for various discharges for hypothetical rivers. The algorithm is applicable to any river type, using any 2D hydraulic modeling software, potentially reducing the need for extensive calibration efforts.

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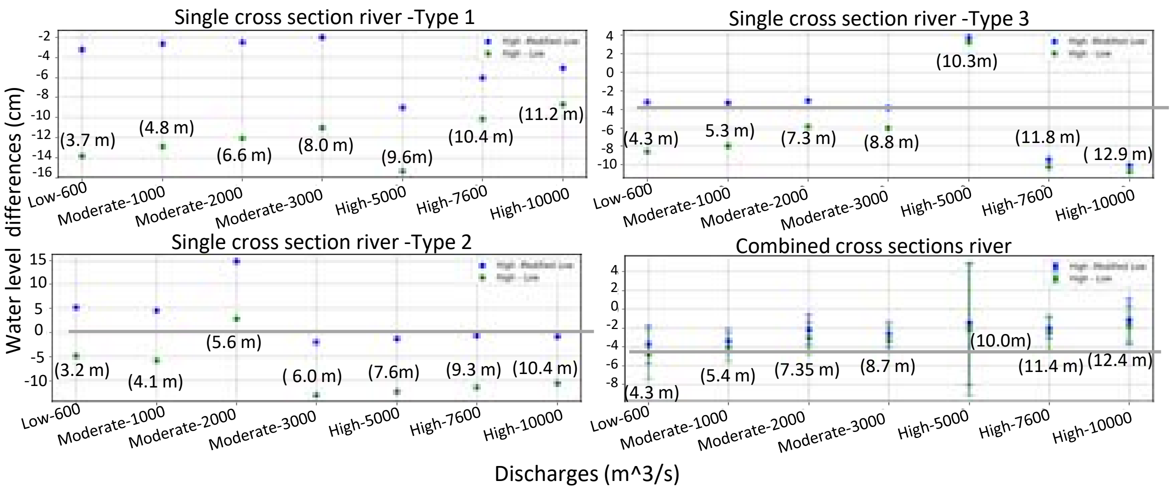

Figure 2: Water level improvement, The blue points represents the difference between the water levels simulated by the high-resolution mesh and the modified low-resolution mesh (WL_H-WL_{ML}), while the green points illustrates the difference between the water levels simulated by the high-resolution mesh and the low-resolution mesh (WL_H-WL_L).

Fast computation of dike breach growth and outflow

Leon S. Besseling[a], Anouk Bomers[a], Jord J. Warmink, Suzanne J.M.H. Hulscher[a]
[a] *University of Twente, Department of Water Engineering and Management*
P.O. Box 217, 7500 AE, Enschede, the Netherlands

Keywords — dike breach, surrogate model, real-time flood forecasting

Introduction

Dike breaches are a risk along many major rivers. When a breach occurs, the rapid outflow of water from the river to the hinterland can have severe consequences for both people and economic activities. A contributing factor to the danger is the fact that these events are often unexpected, and that timely warning and evacuation are key to limit the consequences.

A driving factor in dike breach severity is the flood volume that enters the hinterland. Ultimately, the volume is determined by the water level difference that occurs across the breach. With high river water levels compared to the hinterland water level, the breach will grow quickly and outflow will be high. If the river water level is comparable to the hinterland water level, the breach will grow slowly and outflow will be lower.

To map the consequences of dike breaches, hydrodynamic models with a 1D part for the river and a 2D part for the hinterland are often used. However, these models are time-consuming and not applicable during an emergency for scenario analysis. Therefore, faster ways to compute the breach outflow and corresponding flood volume are evaluated in this study.

Methodology

We create a simplified model that computes the breach outflow during a flood event. The model forcing is the discharge at Lobith, close to the Dutch-German border. The model computes the river water level that occurs at a possible breach location. As soon as the water level exceeds a predefined critical threshold, a breach occurs and inundation of the hinterland starts. The water level difference between the hinterland and the river are the further drivers of breach growth and breach discharge. We discuss each of these steps below.

River water level & breach threshold

A river discharge wave is used as a forcing at Lobith. Using QH relationships available for every dike segment along the Dutch Rhine branches, the water level at a segment of interest is computed. The travel time between Lobith and the considered dike segment is not taken into account.

The breach threshold is defined as a critical water level. Fragility curves for each of the dike segments for piping, macro-stability and overtopping are used. These fragility curves are uncertainty distributions expressed with a mean and a standard deviation. Sampling from the distribution gives a critical water level, which triggers a breach as soon as the river water level reaches this threshold. With repeated sampling, this approach allows for a probabilistic analysis of breach outflows.

Breach growth

The breach growth is modelled using the Verheij-van der Knaap equation (Verheij, 2003). This equation is driven by the difference in water levels of the river and the hinterland: steeper water level gradients result in faster breach growth.

The breach discharge is driven by the water level difference, as well as the dimensions of the breach. The broad-crested weir equation is used to compute the breach discharge (Visser, 1998).

Hinterland water level

The hinterland is schematized as a 0D storage area. The inflow volume is spread across the area evenly, leading to a steady increase in water level in the hinterland. Calibration of the area in km^2 is required, since the rise rate of the hinterland water level is a determining factor in how fast the breach outflow diminishes. The calibrated values do not relate to the actual area of the case study.

Preliminary results

Through initial testing, it was found that the model performs well for breach locations where the hinterland water level barely affects the breach outflow. This is in areas where the water is free to flow into a large polder area. For locations where the water encounters obstacles in the hinterland, the area parameter needs to be calibrated using a hydrodynamic simulation.

* Corresponding author
Email: l.s.besseling@utwente.nl (L.S. Besseling)

A breach location along the IJssel river in the Netherlands is shown as a case study. This location is near the town of Loo, and the breach occurs at the peak of the river discharge wave around day 16. A hydrodynamic simulation of a breach in a D-Hydro model of this area is used to calibrate the model. After calibration, the area parameter for this location has to be set at 6000 km^2, because a large volume can enter before the hinterland water level affects the breach at this location.

Figure 1 shows reasonable agreement between the models, with the simplified model performing within 10% of the DHydro model results. Especially the breach width is reproduced highly accurately by the simplified model.

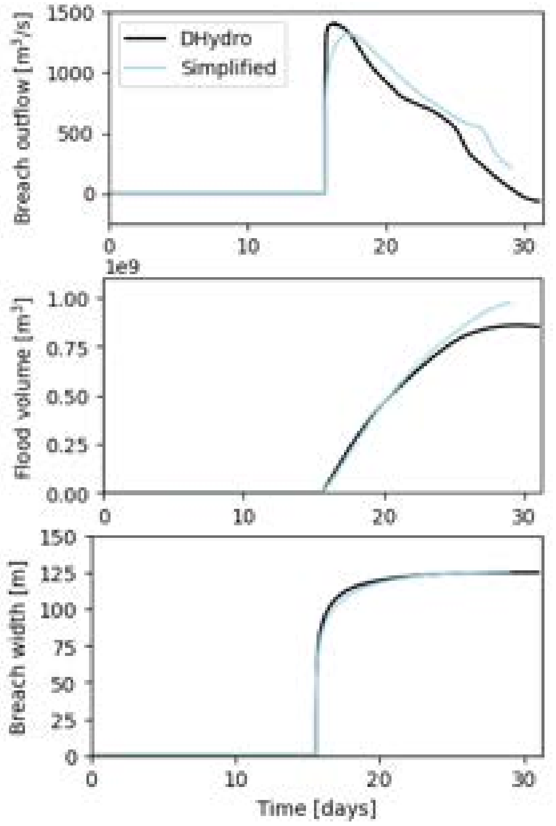

Figure 1. Model outputs of breach outflow, flood volume and breach width for DHydro and the simplified model.

Probabilistic breach initialization

A large benefit of the simplified approach is the computation time: the D-Hydro model completed the 30 day simulation period in 18 hours, while the simplified model runs for 0.1 seconds on the same computer.

The low computational cost of the simplified model allows for repeated simulations of this event with different moments of breaching. For each simulation, a new critical water level is drawn from the fragility functions for piping, macrostability and overtopping. The lowest water level from these three distributions is picked as the breach threshold.

Figure 2 shows preliminary results of the effect of the breaching moment to the breach discharge. For earlier breaches we see lower peak breach outflow, because the hinterland has already filled up slowly. This means that when the peak of the river discharge wave passes, the water level difference between river and hinterland is smaller, and a lower peak breach outflow occurs.

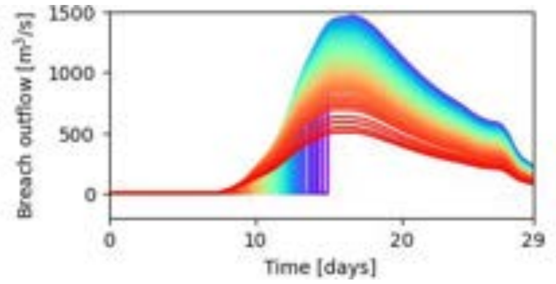

Figure 2. Breach outflow for varied breaching moments.

Conclusions and future steps

The current simplified model performs well in areas where the breach is not quickly affected by the rising hinterland water level. For study areas where the hinterland water level interacts with the breach outflow, calibration of the hinterland area is required.

As a future step, usage of a Digital Elevation Model (DEM) and the concept of Height Above Nearest Drainage (HAND) (Nobre et al., 2011) is investigated to remove the need for calibration of the hinterland area. From the DEM, a relationship between the volume entering through the breach and the hinterland water level near the breach can be computed to simulate the feedback effects from the hinterland to the breach.

Ultimately, the fast evaluation of breach outflow opens up possibilities to assess dike breaches probabilistically during an emergency. Interesting work on other emulators such as machine learning models for flood inundation often use breach outflow as input (e.g. Bentivoglio et al., 2023). Coupling of this rapid breach outflow estimator and such a flood propagation emulator model opens up new ways of providing flood insights to decision makers.

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Challenges in numerical modelling of bifurcations

Victor Chavarrias[a*], Marco Redolfi[b], Marco Tubino[c]

[a] *Deltares, Boussinesqweg 1, 2629 HV Delft, the Netherlands.*
[b] *Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Via P. Vivarelli, 10, 41125 Modena, Italy.*
[c] *Department of Civil, Environmental and Mechanical Engineering, University of Trento, Via Mesiano 77, 38123 Trento, Italy.*

Keywords — Bifurcations, analytical/numerical solution, sub/super-resonant.

Introduction

Studying river bifurcations is crucial for a comprehensive understanding of fluvial systems and their impact on the surrounding environment. These geographical features, where a single river splits into two branches, play a vital role in shaping landscapes and influencing the distribution of water, sediment, and ecosystems.

Wang et al. (1995) are, to the authors knowledge, the firsts to analytically study the properties of river bifurcations, deriving a relation to discern between stable and unstable bifurcations. This influential research, however, has an important caveat: it depends on an empirical 1D nodal-point relation describing the partitioning of sediment discharge as a function of the partitioning of water discharge and parameters. Several improved relations have been proposed, such as the mechanistic relation by Bolla Pittaluga et al. (2003). However, all nodal-point relations remain, to date, a difficult-to-calibrate as well as crucial feature.

A step forward was conducted by Redolfi et al. (2016), who derived a 2D analytical solution for the flow and bed level reconciling the theory of bar formation and bifurcation stability. They predict that, when the width-to-depth ratio is below a resonant value (Blondeaux and Seminara, 1985), the only solution is that both downstream branches transport an equal amount of discharge. On the contrary, when the width-to-depth ratio is above the resonant value, the bifurcation has an influence upstream, allowing for the formation of alternate bars that cause an unequal discharge distribution.

The resonant value differs from the critical value at which free bars form (e.g., Fredsøe, 1978).

The analytical solution is limited by the fact that it is a based on a linear approach and, as such, neglects higher-order features like the coexistence of free bars, is unable to predict the final discharge distribution, and is restricted to idealized conditions. For this reason, practical applications require numerical solutions. These are, unfortunately, not the panacea, as discretization errors, among other factors, may cause the numerical solution to diverge from the actual solution. Testing against analytical solutions is the only possible way to gain certainty on the application of numerical models. Here, we test the ability of Delft3D-4 in recreating the solutions predicted by Redolfi et al. (2016).

Methodology

The case concerns modelling bed evolution in an idealized rectangular domain, where a thin dam separates the downstream half of the domain into two equal branches. The channel is fed with a constant discharge and downstream water level initially under equilibrium conditions. The sloping bed consists in a single uniform sediment size that is transported as bedload. Three different conditions are created by changing the discharge (hence also the initial flow depth), and sediment size: (1) sub-resonant and sub-critical, (2) sub-resonant and super-critical, and (3) super-resonant and super-critical. We stress that super-critical refers here to the value for free bar formation and not related to the Froude number, which is 0.5 for all cases. We model the cases using the standard first-order scheme for updating the bed level as well as a research version of Delft3D-4 featuring a second-order implementation.

Results

The linear theory predicts normal flow to remain for the sub-resonant cases (1 and 2). The numerical solution of the sub-resonant and sub-critical case (Case 1) shows indeed normal flow to prevail. However, the sub-resonant and super-critical Case 2 shows one branch capturing more water with time (Figure 1).

An unequal bifurcation is expected from the super-resonant Case 3, which is consistent with numerical predictions (Figure 2). Moreover, the detailed pattern of bed deformation given by the analytical solution is correctly reproduced, with

* Corresponding author
victor.chavarrias@deltares.nl

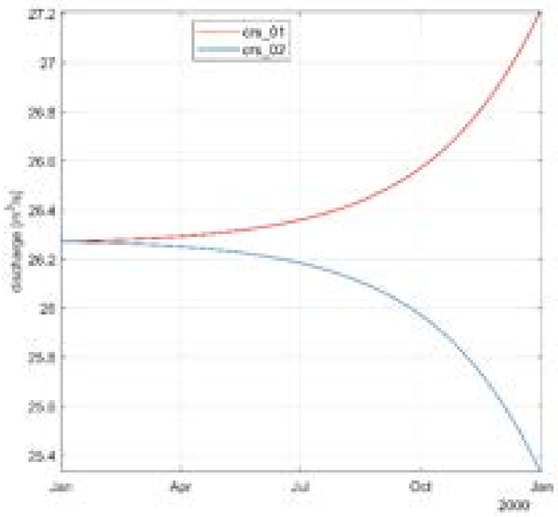

Figure 1. Discharge of the downstream branches with time for Case 2 showing the typical exponential divergence from unstable configurations.

a clear overdeepening (and overshallowing in the other branch) occurring near the banks right downstream of the bifurcation. Notably, this behaviour is clearly captured only when using the second-order numerical scheme. Indeed, the first order solution shows a poorer agreement as well as a faster development out of equilibrium.

Discussion and Outlook

Obtaining a uniform solution when expected (Case 1) should not be considered trivial, as a poor numerical discretization may be unable to capture this basic solution. Equally remarkable is the agreement of the super-resonant case, as it is the fact that the 2nd order scheme is crucial. This shows the importance of making General Available the feature currently in a research branch.

The most striking result is the instability of the sub-resonant and super-critical Case 2, which was expected to remain uniform. A simple explanation is that the case is not correctly set, as matching the analytical solution with the numerical input is challenging. For verifying the correct input of the numerical solution, simpler cases are to be modelled, to test whether the expected upstream/downstream influence and growth of alternate bars is obtained.

Another explanation lays on the neglected higher-order terms in the analytical solution. While the only possible linear solution for the sub-resonant case is normal flow, non-linear effects caused by growth of alternate bars in the upstream reach (due to the fact it is super-critical) may trigger growth of perturbations. A longer simulation time is needed to check whether the exponential growth seen in Figure 1 becomes saturated and the solutions evolves back to uniform flow or, on the contrary, one branch becomes closed.

In general, this work may be considered as a basic test for a wider class of problems regarding the possible upstream propagation of a three-dimensional bed deformation exerted by bridges or other instream structures.

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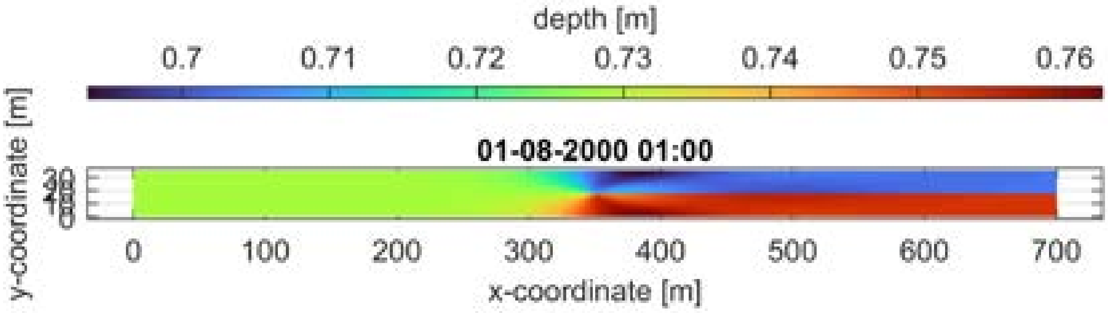

Figure 2. Flow depth after 7 months for Case 3. Flow is from left to right.

Rapid simulation and assessment of the Derna (Libya) dam failures

Robert J.L. Groenewege[a*]
[a] *Deltares, Boussinesqweg 1, 2629 HV Delft, the Netherlands*

Keywords — wadi, dam collapse, 2D numerical modelling

Introduction

Wadi (meaning "dry river valley") flash floods are becoming more frequent, especially in the Middle East and North Africa, due to climate change. In September 2023, the city of Derna in Libya was hit by a devastating wadi flash flood (WFF) that was caused by the failure of two upstream dams. This event was the second-deadliest dam failure in history, once again underscoring the need for a robust WFF modelling solution that enables "a comprehensive and holistic hazard risk assessment framework" (Groenewege, 2023) and facilitates contingency planning.

Previous work by Groenewege (2023) and Khorchani (2023) has shown that the Delft3D Flexible Mesh (FM) software is capable of accurate and detailed modelling of WFF hydraulics and hydrology, mainly using globally available (input) data. This research has built upon this work, and its primary objective was to validate this capability in combination with the implementation of dam failure(s). The Derna dam collapses were used as case study, which provided the secondary objective, i.e. improve our understanding of the cause and the chain of events in the context of very limited available information (at the time).

Derna dam collapses

Around September 5, 2023, a severe tropical-like cyclone named Storm Daniel developed in the Mediterranean Sea that hit northern Libya on September 10. This storm brought heavy rainfall to the predominantly arid country, with some coastal regions experiencing over 400 mm of precipitation (Qiu et al., 2023). Most areas received between 150 and 250 mm of precipitation. This triggered widespread and catastrophic (flash) floods, resulting in thousands of deaths and displaced people (Oduoye et al., 2024).

* Corresponding author
Email address: robert.groenewege@deltares.nl (Robert Groenewege)

The coastal city of Derna was particularly affected by Storm Daniel. Derna is located at the downstream end of Wadi Derna, an intermittent river that drains a catchment area of 575 km^2 (Fig. 1). Along this river, two embankment dams intended for agricultural irrigation and water supply were constructed in the 1970s (Hidrotehnika, 2023). The typically empty reservoirs behind the dams started filling during Storm Daniel, and eventually both dams failed from excessive load, which released a massive flash flood wave of 7 metres high (Qiu et al., 2023) with a total volume of 30 million cubic metres (Oduoye et al., 2024). In just a matter of seconds (Martin, 2023), the wadi that cuts right through the city flooded its banks and large residential parts of Derna were completely submerged. This led to thousands of destroyed or severely damaged buildings, 4,700 deaths, and over 8,000 missing people.

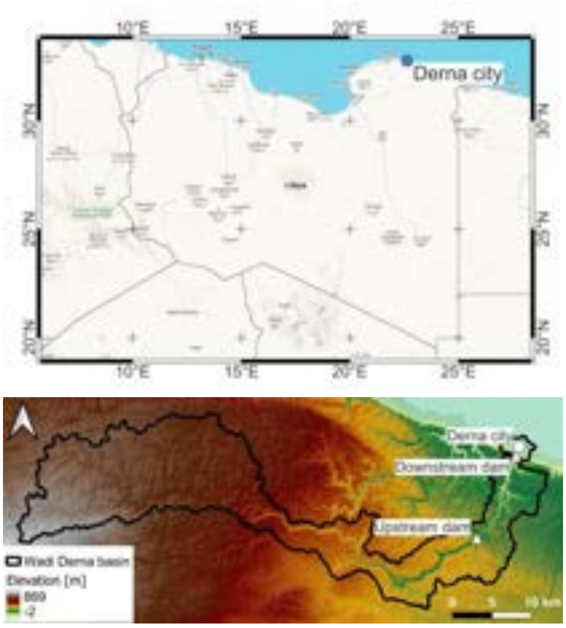

Figure 1. Top: location of Derna in Libya. Bottom: Wadi Derna study area.

Modelling methods

A Delft3D FM model of the study area was set up shortly after the event by following the same approach as developed by Groenewege (2023). A base model was created in one day and iteratively calibrated to match the sequence of events as close as possible. However, due to the uncertainties at the time, two possible scenarios emerged which were both modelled: one where the upstream dam collapsed prior to the downstream dam, and the other where this order was switched. This was represented in the model by fixed weirs with a Real-Time Control (RTC) component to lower their crest level at a predefined water level threshold, effectively representing their collapse. Meanwhile, the rainfall was represented by a triangular, spatially uniform time series totaling 200 mm of precipitation. Finally, each scenario run simulated 48 hours of the event and took approximately 9 hours (i.e. overnight) in real time.

Results

In general, both scenario runs displayed similar results that were in accordance with the observations at Derna as well. First, the modelled hydrograph had an extremely steep rising limb (Fig. 2); second, the inundation extent and depth (Fig. 3) approximated various estimates, e.g. by BBC News (2023) and Olorenshaw et al. (2023).

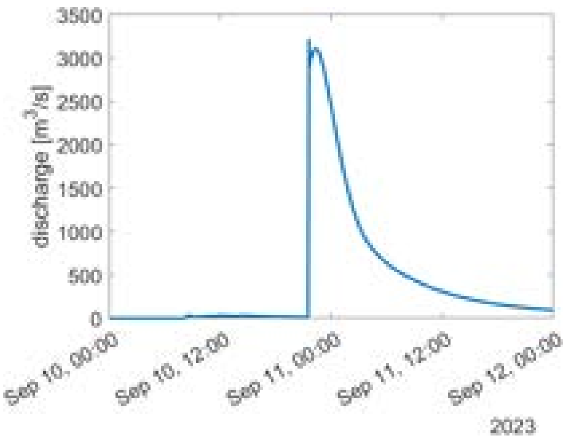

Figure 2. Hydrograph at Derna using the Delft3D FM model.

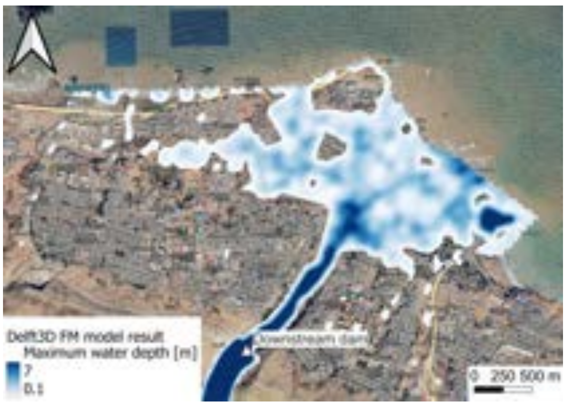

Figure 3. Flood extent and depth at Derna using the Delft3D FM model.

Despite little insight into the exact chain of events, it was notable that the downstream dam was not subjected to overtopping in the model (in contrast to the upstream dam) despite a total flood volume twice as much as estimated. This indicated that overtopping may not have been the cause of failure of the downstream dam.

Recommendations

The Wadi Derna Delft3D FM model could benefit from the use of the Verheij-Van der Knaap (2002) dam breach formula (Verheij, 2002) instead of the simplistic RTC approach presented here, as well as a higher-resolution topography and computational grid at Derna city to improve the flow routing and model performance there. More importantly, it is recommended to upscale from case studies to a global wadi risk assessment framework/tool.

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POSTERS

Roman-aged counterpoint deposition in the Waal River near Nijmegen

Jasper Candel[a], Lisa Boterman[a], Bart Makaske[a], Jakob Wallinga[a]
[a]*Wageningen University & Research, Soil Geography and Landscape group, P.O. Box 47, 6700AA, Wageningen, The Netherlands*

Keywords — River dynamics, Holocene, Fluvial Sedimentology

Abstract
Channel deposits from meandering rivers have proven to be far more complex than the well-known lithofacies model consisting of coarse-grained channel, gravelly channel-lag, and fine-grained overbank deposits. In sharp river bends, inner bank erosion and deposition of fine-grained sediments in outer bends can take place, resulting in downstream migration. This phenomenon is known as counterpoint deposition, forming counterpoint bars (Fig. 1).

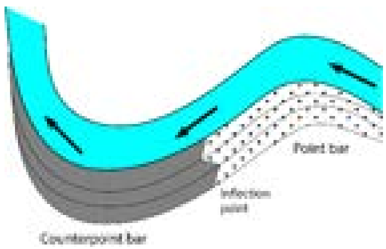

Figure 1. Difference between a point bar and counterpoint bar illustrated. Counterpoint bars form as a result of inner-bank erosion and outer-bank deposition of fine-grained sediments.

This research investigates a potential counterpoint bar deposit in the Waal River near Nijmegen (Fig. 2). A counterpoint bar is expected based on: 1) the typical scroll bar surface morphology; 2) the confinement of the river by a push-moraine resulting in a sharp bend; and 3) the archaeological context of successive Roman settlements atop the push-moraine, potentially moving downstream with the migrating river bend. This hypothesis is tested through borehole descriptions combined with optically stimulated luminescence (OSL) dating. The deposits consist of clays and sandy clays with fine sand laminations, and sporadic larger sand bodies. Further upstream these grade into channel deposits dominated by coarser sands with gravels, and occasional clay and plant material layers. These lithologies match those described in previously studied counterpoint deposits and their point bar counterparts. OSL dates indicate downstream migration of the river bend, confirming counterpoint deposition (Fig. 3).

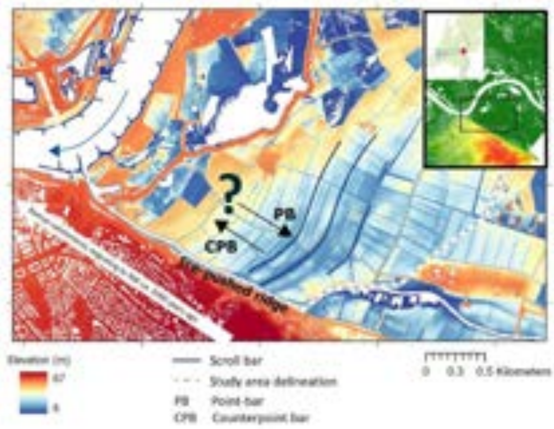

Figure 2. Digital elevation model showing the scroll-bar surface along the ice-pushed ridge near Nijmegen, and the direction of Roman settlement migration.

This study demonstrates for the first time the potential of OSL dating to investigate counterpoint bar presence. The findings of this study may explain the relocation of Roman settlements on the adjacent push moraine, and provide important insight into meandering river dynamics that is crucial for river restoration and rewilding initiatives.

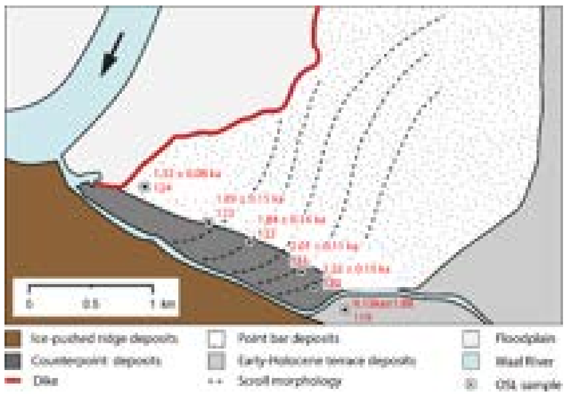

Figure 3 Schematic overview of the counterpoint bar, showing the OSL ages.

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Nature-based solutions for flood and drought protection: Comparison between Thailand and Western Europe

Patit Chotemankongsin [a]

[a] *Wageningen University and Research, Department of Environmental Sciences, Earth System and Global Change Group, P.O. Box 47 6700 AA Wageningen The Netherlands*

Keywords — Floods, Droughts, Room for the River, Climate Adaptation, Risk Reduction

Abstract

Thailand, like many other nations across the world, is facing the harsh effects of climate change. The increase in heavy rainfall has led to floods, while extended dry spells have resulted in prolonged droughts, posing significant challenges. These issues have severely impacted the agricultural industry, which is a primary source of income for many people.

To address these challenges, Thailand is actively seeking solutions that not only mitigate the damage caused by climate change but also contribute to the restoration of ecosystems that have been adversely affected by both environmental changes and human activities.

The Netherlands, known for its expertise in water management, is a source of inspiration for Thailand. Their recent project, "Room for the River," has made the country a global role model, transcending borders both within and beyond Europe. The Netherlands has adopted an innovative approach to Nature-Based Solutions (NbS), demonstrating a strong commitment to enhancing resilience against floods while also revitalizing ecosystems and creating recreational spaces.

Thailand and other Southeast Asian nations have an excellent opportunity to learn from the Netherlands' experiences, drawing insights and lessons, particularly through the adoption of similar approaches and the integration of Nature-Based Solutions. As well as combine local knowledge such as traditional irrigation systems to modern solutions. By doing so, Thailand can navigate its climate-related challenges more effectively, leading the way to a sustainable and resilient future.

Approach

Researchers worldwide are showing increased interest in nature-based solutions (NbS). There have been numerous site studies that have looked at NbS on a small scale (such as green roofs and constructed wetlands) as well as on a large scale (including floodplain restoration and forest restoration), which have already been implemented. However, the performance of NbS in both risk reduction and co-benefit to the surrounding environment is still unclear. To gain more clarity on its effectiveness, the literature on NbS will be analyzed to identify the conditions that make NbS helpful in reducing the risk of flood and drought. This will help in adapting it to other regions that have different contexts.

Figure 1. River map of Thailand

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Sorting out sediments: trends in the 2021 flood deposition of the Meuse, Rur and Geul

Daan Eldering[a*], Willem Toonen[a], Cheyenne Welters[a], Saul van den Berg[a], Maarten Prins[a], Oeki Verhage[a], Martine Hagen[a], Hessel A.G. Woolderink[b], Kees Kasse[a]
[a]*Dept. Earth Sciences, Vrije Universiteit Amsterdam. De Boelelaan 1085, 1081 HV Amsterdam.*
[b]*Wageningen Environmental Research. Droevendaalsesteeg 3, 6078 PB Wageningen.*

Keywords — Extreme flooding, grain size-shape analysis, sediment budget.

Introduction

Following extreme precipitation in the summer of 2021, several catchments in the south of the Netherlands were affected by severe flooding. Unprecedented peak discharges were recorded in the catchments of the Meuse, Rur and Geul rivers in Limburg (Fig. 1). Recent studies have looked into the climatological and hydrological aspects of this event (ENW, 2022). Here we focus on the morphodynamics, by investigating the sedimentary processes that occurred in the overbank zones. Our main aim was to enhance our understanding of the dominant factors that drive overbank deposition by comparing the spatial grain size-shape sorting of deposits in the aforementioned catchments.

Figure 1. (top-left) Sandy levee deposit in the Rur. (lower-left) Clay deposition in the floodplain of the Meuse. (right) Fieldwork locations.

Methods

One hundred ten sediment samples were collected in the field immediately after floodwaters receded. The thickness of fresh overbank deposition was measured at each sample location. Other parameters, such as the lateral distance to the river channel, local elevation, and the local configuration of the river channel, were recorded. These variables allow to test which factors are most important for the observed patterns in deposition.

Grain sizes were measured in 57 classes between 0,12-2000 μm, using a HELOS Sympatec laser diffraction particle sizer. Grain shapes were based on the aspect ratios measured at the Sediment Laboratory of the Vrije Universiteit Amsterdam with a Sympatec QICPIC digital image analyser.

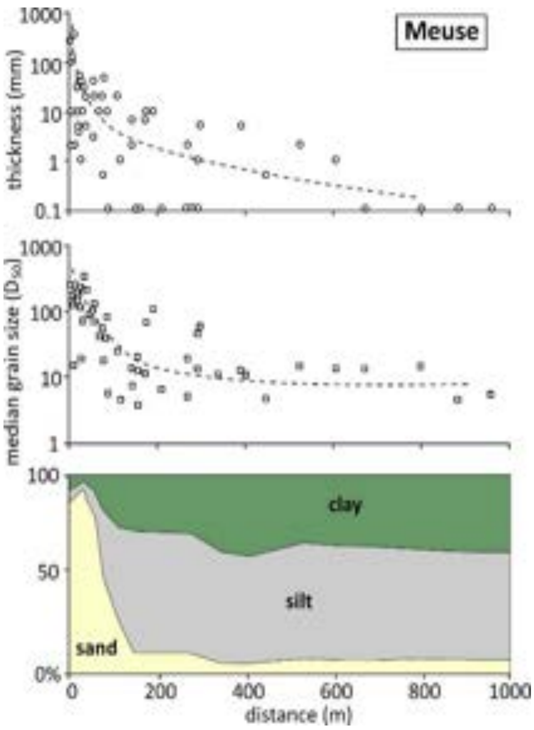

Figure 2. Thickness of flood deposits, median grain size and grain-size classes over the lateral distance to the active channel of the Meuse river.

Results

For all three catchments a predominant lateral trend in the volume of deposition, the median grain size, and texture was found – see Fig. 2 for the Meuse. The Rur and Geul featured comparable trends, with a similar coarseness and lateral fining. The main difference lies in the width of the proximal zone in which the deposition of sand occurred. For the Meuse this zone was c.

* Corresponding author
Email address: d.s.eldering@student.vu.nl (D. Eldering)
URL: NA

80m wide, for the Rur c. 20m, and for the Geul c. <10m, so broadly scaling according to river size. While the silt/clay ratio stabilised in the overbank zone of the Meuse and the Geul, sediments kept fining in the Rur Valley. This potentially reflects the morphology of these river valleys with the Rur having a relatively oversized Holocene valley that experienced still-standing water in its distal zones that allowed further sorting of fine-grained deposits. Prolonged backwater effects from the Meuse at Roermond also caused ponding in the Rur Valley, and promoting the advanced sorting of fines. The more confined settings of the Meuse and Geul led to downgradient flow in the entire valley, which limited the existence of such slackwater zones and thus did not allow for further sorting in texture.

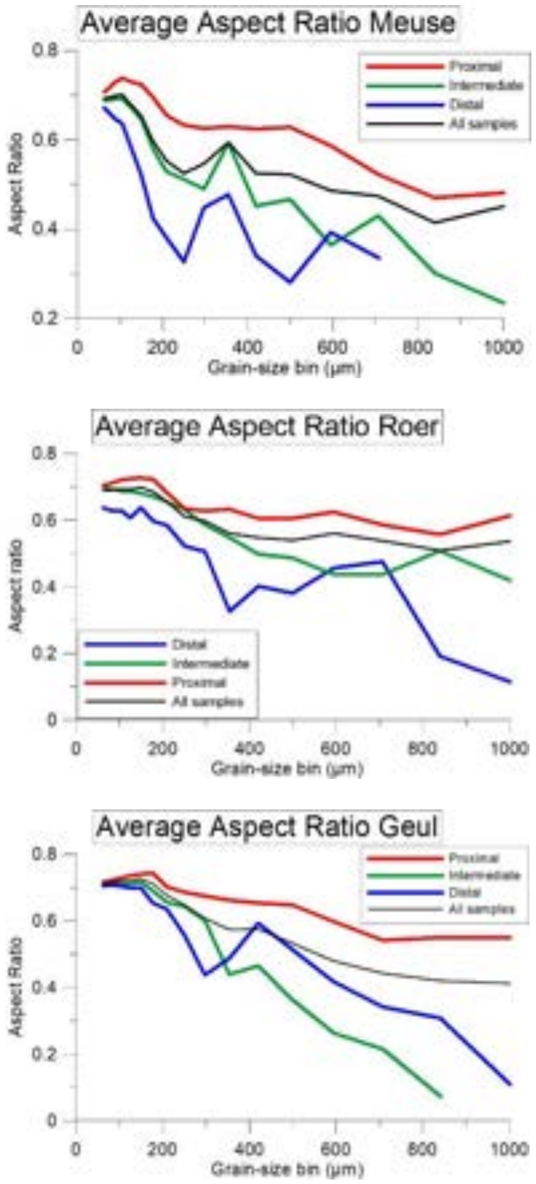

Figure 3. Aspect ratios of sand grains contained in overbank deposits of the Meuse, Rur and Geul, grouped according to lateral position.

The grain shape results were grouped into three main zones, according to distance to the main channel (this classification was based on the trends in texture and sediment volume). Grains in the proximal zone have a higher aspect ratio (AR) value than those found in the intermediate and distal zones (Fig. 3). AR in the most distal zone are the lowest. This implies that there is a trend of increased elongated grain shape with increasing distance, for grains of similar size. Furthermore, a second trend can be observed with increasing grain size (Fig. 3), so larger grains were more elongated in each depositional zone. We found such patterns for all three catchments, revealing a consistent trend in the sorting of grains by their shape.

Discussion and Conclusions

The sorting by grain shape over distance may largely be explained by enhanced buoyancy caused by a larger surface area (kite-effect). This results in a generally slower settling speed of elongated grains compared to rounded grains, thus allowing similar sized particles to be transported further when having a lower aspect ratio.

Strong parallels exist with findings in aeolian research, where similar trends in grain shape sorting are observed (Van Hateren et al., 2020; Shang et al., 2018). In those studies the grain size-shape distribution of sediment populations is found be indicative of specific modes of transport, such as saltation or suspension. Through end member modelling on the current data we hope to identify such transport modes, and to quantify the sources (e.g. bed or wash load) in such mixed populations in fluvial sediments.

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Flow partitioning between branches of the Karnali river in Nepal

Kshitiz Gautam[a*], Marijn Wolf[a], Thom Bogaard[a], Astrid Blom[a]
[a]*Faculty of Civil Engineering and Geosciences, Delft University of Technology, the Netherlands*

Keywords — River Bifurcation, field observation, numerical modelling

Introduction

The dynamics of the bifurcating Karnali river in the western plains of Nepal and India is governed by the geomorphological processes in an alluvial fan. The dynamic branches showcase a notable degree of braiding, dominant channel switching and unequal discharge partitioning. Since recent switching of the dominant channel of Karnali system occurred after an intense monsoon in 2009, the

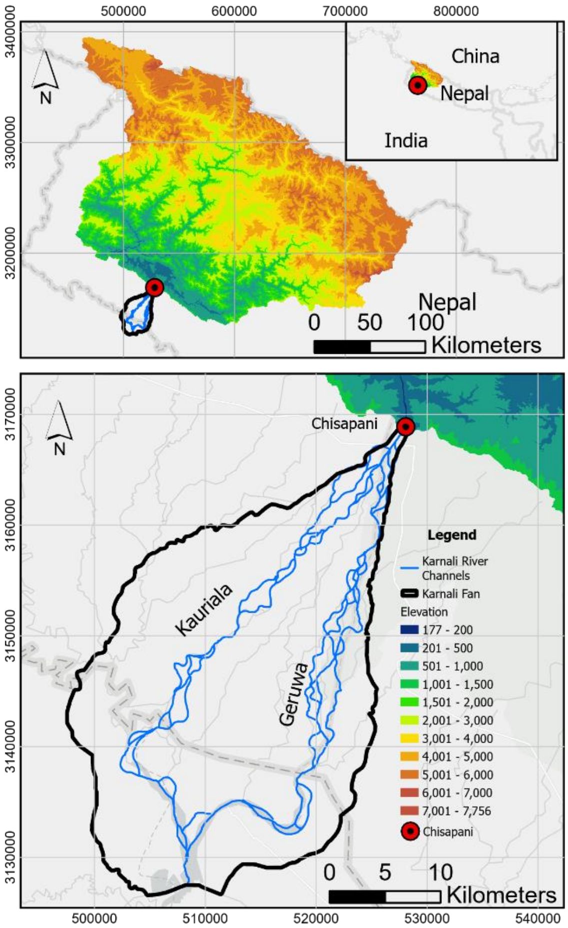


Figure 1: Karnali Discharges from mountain catchment (Top) at Chisapani and bifurcates into two branches Kauriala and Geruwa and gives rise to the Karnali Fan (Bottom)

eastern Geruwa branch of the system, which used to be dominant channel passing through the Bardiya National Park, is now receiving a lower share of discharge. This situation exacerbates in the low flow periods when there is very small flow in the Geruwa branch. This decreasing discharge has been associated with depleting diversity of wildlife habitat in Bardiya National Park (Bijlmakers et al., 2023). For sustainable habitat management in the Bardiya National Park, there is a necessity to study the dynamic Karnali river and its two branches, the eastern Geruwa branch and the western Kauriala branch. Activities such as sediment mining, construction of irrigation and hydropower and inter-basin water transfer projects will potentially influence the system dynamics. Our objective is to understand the switching behaviour of the Karnali system to the natural dynamics such as bend sorting (Baar et al., 2020; Parker & Andrews, 1985) of sediments at the location where water from the main Karnali enters the Geruwa branch, and offer understanding of system response to human interventions especially with regards to the distribution of discharge between the Geruwa and Kauriala branches. We combine the technique of field observations and numerical modelling to study the system.

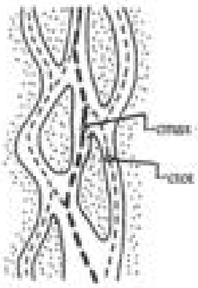
Methods

The initial screening of the system is done via available historical maps and optical satellite images. This sediment distribution serves for setting up our numerical model. The cross sections are used for model setup and also to understand the slope of different sections of the Karnali system. The numerical models, still in the phase of development, can be expected to provide an insight into the dynamics and the associated causes of water distribution between the Geruwa and Kauriala branches of the Karnali system and possible closure of the Geruwa branch. We set up a one dimensional hydrodynamic model to study the discharge partitioning in the two branches, the eastern Geruwa branch and the western Kauriala branch, of the Karnali system. We utilize the information from the field work and satellite images to setup and validate the model.
For the bifurcation area, we develop a two dimensional hydro-morphodynamic model in order to understand the effect of bend sorting on the closure of Geruwa channel.

* Corresponding author
Email address: k.gautam@tudelft.nl
URL: https://www.tudelft.nl/staff/k.gautam/

Remote sensing

Maps since 1817 are used to identify the bimodality (two branch) of the system. Satellite images between 1972 and 2022 from different Landsat and Sentinel missions are observed and analysed. For estimating the distribution of the water in the two branches, the area covered by water in each branches is taken as reference and the percentage distribution of area is used as the first estimate of percentage distribution of water in each branch. The braiding index (BI) at different sections of each branch is calculated as:



$$BI = \frac{L_{ctot}}{L_{cmax}}$$

Sediment analysis

We perform sediment analysis by photo-sieving (Ibbeken & Schleyer, 1986). We take photographs of the sediment across river cross-sections in different locations along streamwise direction and use them in computer aided tool BASEGRAIN (Detert & Weitbrecht, 2013) to determine the grainsize distribution.

Channel Geometry

We measure channel geometry as function of depth and width. We use Real Time Kinematic positioning to determine the elevation of the river bed, water level and high flow levels as well as to obtain the cross section of the river. We use single beam sonar for determining the depth of water where it is deep and use the RTK water level with depth obtained from the sonar to determine the cross sections of the river.

Results

Analysis of historical maps and satellite images show that Karnali has been a bifurcating river system at least since 1817. The discharge partitioning from the satellite images show increasing discharge in Kauriala branch after 2009. More than 50% of discharge during the low flow conditions flow in Kauriala branch. The BI of Kauriala has increased by a range of 1.0 to 1.5 near the bifurcation areas whereas decreased by 0.9 to 1.2 in the areas downstream of the bifurcation. The BI of Geruwa has decreased by 1.8 to 3.0 in different sections. The field observation shows abundance of large size sediments in Geruwa. The average slope of the Kauriala branch is 1.6×10^{-3} and that of Geruwa branch is 1.5×10^{-3}.

Conclusion

The Karnali is a river flowing in two branches since at least past two centuries which occasionally switches the dominant channel. It is still a matter of investigation if this type of switching occurred in the past or will happen in the future especially with recent and planned anthropogenic interventions in the future. The Kauriala branch is prone to lose its braiding pattern given its confinement with the dikes as observed in the field and from the timeseries of satellite observations. The elevation of the inlet, which is the outer side of the bend, to Geruwa is higher and that may be attributed to the deposition of larger sediments in the outward bend due to bend sorting of the sediments. The higher slope of the Kauriala and increasing bed level of the Geruwa at its inlet will increase the flow in Kauriala and decrease it in Geruwa. The issue of lowering wildlife habitat heterogeneity may exacerbate given the decreasing BI and flow in Geruwa.

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Towards understanding the physics of biofouled microplastics transport in rivers

Derk van Grootheest[ab*], Kryss Waldschläger[a], Merel Kooi[b], Ton Hoitink[a], Albert A. Koelmans[b]
[a] Wageningen University, Hydrology and Environmental Hydraulics Group, Droevendaalsesteeg 3a, Lumen (building nr. 100), 6708 PB, Wageningen, The Netherlands
[b] Wageningen University, Aquatic Ecology and Water Quality Management Group, Droevendaalsesteeg 3a, Lumen (building nr. 100), 6708 PB, Wageningen, The Netherlands

Keywords — Microplastic transport, Biofilm

Introduction

Microplastics are found across all aquatic environments (Wu et al., 2019, Napper et al., 2023). To understand the implications and possible risks of their presence in the environment, we need to understand the fate of microplastics. Because acquiring spatial-temporal relevant samples is difficult and labour intensive, numerical models are a necessary tool to predict the fate of microplastics in the environment (Cowger et al., 2021). One of the processes, which influence the transport of microplastics, is biofouling. Biofouling is the process of microorganisms attaching to the substrate surface, after which a film develops due to the microorganisms secreting extracellular polymeric substances (Waldschläger et al., 2023). The biofilm on a microplastic fibre and cube are shown in Figure 1. Biofouling alters particle properties such as size and density, and plays an important role in the aggregation of particles (Zettler et al., 2013).

Project overview

In this project we aim to quantify the impact of biofouling on microplastic transport in rivers.

The starting point is to investigate current microplastic transport models, such as by Besseling et al. (2017) and Kooi et al. (2017), which incorporate biofouling in different ways. A comprehensive overview will be made of the numerical implementations, containing the important parameters and underlying factors at play.

The major part of the project consists of three lab experiments. First the growth of biofilms on different microplastic particles in river water will be investigated. The experiment will look at the effects of polymer type, specific surface area and turbulence on biofilm growth. The outcome will be the development over time of the biofilm thickness and density as a function of the varied parameters. The other two experiments will investigate the effect of biofouling on the rising, settling, and resuspension of microplastics. Each of these experiments will provide an equation describing the transport process as a function of biofouling. These equations will be compared to the numerical implementations which were summarized from literature, to assess those implementations.

The final part will consist of an updated numerical implementation of biofouling in a microplastic transport model. This updated model will be used to quantify the impact of biofouling on microplastic transport in rivers.

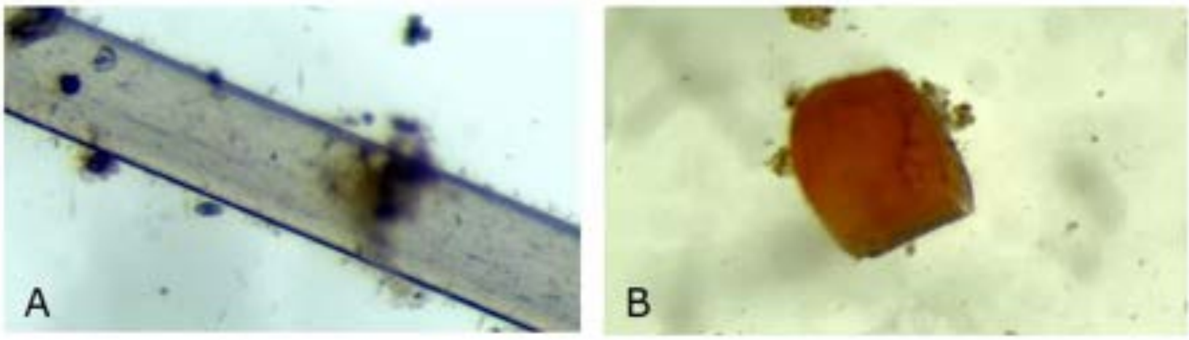

Figure 1. Microscope images of a biofilm forming on A) a microplastic fibre and B) a microplastic cube.

* Corresponding author
Email address: derk.vangrootheest@wur.nl (Derk van Grootheest)

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Morphological development of the Vecht river due to changes in the weir policy

Lieke van Haastregt[a,d*], Bas Gradussen[b], Gerben Tromp[c], Vasileios Kitsikoudis[a], Denie Augustijn[a]
[a] *University of Twente, Department of Coastal Systems & Nature-Based Engineering, P.O. Box 217, 7500 AE Enschede, The Netherlands*
[b] *Witteveen+Bos, P.O. Box 233, 7400 AE Deventer, The Netherlands*
[c] *Waterschap Drents Overijsselse Delta, P.O. Box 60, 8000 AB Zwolle, The Netherlands*
[d] *Sweco Nederland, De Holle Bilt 22, 3732 HM De Bilt, The Netherlands*

Keywords — River morphology, morphological modelling

Introduction

The Vecht river, located in Overijssel in the eastern part of the Netherlands, has been canalized over time by cutting of meanders, constructing weirs, and covering the banks with revetments. However, recently river management practices started focusing on the environmental wellbeing of the river system, which resulted in the formulation of a new vision and implementation of measures to rebuild the Vecht into a semi-natural river (Helder et al., 2017). Such a semi-natural river can be characterized by a.o. the presence of meanders and clearly visible morphological processes like sedimentation and erosion.

The current weir policy that is applied in the Vecht is based on maintaining target water levels. A reversed seasonal water level variation is maintained so that water levels are higher in summer than in winter. The weirs also block the flow of water and sediment. This is non-fitting for semi-natural rivers. Implementation of a discharge controlled weir policy is expected to increase the flow through the river and bring back natural seasonal water level variations.

Research about the effect of alternative weir policies on the morphology of rivers is limited (Ni et al., 2021). The objective of this exploratory research is therefore to evaluate the effect of certain changes in the weir policy on the morphology of the Vecht.

Alternative weir policies set-up

With the help of experts from Waterschap Drents Overijsselse Delta and Waterschap Vechtstromen, four different weir policies were formulated. These weir policies are:

1. The current weir policy, a reference scenario in which target water levels are maintained;
2. A discharge controlled weir policy, in which the weir gates are fully opened at a discharge of 50 m^3/s (measured at Ommen) and maintain the original target water levels if the discharge threshold is not met;
3. Same as above but with the weir gates opening at a discharge of 30 m^3/s;
4. Full opening of the weir gates at all times (closest to complete removal of the weirs).

Morphological model set-up

An available 1D SOBEK3 model of the Vecht, covering the area between Emlichheim (Germany) and weir Vilsteren was updated to include recent bed level developments and river interventions such as the construction of new artificial meanders and side channels. The bed roughness along the main channel was calibrated and validated to increase the hydrodynamic accuracy of the model. The morphological calibration parameter α and the median sediment grain size were calibrated and validated based on multibeam measurements of the main channel to increase the morphodynamic accuracy.

As input for the hydrodynamic calibration and validation historical discharge series were used with a duration of several days (for low, medium and high flow), compared to historical discharge series with a duration of nine years for the morphodynamic calibration and validation. The morphodynamic calibration was performed on one weir section (weir Hardenberg to weir Mariënberg), the rest of the river trajectory was used for the morphodynamic validation.

Subsequently the different weir policies were implemented by adjusting the PID controllers of the RTC module. For each weir policy a simulation was performed for a period of 50 years. The nine-year historical discharge series that were used previously were cycled for input. As upstream morphological boundary condition a fixed bed was assumed, since almost no change in the bed level had occurred in the past ten years according to observations.

Accuracy of the model

After calibration and validation the simulated water levels showed a Root Mean Square Error (RMSE) of 15 cm for low and medium flow and

* Corresponding author
Email address: lieke.vanhaastregt@sweco.nl
(Lieke van Haastregt)

30 cm for high flow. Deposition and erosion patterns were generally simulated well compared to observations. The simulated bed level change had an RMSE of 40 cm in the calibration section and 55 cm from the validation section. These relatively high values can likely be contributed to the fact that some of the river interventions were done during the simulation period in reality, which could not be reproduced.

Morphological model results

For all weir policies the morphological patterns that were observed consisted of local deposition peaks upstream of the weirs and erosion downstream of the weirs. These changes were mainly initial changes in the bed level, but also long-term changes occurred in the form of erosion and deposition waves that propagated downstream (see Fig. 1 from km 20-35), even though their propagation was partially blocked by the weirs.

Regarding local patterns, the magnitude of deposition peaks and erosion pits was largest for the reference scenario and smallest if all weirs were fully opened at all times (Fig. 2). The propagation of the waves was blocked less if the weirs were opened more frequently. These local patterns agree with existing literature (Ni et al., 2021; Nguyen et al., 2015).

Regarding large-scale patterns, a decrease in deposition upstream of weir De Haandrik was simulated for all weir policies compared to the current weir policy (Fig. 2). Downstream of the weirs a large-scale decrease in erosion occurred for all weir policies compared to the reference scenario, even leading to deposition, which was largest when the weirs were fully opened at all times (Fig. 2). However, these downstream large-scale patterns differ from earlier research, which expected a large-scale bed level decrease (Duró et al., 2022). This difference can be caused by various factors, such as the use of different time scales, but more research is required to pinpoint what exactly causes this different outcome.

Conclusion

This research has shown that the implementation of a discharge controlled weir policy affects the morphology of a river, in terms of local and large-scale deposition and erosion patterns.It can be concluded that opening the weir gates more frequently contributes to the achievement of a semi-natural river, since there is more large-scale morphological activity compared to the reference scenario the more the weir gates are opened, since the flow past the weirs is blocked less.

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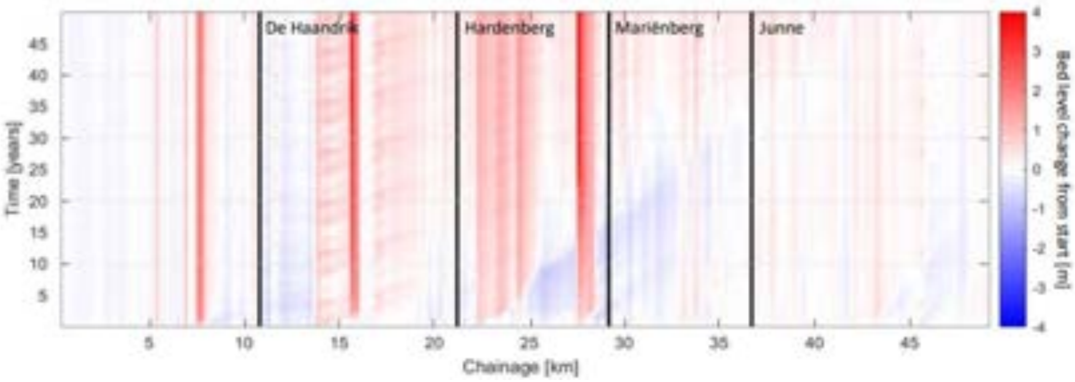

Figure 1. Simulated bed level change in the Vecht for 50 years (compared to initial situation) for the weir policy with all weirs fully open at all times. Positive (negative) values represent deposition (erosion). Black lines represent location of the weirs

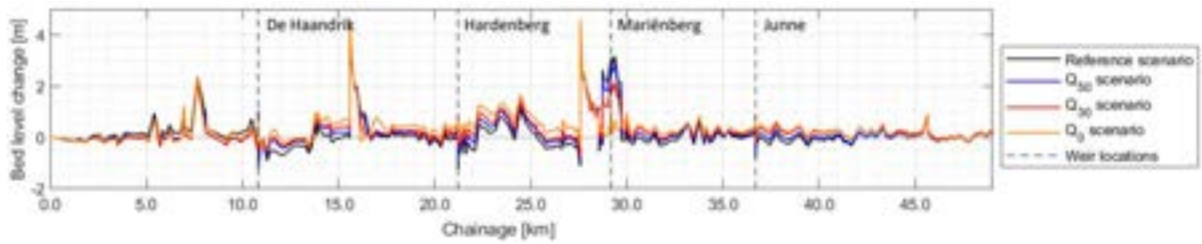

Figure 2. Bed level change of the Vecht for 50 years (compared to initial situation), simulated for the different weir policies

Plastic transport dynamics revealed through flood induced buttertub spill

Rahel Hauk*[a], Martine van der Ploeg[a], Adriaan J. Teuling[a], Winnie de Winter[b], Tim H.M. van Emmerik[a]
[a]*Hydrology and Environmental Hydraulics Group, Wageningen University, PO Box 47, 6700AA Wageningen, the Netherlands*
[b]*The North Sea Foundation, 3511 MJ Utrecht, the Netherlands*

Keywords — Plastic pollution, Tracers, Freshwater, Extreme Events

Introduction

Rivers play a substantial role in plastic pollution transport and storage but the transport processes that determine macroplastic fate in the riverine environment are not fully understood yet. Usually it is unknown when and where specific plastic litter items entered the environment, therefore macroplastic transport is often studied via e.g. GPS trackers. However, the July 2021 flood provided an unique opportunity of spilled macroplastic items, with clearly known time and space of emission.

In July 2021 severe floods affected multiple European river catchments, including the Meuse catchment in Belgium. A dairy company located at the Meuse tributary Vesdre was flooded, with parts of their facilities and a lot of material washed away. Among the washed away material was also ~8 million empty dairy packages ("buttertubs"), which have a printed ID code that can be traced to their emission point.

Sampling

During macroplastic sampling immediately after the flood event, and in the following two years, we found 617 of these buttertubs along the Dutch section of the Meuse river (between ~66 to 328 km downstream of the dairy company). We used the buttertubs as tracers for macroplastic transport in the period that includes the flood event, and the following two years.

Transport distance and velocity

Within 20 days of the flood event, some of the buttertubs were transported ~328 km and were found close to the Rhine-Meuse-Delta (Fig. 1). However, the majority of buttertubs was transported less than 100 km within these 20 days, with an average transport distance between 9.75 to 18.25 km/day (Fig. 2). Over the following two years the average transport distance decreased to 0.23

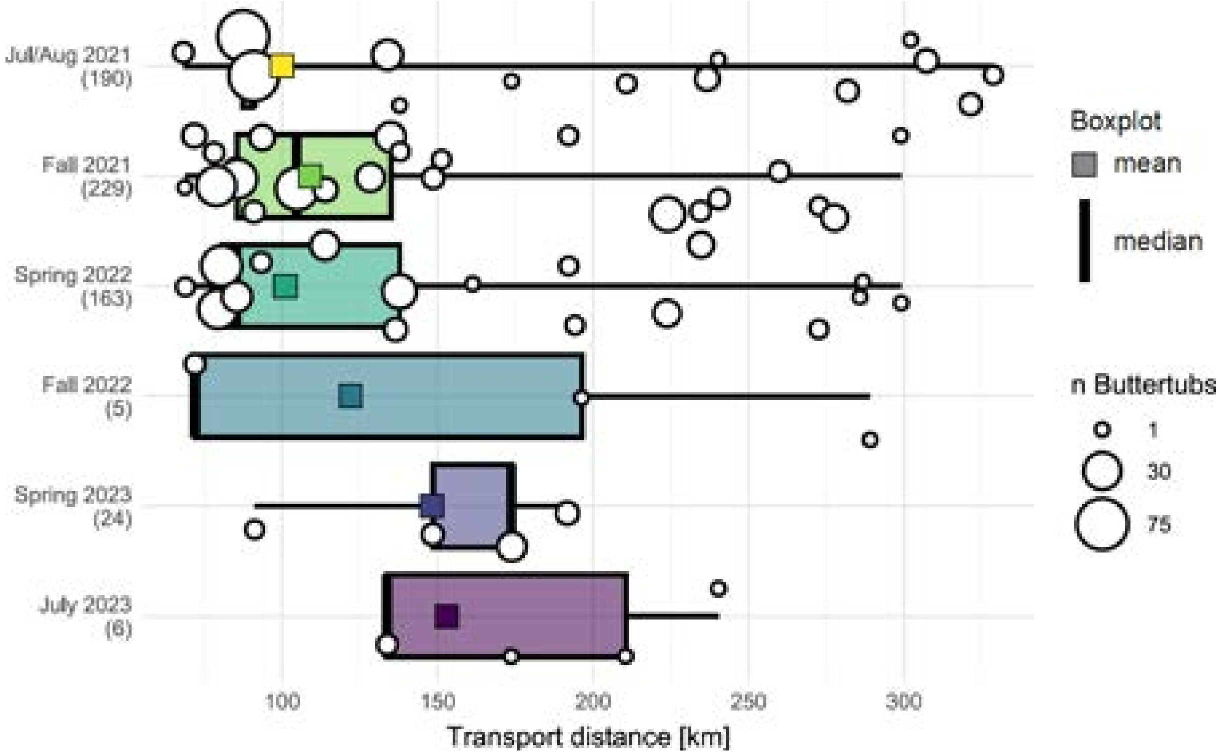

Figure 1. Transport distance of buttertubs along the Dutch Meuse in different measurement rounds. The whiskers extent to the least and furthest found buttertubs, with no regard for the interquartile range (no outliers were defined).

km/day. Which could imply that the buttertubs either were only transported across smaller distances in the following two years, or even not remobilized at all after being deposited during the flood event.

In this unique opportunistic study, we found that the buttertubs mean transport distance moved downstream over the course of two years. The majority of them however, was deposited rather close to their emission point, even given the extreme flood situation.

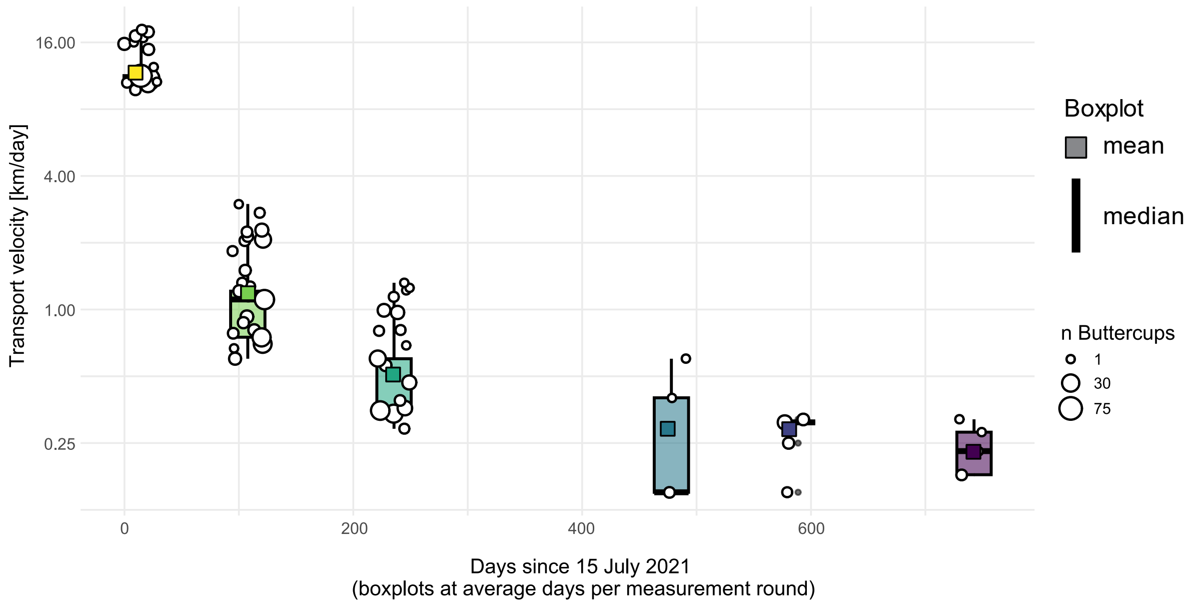

Figure 2. Transport velocity of buttertubs in the Dutch Meuse for the different monitoring rounds.

* Corresponding author
Email address: rahel.hauk@wur.nl (Rahel Hauk)

A Field Study on Groyne Field Nourishments

Eki Liptiay[a,*], Astrid Blom[a], Kees Sloff[b,a]
[a]*Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands*
[b]*Deltares, P.O. Box 177, 2600 MH Delft, The Netherlands*

Keywords — groyne fields, sediment nourishments, river morphology

Introduction

Over the past century, the main channel of the Waal has experienced erosion of approximately 1-2 metres (Ylla Arbós et al., 2021; Chowdhury et al., 2023). This erosion leads to various problems such as instability of structures or disruption to shipping. To address this ongoing degradation, a potential solution is the implementation of sediment nourishments.

Recent pilot studies have been conducted in 2016 and 2019 to investigate the feasibility of using sediment nourishments in the main channel of the Dutch Rhine (Becker, 2023). Another possibility of nourishing is to add sediment to the groyne fields. Under the influence of currents and ship waves, sediment is expected to be transported to the main channel, causing a groyne field to act as a *sand motor*. To explore this concept, Rijkswaterstaat initiated a pilot project with sediment nourishments in three groyne field clusters along the Waal during the fall of 2023. The pilot includes an extensive measurement campaign.

Dynamics of Groyne Fields

Studies on groyne fields have explored their hydrodynamics, sediment exchange and flow patterns. Uijttewaal et al. (2001) employed flume experiments, investigating exchange processes between rivers and groyne fields. They concluded that the overall exchange of matter can be described as a first-order process. The significance of the three-dimensionality of the flow was highlighted by Sukhodolov (2014) as they demonstrated high variability of the flow characteristics both across and along the flow depth for both emerged and submerged conditions. Yossef and De Vriend (2011) explored the differences in turbulence nature regarding submerged and emerged conditions. This offers insights into flow patterns near groynes, mixing layer characteristics at different flow stages, and dynamic velocity behaviour along the mixing layer between the main channel and groyne fields. Yossef and De Vriend (2010) found that under all flow conditions, a net sediment import occurs in groyne fields in straight reaches. For emerged groynes, aggradation is dominated by advection by the primary circulation cell, whereas during submerged conditions it is rather residual advection by large-scale coherent flow structures.

Ten Brinke et al. (2004) investigated groyne fields along the Waal, using in situ measurements, aerial photographs, and bed level timeseries to grasp the dynamics equilibrium of groyne fields. They concluded that there is a balance between erosion due to increased flow velocities induced by navigation and sedimentation due to high flows. Brouwers (2022) explored the effects of vessel characteristics on water level and flow velocity from field measurements in the Waal near Nijmegen, finding significant variance for all characteristics and concluded that is difficult to predict the impact of a single vessel.

Furthermore, Kok (2020) used a numerical modelling approach to investigate groyne fields as nourishment locations. She demonstrated that for emerged groynes, nourishments can effectively release sediment into the main channel. She underscores the limitations of the modelling approach used and the need for further exploration regarding nourishment compositions, extended simulation periods, and practical tests to optimise the effectiveness of groyne field nourishments.

New Field Study

The pilot study area includes three groyne field clusters along the Waal shown in Fig. 1. These clusters were chosen so that there is variability in the characteristics of the groyne fields. This includes clusters on the northern and southern banks and clusters along a straight part of the river as well as on a river bend. Each cluster consists of five groyne fields: four fields where nourishments are executed and one upstream field for reference.

Morphodynamic and hydrodynamic measurements were performed in situ using frames in both the shallow and deep parts of the groyne

*Corresponding author
Email address: e.j.a.liptiay@tudelft.nl (Eki Liptiay)

Figure 1: Locations of the three groyne field clusters.

fields (Fig. 2). These measurements included flow velocity, water depth, and turbidity. The influence of shipping on these properties will be investigated by analysing vessel tracking (AIS) data. This includes vessel velocity, draught and dimensions. In addition, measurements were taken of the bathymetry and velocity flow fields (Fig. 3).

The combined data sets may contribute to construct a 3D view of the dynamics of flows and sediment transport during a ship passage, as well during undisturbed conditions without ships passing. Regular velocities in the primary eddy are in the order of 0.3 m/s, whereas passage of ships can at least double these. Following the recent high flows, we will also explore whether additional sedimentation in the groyne fields has occurred and what this means for their dynamic equilibrium.

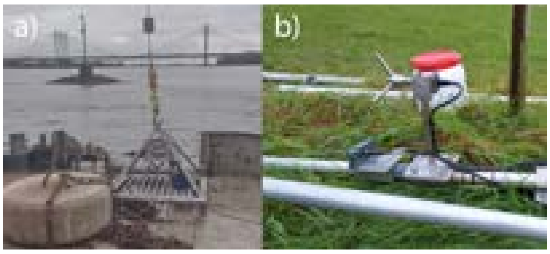

Figure 2: Measurement frames for both the a) deep and b) shallow parts of the groyne fields.

Future Work

Measurement data will be used both for a standalone analysis of inherent properties and for integration into numerical modelling processes. This approach aims to identify controlling processes at various spatial and temporal scales, particularly in the interactions between the main channel and the groyne fields.

If we understand the physical processes and we are able to model them, we will be able to design and upscale these sand motors in an optimal way that suits the location and targets of this measure.

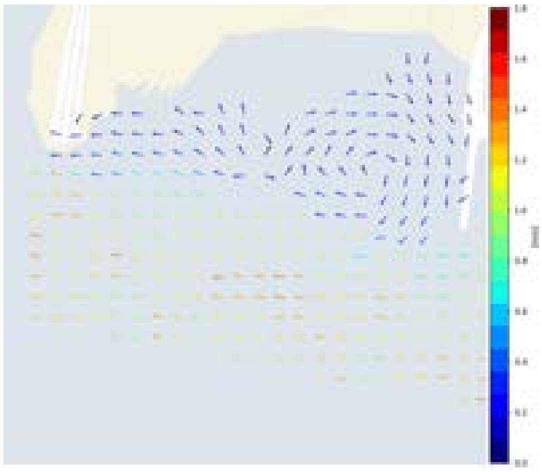

Figure 3: Velocity flow field within a groyne field.

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Understanding the long-term dynamics of scour holes in lowland rivers

Marthe Oldenhof[a*], Anouk Bomers[a], Suzanne J. M. H. Hulscher[a]
University of Twente, Department of Water Engineering and Management, Faculty of Engineering Technology, P.O. Box 217, 7500 AE, Enschede, the Netherlands

Keywords — Scour holes, morphology

Introduction

Scour holes are common features in lowland rivers. Scour holes are local depressions in the channel bed caused by erosion processes induced by hydrodynamic conditions (Ferrarin et al., 2018). The holes can have a depth of several meters and are generally no longer than 1 km in longitudinal direction. Deep scour holes are found all over the world, for example, in channel bends in the river Mahakam in Indonesia (Vermeulen et al., 2015), at channel confluences in the Venice lagoon in Italy (Ferrarin et al., 2018), and in the Grensmaas caused by the flood of 2021 in Limburg in the Netherlands (Barneveld et al., 2022). These deep scour holes may threaten the stability of infrastructure, like pipelines, embankments, and the foundation of bridges. Therefore, scour holes are generally filled up manually. Room for the river and nature-based solution projects aim to improve the river system's natural conditions, and therefore it might be desirable to leave these scour holes open after formation. A lot of research has been done on the formation of scour holes. However, by manually filling up the scour holes, less is known about the migration of the holes after formation and the possible threats of the scour holes in the long-term. For this reason, a better understanding of the long-term dynamics of scour holes in lowland rivers is required.

Formation of scour holes

The formation of scour holes is driven by hydrodynamic and geotechnical conditions (Wang et al., 2017; Knaake et al., 2023). The hydrodynamic conditions result from historical events (e.g., the flood in Limburg in 2021), channel geometry (bend, confluence, local narrowing), and constructions (bridge pillars, groynes, non-erodible fixed bed). Historical events result in peak discharges and high flow velocities. Changes in channel geometry and the presence of constructions cause local flow perturbations and additional turbulence to the flow. This local acceleration in flow velocity creates vortexes that remove the surrounding sediment if the river bed is susceptible to erosion, (Wang et al., 2017), resulting in deep scour holes. However, hydrodynamic conditions alone cannot account for all scour hole formations (Knaake et al., 2023). The geotechnical condition is also a key control for scour hole formation. The composition of the subsurface can explain the spatial variability in the occurrence and dimensions of scour holes. A heterogeneous subsurface consists of alternating easily erodible layers, like sand, and non-erodible layers, like clay or gravel. If the river bed consists of an erosion resistant top layer with an underlying layer with higher erodibility, deep scour holes can develop within a short amount of time, once the erosion resistant top layer breaks up (Huismans et al., 2021).

Migration of scour holes

After the formation of a scour hole, a hole can grow, decrease in size, or stabilize. The hydrodynamic and geotechnical conditions determine how a scour hole will evolve.

Van Denderen et al. (2022) analysed a scour hole downstream of the non-erodible fixed layer in the river Waal near Hurwenen in the Netherlands (see Figure 1). The scour hole deepens in the years with peak flow conditions and becomes shallow in the years with solely low to intermediate discharges.

Huismans et al. (2021) concluded that the growth of scour holes is bounded by the composition of the subsurface. Scour holes with edges composed of sand or a thin layer of clay are generally more elongated than scour holes in which both edges are composed of a thick layer of poorly erodible material.

Previous studies have related the migration of scour holes either to hydrodynamic or geotechnical conditions solely while we assume that in rivers with a heterogeneous subsoil, the migration of a scour hole is caused by a combination of hydrodynamic and geotechnical conditions. Little research has been done on how these combined conditions influence the evolution of a scour hole, for example how scour holes migrate during peak discharges. This

* Corresponding author
Email address: m.oldenhof@utwente.nl
(Marthe Oldenhof)

knowledge is relevant to understand the long-term dynamics of scour holes and make a deliberate choice whether to fill a scour hole or remain the hole open after formation.

Method

In the river Waal, several scour holes with a depth of more than one meter are found. The scour hole downstream of the non-erodible layer at Hurwenen is one of them, see Figure 1. The navigation channel of the river Waal is measured bi-weekly using multi-beam measurements (Van Denderen et al., 2022) and is, therefore, a good dataset to analyse the effect of peak discharges on the migration of scour holes. In the present study, the dimensions of the scour holes (area, maximum depth, width) will be compared before and after the flood of 2021.

To get a better understanding of how the characteristics of the scour hole (e.g., upstream slope, depth, length) and the composition of the subsurface (thickness of the erosion resistant layer) contribute to the migration of the scour hole, an experimental study will be executed. With flume experiments with unsteady flow conditions, the dimensions, and the composition of the subsurface of the scour hole will be systematically varied to identify the key controls of scour hole migration.

The findings of the experiments will be used to set up an idealised (one-dimensional) numerical model for a first analysis of the processes in and around a scour hole.

Finally, a three-dimensional numerical model will be developed using an open source CFD (Computational Fluid Dynamics) model like OpenFOAM or a more applied model like Delft3D. The model will be validated with field data and experimental data. The scour model will be used to make estimations on the long-term evolution of scour holes and their effect on the stability of infrastructure.

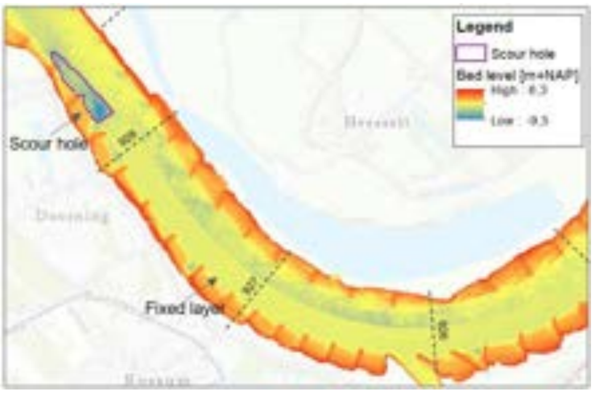

Figure 1. Bathymetry of the Waal near the side channel at Hurwenen (Source: RWS GeoWeb 12-06-2023).

Results

The analysis of the multi-beam measurements will show whether scour holes grow under peak discharges and eventually become stable over time. If possible, a relation between the initial dimensions and the migration rate will be found. The experiments and the numerical model are used to prove the relation by varying systematically the characteristics of the scour hole.

Based on model simulations a conclusion will be drawn whether a certain scour hole could be left open after formation. If the stability of infrastructure is at risk, a strategy will be developed on how to fill the scour hole manually, with the least negative effect on the long-term morphology of the river.

Conclusion

Analysing and identifying the key characteristics of scour holes and the processes in and around scour holes that cause the hole to migrate helps to understand the long-term evolution. Based on this knowledge a deliberate decision can be made to leave the scour holes open or to fill the scour holes manually after the formation. In this way, the stability of infrastructure is guaranteed, with the least possible disturbance of the natural conditions of the river system.

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Gelderse Poort: A nature-based solution for conservation and flood protection

Merel Hendriksen[a], Frans Hoefsloot[a], Paul van der Wal[a], Pendula Ferdinand[a*]
[a]*WSP Nederland B.V., Ringwade 41, 3439 LM Nieuwgein, the Netherlands*

Keywords — river management, flood protection, forest expansion, nature-conservation

Introduction

The Nature 2000 network is a European Union initiative aiming to protect and conserve European wildlife and natural habitats. In the Netherlands, the Nature 2000 goal is divided into specific areas. The Province of Gelderland has drafted a binding European Natura-2000 task for three habitat types: expansion of moist alluvial forests, dry hardwood riparian forests and stream valley grasslands. In this context the province Gelderland, together with Rijkswaterstaat (RWS) and Staatsbosbeheer (SBB), is looking for locations where hardwood riparian forests development in the floodplains is possible. That is why WSP was contracted to designate areas that would be suitable for hardwood floodplain forest in floodplains of the Dutch Rhine in the Gelderse Poort (see Fig. 1).

The project's objective is to achieve this goal through a nature-based solution without hard and expensive compensating measures. The project's success will contribute to the overall goal of the Nature 2000 network in the Netherlands and the European Union. The challenge of this project is to maintain flood safety while expanding forest area and redesigning the spatial planning of vegetation in the flood plains of the Rhine. This project is an opportunity to show that flood safety and forest development have the potential to be combined in floodplains and do not necessarily need to be separated.

Figure 1. Study area: Floodplain Rhine, Gelderse Poort

Suitability analysis and hydrodynamic modelling

The methodology for this project involved a comprehensive approach to assess the potential for developing riparian forest in the Dutch flood plains, specifically focusing on the "Hardhoutooibos" or dry riparian forest along the river Rhine. The initial step was a multi-criteria analysis to identify potential riparian forest locations, leading to the selection of 115 hectares in the flood plains of the Waalbochten as part of the Gelderse Poort. The project area covered over 2000 hectares along 20 kilometres of the river, a significant size in the Dutch context.

To predict the impact of the proposed forest development on flood safety, a 2D hydrodynamic model was employed. The model considered the Dutch Rhine System, with a design discharge of 16,000 m3/s and a return period of 1:10,000 years. Given the potential for increased discharge due to climate change, the study aimed to ensure that changes in the flood plains would not negatively affect water levels during peak floods. The model incorporated isolines of discharge to analyse water flow, roughness, and the impact of vegetation on water levels.

Through iterations and adjustments in the design, involving smart vegetation management, relocation, and a deep understanding of the river system, the team aimed to mitigate any adverse effects on water levels. The methodology included scenario-based calculations to refine the spatial plan for vegetation. The goal was to achieve a spatial plan allowing for riparian forest without causing an increase in water levels, adhering to the strict safety standards.

Results

The results of the study demonstrated the success of the methodology in achieving the project objectives. The final spatial plan, as illustrated in Fig. 2 and Fig. 3, allowed for an increase in the space allocated to forest, reaching a total of 225 hectares, with 115 hectares specifically designated as riparian

Figure 2. Vegetation change preferred design compared to reference - where the change in vegetation class is indicated in percentile - for example, 30% increase means from grass field to 70/30 class, 20% increase is from 90/10 class to 70/30,

forest. The spatial planning involved a meticulous rearrangement, removing 17 hectares to prevent flow disturbances and water level increases, while adding 242 hectares in new areas suitable for forest development.

The hydrodynamic model, validated through careful adjustments and simulations, showed that the redesigned spatial plan met the strict safety standards. The water level effect, initially exceeding the allowable 1 mm, was successfully reduced to below this threshold. The project demonstrated the feasibility of integrating nature-based solutions into floodplain management, showcasing the potential for collaboration between governance and nature conservation entities.

Conclusion

As a pilot project, this study not only achieved the Nature 2000 goals for the client but also served as a model for integral river management. By bringing together various stakeholders and demonstrating that seemingly conflicting objectives, such as accommodating high water flows and riparian forest, can coexist through smart spatial planning and river system knowledge, the project provided valuable insights for future initiatives in the Netherlands. The success of this project highlighted the potential for creating an integral river system where nature-based solutions and water management can harmoniously coexist.

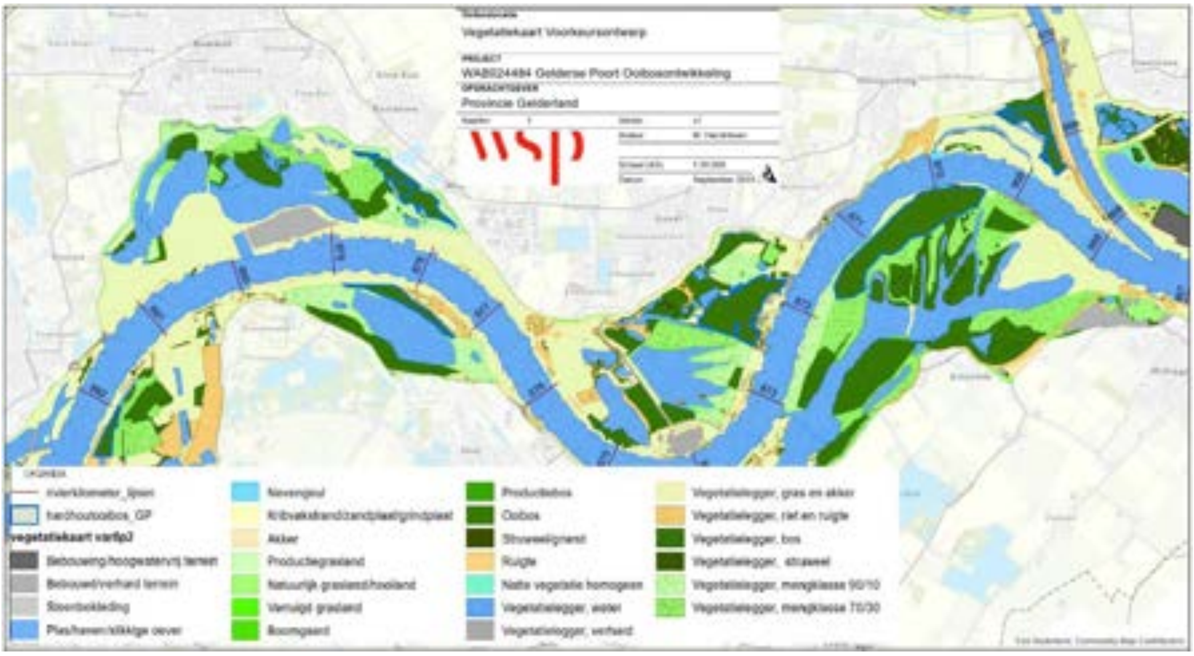

Figure 3. Vegetation design Gelderse Poort

* Corresponding author
Email address: pendula.ferdinand@wsp.com (P.A. Ferdinand)

Can we attribute river flood events?

Authors: Paolo Scussoli[a*], Linh Nhat Luu[b,c,d], Sjoukje Philip[b], Wouter Berghuijs[e], Dirk Eilander[a], Jeroen C.J.H. Aerts[a], Sarah F. Kew[b], Geert Jan van Oldenborgh[b], Willem H.J. Toonen[e], Jan Volkholz[f], Dim Coumou [a,b]

[a]*Institute for Environmental Studies, VrijeUniversiteit Amsterdam, Amsterdam,Netherlands*
[b]*Royal Netherlands Meteorological Institute, De Bilt, Netherlands*
[c]*Department of Geography, University ofLincoln, Lincoln, UK*
[d]*Vietnam Institute of Meteorology,Hydrology and Climate Change, Hanoi,Vietnam*
[e]*Department of Earth Science, VrijeUniversiteit Amsterdam, Amsterdam,Netherlands*
[f]*Potsdam Institute for Climate ImpactResearch, Potsdam, Germany*

Keywords — extreme event attribution, climate change impacts, hydrology, flood risk management

Abstract

When a weather-generated disaster occurs, it is now possible to obtain an estimate of how much its occurrence was altered by man-made climate change. This is possible thanks to recent advancements in the climatological science of extreme event attribution. This is based on the comparison of climate model simulations of factual and of counterfactual climates, i.e., with and without anthropogenic greenhouse gases. Both the public and policy makers comprehensibly assign a lot of value to these results. After river floods, the attribution generally only looks at the triggering precipitation event. However, hydrologists, and the public, know that river floods are not simply generated by precipitation: they only relate to precipitation non-linearly, due to mediating hydrological process and to antecedent conditions; other, local hydrological drivers of floods matter - land-cover, river management, dams, irrigation and other human interventions. These drivers have changed over time, with effects that are super-imposed to those of man-made climate change. Consequently, these changes can amplify, dampen or outweigh the effects of climate change on flood occurrence. Current methods and practice neglect the hydrological drivers of river floods, and all that happens on land during and (long) before the event. This means that we do not yet attribute river flood events. In this contribution we explain what has been done so far in the direction of flood attribution, we detect the research gaps and the challenges ahead, and propose possible solutions. We differentiate between near-natural and complex cases. Near-natural cases are contexts where the flood seems unlikely to have been influenced by hydrological change. Here, the existing framework of probabilistic flood attribution can be extended, by using flood data and flood modelling, to attribute river floods. Complex cases are those where flood occurrence seem to be affected by changes in hydrological conditions. To attribute these events new methods are needed. We propose a multi-driver framework for conditional event attribution. This will enable addressing conditional questions about the effect of each driver of the flood event, separately and in combination. A key advantage of this work will be that it dovetails attribution with the needs of flood risk management. This is done by including simulations that reflect past scenarios and future scenarios of plausible change in climate, hydrology, land-cover and management or adaptation. As such, flood event attribution can also provide a suitable effective scientific base for decision making.

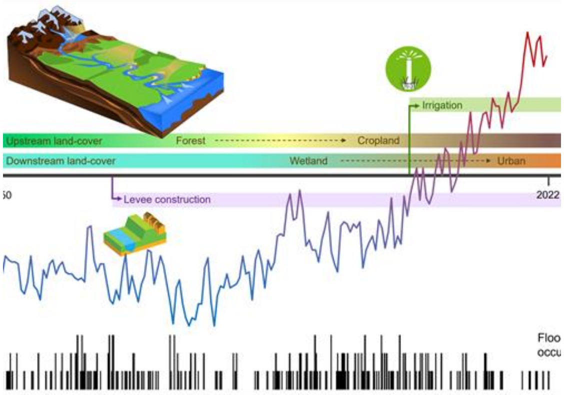

Figure 1. Conceptual illustration of how drivers of river floods change through time. Global warming, affecting temperature and precipitation, overlaps with hydrological change: land-cover change, construction of levees and irrigation. In this contribution we propose solution to deal with this complexity and attribute river flood events.

* Corresponding author
Email address: p.scussolini@vu.nl (P. Scussolini)
URL https://research.vu.nl/en/persons/paolo-scussolini (P. Scussolini)

Superposition of large interventions and succession

Menno Straatsma[a], Gertjan Geerling[b], Marcel van der Perk[a], Maarten Kleinhans[a]
[a]*University Utrecht, Princetonlaan 8, 3584CS Utrecht, 3508TC Utrecht, Netherlands*
[b]*Deltares, Boussinesqweg 1, 2629 HV Delft, Netherlands*

Keywords — Floodplain interventions, vegetation management, superposition effect,

Introduction

Natural succession of floodplain vegetation strongly increases the water levels during flood events [*Makaske et al.*, 2011]. At the same time, climax vegetation, such as softwood and hardwood forest, provides important habitat for mammals and dragon- and damselflies. Currently, it is unknown how the water level lowering effect of floodplain interventions compares to the increase in water levels from natural of seminatural vegetation management. Independent of this knowledge gap was the search for vertical space for the river to allow more dynamic vegetation [*Oerlemans et al.*, 2023]. Potentially, the superposition effect (SE) between a bypass and a new floodplain forest (Fig. 1) could benefit the ecology. A bypass lowers the water level, decreasing the roughness upstream due to the backwater effect. It also reduces the flow velocities, albeit only over the longitudinal extent of the bypass. Therefore, increasing roughness could have a reduced effect.

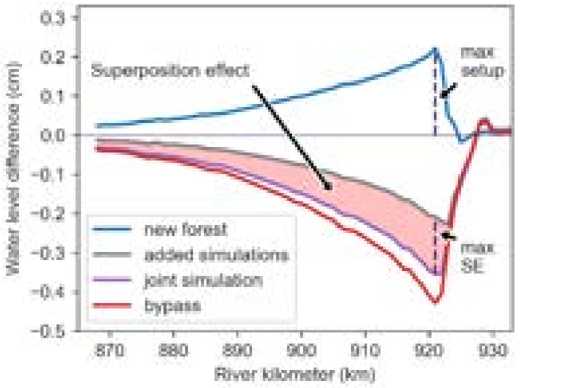

Figure 1. The superposition effect between a bypass and new floodplain forest, both centered around river kilopmenter 920. The joint simulation (purple line) gives a larger reduction than the added differences from the bypass and new forest (grey line).

Given these knowledge gaps, we aimed at (1) an integrated overview of water level effects of autonomous developments, floodplain interventions and vegetation management and (2) quantification of the superposition effect between a river bypass and new floodplain forest.

* Corresponding author
Email address: m.w.straatsma@uu.nl
URL: https://www.uu.nl/staff/MWStraatsma/Contact

Methods

We studied the Waal river in the Netherlands up to Gorinchem. We used RiverScape [*Straatsma et al.*, 2019] to assess the integrated effects on the peak water level of (1) autonomous processes (floodplain sedimentation, silting up of side channels, incision of the main channel [*Sloff et al.*, 2014]) and (2) floodplain interventions (dike raising, floodplain lowering, embankment relocation, side channels and roughness lowering), and (3) vegetation succession under management (smooth, seminatural, and natural). The simulated period started in 2020 and ended in 2120 with a five-year time step. For each combination of floodplain intervention and vegetation management, a 2DH simulation with Delft3D FlexibleMesh provided the water levels at the river axis, which we compared with the reference situation.

For the superposition effect, we modelled a bypass (Varik-Heesselt) and set the forest fraction to 5, 50, and 100 percent in 13 floodplain sections alongside and upstream from the bypass. For comparison, we calculated a dimensionless version of the SE as the maximum SE divided by the maximum setup by the new forest (Fig. 3), i.e. 66% for this example.

Results

The autonomous processes let to an increase in water levels of three cm for floodplain deposition and 2 cm for silting up of side channels, whereas the main channel degradation lowered to peak water levels with 13 cm. The integrated effect of interventions and succession over time (Fig. 2) showed that natural and seminatural vegetation succession counteracted the large scale floodplain lowering in around 20 years, relocation in 15 years and roughness smoothing in five years. Dike raising showed the effects without floodplain interventions. Side channels were much smaller in extent and showed lower water levels, due to main channel degradation.

The spatial distribution of the dimensionless SE (Fig. 3) ranged between 54 and 69 percent lateral of the bypass and between -9 and -3 percent upstream of the bypass inflow. The sections with a positive SE coincided with strongly reduced flow velocities, whereas the negative SE coincided with slightly increased flow velocities.

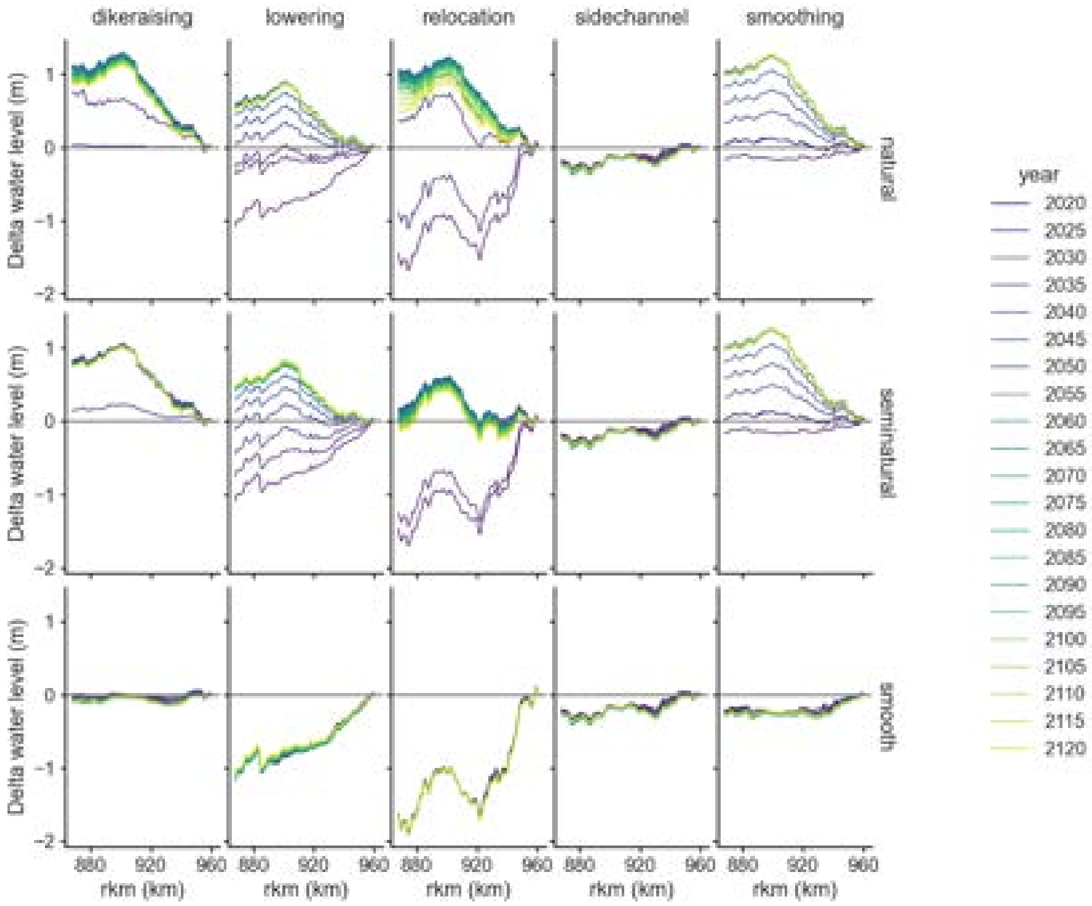

Figure 2. Longitudinal water level differences between 2020 and 2120 from the combinations of five floodplain interventions along the columns and three vegetation management along the rows.

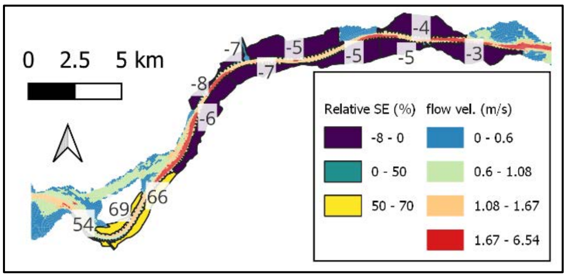

Figure 3. Dimensionless superposition effect with a bimodal distribution between floodplain sections lateral and upstream from the bypass.

Conclusion

The integrated assessment showed that natural or seminatural vegetation successions counteracted the lowering of the peak water levels due to large scale interventions within 15 to 20 years. This held even for the most extreme scenarios, indicating that intensive vegetation management remains necessary. The next step should involve a more physically based vegetation succession and management model.

Surprisingly, the superposition effect between a large intervention and increased roughness showed a strong spatial pattern with positive effects only laterally from the bypass. Upstream the negative effects were an order of magnitude smaller in absolute value. The positive effect could be further exploited in future vegetation management plans. A superposition effect of up to 69 % underlines the call for more ‘room for the river’ in the fluvial future.

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Accuracy of Numerical Morphological Models based on Simplified Hydrodynamics

H.J. Barneveld[a,b], E. Mosselman[c,d], V. Chavarrías[c] and A.J.F. Hoitink[a]

[a] *Wageningen University and Research, Hydrology and Quantitative Water Management Group, Department of Environmental Sciences, Wageningen, the Netherlands, hermjan.barneveld@wur.nl, ton.hoitink@wur.nl*
[b] *HKV, Lelystad, the Netherlands, barneveld@hkv.nl*
[c] *Deltares, Delft, the Netherlands (Erik.Mosselman@deltares.nl, Victor.Chavarrias@deltares.nl)*
[d] *Delft University of Technology, Faculty of Civil Engineering and Geosciences, Delft, the Netherlands (E.Mosselman@tudelft.nl)*

Keywords — Numerical modelling, Morphology, Stability Analysis

Introduction

Sustainable river management often requires long-term morphological simulations. As the future is unknown, uncertainty needs to be accounted for, which may require probabilistic simulations covering a large parameter domain. Even for one-dimensional models, simulation times can be long. One of the acceleration strategies is simplification of models by neglecting terms in the governing hydrodynamic equations. Examples are the quasi-steady model and the diffusive wave model, both widely used by scientists and practitioners. We established under which conditions these simplified and often more efficient models are accurate.

Method

Based on results of linear analyses of the St. Venant-Exner equations, we assessed migration celerities and damping of long riverbed perturbations (Barneveld et al, 2024). We did this for the full dynamic model, i.e. no terms neglected, as well as for simplified models. For the quasi-steady model the time derivatives in the Saint-Venant equations are neglected. The discharge may still vary over time, but for every time-step steady flow conditions are simulated. The diffusive wave model neglects both inertial terms in the momentum equation. This model has been proven accurate for predicting migration and damping of flood waves in lowland rivers.
The accuracy of the simplified models was obtained from comparison between the characteristics of the riverbed perturbations for simplified models and the full dynamic model.
We executed a spatial-mode and a temporal-mode linear analysis, which differ only in the periodic solution for the linearized set of equations.
We compared the results of the linear analyses and numerical modelling results in terms of propagation and damping of riverbed waves. For the numerical modelling we applied the numerical modelling code ELV (Chavarrías et al., 2019), which allows simulating the full dynamic and both simplified models.
For very small bed waves the linear analyses and numerical modelling should provide identical results. Simulations with larger bed waves are performed to assess whether the linear analyses results can be used for field cases.

Results

The results from the linear analyses and numerical simulations for small (infinitesimal) riverbed perturbations, show to be in good agreement. This provides confidence the approach is valid.
For longer and higher river bed waves the ratio of celerities are shown in Figure 1 as a function of the Froude Number *F* and the dimensionless sediment transport parameter Ψ:

$$\Psi = n \frac{s_o}{q_o} \qquad (1)$$

With

n = the power in the sediment transport relation ($s = m \cdot u^n$). For Engelund-Hansen transport predictor *n*=5

s_o = steady uniform sediment transport per unit width ($m^2\ s^{-1}$)

q_o = steady uniform discharge per unit width ($m^2\ s^{-1}$)

In the spatial mode analysis the dimensionless flow variation parameter *E* is the third parameter of importance, which expresses the influence of unsteadiness and non-uniformity of the flow on a scale larger than the local flow depth. For river cases *E* is normally well over 10,000. In the temporal mode analysis the wave length of the river bed waves *L* is the third parameter determining the bed dynamics.

Figure 1 shows that the temporal mode analysis and numerical results for several years are well in line. The spatial mode results deviate from numerical results when *F*>0.2.

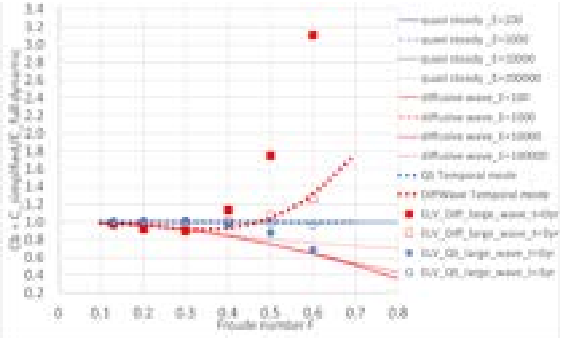

Figure 1. Ratio of celerities obtained from simplified (QS=quasi-steady) and full dynamic models for linear stability analyses and numerical results for long (L = 3,000 m) and large (0.5 m amplitude) bed perturbations under a flood wave regime, Ψ = 5.15 · 10 −5, Δt = 1 s, Δx = 25 m.. The spatial model results are illustrated with the thin lines. The temporal mode analyses results are shown with thick dotted lines and the numerical results are with the markers. Source: Barneveld et al. (2024).

Conclusions

The numerical results appear to match best with the temporal-mode linear analysis.
We show that the quasi-steady model is highly accurate for Froude numbers up to 0.7, probably even for long river reaches with large flood wave damping. Although the diffusive wave model accurately predicts flood wave migration and damping, key morphological metrics deviate more than 5% (10%) from the full dynamic model when Froude numbers exceed 0.2 (0.3). Based on the temporal model analysis Figure 2 provides a design graph for assessing the error of simplified models for various combinations of the parameters Froude number *F*, wave length *L* and one value for the transport parameter *Ψ*.

Acknowledgments

We thank Rivers2Morrow, Rijkswaterstaat, and HKV.

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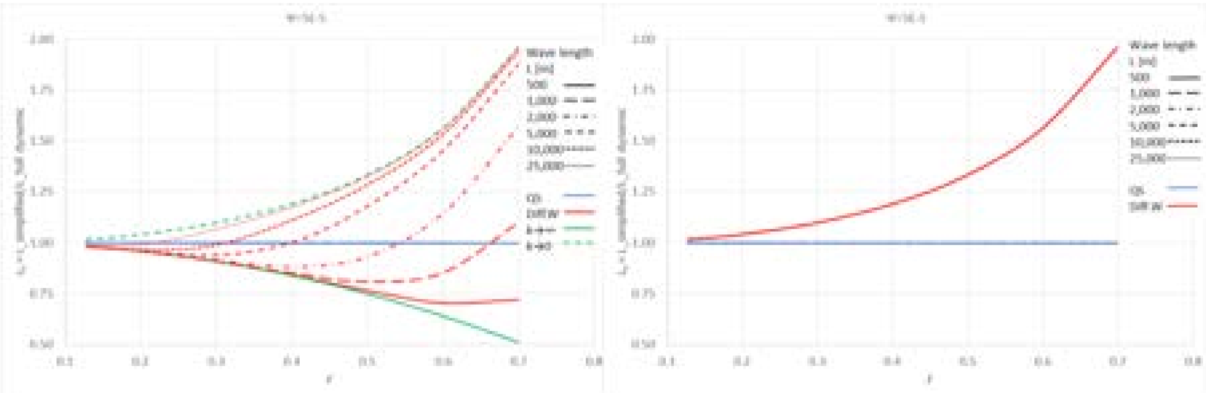

Figure 2. Ratio of migration celerities (left) and ratio of damping length (right) obtained from simplified and full dynamic models for the sediment transport parameter Ψ= $5{\cdot}10^{-5}$. Green lines in the left panels indicate, for the diffusive wave, limit cases for the wave number $k_r \rightarrow \infty$ (short bed waves, firm line) and $k_r \rightarrow 0$ (long bed waves, dotted line).

* Corresponding author
Email address: hermjan.barneveld@wur.nl (Hermjan Barneveld)

Developing a Model to Study the Climate Change Impact on River Bifurcations in Engineered Rivers

M. Kifayath Chowdhury[a,*], Astrid Blom[a], C. Ylla Arbós[a], Ralph M.J. Schielen[a,b]
[a] *Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands*
[b] *DG Rijkswaterstaat, Ministry of Infrastructure and Water Management, Utrecht, The Netherlands*

Keywords — river bifurcation, Rhine River, climate change, long term morphological change, Pannerdense Kop

Introduction

Climate change is responsible for global shifts in precipitation patterns and an overall increase in global temperatures. The transitions are anticipated to modify the river hydrograph and sea level. The changes to the hydrograph are also likely to influence sediment flux. These alterations imply shifts in both upstream and downstream boundaries for river bifurcations. However, the resulting bifurcation response remains uncertain and warrants further investigation. Our objective is to understand the extent of large-scale and long-term response of river bifurcations to climate change. We take the Upper Dutch Rhine bifurcation region as our case study and develop a 1D hydro-morphodynamic model representing the system to achieve this goal.

General Model Specifications

We set up a 1D hydro-morphodynamic model of the Rhine branches suitable for mixed-size sediments using the 1D numerical solver SOBEK-RE. The upstream boundary of our model domain is at Cologne at the Niederrhein. Vuren, Schoonhoven, and Keteldiep are the downstream boundaries of the Waal, Nederrijn, and IJssel branches, respectively. The downstream boundaries are located upstream of the estuarine zone. We smoothen the initial bed, channel cross sections, and initial texture to exclude local variations. Using a 1D model excluding the local variations allows us to efficiently focus on the large-scale and long-term response of the bifurcation region to climate change scenarios. Further details on the model and schematization technique can be found in Ylla Arbós et al. (2023).

Model Initial Conditions

Chowdhury et al. (2023) indicated that the flow partitioning trend at the Pannerdense Kop bifurcation changed following a sequence of peak flows in 1993 and 1995 (and possibly 1998). To capture and better understand the phenomenon, our initial state of the model corresponds to the situation during 1980-1990. We focus on bed material load in this model and consider five-grain size classes- fine sand, medium sand, fine gravel and two coarse gravel fractions based on data availability. Our initial bed composition is representative of 1980-1984 and based on the bed texture surveys of 1984 along the Rhine branches and 1981-1983 for Niederrhein (e.g., De Ruijter (1988)). We averaged the data over the width and smoothened the data using shape-preserving interpolation through 3rd-order splines (Fig.1).

Model Calibration

We perform a hydraulic calibration of the model. We calibrated the model against the water level at Arnhem and Nijmegen (Fig. 2) and the annual mean flow partitioning ratio at the Pannerdense Kop and IJsselkop bifurcations, using the total friction per branch as a calibration parameter.

We are currently performing a morphological calibration of the model against the channel bed aggradation rate and the annual mean flow partitioning ratio trend at the bifurcations from 1985 to 2010. Calibration parameters include sediment transport pre-factor, critical shields stress, and nodal point relation per fraction. The verification period of the model is between 2010 and 2020.

Boundary Conditions and Climate Scenarios

We develop our scenarios of boundary conditions (hydrograph and base level) for the model based on KNMI 2023 scenarios covering different magnitudes of change till 2150 (KNMI, 2023).

Our base case hydrograph is a cycled hydrograph with a daily discharge for 20 years with the same statistical properties as the historical record. A cycled hydrograph allows us to capture natural flow variability and guarantees the existence of an equilibrium state. We adjust our hydrograph for climate scenarios by using the flow duration curve statistics from KNMI 2023 scenarios (Buitink et al., 2023) to calcu-

*Corresponding author
Email address: m.k.chowdhury@tudelft.nl (M. Kifayath Chowdhury)

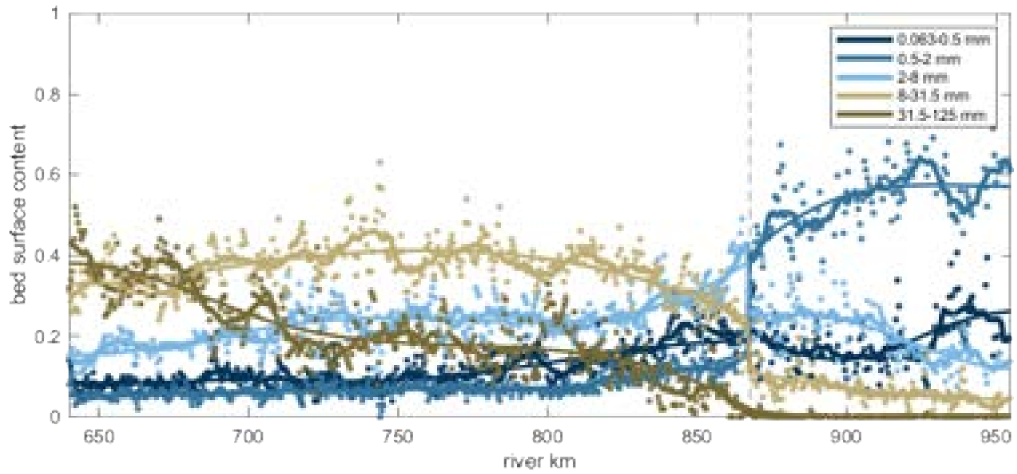

Figure 1: Schematized initial bed surface content for Niederrhein-Bovenrijn-Waal based on 1980-1984 survey. Dots represent data and solid lines represent the spline approximation.

late a factor reflecting relative changes in percentile discharge for each scenario (Ylla Arbós et al., 2023). We approximate the downstream boundary water level relative to sea level by using the De Vries (1994) empirical fit to the analytical solution of the backwater equation (Ylla Arbós et al., 2023). We include sea level rise (SLR) scenarios based on KNMI (2023).

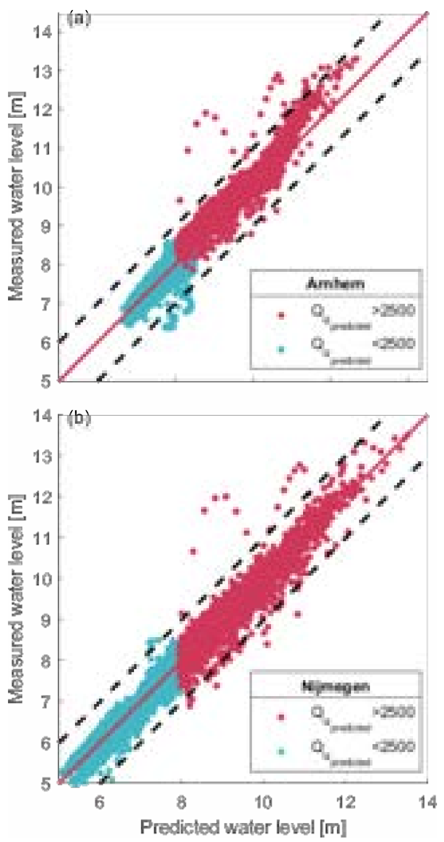

Figure 2: Measured and predicted water level data from (a) Arnhem and (b) Nijmegen for hydraulic calibration.

Based on the scenarios for climate change, the model is expected to provide insight into the morphological response and related flow distribution adjustment at the bifurcation region due to the various magnitude of changes in the upstream hydrograph and base level in the North Sea due to climate change.

Acknowledgements

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Investigating drivers of the ecological functioning of the Common Meuse

Joshua D. Climo[a,*], Wilco C.E.P. Verberk[a], Gertjan W. Geerling[b]
[a] Radboud University, Department of Ecology, Faculty of Science, Heyendaalseweg 135, 6525AJ Nijmegen
[b] Radboud University, Department of Environmental Sciences, Faculty of Science, Heyendaalseweg 135, 6525AJ Nijmegen

Keywords — riverine ecology, macro-invertebrates, conservation and restoration

Introduction

The Common Meuse (Limburg, the Netherlands) is designated as a Natura 2000 area and has considerable potential for ecological conservation and restoration. However, myriad stressors adversely affect distinctive riverine plant and animal species, thereby compromising the ecological functionality of the river (Klink 1985; Klink and Vaate 1996).

Our research aims to comprehensively understand the current aquatic ecological state, identify potential stress factors, and contribute to the conservation and restoration of the system. With these overarching goals in mind we performed fieldwork in August 2023 with two specific questions; 1) what is the effect of hydropeaking on the riverine communities and 2) how do the streams and river compare (a)biotically?

Methods

Along the river and in the confluence of streams we performed measurements of biotic and abiotic factors (for locations, see Fig. 1). We continuously monitored depth in the river (n=5), and temperature in the river and streams (n=12). Additionally, oxygen saturation and flow velocity were measured during macro-invertebrate collection (n=12). Macro-invertebrates were collected using kick-net sampling. For each location, five and three samples were taken in the river and streams, respectively (resulting in a total of 15 stream and 35 river samples).

Results

Abiotic

The river is subject to strong, non-natural fluctuations in water level (i.e., hydropeaks) that attenuate with distance downstream (Fig. 2). Compared to streams, rivers were warmer, with lower flow velocity and higher daytime oxygen saturation. Temperature in the river was significantly higher than in the streams (Δ median: 3.3 C; Fig. 3). Furthermore, flow velocity was lower in the river with a median of 0.006 m/s, while streams had a median velocity of 0.696 m/s. Daytime oxygen saturation ranged from 77.1 - 153.9 % (median: 99.3) in the river compared to 30.4 - 102.5 % (median: 85.9) in the streams.

Figure 1: Sample locations along the river and in the streams.

*Corresponding author
Email address: `joshua.climo@ru.nl` (Joshua D. Climo)
URL: `https://www.ru.nl/personen/climo-j` (Joshua D. Climo)

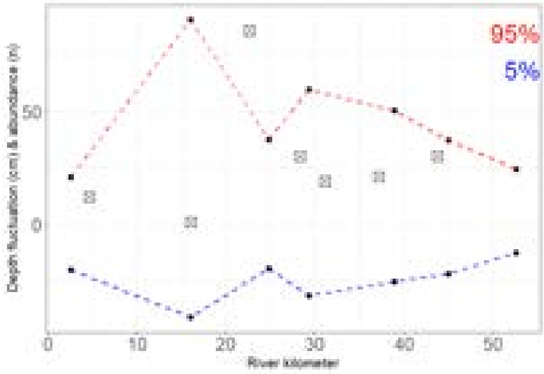

Figure 2: Centered fluctuations in water level by river kilometer. The red line represents the upper 95% interval and the blue line the lower 5% of the water level fluctuations. Squares with crosses indicate median macro-invertebrate abundance.

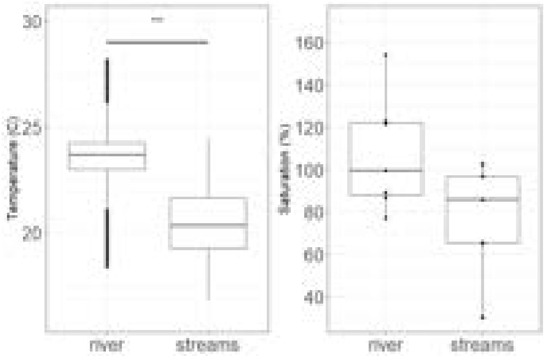

Figure 3: Comparison between the temperature (left) and oxygen saturation (right) for the river and streams.

Biotic
Macro-invertebrate abundance was not related to the longitudinal gradient of decreasing fluctuations in water level (Fig. 2), but the overall abundance in the river was much reduced compared to that of the streams (Fig. 4; left panel). Additionally, the river is characterized by a lack of mayflies and caddisflies (Fig. 4; right panel) and dominance of chironomidae, invasive amphipods (i.e., *D. villosus*) and Oligocheata (i.e., dominance by very tolerant species while lacking sensitive groups).

Conclusion

Based on this (brief) field campaign differences in macro-invertebrate abundance along the river do not seem to be driven by hydropeaking as the encountered water level fluctuations do not explain the species abundance. However, the river and streams are strongly different regarding macro-invertebrate community composition and abundance. The difference between the streams and river can at least

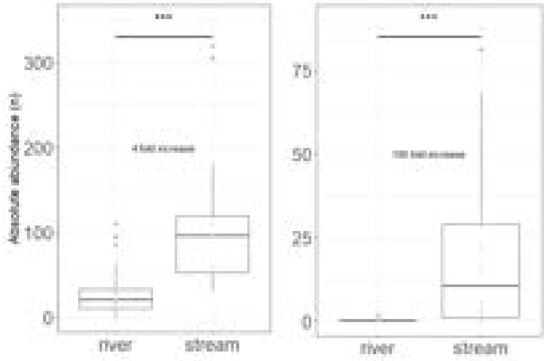

Figure 4: Absolute macro-invertebrate (left) and ept abundance (right panel. ept taxa include sensitive species and are e.g. also used as positive indicators for ecological WFD scores) in the river and streams. The river harbors approximately 4 times as few macro-invertebrates in general and over 100 times as few ept individuals.

partially be explained by a different temperature, oxygen concentration and flow velocity (Verberk et al. 2023), but further contributing factors remain to be elucidated.
To conclude; currently, macro-invertebrate abundance in the river was to low to conclude anything with certainty save concluding dreadful ecological functioning.

Future research & Acknowledgments

Future efforts will focus on elaborating the differences between the river and reference systems and include investigating sediment and water quality. Furthermore, the data from the Common Meuse will be compared with data from a more pristine system; River Eden (UK). This study is carried out as part of the rivers2tomorrow project and is performed in close collaboration with Rijkswaterstaat and Utrecht University.

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Reevaluation of the Japanese traditional river training structure “Seigyu”

Temma Fujii[a], Sameh Ahmed KANTOUSH[b], Amgad Omer [c]
[a]*Guraduate School of Kyoto University, Disaster Prevention Research Institute, Faculty of Engineering*
S-511d, Gokasho, Uji-shi, Kyoto-fu 611-0011, Japan
[b] *Kyoto University, Disaster Prevention Research Institute*
[c] *Deltares*
Boussinesqweg 1, 2629 HV Delft, the Netherlands

Keywords — Nature-based solution, sediment transport, traditional river training structure

Background

The Kizu River (Fig. 1), which is one of the tributaries of the Yodo River in Japan, is facing severe riverbed incisions similar to many other rivers in Japan. This decrease was caused by the decrease in the sediment supply from upstream due to construction. The Kizu River has 5 dams in the upstream region, and their sedimentation is becoming a problem. (Kantoush et al., 2020)Sediment replenishment is considered one of the solutions to these problems. To ensure the safe life of the downstream area, a means of controlling the sediment in the downstream reach needs to be developed to increase the scale of sediment replenishment.

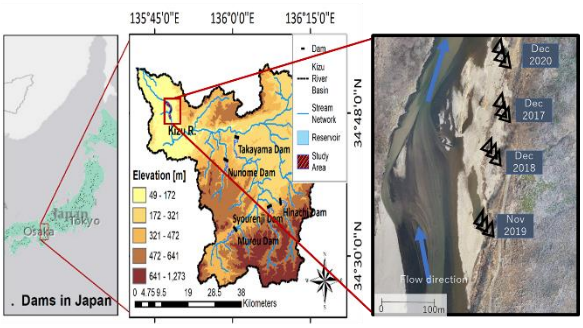

Figure 1. Location of the Kizu River Basin and the installation site

Introduction of Seigyu and construction activity in the Kizu River

A single gabion is a groin consisting of a triangular pyramid-shaped wooden structure and a bamboo gabion filled with rocks (Figure 2). It has been used in Japan for more than 500 years for bank protection. It is a pure nature-based solution, made of wood, bamboo, and rocks. These materials are usually easy to obtain from areas close to rivers, and construction can be performed at low altitudes.

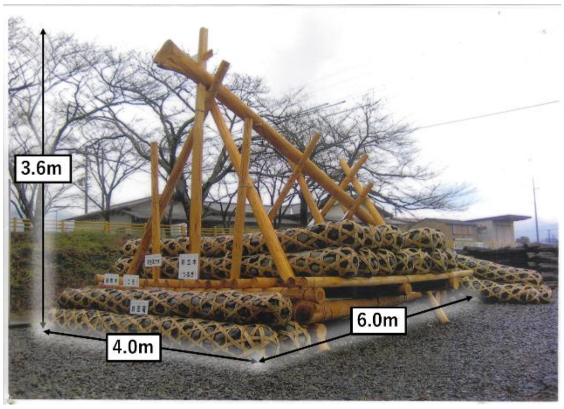

Figure 2. Structure and dimensions of Seigyu

12 Seigyus were installed on the sand-gravel bar in the Kizu River to assess their effects on flow, topography, and the environment. Previous monitoring and studies revealed the following three effects of Seigyu.

1_Diversity the flow
2_Reduce flow velocity (Fig. 3)
3_Promotion of geomorphological change (Tamagawa et al., 2022)

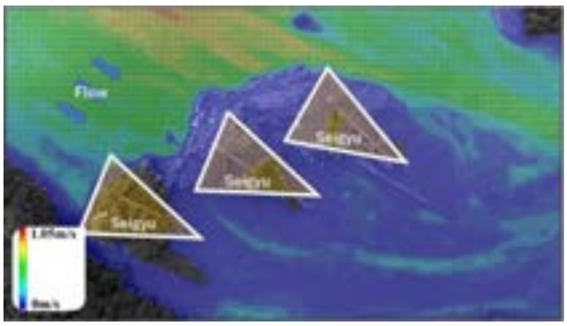

Figure 3. Flow pattern around Seigyu during a flood.

Since the first installation in the Kizu River, Seigyus has experienced several floods, which fully submerged them. Following such floods, the transformation of Seigyu, such as inclination, debris trapping, and corruption, was observed. This transformation was long believed to lead to a decreased capability of Seigyu. However, no study has investigated this transformation in depth. Hence, a study was conducted to

* Corresponding author
Email address: temma.fujii.34a@st.kyoto-u.ac.jp (Temma Fujii)
kantoush.samehahmed.2n@kyoto-u.ac.jp (Sameh ahmed KANTOUSH)
Amgad.Omer@deltares.nl (Amgad Omer)

investigate the impact of transformation on the effects of Seigyu.

UAV survey and data processing

UAV surveys were also conducted to obtain images for generating DEMs and 3D models. DEMs and 3D models were generated using the photogrammetry software Metashape (Agisoft LLC, St. Petersburg, Russia). 3D models were used to assess the status of Seigyu goats, including the inclination angle. Using the 3D model for assessing Seigyu conditions was confirmed to be possible. This approach will reduce the duration of the field measurements and make it possible to perform the same analysis in the laboratory. This method is suited for monitoring and recording historical changes in Seigyu goats, which are continuously changing in appearance.

Videos were recorded by the UAV during floods. Using the large-scale particle image velocimetry (LSPIV) method, these videos were processed to determine the flow velocity distribution around Seigyu.

Transformation and the Effects of Seigyu

Seigyu's effect on flow velocity reduction increased when it trapped debris. The debris was trapped in front of Seigyu and blocked the flow. As a result, the low-flow velocity zone behind Seigyu became wider (Fig. 3).

The inclination of Seigyu was more prominent when it experienced the first flood after installation and tended to decrease afterward regardless of the flood scale. (Fig.4)

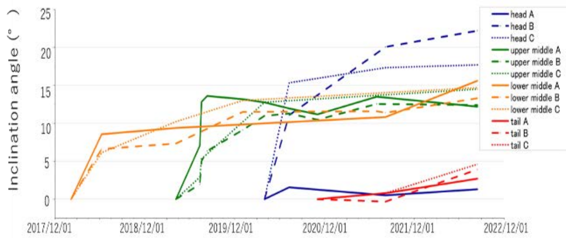

Figure 4. Change in the inclination angle of Seigyu upstream

The volumetric characteristic of sediment transport around Seigyu was calculated by dividing the net change in the sediment volume of the sand-gravel bar by the summation of the discharge throughout each year (F in Fig. 5). Figure 5 indicates that Seigyu changed the erosional sand-gravel bar into the depositional area.

Geomorphological changes around Seigyu continued after inclination occurred, and the effect of enhancing deposition increased. Trapped debris contributes to the reduction in the flow velocity. These findings confirmed that Seigyu continues to contribute to riverbed changes despite its transformation.

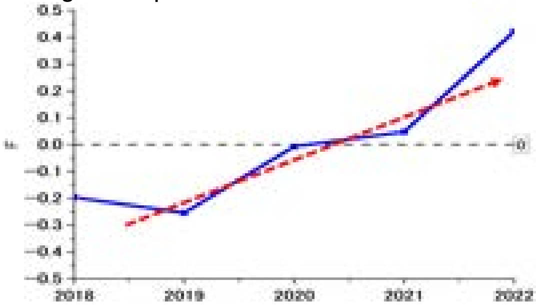

Figure 5. Changes in the geomorphological change characteristics of the sand-gravel bar around Seigyu

The need for 3D simulation in future work

According to the hydraulic model experiment of Zhang et al. (2023), Seigyu creates an area with a low flow velocity, and this area is much larger than that of other types of groin. They also noted that the geometry of Seigyu, which consists of pervious and impervious parts, results in a complex three-dimensional flow structure.

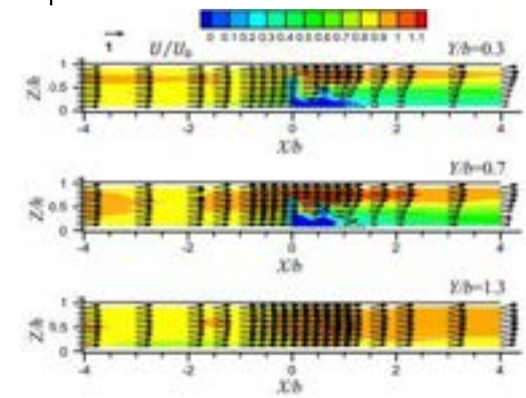

Figure 6. Flow vector and velocity contour map of the three different longitudinal cross-sections (Zhang et al. *2023, modified)*

The final goal of studying Seigyu is to implement it as a device for riverbed management and combine it with sediment replenishment from upstream dams. The next step is to represent Seigyu in the model and develop a way to simulate the effect numerically. Given the complex flow regime around Seigyu, 3D simulation is needed.

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Hydrodynamic modelling of Wadi flash flood in arid regions

Nabil Khorchani[a, b*], Amgad Omer[b], Leonardo Alfonso[a]
[a] *Institute for Water Education IHE Delft, Westvest 7, 2611 AX Delft, Netherlands*
[b] *Deltares, Boussinesqweg 1, 2629 HV Delft*

Keywords — flood hazard, hydrodynamic modelling

Introduction

The rapid and unexpected onset of flash floods in arid environments presents a significant hazard, often resulting in fatalities, property damage, and interference with sensitive ecosystems.
Ephemeral yet impactful, flash floods in Wadis represent a persistent natural challenge that confronts countries throughout the MENA region and are considered the most damaging (economic, social, environmental) natural hazard (Saber & Habib, 2016). This region is facing flash floods due to a complex dilemma where precipitation is expected to decrease, in the world's most water-scarce area, as well as an increase in Wadi Flash Floods (WFFs) in a variable rainfall pattern (intense rain in a short time out of the normal season) (Hassan et al., 2022). The 6th IPCC report made a highly confident prediction that more frequent severe rainfall events will occur in the MENA region (Tanaka et al., 2020). Prediction of WFFs is still very difficult and few studies have been conducted to model historical flood events in an environment where less measurement and well-distributed gauge stations are available. According to Abdel-Fattah et al (2017), the majority of researchers have used lumped and semi-distributed models to study WFFs and only limited studies focused on the use of distributed models because of the amount of data required. Dahri and Abida (2022) recommended the use of hydrodynamic modelling to predict the variation of water depth in Wadi Gabes in Tunisia within extreme events and produce flood zones. The use of modelling could, potentially, simulate WFFs depth, velocity, and duration providing decision-makers with the necessary information to raise awareness regarding the extent of future inundations. Therefore, this research seeks to develop a 2D hydrodynamic model utilizing available data to simulate a historical WFF event in an arid region located in the southeast of Tunisia to study the Wadi Gabes catchment that covers an area of 123 km^2, empowering decision-makers in their endeavors to mitigate the impact of natural hazards.

* Nabil Khorchani
Email address: nabil.khorchani@gmail.com

WFF model simulation

To model WFF, a distributed 2D hydrodynamic was used to simulate the flash flood event of 2-3 June 2014. Delft3D FM (also called D-Hydro) developed by Deltares, is an advanced water modelling for 1D/2D and 2D/3D computations. It's the suite and successor to Delft3D 4. This software was chosen as it provides a faster simulation time compared to other models (according to Muñoz et al.,2022), Delft 3D FM is 6 to 10 times faster than HECRAS) and for being used for the first time in our case study.
To set up the Delft3D FM model, there's a need to prepare several input data. These inputs include; Grids, DEM, rainfall data, evaporation, land cover, soil type and boundary conditions. The considered outputs from the model are mostly; discharge, water depth and water velocity.

Model calibration

To calibrate the 2D model two parameters were used: the infiltration and roughness. Being in a format of raster files, it was quite easy to modify each parameter's values for each calibration step. This was processed in GIS software (ArcGIS and QGIS) where we started with varying the maximum and minimum infiltration intervals for each raster and as a second step, we changed the roughness values after setting the sensitivity ranges of maximum and minimum infiltration. The observed rainfall with a total of 72 mm falling in 5 hours was used as input in the model to predict the observed discharge. The peak flow of the observed measurement was attenuated after 2 hours from the rainfall peak (at 03:20 for rainfall and at 05:20 for discharge). Several calibration runs were operated in order to achieve the best fit with the observed discharge.
Figure 1 represents the final result from the calibrations, the simulated discharge slightly overestimates the observed by almost 5 m3 /s at the peak. Moreover, there was a problem with a time interval shift since the beginning of the calibration. We thought of reducing the roughness to speed up the flow wave. We succeeded in shortening the interval from 3 hours to only 50 minutes (the observed peak is at 05:20 while the

simulated peak is at 06:10). We decided to end the calibration phase at this
stage due to the time limitation (the delay can be linked to some uncertainties in infiltration meaning need of detailed soil and land cover types in addition to the DEM). In terms of total volume, the observation station received 1.091 M m3 and 1.096 M m3 for the observed and simulated discharge respectively (a difference of 4209 m3 due to the overestimation). Although the problem we faced with the model in correcting (slightly) the shift in timing, Delft3D FM could initially, even before the calibration, capture the form of the observed hydrograph.

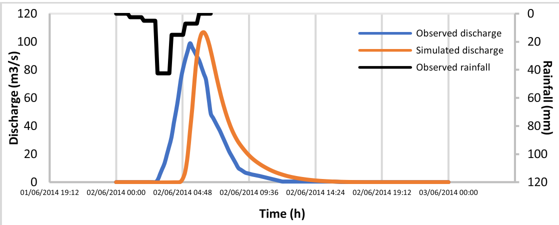

Figure1. Simulated hydrograph of the flood event (June 2014) in Wadi Gabes catchment.

Model verification

Due to the lack of another observed discharge data during a flood event, and as no satellite images were captured for previous events, an inventory in social media was carried out in order to find the best representation of the water depth (benchmarks, e.g., cars, bikes, etc) within the city of Gabes during the historical flood event of 2014. A specific location was chosen after being checked in Google Maps (33°53'16.4"N 10°05'57.9"E) and asking local people for verification. Based on the ground truth and the table provided by Chaudhary et al., (2019). The estimated water depth in the roads is level 3 which means an interval of 10.0–21.25 cm if we consider that the flood covered half of the car's tire as decided from the images.

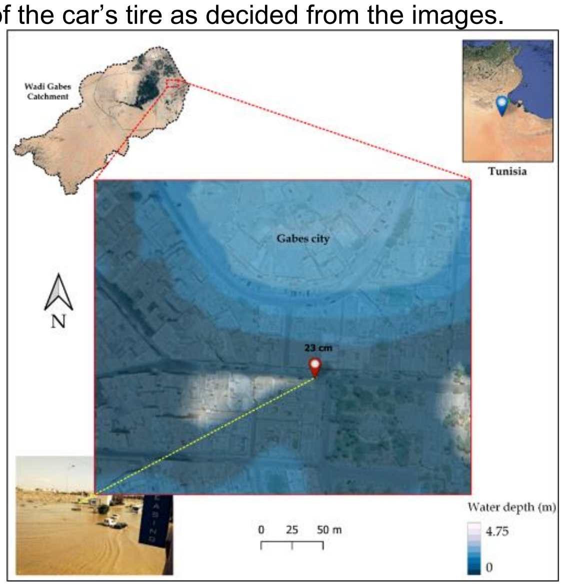

Figure 2. shows the water depth of the same chosen location which is 23 cm exported from Qgis canvas

Table 1. Estimated water depth of the 2014 flood event based on literature and the result of the model

	Estimated water level (literature)	Simulated water level (Delft3D FM)
Water depth	10-21.25 cm	23 cm

Overall, the hydrodynamic model succeeded in simulating the historical WFF event. The best calibration reached an R^2=0.71 and the verification was very close to the estimated water depth from the literature in the same chosen location. Thus, in a data scarce area, the social media inventory could potentially be very useful to overcome data's limitation. This result can be used to generate a hazard map and then a WFF risk map if the information regarding vulnerability and exposure are available. This research serves as the base for future studies toward WFF risk reduction in a data-scarce area.

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Short-term bed level predictions for the Waal River: a machine learning approach

Luuk I. van Laar[a], Thomas Stolp[b], Fredrik Huthoff[a,b,c],
[a] *University of Twente, Department of Water Engineering and Management, Faculty of Engineering Technology, P.O. Box 217, 7500 AE, Enschede, the Netherlands*
[b] *HKV Lijn in Water, 8232 JN Lelystad, the Netherlands*
[c] *IHE Delft Institute for Water Education, Department of Water Resources and Ecosystems, PO Box 3015, 2601 DA Delft, the Netherlands*

Keywords — Machine Learning, Waal River, river morphology, bed level prediction,

Introduction

The Dutch rivers belong to the busiest navigation routes in Europe (Sys et al., 2020; Vinke et al., 2022). To keep the Dutch waterways navigable, they are maintained via dredging and various river engineering works (Rijkswaterstaat, 2023). Among the Dutch river branches, the Waal River undergoes the most frequent dredging (Rijkswaterstaat, 2023), with an annual dredging volume reaching 700,000m^3 (Rijkswaterstaat, 2020). Due to climate change, low flows in the Waal are expected to become more extreme in the future (Sperna Weiland et al., 2015), which could increase the need for dredging and efficient dredging strategies.

Current decisions on dredging activities rely on bed level monitoring data. No use ifs made of any kind of bed level predictions, and therefore the dredging activities are more of a reactive than of anticipatory nature. Dredging is initiated when the bed level measurement exceeds the critical dredging reference level set by Rijkswaterstaat (Kruis et al., 2023). Providing a short-term prediction on the bed levels can contribute to more effective and efficienet channel regulation (Liu et al., 2022). Such predictions can offer insights into potential future bottlenecks, identify deeper locations for sediment disposal and pinpoint areas where subsequent measurements may not be necessary due to low bed level predictions. Also, they could offer better guidance on the optimal timing of dredging activities.

In this study we explore the use of deep learning for short-term forecasts (two weeks) of bed elevation in the Waal. For this purpose, we use the Trajectory Gated Recurrent Unit model (TrajGRU) originally developed for precipitation nowcasting (Shi et al. 2017). This study explores the ability of the short-term bed level prediction accuracy of the TrajGRU machine learning model for the Waal River by implementing data pre-processing and hyperparameter optimisation.

Method

The TrajGRU model is used to predict a bed level map for a selected reach of the Waal of 180 m by 250 m near river kilometre 902 (see Figure). The model is trained on historical bed level data in this river section, for which we use high resolution multibeam echosounder data that has been collected by Rijkswaterstaat on a bi-weekly basis since 2006. Next, various data pre-processing techniques are used to see how they affect the accuracy of a two-week bed level prediction of the model.

The considered data pre-processing steps are:

1. Selection in samples: *The input data of the model contains measurements with varying time intervals.* A *selection* of data is made to have more homogenous *time intervals.* Also*,* data under extreme river discharge conditions *are removed from the data,* because *the model is meant for simulating median to low flows.*
2. Stream coordinate transformation: To simplify the learning of bedform developments for the TrajGRU model, grid is transformed to a channel-fitted coordinate system that removes curvature of the channel section.
3. Wavelet reconstruction: Small bedform noise such as ripples are removed as their dynamic timescale is smaller than the 14-day median time interval using a 2D Wavelet model (Kruis et al. (2023).
4. Raster shifting: Time interval inconsistencies are further removed via raster shifting. If the time interval between consecutive measurements deviates from the 14 day median, the bathymetry raster frame is shifted along the channel axis, such that the time intervals become consistently 14 days.

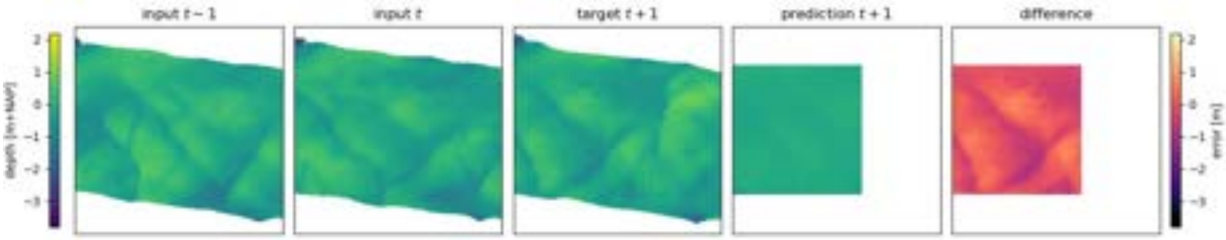

Figure 1. First results from the TrajGRU model.

Results

The explored pre-processing steps in this research improve the bed level predictions. However, the predictions show little spatial detail in the selected river section, and therefore have limited added value for improving dredging strategies. As a next step, we will reduce the number of free parameters in the model (i.e. *hyperparameter optimisation*) to see if this would lead to more pronounced bed level features in the predictions of TrajGRU model.

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The influence of vegetation occurrence on water levels

Anna Maria Łoboda[a*], Anouk Bomers[a], Trang Minh Duong[a,b,c]
[a] *University of Twente, Department of Civil Engineering and Management, Enschede, the Netherlands*
[b] *IHE Delft Institute for Water Education, Delft, The Netherlands*
[c] *Deltares, Delft, The Netherlands*

Keywords — river modelling, vegetation, flood

Introduction

Vegetation is one of the fundamental river system components, which significantly shapes river processes (Nikora, 2010; Sun et al., 2010). A wide role of aquatic and riparian plants may contain control of physical phenomena, e.g., the increase of riverbank stability and thus, the erosion reduce. Moreover, they are very important from an ecological point of view by providing habitats for communities (Sun et al., 2010).

Historically, the ecological significance, particularly as a wildlife habitat, of vegetation along riverbanks was overlooked (e.g., Rae, 1949). Consequently, efforts were primarily concentrated on minimizing flow resistance by cutting vegetation to mitigate flooding. A present challenge involves striking a balance in predicting channel resistance in the presence of vegetation, considering both ecological management and flood control objectives (Nilsson et al. 2005; Nepf, 2012). Recognizing their significance, plants have been integrated into nature-based solutions for effective river engineering and management. Phenomena based on flow-biota interactions, however, face multiple research gaps due to continuous changes in vegetation development (Nikora, 2010). Thus, this study aims to investigate the effect of changing river vegetation on rising water levels, meaning, e.g., differences between winter and summer occurrence of plants and their dimensions, which is usually neglected in model predictions.

Methods

The Meuse River, one of the main rivers in the Netherlands, was investigated in this study, specifically the river reach from the Eijsden grens (upstream) to Maaseik (downstream) gauging stations (Fig.1). Performed calculations were based on the hydrodynamic model (D-Flow FM 2DH model of the Meuse River; Deltares, 2022), where numerical simulations were used to investigate the impact of riverbank and floodplain vegetation on water levels before and during a flood event. Above mentioned stations created boundary conditions for the model with discharge and water level values. Those boundary conditions as well as, for example, the initial water level or bed level were based on the real conditions from July 2021.

Figure 1. Studied river reach of the Meuse River from Eijsden grens to Maaseik gauging station.

To simulate various conditions of the vegetation coverage, in specific areas (Fig. 2), vegetation changes were implemented in the model using Manning's roughness coefficient. In total, seven scenarios were run (Tab. 1), where five of them were based on changes on riverbanks only (Fig. 2a) and one of them covered both, riverbank and floodplain vegetation (Fig. 2b). The baseline model scenario, validated on real data from July 2021, had a uniform friction coefficient for the entire model grid equal to 0.023 s/m(1/3), a value that corresponds to the absence of vegetation.

* Corresponding author
Email address: a.m.loboda@utwente.nl (A.M. Łoboda)

Table 1. Roughness values in changed area for different variants in the model.

Model variant	Area with changes	Manning roughness coeff. [s/m(1/3)]
W 0	-	0.023
W 1	riverbank	0.030
W 2	riverbank	0.040
W 3	riverbank	0.050
W 4	riverbank	0.060
W 5	riverbank	0.070
W F	riverbank + floodplains	0.070 + 0.100

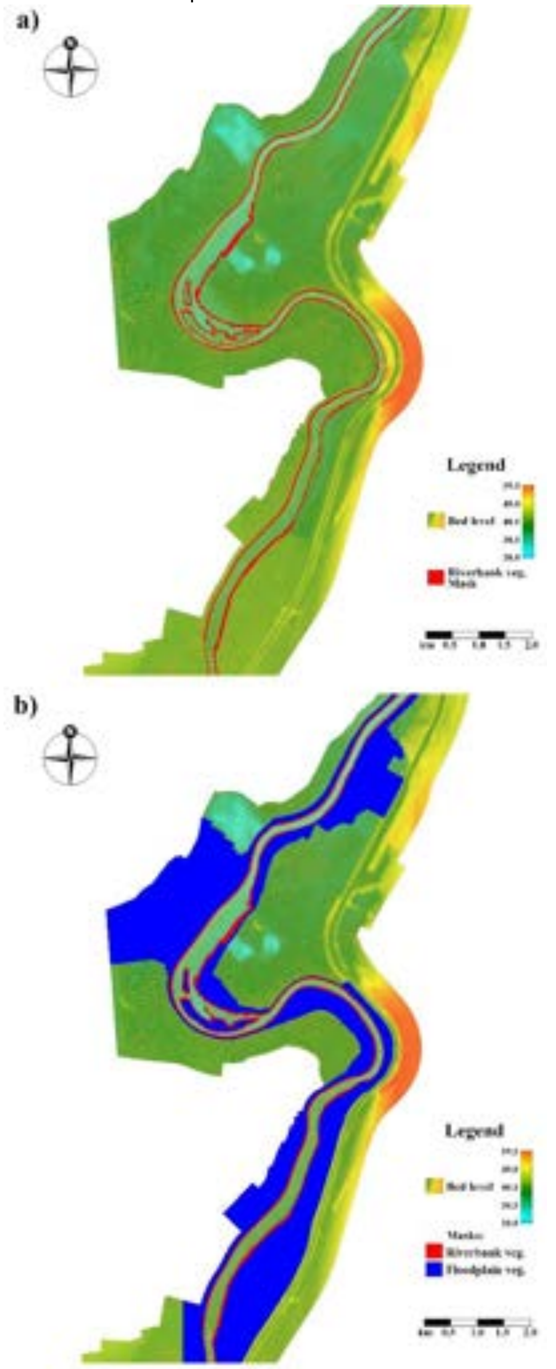

Figure 2. Exemplary area of roughness masks, where changes were implemented on riverbanks (a) and on floodplains (b).

Preliminary results

The model results presented water levels for various scenarios, examining six distinct versions of the riverbank roughness, including the baseline model scenario (W 0, Tab. 1). It was discovered that no substantial differences in water levels were observed during the flooding event after adjustments were made along the riverbanks (example on Fig. 3). Concerning riverbank outcomes, slight variations in water level values emerged before the flood event, suggesting that the riverbank might influence discharges, particularly in the range where floodplains begin to inundate. Therefore, further investigations are needed to delve into the effects on water levels and the extent of inundation for discharges during the initiation of overbank flow. As regards floodplains, trial changes implemented in the roughness of these areas (Fig. 2b) showed that vegetation is an important component of the river system during flood event and should not be neglected, however, more scenarios is required to assess the impact.

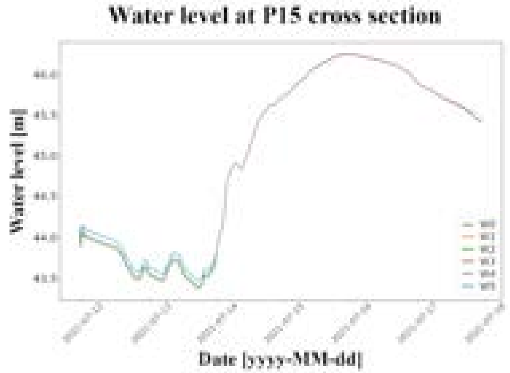

Figure 3. Water level for various variants of roughness on riverbanks in exemplary cross section, P15, throughout the modelled time frame.

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Developing an integrated assessment model for salt intrusion mitigation measures in delta systems

Paran Pourteimouri[a,b*], Robert-Jan den Haan[b], Jaap Kwadijk[a,c], Mascha van der Voort[b]
[a]*Deltares, P.O. Box 177 2600 MH, Delft, The Netherlands*
[b]*University of Twente, Department of Human Centered Design, Faculty of Engineering Technology, P.O. Box 217, 7500 AE, Enschede, The Netherlands*
[c]*University of Twente, Department of Multidisciplinary Water Management, Faculty of Engineering Technology, P.O. Box 217, 7500 AE, Enschede, The Netherlands*

Keywords — Salt intrusion, Rhine-Meuse delta, Water resources management, Integrated assessment model

Introduction

Effective freshwater management in delta regions, especially densely populated areas like the Rhine–Meuse delta, faces a critical challenge due to seawater intrusion and salinization. Climate change significantly intensifies the risk of salty seawater encroaching into deltas, threatening freshwater quality and availability (van den Brink et al., 2019). With rising sea levels and reduced river flows, regions like the Rhine-Meuse delta are increasingly vulnerable to salt intrusion, demanding urgent actions to protect these essential resources. As climate change exacerbates this threat, addressing and mitigating salt intrusion in deltas becomes imperative for ensuring sustainable freshwater access.

The mitigation of salt intrusion involves various stakeholders—drinking water providers, ports, agriculture, industries, among others—each implementing their strategies. It has been clearly established that stakeholder engagement is essential in pursuing unified goals in integrated natural resources management (Haasnoot et al., 2013). Essentially, the involvement of stakeholders and adopting a holistic perspective are pivotal to enhancing the quality of decision-making and fostering wider acceptance of implemented strategies. In this context, Integrated Assessment Models (IAMs) emerges as a crucial tool (Haasnoot et al., 2014). By facilitating comprehensive system understanding and predictive capabilities, IAMs actively engages stakeholders and offers a structured framework for monitoring key indicators in environmental decision-making. Consequently, IAMs enhance decision-making processes and optimize resource allocation.

* Corresponding author
Email address: paran.pourteimouri@deltares.nl; p.pourteimouri@utwente.nl (Paran Pourteimouri)

In a salt intrusion context, the importance of an IAM to support decision-making is recognized. However, exploration into how effectively IAM fosters stakeholder engagement has been limited. This study aims to address this gap by emphasizing an IAM's crucial role within stakeholders' involvement in salt-intrusion decision-making.

Our main objective is to identify key indicators essential for making decisions related to salt intrusion. Furthermore, we aim to explore how actions taken in one sector can profoundly affect and connect with other sectors. To accomplish this, we are developing a numerical model that integrates multiple models, each designed to address a specific aspect or key component fundamental to our objective. In this paper, we present the proposed IAM, its modules, and key indicators.

Assessing salt intrusion mitigation measures: Impact on key indicators

The IAM comprises seven distinct modules, each serving a vital role in evaluating critical aspects of salt intrusion mitigation within the Rhine-Meuse Delta (see Fig. 1). The *Salinity Module* assesses Chloride concentration at key delta locations, while the *Hydrodynamics Module* examines flow features such as discharge, water depth, and flow velocity. The *Signal Module* monitors alarm statuses and factors like Chloride concentration exceedance frequency, consecutive days exceeding thresholds, and flood risk assessment. The *Drinking Water Module* evaluates the total number of individuals or households currently connected to and being served by each water intake point. The *Nautical Traffic Module* addresses water depth suitability for shipping and optimizes vessel waiting times. Meanwhile, the *Nature Module* explores the sensitivity of aquatic organisms and plants to salinity, alongside their adaptability to changing conditions. Finally, the *Cost Module* analyzes implementation costs and long-term maintenance expenses, crucial for determining the feasibility and sustainability of measures undertaken.

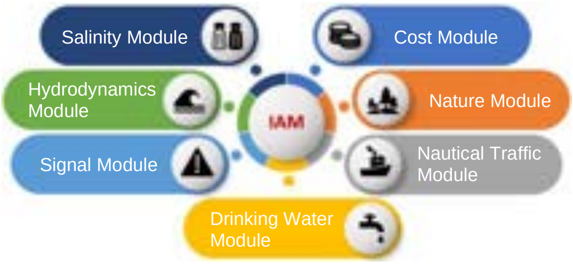

Figure 1. Components of the Integrated Assessment Model (IAM)

IAM front-end: Engaging stakeholders in salt intrusion management

If the seven modules are considered the back-end of the IAM, the IAM also needs a front-end to support decision-making. The proposed IAM's front-end comprises an online dashboard accessible to stakeholders, facilitating self-exploration and experiential learning. Within this platform, stakeholders explore scenarios that include: 1) climate-induced effects like sea level rise, droughts, and salt intrusion; 2) socioeconomic impacts such as urbanization and population growth; and 3) human-induced factors like channel deepening/widening and implementing locks. Stakeholders have the flexibility to choose measures varying from infrastructure modifications to the implementation of nature-based solutions (see Fig. 2). Utilizing the IAM, stakeholders can experiment with these measures to evaluate their effects on the key indicators.

Additionally, a simplified version of the IAM will be used in a salt intrusion serious game to base in-game feedback on trends and scores on various key indicators, as depicted in Fig. 3. Goal here is to offer quick yet realistic feedback on player actions in the game, enabling them to take a holistic perspective on the delta and salt intrusion management. For this simplified version, the IAM's front-end is the game interface, a physical game board (Fig. 3), as both input and output location to the IAM.

ACKNOWLEDGEMENT

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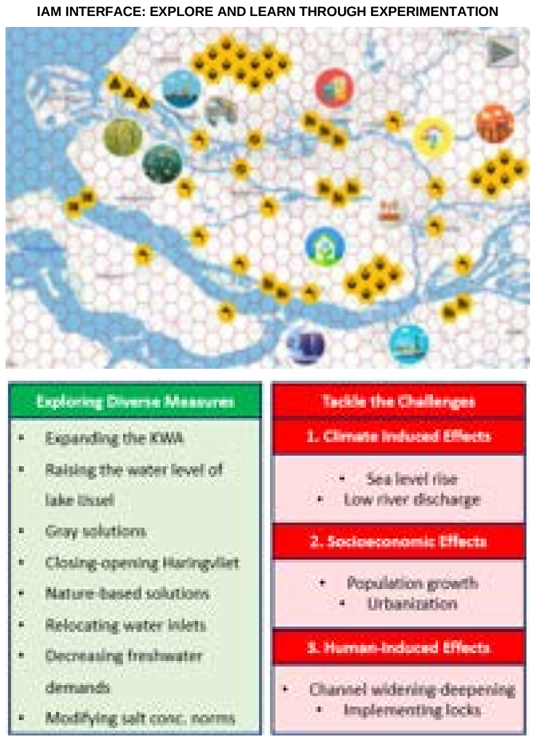

Figure 2. Overview of the Integrated Assessment Model (IAM) interface, highlighting challenges faced by stakeholders during the game and the corresponding strategic measures.

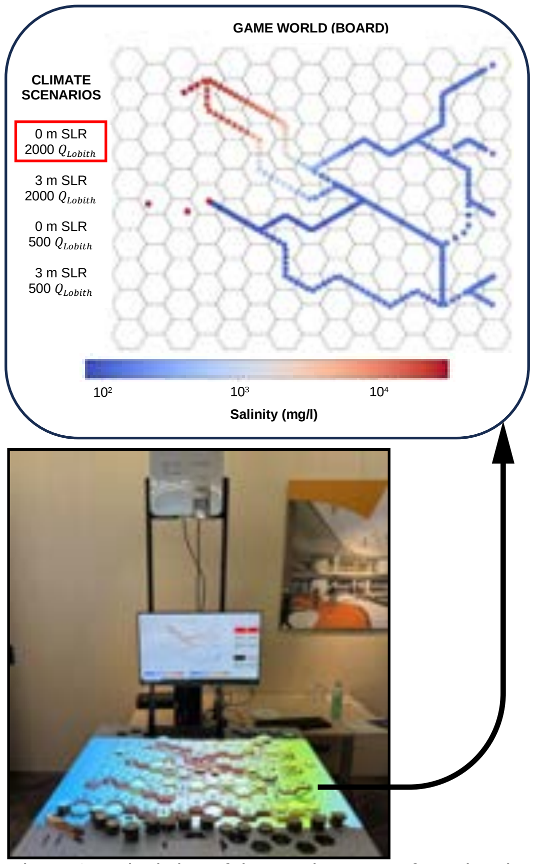

Figure 3. A depiction of the gaming setup, featuring the physical board, touchscreen monitor, projector, and webcam.

Do we really have the right tree in our freshwater floodplain forests?

Eleonora Saccon[a]*, Suzanne Hulscher[b], Tjeerd Bouma[a], Johan van de Koppel[a]
[a]*NIOZ, Department of Estuarine and Delta Systems, PO Box 140*
4400 AC Yerseke
[b]*University of Twente, Department of Water Engineering and Management, Faculty of Engineering Technology, P.O. Box 217, 7500 AE, Enschede, the Netherlands*

Keywords — Saltwater intrusion, flood forest

Introduction

Estuarine wetlands are facing a growing threat from saltwater intrusion, caused mainly by climate change and human alteration of estuaries. As saltwater reaches these areas, it triggers vegetation loss with cascading negative effects on the whole system.

In the near future, the floodplain forests in the Rhine-Meuse delta are going to experience increased saltwater intrusion. Presently, these forests primarily consist of former willow plantations, dominated by white willows (*Salix alba*) (Fig. 1, Wolf et al., 1997). When willow cultivation rose (around the 14th century) it replaced the existing forests, dominated by various species of willow (mainly *Salix alba* and *Salix fragilis*), black alder (*Alnus glutinosa*) and reed beds (*Phragmites australis*) (Struyf et al., 2009; Wolf et al., 1997).

Nonetheless, the precise impact of increased saltwater levels on these wetlands remains poorly understood. Understanding how saltwater, alongside its interaction with other environmental factors, affects vegetation is crucial for conservation managers striving to safeguard estuarine wetlands.

Figure 1. Carnisse grienden: a willow-dominated wetland in the Netherlands (image courtesy: E. Saccon).

Methods

We tested the response of three common wetland trees (willow *Salix alba*¸ alder *Alnus glutinosa*, and elderberry *Sambucus nigra*) to temporary and continuous saltwater stress (continuously exposed to saltwater or only one week each month for three different salt concentrations) under different tidal regimes (tidal and non-tidal).

Results

Contrary to common belief, our results suggest that alders can live in tidal conditions and tolerate saltwater better than willows. Moreover, these freshwater species were remarkably resistant to saltwater: two months were required to see the effects of salinity and only continuous high salinity were detrimental for the plants. As most Dutch flood forests are now dominated by willow trees (mostly planted for human use), they might be more vulnerable than alder wetlands. Rather than completely exclude saltwater from wetlands, increasing species composition (e.g., by planting alder) and reducing the time plants are exposed to saltwater might provide a cost-effective method to improve wetland resilience in a saline future.

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* Corresponding author
Email address: eleonora.saccon@nioz.nl (Eleonora Saccon)

The effects of river re-meandering on flood extent and inundation depth in the Geul river catchment

Job Thijssen[a], Willem Toonen[a], Hans de Moel[b], Eric Mortensen[b], Ronald van Balen[a]
[a]*Dept. Earth Sciences, Vrije Universiteit Amsterdam. De Boelelaan 1085, 1081 HV Amsterdam.*
[b]*Institute for Environmental Studies, Vrije Universiteit Amsterdam. De Boelelaan 1111, 1081 HV Amsterdam.*

Keywords — re-meandering, flood inundation, mitigation

Introduction

Between the 10-15th of July 2021, heavy rainfall caused widespread flooding in large parts of Western Europe. In Limburg (Southern Netherlands), a number of small rivers located in the foothills of the Ardennes caused significant damage. The Geul, a tributary of the Meuse, discharged 3000% (130m^3/s) of its normal discharge during this time period (Asselman and van Heeringen 2023). While no fatalities were reported, an estimated €400 million of damages occurred (Metsemakers 2021). The KNMI (Dutch meteorological institute) estimated that the weather conditions that caused the July 2021 flood occur about once every 500 years in our current climate. However, the KNMI also indicates that such events may be thrice as likely by 2050 due to climate change (van Heeringen, et al. 2022). Following an explorative study by Deltares (Slager et al., 2023) for effective mitigation measures, we calculate the potential effects of re-meandering on river discharge and flood inundation.

Method

The 2D HEC-RAS model was used to set-up three scenarios in which we tested the potential effects of re-meandering on retention and peak discharge attenuation. For each scenario we used identical boundary conditions and flow parameters (inflow, manning's n, grid resolution).

Real Morphology (RM)

The RM scenario was used to calibrate the HEC-RAS model for observed flood conditions, as modelled previously by Deltares. No major changes were made to the Digital Terrain Model (DTM: Algemeen Hoogtebestand Nederland; AHN 2022) apart from etching a realistic channel geometry into the DTM. The channel shape corresponds to river channel data obtained from Waterschap Limburg and field measurements.

Lowered Point Bars (LPB)

In the LPB scenario, river morphology was changed significantly. Point bars in meanders were lowered in the DTM to resemble the morphology of historically freely meandering parts of the Geul. Lowering these zones increases the storage capacity river channel.

Freely Meandering (FM)

In the FM scenario, drastic changes were made to the river morphology and also the floodplain. Straightened parts of the river were first filled in the DTM and replaced with a morphology that resembles a valley that experienced freely meandering conditions for an extended period, so featuring oxbow depressions and the lowering of floodplains by lateral fluvial erosion. Urban areas were excluded as such morphology will never exist at those locations. This morphology was loosely based on the morphology near Partij, which was used as a representation for the natural state.

Results: inundation depth

In the LPB scenario, inundation depths are locally lowered by up to 0.5m (fig 1), compared to the real 2021 situation. This reduction can most likely be attributed to increased capacity of the riverbed in regions where point bars were lowered. In urban areas where only few point bars could be lowered, the effects were much less pronounced.

Inundation depths decreased locally even >1 m when a full free meandering river pattern was modelled (fig 2). Again, the decreases were especially strong in the immediate surroundings of the newly introduced meander bends, as the capacity of the streambed and retention capacity of the direct floodplain was increased significantly.

* Corresponding author
Email address: jobthijssen1@gmail.com (J.B. Thijssen)
URL: NA

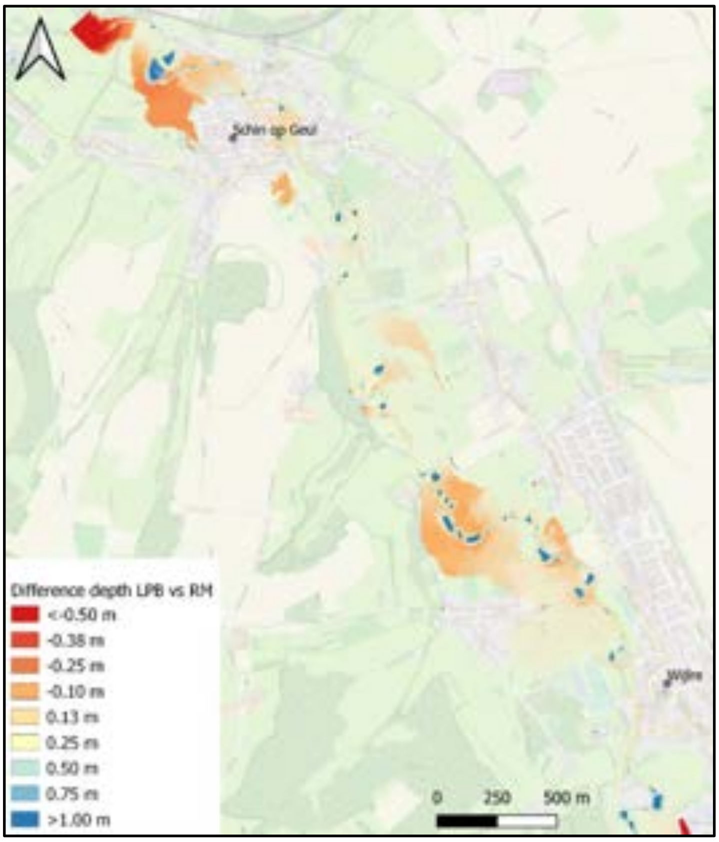

Figure 1. Changes in inundation depth (RM to LPB), based on the implementation of lowered point bars (LPB-RM scenario).

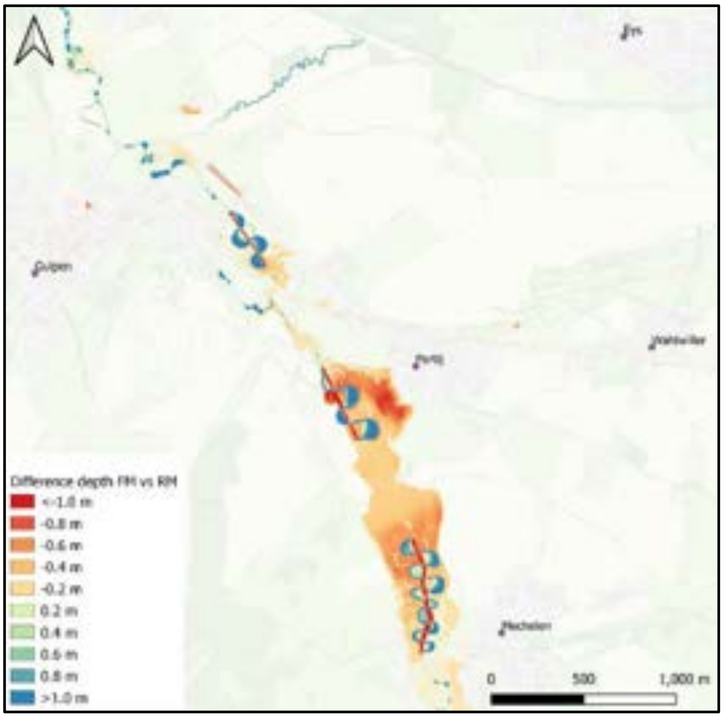

Figure 2. Changes in inundation depth based on the implementation of a freely meandering river system (FM-RM scenario)

Results: peak discharge

The hydrograph at the outflow of the model remained largely unchanged through the three scenarios (fig 3). The FM and LPB scenarios had a slightly higher peak discharge (+~3m^3/s), which may be due to the increase in effective conveyance of discharge due to the lowering of the point bars. No changes were made to the Manning's n coefficient between scenarios.

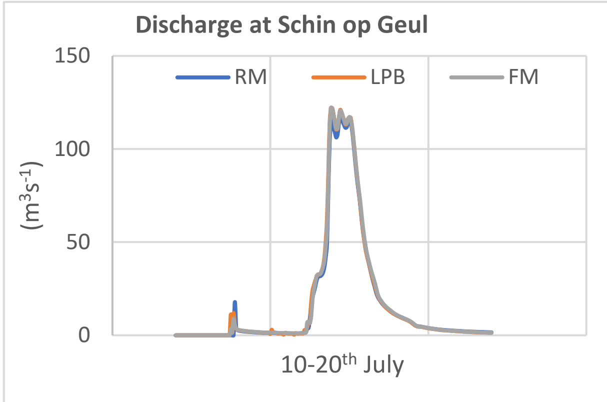

Figure 3. Discharge at Schin op Geul in the RM, LPB and FM scenarios.

Conclusion

The modelled scenarios show that locally the inundation depths can be reduced with >0.5 m using extensive re-meandering. While re-meandering increased retention capacity of the direct floodplain, the peak discharge remained largely the same at Valkenburg. This may be due to the increased transportation capacity of the Geul river through the lowered valley corridor, in combination with the flash-flood type of flooding. To conclude, re-meandering has strong local flood mitigating potential, but will by itself not decrease peak discharge in urban areas where there is no re-meandering potential. Therefore, a combination of a multitude of adaptation measures should be considered in the case of the Geul river catchment to adequately reduce flood risk.

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How accurately can we model estuarine salt intrusion in the Rhine-Meuse Delta?

Chanoknun Wannasin[a,b*], Bouke Biemond[c], Bas Wullems[d], and Jaap Kwadijk[a,b]
[a] *Faculty of Engineering Technology, University of Twente, Enschede, The Netherlands*
[b] *Deltares, Delft, The Netherlands*
[c] *Institute for Marine and Atmospheric Research Utrecht, Utrecht University, Utrecht, The Netherlands*
[c] *Hydrology and Environmental Hydraulics Group, Wageningen University, Wageningen, The Netherlands*

Keywords — chloride, models, performance

Introduction

Estuarine saltwater intrusion poses a significant hydrological and environmental challenge in the Rhine-Meuse delta (Huismans et al., 2018). The interchange between freshwater discharge from the Rhine and Meuse Rivers and saltwater with tidal forces from the North Sea at the estuary is naturally dynamic and complex. Moreover, Human interventions (e.g., river engineering and land use change) and extreme phenomena induced by climate change (e.g., droughts, storm surges, and continuous sea-level rise) have escalated the complexity of the saltwater-freshwater interchange (Van den Brink et al., 2019). Consequently, the natural balance of saltwater and freshwater is altered, enabling saltwater to intrude further inland. Saline water in the river directly affects freshwater supplies for drinking, agriculture, and ecosystems in this densely populated region.

In recent years, the Rhine-Meuse delta have experienced more frequent and severe salt intrusion events induced by droughts and storm surges. The drought-induced salt intrusion events were particularly problematic during the summers of 2018, 2020 and 2022. This growing issue addresses the need for accurate and reliable models that can predict salt intrusion in real-time (Huismans et al., 2019), in terms of both concentration (how salty water becomes) and duration (for how long water becomes too salty). Water managers and stakeholders (e.g., drinking water companies) increasingly rely on such models to effectively and timely tackle the impacts of salt intrusion, and thus sustaining freshwater availability in the delta.

The goal of this research is to assess and compare the performance of currently available models for simulating and predicting historical drought-induced salt intrusion events in the Rhine-Meuse delta. We focus on modelling chloride concentration and intruding duration at the daily timescale at critical locations, including Krimpen aan den Ijssel and Bernisse.

Models

Currently available salt intrusion models as part of the SALTISolutions research project are implemented and their performance, in terms of result accuracy, are assessed. These models include:

Process-based models

- SOBEK: spatially one-dimensional hydraulic model (Deltares, 2019)
- 2D Idealized Network: a two-dimensional vertical width-averaged model in a simple channel network. (based on the extended version of Biemond et al., 2023).
- RMM 3D: a 3D hydrodynamic model (Van der Kaaij et al., 2022).

Data-driven/statistical models

- LSTM: a deep learning model built on Long Short-Term Memory, a recurrent neural network algorithm (Wullems et at., 2023).
- Rules of Thumb: a simplified statistical model based on hydrodynamic parameters (Huismans et al., 2019).

Model accuracy assessment

Daily time series of chloride concentration simulated by the models are evaluated against the observations and compared against each other. The simulation accuracy is investigated in three aspects: daily means, peak timings, and intruding durations above warning thresholds.

Expected results and utilization

As of the day of this abstract submission, the research is in progress and the model results are being analysed. The research finding will be demonstrated during the NCR Day 2024.

This model evaluation is part of the Digital Twin development as a toolbox for real-time forecasting and management of estuarine saltwater intrusion in the Rhine-Meuse delta within the SALTISolutions research project. In

* Corresponding author
Email address: mo.wannasin@deltares.nl
(Mo Chanoknun Wannasin)

the next step, we expect to further implement the most accurate and reliable models for real-time forecasting and explanatory simulations to support real-time decision-making.

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Action perspectives on climate extremes in the Dutch river system: system-level impacts and mitigation strategies

Niels M. Welsch[a*], Jord J. Warmink[a], Denie C.M. Augustijn[a], Suzanne J.M.H. Hulscher[a]
[a]*University of Twente, Department of Water Engineering and Management, Faculty of Engineering Technology*
P.O. Box 217, 7500 AE, Enschede, the Netherlands

Keywords — Climate extremes, River systems, Uncertainty

Introduction

Worldwide climate change affects the Dutch deltaic river system: recent dry years led to (extremely) low discharges in summer, while an extreme rainfall event in the summer of 2021 led to large-scale flooding in the Meuse catchment. Increased sea level rise (SLR) will in turn cause higher water levels reaching further upstream, higher closing frequencies of storm surge barriers and reduced discharge capacities of sea locks. As the Dutch delta is densely populated, such negative impacts of climate change will lead to large socio-economic impacts. Understanding how climate change influences the Dutch river system in the long term (> 2100) is thus important to timely adapt to these developments.

Recent publication of the new climate scenarios by the KNMI shows that climate change will continue to affect the climate in the Netherlands. Overall, in all scenarios the precipitation in summers will decrease, while winters will become wetter (KNMI, 2023). Additionally, long term land-use developments, driven by climate change and population growth, will effect runoff towards rivers. This all inevitably impacts the discharge regime of the Rhine and Meuse, as well as the lateral inflow to these rivers. Alongside, SLR is expected to increase and accelerate, with extreme scenarios of up to 8 meters SLR by 2300 (KNMI, 2023).

Besides future developments, interventions in the past still impact the river system. An example is the ongoing bed degradation in the river Waal due to normalisation works in the past century, which influences the discharge distribution at one of the main bifurcations (Klijn et al., 2022). This bed degradation will continue in the future (Ylla Arbós et al., 2023).

* Corresponding author
Email address: n.m.welsch@utwente.nl (Niels Welsch)
URL: www.people.utwente.nl/n.m.welsch

Interconnectivity in the Dutch river system

The Dutch river system is a complex network of two major rivers (*Rhine* and *Meuse*), two bifurcations (*Pannerdensche Kop* and *IJsselkop*), multiple channels, estuaries and lakes (with highly controlled water levels). All of which are connected either in open connection or through some kind of regulating construction. This enables river managers to intervene in the system: e.g., diverting water to where it is needed during low discharges, or efficiently discharging water during flood waves. Simultaneously, this interconnectivity of rivers, lakes and channels makes that changes in river discharge, sea level rise and the water level strategy of Lake IJssel, affect the complete river system and the water distribution at the two major bifurcations.

Figure 1. Main water system in the Netherlands with a schematic representation of possible impacts of climate change on the main water system. (1) Sea level rise, (2) more extreme discharges, (3) adaptive weir management Lake IJssel, (4) increased (fresh) water demand. Background image adapted from PDOK (2023).

Action perspective

Much research has already been carried out on the effects of climate change on river(functions) within the Netherlands: e.g., SLR

(*Kennisprogramma Zeespiegelstijging*), fresh water supply (*Slim Water management*) and an integral assessment of the current river system and functions (*Integral River Management*) (Kosters and Asselman, 2022).

What is missing, is insight into how all these individual developments combined will affect the complete river system and what this means for a river manager. Within this research we aim to provide action perspectives on the consequences of climate change forced upon the river system in the long term (around the year 2100). What challenges or bottlenecks will occur in the river system and what are possible mitigation measures? The focus here is not so much on the magnitude of the extremes, but rather on the consequences, mitigation and adaptation to the extremes.

Approach

We start with a sensitivity analysis of water levels and discharges within the Dutch river system to autonomous and climate change driven changes, taking into account the interconnectivity between rivers, channels and lakes. This provides perspectives on which changes have the most negative impacts on the systems' functions. We consider different scenarios in which we capture possible impacts of climate change extremes on the forcings of the Dutch river system, combined with different autonomous developments. These scenarios will be modelled using a snap-shot approach as presented by Duong et al. (2017) using a hydraulic one-dimensional river model. Simulation results will be assessed based on:

- water levels (for flood safety and ground water effects);
- water depths (for shipping), and;
- discharges (for water availability).

Special focus will be put on uncertainties in the (model)results and how to address these uncertainties in river management.

Gained insights into future bottlenecks will be used to formulate and assess mitigation measures on a system level.

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About NCR

Objective of NCR

NCR was founded as a formal cooperation between several Dutch institutions. On October 4, 2012, the partners of the 'Netherlands Centre for River studies' (NCR, Dutch: 'Nederlands Centrum voor Rivierkunde (NCR)') formally renewed their cooperation within NCR.

The objective of NCR is:

> Doelstelling van het NCR is een samenwerking tot stand te brengen tussen de belangrijkste kennisgebruikers en kennisontwikkelaars in Nederland op het gebied van rivieren met als uiteindelijk resultaat een versterking van het kennispotentieel, de profilering van de (inter)nationale positie van het Nederlands rivieronderzoek en het versterken van het onderwijs en het wetenschappelijk onderzoek aan de Nederlandse Universiteiten ten behoeve van een betere inrichting en beheer van de Nederlandse rivieren.

This translates to:

> The objective of the NCR is to establish cooperation between the major knowledge suppliers and knowledge users in Netherlands in the field of river studies, with the ultimate aim of reinforcing the knowledge potential, promoting the international position of Dutch river research and strengthen the education & scientific research at Dutch universities, to better design and manage Dutch rivers.

Domains

NCR encompasses all disciplines relevant to river studies as practices by its institutional partners. They include:

- Hydrodynamics
- Sediment transport and morphology
- Fluvial geomorphology and sedimentology
- River ecology, restoration and water quality
- Governance and spatial planning
- Modelling, serious gaming and digital twins

NCR Organisation

NCR has four main bodies. The mandates for all except Young NCR (YNCR) are documented in the *"Overeenkomst Nederlands Centrum voor Rivierkunde 2012"*.

- **Programme Secretary (Dutch: Programmasecretaris)**
  Safeguards the continuity of NCR activities, secretary to SB and PC; monitors of agreed actions by the SB and PC; reports of NCR finances; management of all NCR communications.

- **Supervisory Board (Dutch: Commissie van Toezicht)**
  Supervises the implementation of the cooperation agreement, settles disputes and approves the scientific programme.

- **Program Committee (Dutch: Programmacommissie)**
  Determines the scientific programme, stimulates and initiates proposals for activities and integration of knowledge, ideas, experiences and results.

- **Young NCR (Dutch: Jong NCR)**
  Established in December 2020, YNCR strives to strengthen the network of young/early-career scientists within NCR.

Institutional partners

The partners of NCR are: Rijkswaterstaat (RWS), Universiteit Twente (UT), Radboud Universiteit Nijmegen (RUN), Deltares, Universiteit Utrecht (UU), Technische Universiteit (TUD), Wageningen University & Research (WUR), Leiden

University Collega (LUC) and Vrije Universiteit Amsterdam (VU).

Each partner contributes in-kind and/or in-cash to realise the annual programme.

Accountability

NCR activities are annually documented in an annual programme, annual report and annual budget. The annual programme and budget are approved by the Supervisory board.

Table 5: The composition of NCR Boards in 2024. Persons marked with * are chair persons.

Person	Partner institution	Email
Programme Secretary		
dr. ir. Koen Berends*	Deltares	koen.berends@deltares.nl
ir. Anna van den Hoek	Deltares	anna.vandenhoek@deltares.nl
Supervisory board		
prof. dr. Jaap Kwadijk*	Deltares	jaap.kwadijk@deltares.nl
prof. dr. Hans Middelkoop	Utrecht University	h.middelkoop@uu.nl
dr. ir. Astrid Blom	Delft University of Technology	astrid.blom@tudelft.nl
prof. dr. Ton Hoitink	Wageningen University & Research	ton.hoitink@wur.nl
prof. dr. Suzanne Hulscher	University of Twente	s.j.m.h.hulscher@utwente.nl
drs. Monique Busnach-Blankers	Rijkswaterstaat	monique.busnach-blankers@rws.nl
dr. Wilco Verberk	Radboud University Nijmegen	w.verberk@science.ru.nl
Vacant	Vrije Universiteit Amsterdam	
Programme committee		
drs. Evelien van Eijsbergen*	Rijkswaterstaat	evelien.van.eijsbergen@rws.nl
drs. Susanne Quartel	Rijkswaterstaat	susanne.quartel@rws.nl
dr. Laura Stancanelli	Delft University of Technology	L.M.Stancanelli@tudelft.nl
dr. Heleen Vreugdenhil	Deltares	heleen.vreugdenhil@deltares.nl
dr. Victor Chavarrias	Deltares	victor.chavarrias@deltares.nl
drs. Valesca Harezlak	Deltares	valesca.harezlak@deltares.nl
dr. Frank Collas	Radboud University Nijmegen	F.Collas@science.ru.nl
dr. Menno Straatsma	Utrecht University	m.w.straatsma@uu.nl
dr. Jord Warmink	University of Twente	j.j.warmink@utwente.nl
dr. Kryss Waldschläger	Wageningen University & Research	kryss.waldschlager@wur.nl
dr. Willem Toonen	Vrije Universiteit Amsterdam	w.h.j.toonen@vu.nl
dr. Paolo Scussolini	Vrije Universiteit Amsterdam	p.scussolini@vu.nl
dr. Paul Hudson	Leiden University College	p.f.hudson@luc.leidenuniv.nl
Young NCR		
Jelle Dercksen MSc*	Delft University of Technology	J.A.Dercksen@tudelft.nl
ir. Anna van den Hoek	Deltares	anna.vandenhoek@deltares.nl
Paul Vriend MSc	Rijkswaterstaat / Leiden University College	paul.vriend@rws.nl
Simon Smits MSc	Rijkswaterstaat-WVL	simon.smits@rws.nl
Henry Amorocho Daza MSc	Delft University of Technology, IHE Delft	h.amorochodaza@un-ihe.org
Tatjana Edler MSc	Deltares	Tatjana.Edler@deltares.nl
ir. Leon Besseling	University of Twente	l.s.besseling@utwente.nl
Miranda Stibora MSc	Wageningen University & Research	miranda.stibora@wur.nl

Eise Nota MSc	Utrecht University	e.w.nota@uu.nl
Joshua Climo MSc	Radboud University Nijmegen	joshua.climo@ru.nl
Joeri Reinders MSc	Leiden University College	j.b.reinders@luc.leidenuniv.nl
Vacant	Vrije Universiteit Amsterdam	

Partners

Radboud University Nijmegen

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