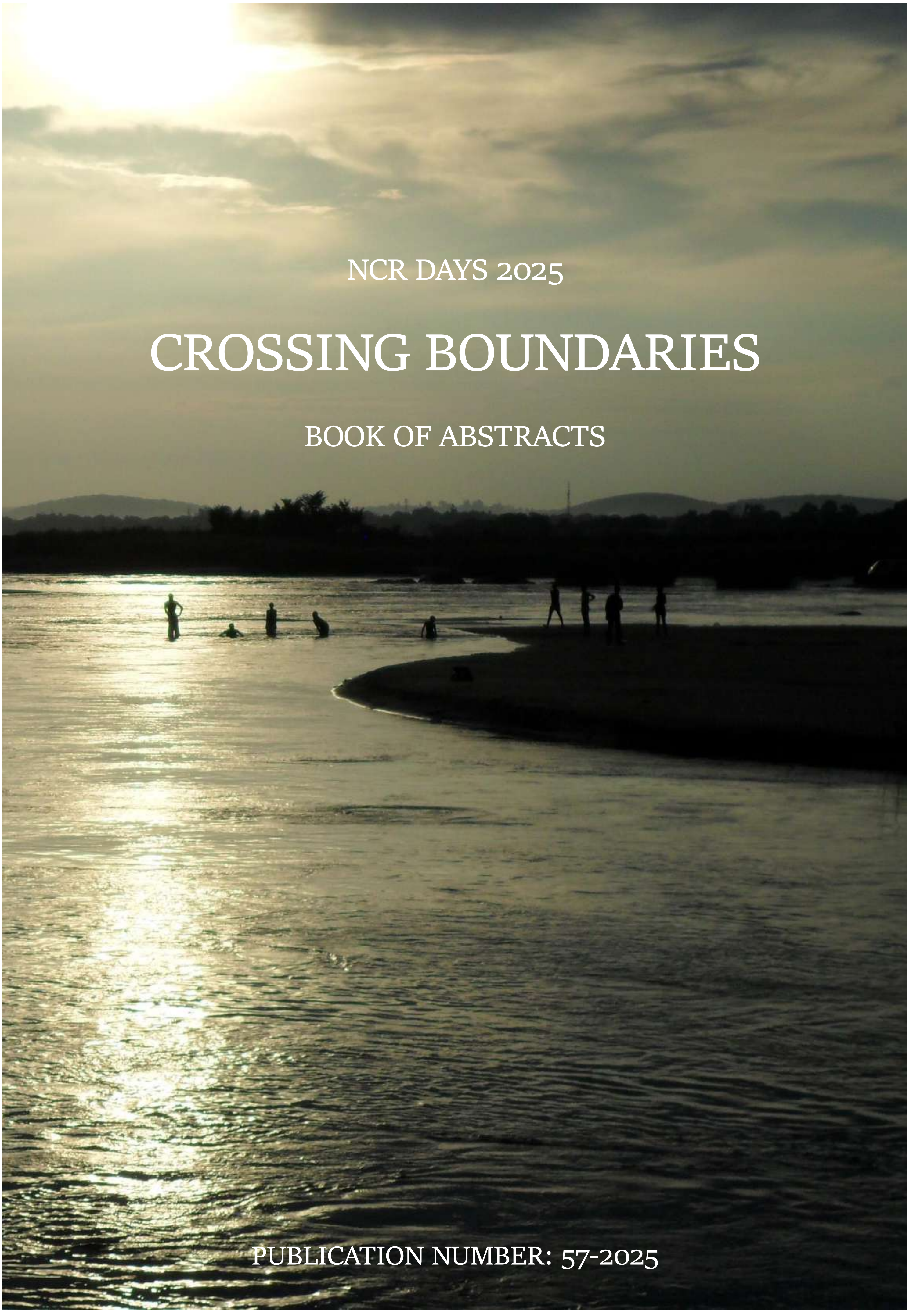

NCR DAYS 2025

CROSSING BOUNDARIES

BOOK OF ABSTRACTS

PUBLICATION NUMBER: 57-2025

NCR DAYS 2025

Crossing boundaries

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Preface

Welcome to the 27th edition of the NCR DAYS, the annual meeting of the Netherlands Centre for River studies (NCR), hosted by Deltares. Organized around the theme "Crossing boundaries", this year's NCR DAYS will take place on May 8th and 9th 2025 in Delft.

This edition of the NCR DAYS presents a two-day program with oral and poster contributions in six thematic sessions: (1) Ecology, nature based solutions and restoration, (2) River monitoring and data-driven innovations, (3) Understanding and managing morphodynamics, (4) Advances in river hydrodynamics, (5) Navigating estuarine challenges and (6) Governance and policy.

We have found four keynote speakers to be willing and able to envision 'Crossing boundaries' from various perspectives. The first is Robert Tögel of Viadonau who will set out his keynote around the Austrian waterway company Viadonau and how it operates within three strategic fields: Environment, Safety, and Mobility. Gudrun Hillebrand of the Bundesanstalt für Gewässerkunde will dive deeper into the sediment dynamics of the German Rhine by focusing on its morphological characteristics, the challenges that arise from these conditions, the management measures implemented in response, and the strategies used to monitor their effectiveness. The keynote of Annunziato Siviglia synthesizes recent research conducted at the University of Trento that investigates the occurrence of chaos in deterministic morphodynamic models at the river reach scale. The NCR DAYS will be closed by former delta commissioner Peter Glas, who will look back on more than 40 years of personal experience in water management.

We very much hope you will all be enjoying this 2025 edition of the NCR Days!

the Local Organizing Committee
Victor Chavarrias and Anna van den Hoek

Delft, May 2025

Conference details

Organizing partner

Organizing partner of the 2025 edition of the NCR DAYS is Deltares.

The venue

The conference venue is the Patio at Deltares in Delft, Netherlands. Deltares is an independent institute for applied research in the field of water and subsurface. It was established on January 1, 2008, following the findings of the Wijffels Committee. The institute was formed through the merger of several organizations, including GeoDelft, Delft Hydraulics (previously known as the Waterloopkundig Laboratorium), parts of TNO–Building and Underground, and specialized services from Rijkswaterstaat. Deltares focuses on major societal issues related to water and soil systems, aiming to keep deltas, coastal, and river areas safe, sustainable, and liveable. The institute employs over 900 professionals from more than 60 nationalities and operates globally.

Local organising committee (LOC)

The LOC consists of the following members: Victor Chavarrias and Anna van den Hoek.


PROGRAMME

Day 1 - Thursday 8 May 2025		
	09:00 - 09:15	Registration, welcome & coffee
	09:15 - 09:30	Opening of the 27th edition of the NCR days
	09:30 - 10:20	**Robert Tögel | Keynote Lecture I**
	10:20 - 10:40	**Poster pitches**
	10:40 - 11:10	Coffee break & poster session
Session 1	**Ecology, nature based solutions and restoration**	
	11:10 - 12:10	**Pepijn van Denderen** *The ecological impact of hydropeaking in the Meuse* **Gertjan Geerling***Towards a resilient ecohydrological future for the IJssel-Vecht Delta – a case study for scientific exploration* **Lodewijk Schulte** *The multi-channel concept explored from Bonn to Biesbosch* **Joshua Climo** *Ecological degradation despite water quality improvements*
	12:10 - 12:40	Lunch
	12:40 - 13:50	Deltares facility tour or Delta Enigma workshop
Session 2	**River monitoring and data-driven innovations**	
	13:50 - 14:50	**Antonio Magherini** *A deep-learning model for predicting the planform evolution of braided sand-bed rivers* **Qusai Khaled Abo Shama** *A semi-supervised graph-based approach for anomaly detection in river monitoring stations* **Paul Vriend** *A national monitoring strategy for riverine macroplastic pollution in the Netherlands* **Thaiënne van Dijk** *Sediment composition and microplastics in the riverbed of the River Waal, Netherlands – active layer and subsurface*
	14:50 - 15:20	Break & poster session
Session 3	**Understanding and managing morphodynamics**	
	15:20 - 16:20	**Francesco Weber** *Chaos in migrating river bar dynamics* **Bahjat Mallak** *Predicting soil erosion and sediment yield in wadi flash floods: a physically-based modelling approach* **Filip Schuurman** *Cross-boundary sediment challenges in the Mekong River Basin* **Sjoukje de Lange** *Migrating subaqueous dunes capture clay flocs*
	16:20 - 17:10	**Gudrun Hillebrand | Keynote Lecture II**
	17:10 - 18:30	Drinks & Bites
	17:10 - 18:30	**NCR Board Meeting**
	19:00 - ?	Conference Dinner @ Wijhaven & Pubquiz by YNCR

Posters Day 1		
	Shiyu Bao	*Acoustic observation of suspended sediment in the hyperturbid Ems Estuary*
	Leon Besseling	*Discussing alternative fast dike breach flood models*
	Markéta Hauferová	*Benthic macroinvertebrate diversity in the Geul River, Netherlands in relation to large woody debris (LWD) and fluvial features*
	Abigail Hillen-Schiller	*Automating sediment budgets with channel recognition*
	Rena Hoogland	*Trend monitoring, the basis for a healthy and clean upper river system*
	Henk Jongbloed	*Describing and modeling river dune unsteadiness*
	Nina van Leeuwen	*A high-resolution paleoflood record of the Meuse, using advanced age-depth modelling*
	Eki Liptiay	*Impact of Groyne Lowering on Groyne Field Bathymetry*
	Jiaqi Liu	*Simulated Study of the interaction between horizontal flow structure and suspended sediment transport in partially vegetated channel*
	Rosalie Marcus	*Public Perception of Erosion and Flooding along the Geul River, Limburg (NL)*
	Madieke Oosterhout	*The influence of riverine wetlands on flood and drought mitigation: a case study for the Aa, the Netherlands*
	Willem Toonen	*Sorting out flood sediments: the role of grain shape in overbank deposition*
	Marijn Wolf	*Climate Change Adaptation through Interventions in a River Bifurcation Region*

	Day 2 - Friday 9 May 2025	
	09:00 - 09:30	Registration, welcome & coffee
	09:30 - 10:20	**Annunziato Siviglia | Keynote Lecture III**
	10:20 - 10:40	**Poster pitches**
	10:40 - 11:10	Coffee break & poster session
Session 4	**Advances in river hydrodynamics**	
	11:10 - 12:10	**Nicolette Volp** *Catching the Physics in Your Model: A Case Study of Steegse Haven* **Ruben den Hertog** *Unveiling the implications of model schematisation on dike breach flow and dike breach growth in large scale fluvial flood models* **Niels Welsch** *The effect of climate change on stage-discharge boundary conditions in interconnected river delta (sub)models* **Julius Overhoff** *Sensitivity Analysis of Side Channel Dimensions on Crossflow Dynamics in the Waal*
	12:10 - 12:40	Lunch
	12:40 - 13:50	Deltares facility tour or Delta Enigma workshop
Session 5	**Navigating estuarine challenges**	
	13:50 - 14:50	**Maarten Kleinhans** *Sediment continuity: (mis)understandings and (mis)management in the 18th to early 20th century* **Wendy Liefveld** *Bottlenecks for the restoration of tidal vegetations in heavily modified river deltas* **Lennard Spaans** *Modelling tidal channel evolution under the influence of tide and river discharge* **Mo Wannasin** *Forecasting and decision support for estuarine saltwater intrusion in the Rhine-Meuse Delta using machine learning*
	14:50 - 15:20	Break & poster session
Session 6	**Governance and policy**	
	15:20 - 16:20	**Cas Pfeijffer** *Groene Rivier Well, a nature based design connecting water safety, groundwater levels, biodiversity and land use* **Jort de Vries** *Knowledge-related challenges in Dutch river innovation* **Merel Verbeek** *Balanced distribution of low discharges requires large-scale measures on the Waal* **Ralph Schielen** *Projected climate-change impacts on the flow partitioning in the bifurcation region in the upper Rhine delta*
	16:20 - 17:10	**Peter Glas | Keynote Lecture IV**
	17:10 - 18:30	Drinks & Bites

Posters Day 2		
	Maria Barciela-Rial	*Rivierwerken: a soil-based approach for floodplain restoration and dike reinforcement*
	Juliette Cortes-Arevalo	*Serious game design to reveal delta ENIGMAs for shifting to more flexible and adaptive flood risk management*
	Lisa Darwinkel	*Experimental study on flow patterns and turbulence in a tight sinuous open-channel*
	Smriti Dutta	*Delta-ENIGMA: an update from its first year of operation*
	Joris Jungblut	*Physics-Informed River Discharge Estimates Throughout aTidal Cycle Based on ADCP Transect Data*
	Antonio Magherini	*Facing Floods: a stakeholder river management game*
	Iris Niesten	*Is the New Waterway self-deepening?*
	Mishel Reyes Castillo	*Development of a dashboard for management of saltwater intrusion in the Haringvliet Estuary*
	Heleen Vreugdenhil	*Institutional influences on transitions in water management*
	Niels Welsch	*Assessing alternative discharge distributions at the Dutch Rhine Bifurcations to address climate change impacts by 2100*

KEYNOTE SPEAKERS

Viadonau's integrative approach

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Keywords — integrative planning, hydro-morphology

The company viadonau

The Austrian waterway company viadonau is a subsidiary of the Federal Ministry for Innovation, Mobility and Infrastructure (BMIMI). It is primarily responsible for managing the Austrian section of the international Danube waterway. However, its mandate extends well beyond traditional waterway management. Based on the Waterways Act of 2005 and its current corporate strategy, viadonau operates within three strategic fields: Environment, Safety, and Mobility.

The environmental pillar includes both the preservation and enhancement of habitats along the Danube (restoration) and the improvement of the environmental performance of inland navigation. The safety field encompasses shared responsibility for flood protection along the Danube, Morava, and Thaya rivers, as well as transport safety—supported, for example, by the national RIS system, DoRIS. The mobility pillar covers the maintenance of safe and efficient navigation conditions and the promotion of Danube navigation through advisory services and related initiatives.

Central to viadonau's mission is an integrated view of the Danube - not only as an efficient transport corridor but also as a valuable and sensitive ecosystem.

Hydro-morphological challenges

Hydro-morphological conditions present one of viadonau's greatest challenges. The Austrian stretch of the Danube and its key tributaries are shaped by a chain of hydropower plants that disrupt the natural bedload balance. Sediment accumulates upstream of the dams, creating a deficit downstream—particularly in the two remaining free-flowing sections, which comprise just 25% of Austria's Danube. This leads to progressive riverbed incision. As the riverbed deepens, water levels drop accordingly.

This effect is intensified by extensive bank stabilisation and rigid low water regulation aimed at improving navigability. Sediment deposits in shallow ford areas require regular dredging to ensure Good Navigation Status. Hydro-morphological issues are among the main obstacles to achieving the goals of the EU Water Framework Directive. On the Austrian Danube, the goal is to achieve both Good Navigation Status and Good Ecological Status (or potential), while maintaining robust flood protection. This calls for an integrative approach - moving beyond classic waterway management towards a holistic river basin management strategy. Such a shift requires open-minded collaboration and the involvement of experts and stakeholders from multiple disciplines.

Catalogue of Measures

This integrative approach is particularly evident in the Catalogue of Measures for the Danube east of Vienna. The roughly 48 km long free-flowing stretch between Vienna's Freudenau hydropower plant and the end of the Austrian-Slovak border section (river km 1921.0–1872.70) presents the greatest challenges along the Austrian Danube. The bedload deficit in this area has led to significant riverbed erosion, averaging 2 to 3.5 cm per year over many years - despite prescribed gravel additions by the hydropower plant operator, Verbund.

Falling water levels directly impact habitats in the strictly protected Donau-Auen National Park, lowering the groundwater table and accelerating the disconnection of the river from its floodplains. Extensive bank stabilisation further compounds this decoupling. In addition, all critical ford areas for navigation - many requiring multiple dredging operations each year - are located in this section.

In 2002, an integrative expert team was formed to jointly develop hydraulic engineering solutions addressing navigational, ecological, and water management challenges. This team comprised specialists primarily from academia, the Ministry of Transport, and the National Park Authority. Together, they developed planning principles that consider both nautical and ecological requirements.
Building on this groundwork, a large-scale project was drafted by a similarly integrative planning team. However, the 'General Project 2006' was never implemented - hindered by a combination of technical, financial, legal, and social barriers. Despite this, several pilot projects proved successful. In 1996, a tributary was reconnected to the main river for the first time. Additional side-arm reconnections followed, increasingly designed in a naturalistic manner. In 2006, the first major bank restoration - nearly 3 km in length - was implemented. In 2014, a

comprehensive 3 km pilot stretch near Bad Deutsch-Altenburg was completed, incorporating side-arm reconnection, bank restoration, innovative groynes, and coarse gravel addition to counteract riverbed erosion.

Based on these experiences, the approach was further developed into the Catalogue of Measures. Rather than relying on a single large-scale intervention, the current strategy combines adaptive maintenance practices with targeted optimisation projects. Bedload management has been ongoing since 2016 and is being progressively expanded. Gravel from maintenance dredging and bedload traps is transported upstream and redeposited, supplementing Verbund's prescribed additions.

Former side-arms, severed during the 19th-century Danube Regulation, are being reconnected. Wherever feasible, hardened embankments are removed, and existing low water regulation structures are modified to reduce their impact. These measures not only create valuable floodplain habitats but also relieve pressure on the riverbed, slowing its degradation. Enhancement works have also been carried out in navigation-critical ford areas, including groyne optimisation and the installation of gravel islands that act as natural regulation structures. This successful balancing of interests has made it possible to build new piers within the National Park, improving both service quality and safety for navigation.

Since 2024, flexible low water regulation has been trialled in this section. For the start, gravel-filled barges are deployed depending on flow conditions and serve as temporary training structures or groynes. Their potential to reduce regulatory pressure during higher water events could add a valuable tool to the management portfolio.

Stakeholder management

The implementation of the Catalogue of Measures is supported by a stakeholder forum, bringing together key representatives from both the navigation and ecological sectors. A similar platform was first established in 2012 to accompany the Bad Deutsch-Altenburg pilot project and has proven highly effective.

Previously, river engineering works within the National Park were the subject of heated public debates and media campaigns. Today, there is a shared understanding of the differing needs and perspectives among stakeholder groups. A jointly developed guiding document (Leitbild) for river engineering east of Vienna reaffirmed the fundamental compatibility of navigation and nature conservation.

Learning from the river

The Catalogue of Measures is conceived as a learning or adaptive system. It does not represent a fixed or pre-defined programme. All implementation steps are accompanied by systematic monitoring at the project level. In parallel, scientific support is provided at a higher level - most notably through two Christian Doppler (CD) research laboratories, one focusing on abiotic and the other on biotic processes.

These CD labs are competitively awarded and funded at the national level, involving collaboration between research institutions and companies. This dual-level approach ensures strong impact orientation. Knowledge gained from individual measures directly influences the planning of future interventions, enabling both ongoing assessment and a cumulative learning curve - despite the long implementation timelines.

A model with a showcase effect

At a time when integrative planning and serious ecological consideration in infrastructure projects were still relatively uncommon, the Austrian Danube measures drew significant attention. Their impact lies not only in their concept but in successful implementation and measurable results.

The integrative approach and the Catalogue of Measures could serve as a model for other Danube sections and similar waterways. They also highlight the restoration potential of waterways.

Through participation in international infrastructure and research projects, viadonau publicises its approach as a possible solution to widespread ecological and hydro-morphological deficits. Since inland navigation and river ecology transcend national boundaries, collaborative solutions are essential.

One such effort is the Horizon 2020 project MERLIN, in which viadonau contributes its integrative strategy as a case study for waterway restoration. As part of MERLIN, another riverbank restoration project was successfully completed in 2025.

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Navigating sediment dynamics: Challenges, management measures, and monitoring in the German Rhine

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Keywords — River morphology, sediment management, bed stabilization

Introduction

The Rhine River, one of Europe's most vital waterways, is a dynamic system shaped by diverse geomorphological conditions and centuries of human intervention. Effective sediment management along the German Rhine is essential for maintaining navigability, mitigating erosion, and safeguarding ecological functions. The presentation explores the sediment dynamics of the German Rhine by focusing on its morphological characteristics, the challenges that arise from these conditions, the management measures implemented in response, and the strategies used to monitor their effectiveness.

Morphological Complexity and Sediment Transport Challenges

The German Rhine can be subdivided into distinct morphodynamic sections, each defined by unique hydraulic, sedimentary, and geologic characteristics that significantly impact sediment transport. Lake Constance serves as an ultimate sediment sink for the Alpine Rhine, effectively decoupling sediment transport from the downstream reaches, with most material settling in the lake. Downstream, the Impounded Section – covering the High Rhine and Upper Rhine up to Iffezheim – is heavily regulated with 21 impoundments significantly reducing flow velocities and disrupting natural sediment continuity. Bed load transport here is largely episodic, occurring mainly during high-flow events or in small sections downstream of individual barriers. As a result, the sediment regime is dominated by finer fractions, and the passability for coarse material is severely hindered.

The free-flowing Upper and Middle Rhine is capable of transporting substantial bed load, including coarse gravel fractions. The riverbed slope gradually decreases until reaching the Mainz Basin, a zone of reduced gradient influenced by the Rhenish Massif, a major geologic uplift structure. This transition results in a shift toward finer sediment sizes, formation of braided channels, islands, and dunes. The basin is underlain by tertiary substrata – mainly fine sands – that are particularly susceptible to erosion, posing long-term stability concerns.

In the Rhenish Massif, steeper gradients and confined floodplains reintroduce higher velocities and coarser sediment transport. Here, the riverbed is defined by fluvial infill atop bedrock, making it morphologically distinct. Further downstream, the Lower Rhine enters a low-gradient, broad floodplain in the Lower Rhine Bay, where finer fractions increasingly dominate both bed load and substrate. This transition marks a significant reduction in bed slope and energy, leading to deposition of coarser materials and a transition to a sand regime. Historical mining-induced subsidence between Duisburg and Wesel (Rhine-km 775–813) adds localized complexity to the riverbed morphology.

Mean annual loads of gravel and sand (bed load and suspended load), derived from a sediment budget for the time period 1991-2010 (Hillebrand & Frings, 2017), are shown in Fig. 1 for the free-flowing German Rhine.

The interaction between geological features like Lake Constance and the Rhenish Massif and extensive human alterations such as dykes, dams, shortening and straightening of the river course, river training etc., has significantly shaped the Rhine River system. These modifications highlight the complex challenges of integrated sediment management in such a large and heavily regulated river.

Sediment Management Measures

To counteract adverse morphologic trends – particularly riverbed incision and sediment deficit – several targeted management strategies have been implemented. Downstream of the barrage of Iffezheim, sediment nourishments aim to locally stabilize the bed and maintain sediment continuity, while maintaining a balance between mitigating erosion and avoiding downstream deposition remains an ongoing challenge. On average, about 400 kt/a of gravel and sand are supplied here to the Rhine from external sources (Hillebrand and Frings, 2017).

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https://www.bafg.de/DE/1_Die_BfG/Organisation/Abteilung_M/M3/gewaessermorphologie_sedimentdynamik_und_management_node.html

The Lower Rhine has seen a suite of measures since the mid-1980s. Between 1991 and 2010, about 6.4 million tons of non-erodible coarse sediments were added to reduce riverbed incision. Concurrent dredging activities extracted about 3.2 million tons of sediment, which were subsequently relocated to sediment-deficient reaches. In parallel, sediments from external sources are added tailored to local bed load grain-size distributions. Engineering interventions such as ground sills, scour filling, and bed remodeling further contributed to morphological stabilization. These efforts collectively reduced average incision rates from −1.68 cm/a (1896–2010) to −0.2 cm/a (2000–2010), highlighting the efficacy of a coordinated sediment management strategy (Quick et al., 2020).

Additional examples include the long-term sediment trap experiment at Mainz-Weisenau, where dredging practices were refined through iterative adjustments to maintain downstream equilibrium. Additionally, the concept of “Morphological Space” has been applied to identify zones of high vertical morphodynamic activity, thereby improving the spatial targeting of maintenance and dredging operations.

Monitoring and Evaluation

An extensive and systematic monitoring program underpins the success of sediment management in the Rhine. It incorporates regular echo-soundings, bedload and suspended load measurements, and longitudinal water level surveys. These data inform sediment budgets, track morphodynamic changes, and evaluate the effectiveness of nourishments and dredging. Regular monitoring also allows for an assessment of navigation impacts, ecological side-effects, and the performance of specific interventions.

Sediment budgets derived from these datasets provide critical insights into sediment transport pathways, sources and sinks, and the cumulative impacts of management measures. They provide essential feedback loops that guide adaptive management and ensure the long-term sustainability of both navigation and ecological integrity in the river corridor.

Conclusions

The German Rhine exemplifies the intricate interplay between river morphology, human interventions, and sediment processes. Through a combination of targeted management measures, adaptive strategies, and comprehensive continuous monitoring, substantial progress has been made in mitigating bed incision, maintaining navigable depths, and preserving riverine function. Ongoing challenges, such as a need for habitat improvement and climate variability, highlight the need for adaptive, evidence-based approaches to sediment management in large regulated rivers.

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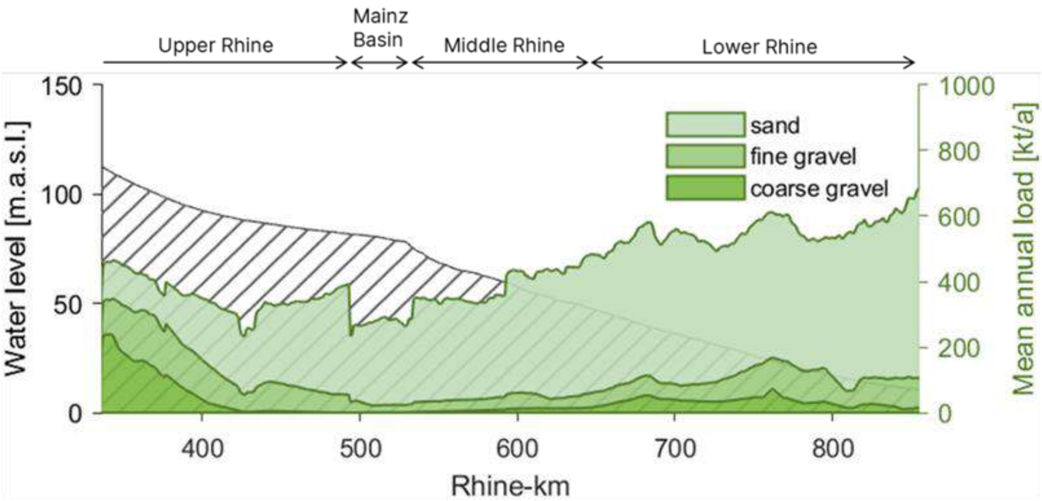

Figure 1. Mean annual sediment loads for sand and gravel in the free-flowing section of the German Rhine, derived from a sediment budget for the time period 1991-2010 (modified after Hillebrand and Frings, 2017). Water levels are depicted as proxy for bed levels.

Uncovering Chaos in River Morphodynamic Models

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Keywords — River Bars, Biogeomorphic interactions, Chaos

Introduction

Numerical predictive models are fundamental tools to explore how river systems respond to environmental changes and to inform effective river management strategies, including mitigation of risk and restoration of ecosystems, and to manage complex river engineering problems(*Wohl*, 2015). To improve the predictive accuracy of these models, it is essential to gain a comprehensive understanding of their underlying dynamical behavior. In particular, it is vital to assess whether deterministic chaos can emerge and to what extent it imposes limits on predictability.

To date, demonstrations of chaos in geomorphyc systems remain limited, but notable examples do exist. As observed in *Phillips* (2003); *Salter* (2020); *Stecca* (2022), deterministic chaos can emerge under specific conditions, potentially limiting the long-term reliability of model-based predictions.

This review synthesizes recent research conducted at the University of Trento that investigates the occurrence of chaos in deterministic morphodynamic models at the river reach scale. We explore the conditions under which such models exhibit chaotic behavior, characterized by long-term aperiodic dynamics and sensitivity to initial conditions (*Strogatz*, 2018) and discuss the resulting implications for the predictability of river morphology. The discussion centers on two examples: migrating free bars in straight channels, and the coupled dynamics of riverbed evolution and a vegetated patch.

Free bars in straight channels

The first example focuses on analytical and numerical investigations of the dynamics of migrating free bars in straight channels. Adopting an approach similar to that of *Schielen* (1993), we consider two-dimensional depth-averaged shallow-water equations coupled with the Exner equation for uniform sediment transport. Two widely used sediment transport formulas are employed: Meyer-Peter & Müller (MPM) for bedload and Engelund-Hansen (EH) for total load. By deriving the complex Ginzburg-Landau equation (CGLE), we analyze the behavior of the rescaled bar amplitude over temporal and spatial scales significantly larger than those typical of bar formation. This analysis reveals chaotic solutions emerging above the Benjamin-Feir instability threshold, particularly when the intensity of sediment transport is high and the roughness of the bed sediment is low. The findings emphasize the limited predictability resulting from sensitivity to initial conditions, indicating that chaotic dynamics could arise under a broad range of realistic river conditions.

Evolution of a vegetated patch subject to flood cycles

By capturing the nonlinear interactions among flow, sediment, and vegetation, recent improvements in ecomorphodynamic modeling represent an important step toward better understanding and predicting river system behavior. These biogeomorphic interactions, however, also introduce considerable complexity into the system dynamics, potentially contributing to the emergence of chaotic behavior. Using a one-dimensional model, we study the evolution of a vegetated patch subject to flood cycles, where vegetation grows and is uprooted when the morphological scour exceeds the root depth (*Cunico*, 2024). In these models, disturbances are intrinsically generated by vegetation: biomass growth modifies the flow field, increases bed scour, and can trigger vegetation uprooting when erosion exceeds the root depth. Our findings demonstrates that nonlinear feedbacks result in deterministic chaos under various conditions, producing complex aperiodic dynamics (Fig. 1) via a period-doubling route to chaos. The associated Lyapunov time is short, ranging between 2-4 growth-flood cycles, suggesting a limited predictability horizon for riverbed evolution.

Conclusion

Our findings suggest that deterministic chaos can arise in standard morphodynamic models commonly adopted for the prediction of river morphodynamics. This suggests the need for ensemble forecasting approaches, employing multiple realizations, to shift the notion of pre-

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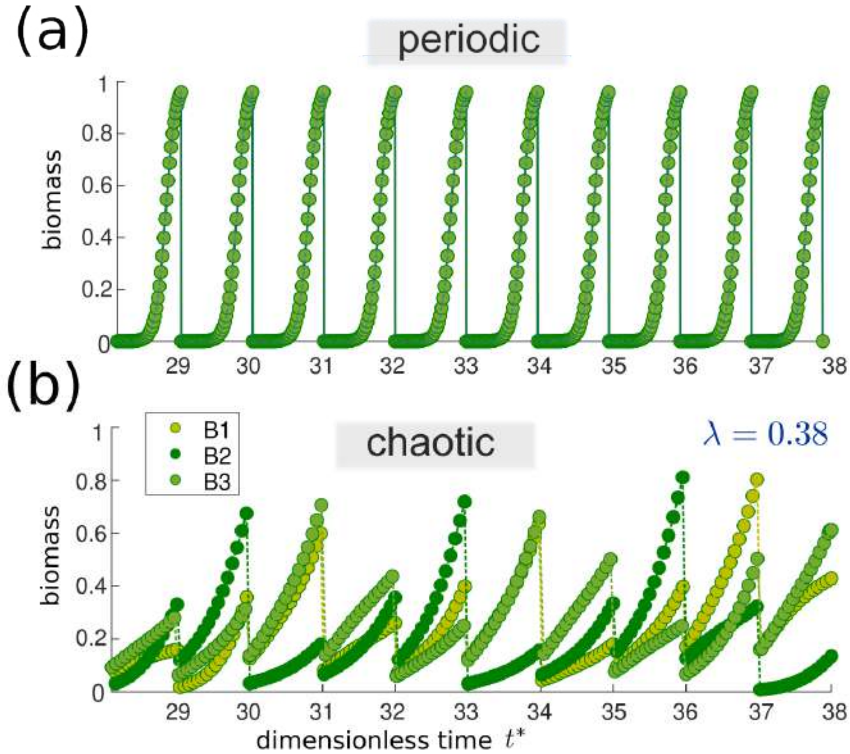

Figure 1: River reach-average vegetation biomass (B) in the vegetated patch over time, obtained from the one-dimensional ecomorphodynamic model. Panel (a) illustrates periodic dynamics, while panel (b) demonstrates aperiodic (chaotic) dynamics. Results from three independent model runs, each initiated with slightly different vegetation biomass distributions (B1 = 1.0×10^{-5}, B2 = 1.1×10^{-5}, B3 = 1.2×10^{-5}), highlight the sensitivity of the model solution to initial conditions. The positivity of the Lyapunov exponent ($\lambda = 0.38 > 0$), calculated from the simulation initialized with vegetation biomass distribution B1, confirms the chaotic nature of the dynamics.

dictability from a single deterministic outcome to a probabilistic envelope of possible system trajectories.

Acknowledgements

This review draws heavily on the PhD research of I. Cunico and F. Weber. The author appreciates the contributions of H. A. Dijkstra, M. Toffolon, W. Bertoldi, and V. Chavarrias, who contributed to the original works summarized in this review. Their collaboration, insights, and guidance have been instrumental in the development of this research.

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Water Management in the 21st century – governance is key

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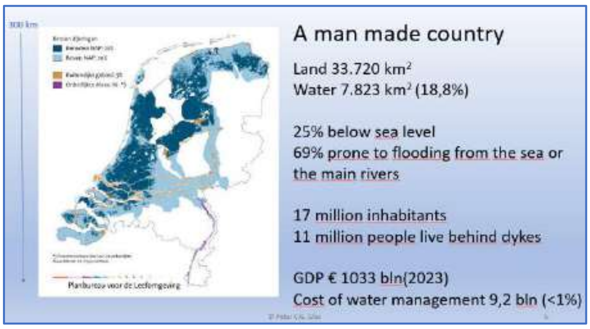
In the presentation I look back on more than 40 years of personal experience in the water management. In the Netherlands and internationally. The Netherlands are a country that out of necessity had to cope with the forces of nature, in particular from the threats of water. From the sea, from the rivers and from rainfall. Floods have been with the Dutch for centuries, but also droughts occurred and in more recent years issues with water quality and ecosystem and biodiversity loss have proven to be persistent. Over time the infrastructure for water management has expanded and we may conclude that to a large extend The Netherlands are a 'man-made country'. Investments, innovations and the upkeep of the levels of flood-safety and availability of water services (irrigation, drainage, sewerage, treatment, drinking water) require about 1% of GDP, which is about 10 billion euro per year. All of this is publicly funded, which may be different in many other countries.



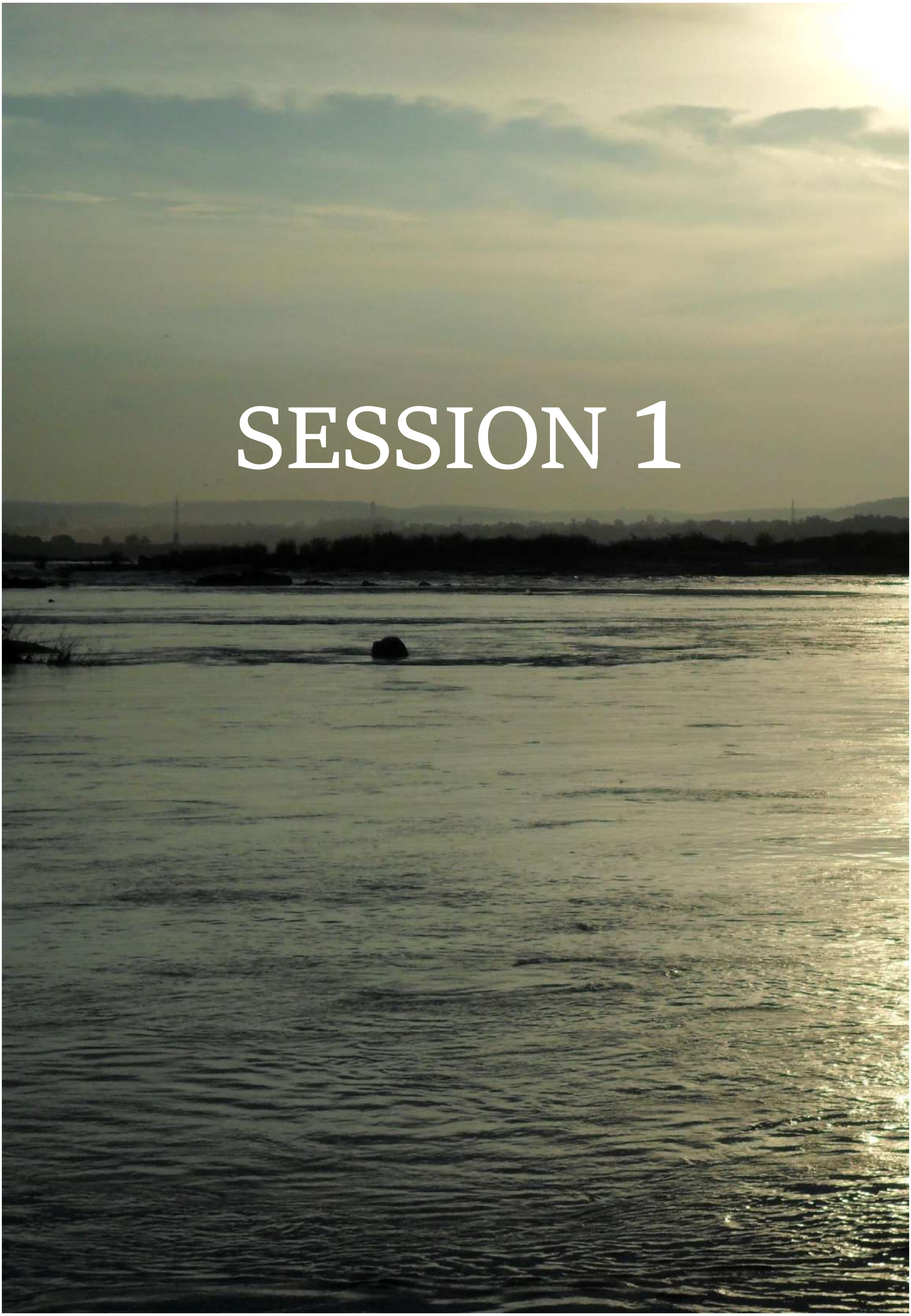
Since the storm surge disaster of 1953, that hit The Netherlands and other coastal Nort Sea nations very hard, over de course of more than 7 decades the underlying paradigms for dealing with water challenges have gradually shifted. From fighting against water, to living with water. The technical and civil engineering skills to day also include the application of nature-based solutions. Examples of this changing policy orientation and implementation are given.

More than a decade ago the Organisation on Economic Cooperation and Development (OECD), together with representatives from academia and civil society also started to look beyond the technical domain in water management. Good water governance is seen by the OECD as an indispensable precondition for the economic development and well-being of nations and regions. After analysing the current status of water governance in a number of countries in 2011, two years later the Water Governance Initiative (WGI) was founded. Is has been an active multi-country, multi-stakeholder thinktank that has developed methodological tools to address issues regarding existing water governance gaps in countries, regions and cities.

Water management has to be efficient, effective and based on trust and engagement. This is illustrated by some of the findings from a policy dialogue between the OECD and water stakeholders in The Netherlands in 2013-2014. Now, more than ten years later, the conclusions and recommendations from that dialogue still resonate in water policy development and discussions about possible institutional changes within the water governance framework of the country.

Finally it is concluded that in order to have a solid rational knowledge base for good water management, we need effective cooperation between alfa, beta and gamma science communities. In other words between applied natural sciences, the humanoria and social sciences. Given the present uncertainties in physical (and other) conditions for water management, reference is made to the ongoing research on Decision Making in Deep Uncertainty.

SESSION 1



The ecological impact of hydropeaking in the Meuse

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Keywords — Hydropeaking, Common Meuse, wavelet analysis

Introduction

The discharge of the river Meuse is largely influenced by human interventions. Several weirs and hydropower plants are located in the French and Belgian sections of the river. These weirs regulate water depth for navigation and optimize hydropower generation by increasing the hydraulic head. The current operation of these weirs generates discharge waves, known as hydropeaks, that propagate through the Meuse. In the Common Meuse, these hydropeaks are expected to generate significant bed shear stresses, making the riverbed an unsuitable habitat for many aquatic species.

Characterizing hydropeaks is challenging due to the natural variability in river discharge (Van Roode, 2001). This study applies a robust and objective methodology to assess the impact of hydropeaks and evaluate mitigation measures. We apply wavelet analysis to separate hydropeaks from natural discharge variations. This allows to assess hydropeak variability along the river Meuse and estimate their impact on bed shear stresses in the Common Meuse.

Method

We use a wavelet transform to identify dominant frequencies in the measured discharge along the river Meuse. Unlike the Fourier transform, wavelet analysis can detect changes in dominant frequencies over time, making it a valuable tool in geophysical studies. This technique has been widely used to analyze different scales of morphological development (Van Denderen et al., 2023), identify riverbed forms (Lokin et al., 2024), and describe river meanders (Vermeulen et al., 2016).

We apply the wavelet transform to data from several measurement stations along the Meuse. Figure 1 presents results from Borgharen (inflow of the Common Meuse) over a three-year period. The wavelet power spectrum reveals several characteristic discharge variations:

- Yearly variation, 300-400 days: Discharge is higher in winter than in summer.
- High water periods, 20-50 days: Within winter, several high-water events occur.
- Peak flows, 5-10 days: Discharge peaks occur over shorter periods.
- Hydropeaks, 0.1-1.5 days: A persistent energy band, except during low discharge periods.

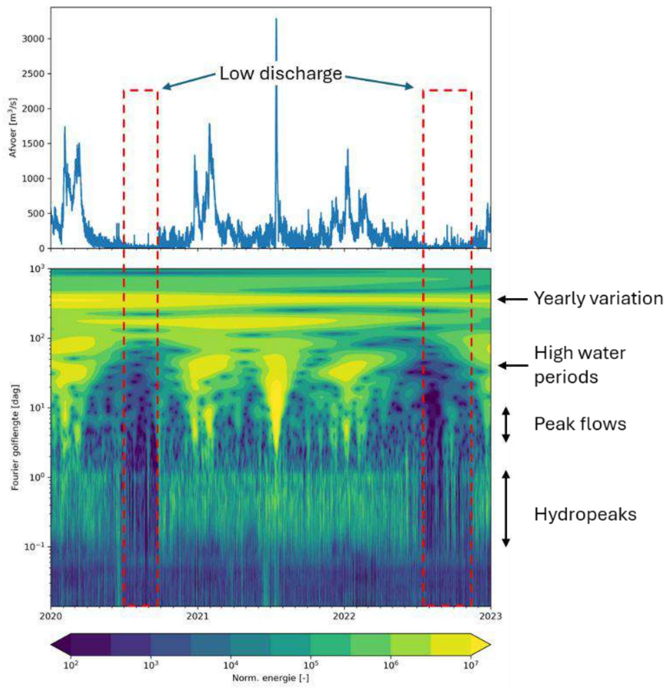

Figure 1. Top: The measured discharge at Borgharen between 2020 and 2023. Bottom: Corresponding wavelet power spectrum showing normalized energy over time for different wavelengths.

By analyzing power spectra across multiple discharge stations, we separate hydropeaking signals from natural discharge fluctuations.

Result

Figure 2 illustrates hydropeak amplitudes at different discharge stations in the Belgian and Dutch Meuse, plotted against the monthly average discharge at Borgharen. Hydropeaks are first visible at Salzinnes (measuring discharge in La Sambre, a tributary of the Meuse). Moving downstream to Amay and Borgharen, hydropeaks increase in magnitude,

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likely due to the presence of multiple weirs and hydropower plants. In the Common Meuse, hydropeaks rapidly diminish in amplitude, likely due to increased river roughness caused by shallow water depths. At Venlo, hydropeaks are no longer distinguishable, suggesting that floodplain lakes contribute to their attenuation.

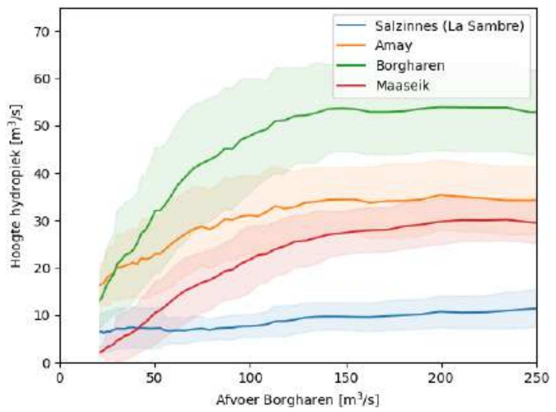

Figure 2. The peak discharge of hydropeaks as a function of the monthly average discharge at Borgharen. The bandwidth shows the standard deviation.

To assess the impact of hydropeaks on bed shear stresses, we utilize a D-Hydro model of the Common Meuse. Figure 3 illustrates the change in bed shear stress resulting from hydropeaks, relative to a stationary discharge of 50 m³/s at Borgharen (base-flow conditions).

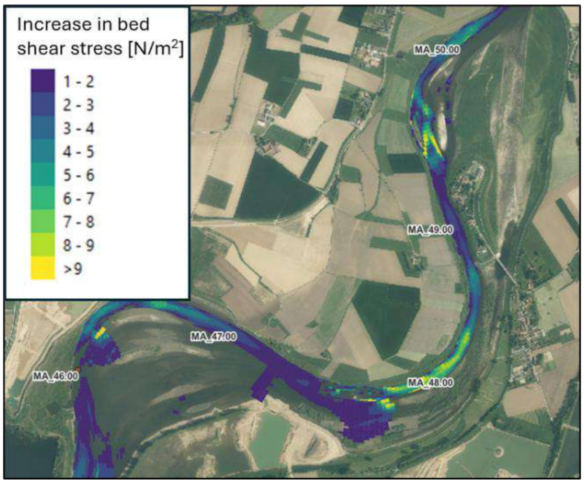

Figure 3. Change in bed shear stress due to hydropeaks compared to stationary discharge (50 m³/s at Borgharen).

Discussion and conclusions

Hydropeaks in the river Meuse originate primarily from the Belgian section. These hydropeaks significantly increase bed shear stress in the Common Meuse, potentially displacing aquatic plants and organisms. Consequently, hydropeaks reduce the suitability of the riverbed as a habitat for aquatic species. To comply with the Water Framework Directive (KRW) and N2000 Grensmaas objectives, it is essential to mitigate the frequency and amplitude of hydropeaks. A different control of the Belgium weirs would be a first step. In addition, the weir at Borgharen could be used to reduce the discharge fluctuations.

Acknowledgements

This project was executed on behalf of Rijkswaterstaat. This abstract is an extended summary of the full report (HKV, 2024)

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Towards a resilient ecohydrological future for the IJssel-Vecht Delta – a case study for scientific exploration

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Keywords — IJssel Vecht Delta, Nature based Solutions, System change

Introduction

The IJssel-Vechtdelta (IJVD), situated at the intersection of riverine and lacustrine systems in the Netherlands, has undergone extensive anthropogenic modification over centuries. As a result, its natural hydromorphological processes have been suppressed, leading to a significant decline in ecological quality, biodiversity, and resilience to climate stressors. The Programmematic Approach to Large Waters (PAGW) seeks to reverse these trends by implementing ecosystem-scale restoration measures aimed at achieving a future-proof, robust aquatic and wetland ecosystem by 2050. The IJVD is one of 4 hotspots for this approach, see Figure 1.

Figure 1. The PAGW programme for the Dutch Large Rivers focusses on 4 hotspots connected by corridors. The IJVD is one of the hotspots (Rijkswaterstaat, 2023).

Preliminary exploration (preverkenning)

The preliminary exploration ('preverkenning') involved multidisciplinary assessment of the ecological degradation across four identified subregions of the IJssel-Vechtdelta. System-level interventions were identified through ecological modeling, stakeholder workshops, and hydrological analyses. Key guiding frameworks included the Natura 2000 directives and the Water Framework Directive (KRW), emphasizing restoration of natural processes and large contiguous habitat areas. Planning was grounded in ecological feasibility, spatial integration, and existing policy frameworks.

Results

Five core interventions were proposed: (1) Establishing large ecologically driven zones; (2) Enhancing water dynamics; (3) Promoting erosion and sedimentation; (4) Integrating river and lake ecology with adjacent landscapes; and (5) Increasing organic matter within the aquatic system. These strategies collectively target a net gain of 8,300 ha in functional ecotopes by 2050 (see Table 1, p.17 Rijkswaterstaat, 2023). Additionally, ecological maps (Fig. 1, p.16, Rijkswaterstaat, 2023) illustrate key habitat goals across the region. The restoration ambition focuses on reintroducing land-water gradients, dynamic flow regimes, and continuous connectivity, supporting species such as the otter, black stork, and barbels.

Figure 2. Among the large systemic changes proposed is the Keteldelta concept (Bert Bijkerk), where the River IJssel is prolonged into the Ketelmeer.

Keteldelta

The “Keteldelta” concept proposes creating a new, adaptive IJssel River delta near the Ketelbrug, between Urk, Ketelbrug, and the Flevocentrale, see Figure 2 for the conceptual idea. This initiative aims to address ecological and water management challenges in the IJssel-Vechtdelta by establishing thousands of hectares of new delta nature that can adapt to potential IJsselmeer water level rises. By facilitating natural delta formation processes, the plan seeks to enhance water safety by reducing storm surges, support biodiversity, and preserve agricultural land on the Kampereilanden. The concept aligns with the Programmatic Approach to Large Waters (PAGW) and the Integral River Management (IRM) program, offering a phased, cost-effective strategy that integrates natural processes with infrastructural development.

Conclusion

The integrative and nature-based perspective provided by the preliminary exploration (preverkenning) provides a robust, adaptive roadmap for the restoration of the IJssel-Vechtdelta, integrating ecological functionality with water safety and economic co-use. Achieving these long-term objectives requires coordinated inter-programmatic collaboration, policy flexibility, and long-term spatial planning.

This pre-assessment sets the stage for region-specific “verkenningen” and further stakeholder involvement to realize the ecological ambitions outlined.

We invite researchers to engage and contribute to addressing the knowledge gaps emerging from these large-scale, nature-based conceptual designs.

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The multi-channel concept explored from Bonn to Biesbosch

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Keywords — Riverbed erosion, multi-channel concept, Room for the River, Niederrhein, Waal, Sobek Modelling

Introduction

The hydro-morphology of the Rhine River has significantly altered due to engineering interventions since the 18th century. These interventions improved navigability and reduced the risk of ice dams. Especially in the Waal River, normalization led to channel bed incisions at a rate of 1–2 cm per year (Blom, 2016). This has resulted in a 1–2-meter degradation of the riverbed in the Waal since the 1950s (Blom, 2016). In the business-as-usual scenario, the riverbed is expected to incise by up to 1.5 meters in the next 50 years (Yila Arbós, 2024). The incision causes shipping bottlenecks, affects the stability of infrastructure and groynes, undermines freshwater intake points, and impacts the ecological quality of floodplains (Beekers et al., 2017). Therefore, action is needed.

Figure 1. Principle of the multi-channel concept. By widening the wetted perimeter, the energy is better divided through summer and winter bed.

In this paper, we explore the multi-channel concept that was developed by Bureau Stroming, WWF and ARK Rewilding to reduce erosion while improving natural quality without affecting navigability. Due to the bypasses the flow velocity in the summer bed decreases, reducing erosion (Figure 1). Exploratory calculations show that large-scale floodplain lowering could potentially reduce the necessary sediment supplementation volume to counter incision by 14–33% (Barneveld et al., 2019).

Method

We evaluate the Lower Rhine from Bonn (GER) to Biesbosch (NL). Because this trajectory is a lowland river, we consider this a logical boundary for a systematic approach to challenges such as morphology, water safety, water quality and ecology. Despite the Niederrhein, up to Bonn, which has been fairly stable since 1985 due to continuous sediment nourishments it could benefit from the multi-channel concept (Frings et al., 2014). It reduces the required sediment volume, improves water quality in line with the Water Framework Directive goals, and contributes to the EU Nature Restoration Law. By creating more room for the river, it could enhance water safety along the Niederrhein.

Therefore, in this study, the multi-channel concept from the Waal River is extended with a design for the Niederrhein. Which is based on on topographical, geomorphological, and fundamental river flow principles. Separate SOBEK Flow1D models for the Niederrhein and Dutch Rhine trajectories are combined, allowing assessing the hydrological effects of the multi-channel concept on a broader system scale. Tributaries are excluded from the model. Together with the existing designs—including widths and depths—for the Gelderse Poort and Waal, the bypasses are implemented in SOBEK (Figure 2). Using multiple discharge scenarios, the water level reduction and decrease in flow velocity can be determined. Given the large scale of the study area, a one-dimensional approach has been applied.

Results & discussion

Model runs have been performed with discharges of 450, 2,200, 7,000, and 12,730 m³/s. Observation points at every kilometre along the trajectory indicate the effects on water level and flow velocity. During average discharge, the model shows a decrease in flow velocity across almost the entire river section (Figure 3). However, this reduction diminishes as discharge increases. With this study initial steps have been taken toward developing an applicable model for gaining further insight into the hydrological effects of the implemented bypasses.

Figure 2. Example of an implemented bypass in the Sobek Model

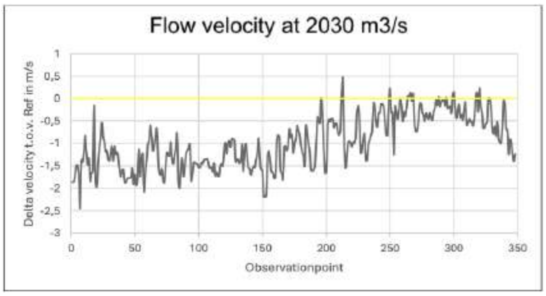

Figure 3. Flow velocities for the multi-channel concept

Further optimization and validation of the model are required to fully utilize its potential. Once optimized, the model outcomes can be linked to various river characteristics for better understanding of the results in relation to river geometry, levees etc. This will contribute to optimizing the multi-channel design along the river profile, which is the overall goal of this study. Based on these results, and the study of sediment balance in the Rhine from Frings et al. (2012) and Frings et al. (2019) exploratory calculations can be conducted to indicate the effect on the needed sediment volumes.

Future research

In contribution to the 1D SOBEK model a 2D model can be conducted using floodplains representative for the trajectory to gain better understanding on the effects on smaller scale. In the process of optimizing the design by finding a right balance for multiple function such as ecology, navigation, and morphology we think assessing designs that maximize a single river function can be useful. Through this approach the design boundaries are clarified in which an optimal design can be achieved.

As the Room for the River 2.0 program and PAGW 'Gelderse Poort' are currently assessing the potential implementation of the multi-channel concept, we believe aligning theoretical research with the program's challenges will accelerate the concept's transition. As the concept is relatively new, many questions remain unresearched. To prioritize which challenges should be addressed, we propose a cooperative approach in which we conduct a discussion to determine the knowledge needs, leading to an improved and detailed design of the multi-beam concept between Bonn and Biesbosch while acknowledging the different river functions.

After cooperatively identifying a research focus, the design can be optimized and modelled to gain insight into the hydro morphological effects. The concept can then be developed further. Through this method, a research direction can be formulated such that the outcome directly benefits the ongoing development of the concept. In preparation for this discussion, a literature review and knowledge sessions with experts will clarify the current knowledge gaps in the multi-channel concept, which can then be discussed and prioritized during the discussion

Acknowledgements

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Declining discharge drives the ecological degradation of the Common Meuse

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Keywords – discharge, macroinvertebrates, traits

Introduction

Riverine ecosystems face growing threats from multiple anthropogenic stressors, including hydro-morphological changes (Poff et al. 2010) and chemical pollution (Sutton et al. 2011), which often interact synergistically (Tockner et al. 2009; Peralta-Maraver et al. 2018). These pressures impact ecological integrity, with low summer discharge further amplifying their effects (Peralta-Maraver et al. 2020).

Relying solely on physicochemical parameters to monitor discharge dynamics and associated stressors provides only a partial view of environmental conditions. In contrast, biological monitoring captures an integrated response of the riverine communities to environmental stress cumulative temporal ecological degradation (Buss et al. 2015).

Combining long-term time series of physicochemical parameters and biotic responses facilitates the prioritization of mitigation strategies for ecosystem restoration (Trabucchi et al., 2014)

Here, we examine how multiple stressors influence macroinvertebrate communities in heavily modified European rivers by comparing composition of species and their traits in the Common Meuse (NL), with those in stream tributaries, and with the River Eden (UK). Using long-term datasets on environmental variables and community composition, we explore macroinvertebrate-abiotic interactions. This study highlights the cumulative impact of anthropogenic pressures and hydrological alterations on riverine biodiversity, offering insights for evidence-based river management.

Methods

Environmental and biological data were obtained from publicly available databases (KNMI, RWS, EA, FWE). The environmental parameters considered in our analyses are oxygen saturation (%O_2), water temperature, river discharge, and concentrations of arsenic (As) and phosphorous (P). The biotic analyses are based on long term macroinvertebrate monitoring. We incorporated trait information to assess patterns beyond taxonomy and we focused on traits related to flow velocity (Verberk et al. 2012), temperature (Halle et al. 2016), and vertical sorting (Schmidt-Kloiber and Hering 2015).

To investigate temporal trends in abiotic conditions and to assess the main drivers of these trends, we applied approximate Bayesian inference using Integrated Nested Laplace Approximation (INLA).

We investigated macroinvertebrate community structures across all the systems and within the Common Meuse using non-metric multidimensional scaling (NMDS) ordination analysis.

Results

In the Common Meuse most parameters associated with water quality improve or are stable over time; oxygen saturation increases towards 100%, summer water temperature is stable, and [As] and [P] decline.

All aforementioned abiotic parameters are mechanistically linked to discharge. However, we observed a decline in summer discharge and consequently, the improvement in water quality is attenuated with water quality conditions remaining suboptimal. E.g., we see an improvement in oxygen saturation. However, this improvement is partly masked by deteriorating discharge. If discharge conditions would be improved, the model predicts that oxygen fluctuations (i.e. the differences between the minima and maxima) become much less pronounced (Fig. 1).

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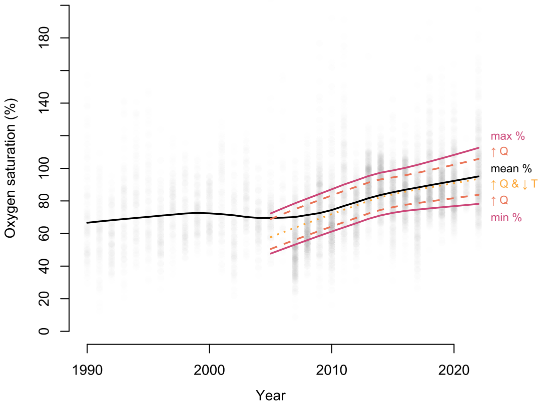

Figure 1 Temporal trends in oxygen saturation. From 2005 onwards min and max are also presented. Dashed lines indicate different discharge or temperature scenarios.

Changes in the macroinvertebrate species composition do not reflect the improvement in oxygen saturation: communities have become increasingly dominated over time by species that prefer stagnant waters with poor oxygenation. Thus, the reduction in summer discharge overshadows any improvements in water quality (Fig. 2). Furthermore, the communities in the Common Meuse have become more heat tolerant, species associated with the interstitial zone are absent, contrasting with the situation in both River Eden and the Meuse tributaries.

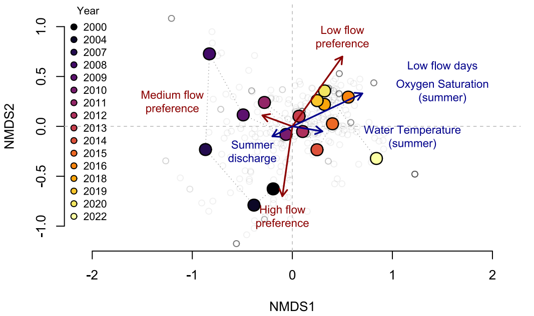

Figure 2 Temporal community change in the Common Meuse, with flow velocity preference (red) and abiotic drivers (blue).

Conclusion

Despite improvements in abiotic conditions in the Common Meuse, we do not see improvements for the macroinvertebrate species composition. On the contrary; they have become more stagnophilic. Arguably, this is driven by a decrease in summer discharge.

Source populations from the tributaries of the Common Meuse do not to establish in the Common Meuse, indicating adverse conditions in the river itself. When compared to the River Eden, none of the sensitive species occur in the Common Meuse.

We showed that improvements in O_2, T_{water}, [As] and [P] would have been stronger under an improved discharge regime. Additionally, the water temperature negatively affects oxygenation.

Both of the aforementioned could be improved by management. E.g., a different distribution of water between the Meuse and canals could potentially improve the discharge regime in the Meuse. Additionally, riparian trees could contribute to shading of the water, reducing the water temperatures. Furthermore, improved discharge would facilitate higher flow conditions which are necessary for characteristic species of gravel bed rivers.

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SESSION 2

A deep-learning model for predicting the planform evolution of braided sand-bed rivers

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Keywords — braided rivers, morphology, deep learning

Introduction

Braided rivers are the most dynamic type of rivers, with a rapid and intricate morphological evolution (*Stecca et al.*, 2019). Being able to predict where and how rivers evolve is crucial for supporting spatial-related decision-making processes in the vicinity of these rivers. However, a limited understanding and inadequate algorithm implementation of specific morphological processes limits the prediction capabilities of physics-based models (*Jagers*, 2003; *Siviglia and Crosato*, 2016). The design of structures, infrastructure, and other interventions is consequently hampered at the expenses of the popoulation safety. In recent years artificial intelligence techniques rapidly gained popularity across different contexts (*Blake et al.*, 2021) and the availability of satellite images increased. This research sets a novel attempt to predict the planform evolution of braided rivers by means of a deep-learning algorithm and using satellite images. The Brahmaputra-Jamuna River, in India and Bangladesh, was selected as case study (*Best et al.*, 2022).

Methods and data

The stretch of river that was considered ranges from the confluence with the Lothi and Dibang River, in India, until the confluence with the Ganges River, in Bangladesh. The training, validation, and testing datasets were obtained by spatially splitting the stretch considered. Thirty rectangular sub-reaches with 60×30 km dimensions were generated, with 60 and 30 km being the longitudinal and lateral dimensions, respectively. The twenty-eight most upstream sub-reaches were used for training the model. The last two reaches were used for validating and testing it, respectively.

A convolutional neural network (CNN) with U-Net architecture was developed (*Ronneberger et al.*, 2015). The model was trained with the Global Surface Water Dataset (GSWD) (*Pekel et al.*, 2016), which contains pre-classified global images with three classes: *no data*, *non-water*, and *water*. An algorithm was implemented to binarize the images by replacing the *no data* pixels with one of the two other classes. The model was trained for a binary semantic segmentation task, aiming at classifying each pixel as either *non-water* or *water*. Four images, representative of the same month over four consecutive years, were used as inputs. The fifth-year image represented the target.

Results

The model demonstrated acceptable skills in predicting the overall planform development, although it often misses finer details and some morphological features (Fig. 1). Processes like the migration of meanders, the abandonment of channels, and the evolution of confluences and bifurcations were often well captured (Fig. 2).

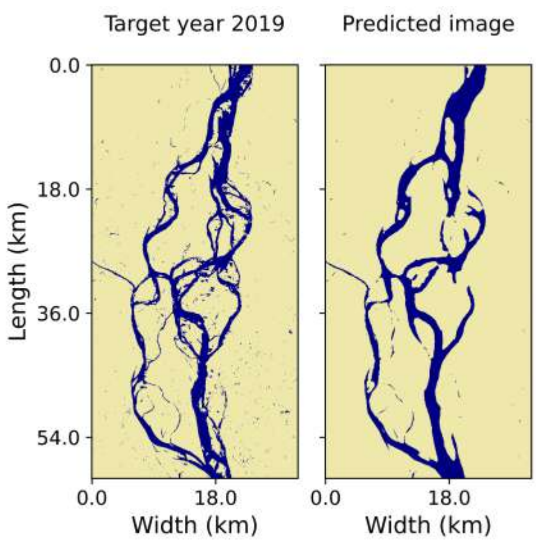

Figure 1: Example of a target and predicted image (year 2019).

However, a lack of temporal patterns was noticed. More complex phenomena, like the formation and shifting of channels, were never predicted, and the total areas of erosion and deposition were constantly underpredicted.
Metrics such as precision, recall, F1-score, and critical success index (CSI) were tracked.

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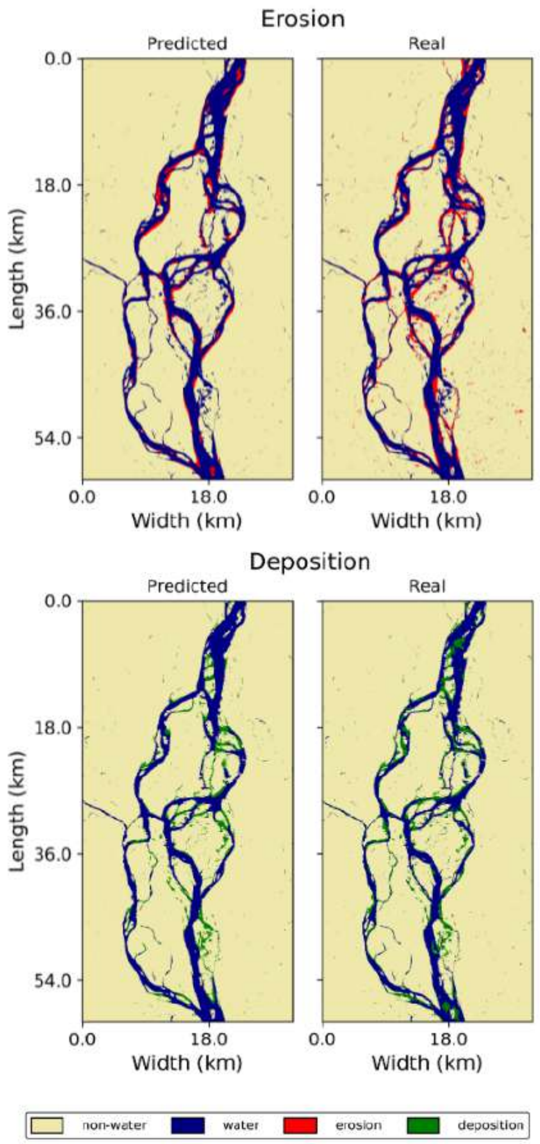

Figure 2: Predicted and real areas of erosion and deposition (year 2019).

These scores show the overall good prediction skills of the model, although larger values are always preferred. A 5-6% total improvement of these metrics was achieved compared to the benchmark method for which no morphological change is assumed to occur (Tab. 1). Additional metrics, like the Receiver Characteristic Operating (ROC) and the Precision-Recall (PR) curves, also show the model ability to accurately predict the *non-water* pixels, whereas struggling more when predicting *water* pixels.

Table 1: Comparison between the metrics of our model and the no-change method benchmark.

Model	Precision	Recall	F1	CSI
Our model	0.72	0.71	0.71	0.55
No-change	0.66	0.66	0.66	0.49

Conclusion and recommendations

Our model could be useful as a preliminary tool for water management authorities in India and Bangladesh. It could support the prioritisation of bank protection measures in areas subject to erosion or land reclamation projects in areas subject to deposition and assist inland navigation. However, given the inherent tendency of the model to underpredict erosion, caution is always advised.

More research is required to improve the current model. Despite this, deep-learning modelling could become a potentially valuable field of research. Testing alternative model architectures, increasing the datasets size, and incorporating additional data, such as water levels or river discharge, are recommended to improve the model performance.

Acknowledgements

This research was developed as a Master's thesis in collaboration between TU Delft and Deltares. Antonio Magherini thanks Bert Jagers and Arjen Haag for their useful help, the material provided and for the interesting discussions during the research.

The code repository is available on GitHub at the following link: `https://github.com/antoniomagherini/jamunet-morpho-braided`.

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A semi-supervised graph-based approach for anomaly detection in river monitoring stations

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Keywords — Anomaly Detection, Graph Neural Networks, Gaussian Mixture Models

1. Introduction

Water quality monitoring is crucial for ensuring safe drinking water and protecting aquatic ecosystems. Traditional methods, like periodic sampling, often fail to detect sudden pollution events, delaying responses that could protect public health and the environment *Zhu et al.* (2022). Anomalies, such as nutrient spikes or oxygen drops, can signal environmental issues like pollution or runoff, necessitating immediate detection. This gap highlights the need for advanced techniques capable of real-time data analysis. Machine learning, particularly graph neural networks (GNNs), has shown promise in enhancing real-time water quality monitoring. GNNs are effective at modeling the spatial connections between monitoring stations, which helps in predicting water quality more accurately *Li et al.* (2024) *Yan and Wang* (2024). This is especially useful for understanding how pollution spreads across a network. However, a significant hurdle is the scarcity of labeled data for training GNNs, as anomalies in water quality are rare and often not well-documented *Buchhorn et al.* (2024). This makes supervised learning challenging, pushing researchers toward novel methods to detect unusual events without extensive labeled datasets.

2. Proposed Methodology

This study proposes a semi-supervised graph-based anomaly detection framework for water quality monitoring. Where significant deviations from the normal distributions of water quality paramaters are detected in real-time without the need for the before-hand knowledge needed in supervised learning approaches. To utilize the topology of river beds, monitoring stations are represented as nodes in a graph, with their position in respect to each other mapped through adjacency matrix from upstream to downstream. The proposed structure, depicted in Figure 1, enables graph-based learning from abundant unlabeled data with minimal labeled anomalies. The selected dataset *Mokin* (2020) includes measurements of 8 water quality indicators—NH_4, NO_3, NO_2, SO_4, PO_4, Cl, O_2, suspended solids—and BSK_5 from 22 stations along the Southern Bug River in the period (2000–2021). These indicators, visualized as heat map in Figure 2 showing spatial variations, are used in our graph-based system for anomaly detection.

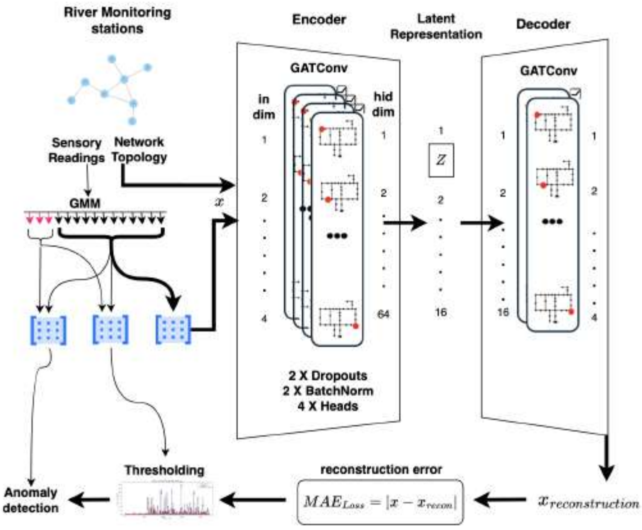

Figure 1: Graph-based Anomaly Detection Framework for Water Quality Monitoring integrating GMMs and GNN encoder-decoder architecture.

Consequently, the proposed methodology combines Gaussian Mixture Models (GMMs) with GNN framework through the following steps:

1. **Anomaly Identification** Water quality measurements are clustered using GMMs, identifying anomalies as entries in the bottom 5% of log-likelihood scores.
2. **Graph Construction** To mirror the river's upstream-to-downstream topology. A graph $G = (V, E)$ is defined where nodes V represents the stations and edges E represent spatial connections
3. **Data Splitting** The GNN is trained on 90% non-anomalous data to ensure robust learning of normal patterns, with the

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remaining 10% reserved for validation and testing.

4. **Training Encoder-Decoder Architecture** A Graph Attention Convolutional encoder transforms input features into a 16-dimensional latent space, while the decoder reconstructs the original nodes from this latent space, aiming to minimize reconstruction error (MAE) during training.
5. **Threshold Tuning** During inference, nodes with reconstruction errors exceeding a tuned threshold are flagged as anomalies, indicating deviations from expected patterns.
6. **Evaluation** The model is assessed using accuracy, precision, recall and F1-score, on a test set containing anomalies.

3. Results and Discussion

Following optimization of GMM using AIC/BIC criteria (as shown in Figure 3), 2 clusters were identified with 129 outliers (bottom 5% log-likelihood) flagged as anomalies. Following training of encoder layers, GNN converged as MAE decreased from 0.4213 to 0.2806 over 110 epochs and stabilized after epoch 60, showing effective learning of normal water quality patterns using river topology. Performance metrics showed promising results: 97.95% accuracy, 79.71% precision, 79.14% recall, and 79.42% F1-score at threshold 0.8493. The model was able to identify normal conditions while maintaining balanced precision-recall for anomaly detection. Station-level analysis revealed spatial variability: Station 1 exhibited an 86.84% anomaly rate (66/76 measurements) with 48 true positives and 18 false positives, indicating oversensitivity. Other stations showed minimal anomalies (Station 2: 2/77, Station 3: 0/262). Such disparity suggests Station 1's anomalies reflect true environmental deviations, validating the graph-based approach for capturing spatial dependencies.

4. Conclusion

The integration of GMMs with GNN encoder-decoder architecture proved potential for water quality monitoring, achieving a competitive F1-score despite lack of labeled data. The semi-supervised approach was able to leverage unlabeled data to learn normal patterns while using river topology to enhance spatial awareness—a critical advantage over traditional periodic sampling. The model's high accuracy (97.95%) and ability to identify stations with frequent anomalies provide actionable insights for targeted interventions. Future work should focus on adaptive threshold tuning per station to account for spatial heterogeneity and explore techniques to mitigate class imbalance, potentially transforming this framework into a versatile tool applicable to diverse river systems and ecological challenges.

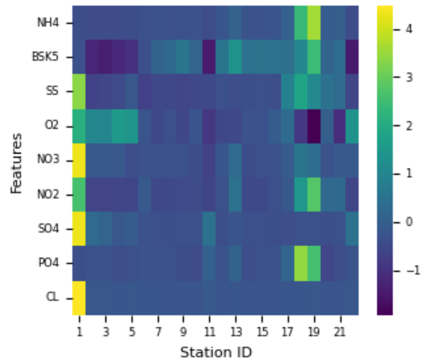

Figure 2: Heatmap of Z-Score Normalized Mean Features Across Monitoring Stations in an ascending order from upstream to downstream

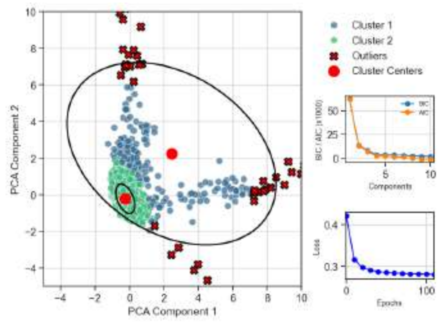

Figure 3: GMM Clusters, AIC/BIC curve and Epoch vs loss curve.

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A national monitoring strategy for riverine macroplastic pollution in the Netherlands

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Keywords — Plastic pollution, litter, Rhine, Meuse, development.

Introduction

Accurate and reliable monitoring data are crucial for the design of effective plastic pollution reduction and mitigation strategies. Since 2020, Rijkswaterstaat (RWS), commissioned by the Ministry of Infrastructure and Water Management, has been developing a national monitoring strategy for riverine macroplastic (>0.5 cm) pollution. This development process has followed the roadmap developed by van Emmerik et al. (2022). RWS has developed monitoring protocols for floating macroplastics and plastics deposited on riverbanks. Protocols for macroplastics suspended in the water column and plastics deposited on river beds are in development. Moreover, RWS has executed pilots with technologies such as drones, acoustic sensors and the combination of cameras and artificial intelligence to improve manual monitoring methods.

The initial year-long assessments of floating plastics and plastics deposited on riverbanks have been completed. This study details the development of these monitoring methods and presents the first national-scale data on macroplastics.

Floating plastics

The protocol for monitoring floating macroplastics is an optimized version of the RIMMEL protocol (González-Fernández & Hanke, 2017), which utilizes visual observations from bridges to quantify plastic flux. This method is applied at ten locations across the Netherlands on a monthly basis. The selected locations ensure coverage of the Rhine, Meuse, and IJssel rivers, with observations near the inflow, river mouth of these rivers, as well as midpoints for the Rhine and Meuse. Observers count the floating items and record the material type, providing insights into the flux, composition, and trends over space and time.

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In 2024, the median observed macroplastic flux in the Rhine-Meuse delta remained relatively stable. The annual median transport was 134 items per hour, with monthly median values ranging from 67 to 288 items per hour (Figure 1). Maximum values varied, with peaks in transport observed in May and September.

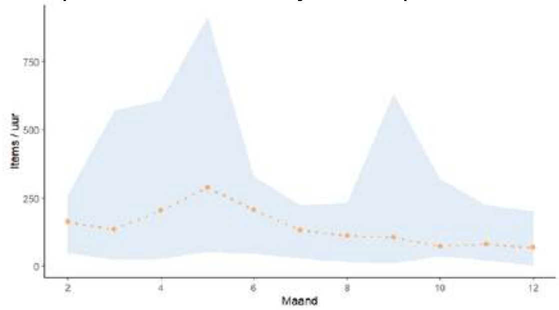

Figure 1 – Monthly median observed macroplastic flux in the Dutch Rhine-Meuse delta in 2024. Blue shading shows the minimum and maximum values for each month.

Riverbank plastics

Riverbank plastics are monitored using protocol that was adapted from the OSPAR beach litter protocol (Boonstra et al., 2023). This method is applied with a frequency of four times per year at 50 locations across the Netherlands. These locations are evenly distributed across the Rhine, Meuse and IJssel rivers, as well as the Western Scheldt. A sampling area of 100x25 meter is set out on the riverbank. Two observers sample the area, picking up every litter item they can see while standing up and categorize this litter according to the OSPAR litter list. A more detailed measurement is done at several 1x1 meter sub-sample areas. Here, smaller items such as mesoplastics and plastic pellets are sampled.

On an annual basis, an average of 332 items/100 m riverbank were observed in the rivers (N=38), and 319 items/100 m in the Western Scheldt (N=9). These annual values are the sum of four measurements taken throughout the year. The median per measurement round is significantly lower: 56 items/100 m for the Maas, 72.5 items/100 m for the Rhine, and 100 items/100 m for the Western Scheldt. The values between locations can vary greatly. The highest recorded pollution values in a single visit are 2103 items/100 m in the river area and 2730 items/100 m in the Western Scheldt.

There is overlap in the composition of litter sampled in the rivers and in the Western Scheldt. In both systems, many undefinable plastic films and fragments between 2.5-50 cm are found: 40%-44% of all found objects are undefinable pieces of plastic between 2.5-50 cm (Figure 2). Additionally, a lot of consumer litter is found, such as food packaging, caps, and cigarette filters. In the Western Scheldt, more fishing-related litter is found, such as fishing line and industrial-related waste. In both systems, the litter mainly consists of plastic: 84% for the rivers and 91% for the Western Scheldt.

Single-use plastics (SUP) constitute 32% and 35% of the total litter found in the river area and the Western Scheldt, respectively, with 9%-10% being chip or candy wrappers or lollipop sticks. Cigarette butts make up 6%-7% of the SUP items.

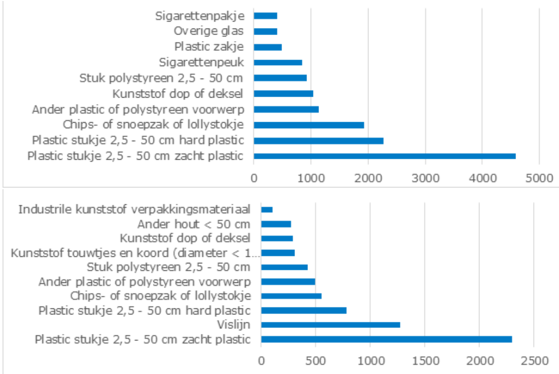

Figure 2 - Top 10 most frequently found items in rivers (top) and the Western Scheldt (bottom).

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Sediment composition and microplastics in the riverbed of the River Waal, Netherlands – active layer and subsurface

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Keywords — Dune preservation, microplastics distribution, microplastics into Pleistocene sediments

Introduction

For the safe and sustainable use, management and maintenance of lowland rivers, a better understanding is required of the links between riverbed morphodynamics and the spatio-temporal patterns of sediment preservation in the subsurface. Furthermore, river valleys are major stores for plastics (e.g. Drummond et al., 2022). Previous field studies on microplastics (< 5 mm) are mostly limited to river banks, floodplains and bed samples, whereas reports on microplastic contents within subsurface sediments are scarce. Establishing the spatial distribution of microplastics within riverbed sediments contributes to the understanding of MP transport paths (from source to sink), processes of MP accumulation and estimates of total microplastic bedload output of rivers (Krause et al., 2022). Alternative hypotheses explaining microplastic accumulation within riverbeds are deposition similar to sediment deposition, inflow by hyporheic flow (where dunes play an important role), or transport into deeper layers by ground water.

In this paper, we present preliminary analyses of three sediment cores and microplastics distribution in the bed of the River Waal, along with the sedimentary architecture, distinguishing between the active layer and deeper sediment layers. These data will permit unprecedented future insight into the development of the sedimentary architecture and its influence on the distribution of microplastics in riverine sediments.

Data and methods

In three areas of the River Waal, Netherlands (Figure 1), high-resolution multibeam echo-sounder (MBES) and sub-bottom profiler data (parametric echo sounder, PES) were recorded simultaneously, as to guarantee their ultimate correspondence in space and time. Per area, four 7 km-long lines were surveyed in the navigation channel, thus creating a near-3-D dataset. These surveys were done in a short time series (Table 1) and combined with 18 vibrocores down to depths of *ca.* 5 m.

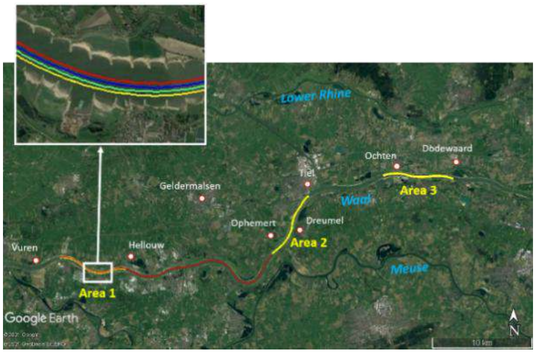

Figure 1. Locations of the three survey areas in the River Waal, Netherlands (yellow). The enlarged inset map of Area 1 shows the four survey lines. Flow is from east to west.

Table 1. Overview of acoustic surveys (S1, S1-Repeat, S2) and vibrocoring.(VCs, during Survey S2)

	Area 1	Area 2	Area 3
MBES & PES			
S1	31 May	1 Jun	2 Jun 2021
S1-R	3 Jun	.	.
S2	21 Jun	22 Jun	23 Jun 2021
VCs (S2)	22 Jun	23 Jun	24 Jun 2021

Core locations were based on the PES data of Surveys S1 and S2. Sediment cores were sub-sampled at *ca.* 20-30 cm resolution for establishing grain-size distributions (by sieving) and microplastic concentrations, particle size and polymer types (by fluorescent microscopy and Raman spectroscopy).

Results

The dune morphology of large and superimposed small dunes in the bathymetric data corresponds to sedimentary structures on the PES data, exhibiting foresets of large dunes and structures of superimposed small dunes.

Active Layer
In nearly all data, the active layer deposits, i.e. the most recent fluvial deposits that are reactivated every few weeks by dune migration, have distinct horizontal reflectors at their base (Figure 2). This bottom boundary of the active layer is also clearly identifiable in the cores by the contrast between the sand and gravel of the active dunes (often gravelly at the base) and the sandy, older fluvial sediments below.

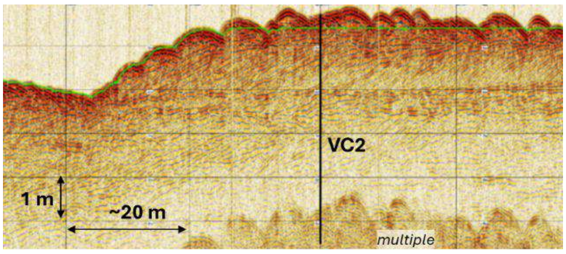

Figure 2: Dune morphology and sedimentary structures (PES).

Three cores were analysed for microplastics:

- Core VC2, located in the western part (lower reach) of the River Waal, where aggradation rates are largest, comprises Holocene fluvial sediments down to 4.20 m below the bed. On the PES data, six dune sets were identified down to a depth of 5 m. The thickness of the active layer is 1.60 m.
- VC17, in the eastern NLds near Ochten, comprises Holocene fluvial sediments overlying an organic, brecciated clay layer and Pleistocene fluvial and or aeolian sediments. The active layer is 1.64 m thick.
- VC18, in the eastern NLds near Druten, comprises Holocene fluvial sediments overlying Late Pleistocene fluvial and aeolian sediments. The active layer is 0.77 m thick.

Subsurface geology
The active layer deposits overly older Holocene fluvial deposits, which display channel-like structures on the PES-data (both Formation of Echteld). The brecciated clay in core VC17 is interpreted as a palaeo-surface (Gouw and Erkens, 2007). The aeolian and fluvial deposits below this and directly below the Holocene fluvial deposits in VC18 are of the Formation of Boxtel.

Microplastics distribution
In all three cores, microplastics occur throughout the depths of the cores, down into Pleistocene sediments in the cases of cores VC17 and VC18 (Figure 3). In core VC2, microplastics concentrations are the lowest of the three cores with the highest concentrations in the top 1 m of the core. Nevertheless, small amounts of MP particles were found down to a depth of 4.20 m below the bed.

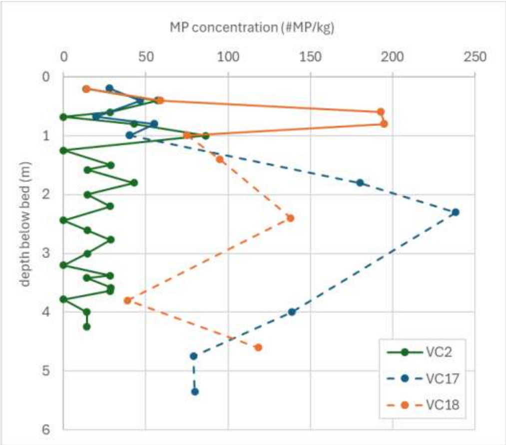

Figure 3. Potential MP concentrations in three cores in the River Waal. Dashed lines: tentative analyses of selected samples so far; solid lines: all samples analysed, representing adjacent sediment layers.

In core VC17, MP concentrations are relatively low in the active layer. A peak occurs just above the brecciated clay layer. Microplastics are detected in large concentrations in the Late Pleistocene sediments below this clay layer. In core VC18, MP concentrations are high in two samples of the active layer and also at depth in Holocene fluvial sediments and in Pleistocene fluvial sediments just above a thin redistributed peat layer. MP concentrations in bed samples (water-bed interface) are relatively low in all three cores.

Discussion & Conclusions

The abundance of microplastics in Pleistocene sediments (pre-plastic era) corroborates that microplastics were incorporated into deeper layers by groundwater flow. Impermeable layers in the subsurface may cause increased microplastics contents, but do not prevent the injection of MPs below these layers. The low concentrations in bed samples may suggest that the continuous reactivation by dune migration keeps MP concentrations low; deeper stable layers that are subject to inflow may show a "cumulative accumulation" of microplastics.

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SESSION 3

Chaos in migrating river bar dynamics

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Keywords — river morphodynamics, chaos, free bars

Introduction

River management strategies require accurate modelling and prediction of morphological trajectories, typically over long time scales. But is there a limit to predictability over such a long time horizon? To assess this, we analytically study the dynamics of free bars in straight channels, taking into account sediment transport formulations widely employed in engineering practice.

Methodology

We consider the 2D depth-averaged shallow water equations coupled with the Exner equation with uniform sediment and two different parametrization of sediment transport: Meyer-Peter & Müller (MPM) for bedload and Engelund-Hansen (EH) for total load. We assume constant discharge and an instantaneous adaptation of hydrodynamics to bed level variations. The goal is to study the behaviour of the rescaled bar amplitude A on temporal and spatial scales (T, X) much longer than those involved in bar formation, i.e. those derived from the critical values and the linear growth rate. This is done by extending the linear perturbation analysis at the weakly nonlinear level, obtaining the Complex Ginzburg-Landau equation (CGLE):

$$\frac{\partial A}{\partial T} = A+(1+i\alpha_1)\frac{\partial^2 A}{\partial X^2}-(1+i\alpha_2)\,A\mid A\mid^2 \quad (1)$$

where α_1 represents diffusion and α_2 the nonlinear saturation of $A(T)$. The CGLE has been studied in the last decades for many other physical processes near critical thresholds (Aranson and Kramer (2002)). In this work, we extend the first derivation of the CGLE for river bars by Schielen et al. (1993) by considering the complete steady hydrodynamic equations and linking the coefficients (α_1, α_2) to crucial dimensionless parameters of MPM and EH sediment transport models. Above the Benjamin-Feir instability line (BF, Fig. 1a):

$$1 + \alpha_1\alpha_2 = 0 \quad (2)$$

chaotic solutions may be expected. Eventually mapping the known dynamics of the CGLE (Eq. 1) coefficients (Fig. 1a) to morphodynamic parameters allows us to assess when free bars may exhibit limited predictability due to sensitive dependence on initial conditions. Finally, we solve the CGLE (Eq. 1) numerically through spectral methods with exponential time-stepping originally developed by D. M. Winterbottom (2005) to compute the spatio-temporal evolution of $A(X, T)$.

Results

We derive analytical expressions of the coefficients (α_1, α_2) in terms of base flow Shields number (θ_0), relative roughness d_s and sediment transport parametrization. In our model, the chaotic behaviour may occur also for bedload (MPM, Fig. 1a,b), provided that sediment transport θ_0 is sufficiently intense and d_s is sufficiently small. Sediment characteristics and transport mechanism typical of lowland rivers (EH), on the other hand, are consistently found above the BF curve. For a given pair of (α_1, α_2) above such instability boundary, a minimum spatial scale L_{mod} necessary to observe chaotic behaviour is found in terms of the distance from the critical conditions for bar formation $\varepsilon = (\beta - \beta_c)/\beta_c$ (in Fig. 1c,d).

Interestingly, our results also seem to provide an explanation for the behaviour found in long-term numerical experiments performed by Crosato et al. (2012) on migrating bars in straight channels, in which trains of bars vanish collectively at certain instances for given morphodynamic parameters. This coherently matches the chaotic behaviour found far from the BF curve in Figure 1a, as the (α_1, α_2) indicated by the red dot and used for the corresponding numerical run in panel b are exactly those used in one of the experiments performed by the authors.

Conclusion

Our results indicate that free bars in straight channels may display chaotic behaviour for many values of fundamental morphodynamic parameters (β, θ_0, d_s), especially when considering sediment transport characteristics repre-

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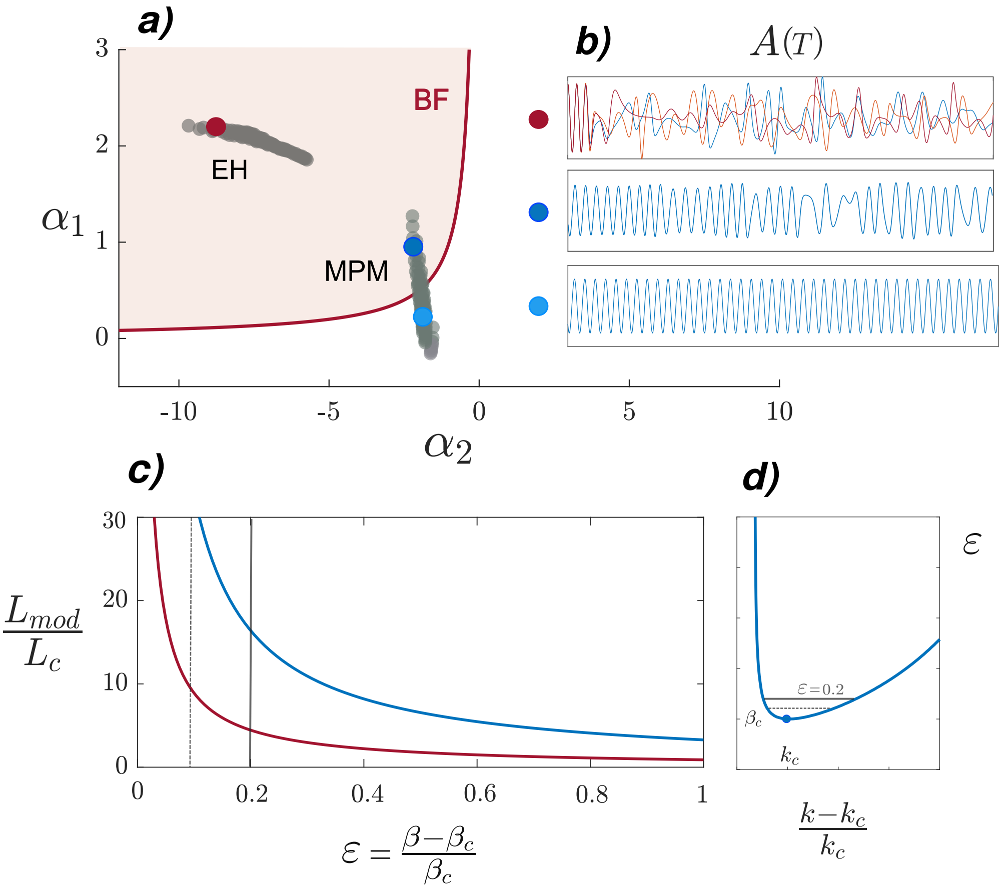

Figure 1: ***a)*** *Plot of the CGLE coefficients (Eq. 1) for both parametrizations of the sediment transport closure (MPM and EH) and an appropriate range of (θ_0, d_s) for each case. Above the Benjamin-Feir curve (Eq. 2) predictability is limited due to sensitive dependence on initial conditions, resulting in* ***b)*** *phase chaos for $A(T)$, represented by the blue dot. As we further move away from the curve, the modulation becomes so strong that bars vanish at given time intervals, as indicated by the red dot.* ***c)*** *Domain length required to observe modulations as a function of the distance from critical conditions $\varepsilon = (\beta - \beta_c)/\beta_c$, shown in panel* ***d)*** *. L_{mod} decreases significantly by moving away from the BF curve, i.e. from the blue to the red curve.*

sentative of lowland rivers (EH). In general, a long-term equilibrium configuration might not be reached, even under constant forcing. This can also occur for gravel bed rivers characterized by bedload (MPM), provided that θ_0 is sufficiently high and d_s sufficiently low. However, near critical conditions for formation ($\varepsilon \to 0$), the required modulation length L_{mod} appears too high to be realistically observed in real rivers. On the other hand, as soon as we move away from the conditions for formation in terms of ε, chaotic behaviour can be observed and expected on realistic lengthscales. This is, far from being just a theoretical exercise, relevant for understanding the dynamics at play in real rivers. Finally, the investigation of the effect of discharge stochasticity through numerical models is considered as consequential future work.

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Predicting soil erosion and sediment yield in wadi flash floods: a physically-based modelling approach

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Keywords —Sediment Yield, Soil Erosion, Wadi Flash Floods, 2D Numerical Modelling, Delft3D-FM

Introduction

Wadis are ephemeral river systems in arid and semi-arid regions that remain dry most of the year, but experience occasionally a sudden high-energy flash floods (Sen, 2008). The frequency and intensity of wadi flash floods (WFFs) have increased due to climate change (Kantoush et al., 2022), posing risks to human lives, infrastructure, and the environment. While WFFs are considered a valuable water source in water-scarce regions, their high sediment load complicates water harvesting and storage. Damming wadi floodwaters is often the chosen solution (El Bastawesy et al., 2009), yet excessive reservoir sedimentation reduces reservoirs capacity, making it essential to study the sediment dynamics in wadi systems for improving floodwater management.

The most commonly used methods to estimate soil erosion rates and sediment yield are empirical formulas such as the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965) and its derivatives (RUSLE & MUSLE) (Djoukbala et al., 2019). However, these formulas provide long-term average estimations, and lack the capability to capture event-driven sediment dynamics at small temporal and spatial scales. Physically based models, on the other hand, offer a more detailed assessment of the sediment dynamics, enabling an accurate identification of erosion and sedimentation prone areas. This facilitates more targeted scenario testing for mitigation measures, thus enhancing sediment management strategies. This study shows an application of Delft3D flexible mesh (FM) software at the catchment scale to evaluate the capability of such physically based models that applies sediment transport capacity equations to simulate sediment dynamics in wadi systems. The selected case study area is Wadi Wala in Jordan.

Study Area

The Wadi Wala Basin is located in central Jordan, covering approximately 1,800 km². Precipitation rates vary significantly in the catchment, ranging from 400-500 mm/a in the far north, to less than 100 mm/a in south-eastern part of the basin (Margane et al., 2009). The northern part of the basin is excessively urbanized, while the remaining area is mostly barren, with little to no vegetation cover (Zanaga et al., 2021). Data processed from SoilGrids 2.0 dataset (Poggio et al. (2021) show that the basin is predominantly covered by fine textured soils with cohesive properties. The Wala Dam, located at the selected catchment outlet (see Figure 1), serves as a key water storage facility but is prone to reservoir sedimentation due to the high sediment load delivered by flash floods, which affects the functionality of the dam and the reservoir life span.

Figure 1. The study area: Wadi Wala Basin, Jordan, main streams and zoom in on the dam and reservoir location (31°34'6"N, 35°48'16"E).

Research Methodology

The study employs a spatially-distributed two-dimensional rain-on-grid model, to simulate the hydrology and hydrodynamics, in Wadi Wala, Jordan, corresponding to the flash flood event dated 22/11/2004. A spatially-distributed rainfall input was used to account for rainfall variability across the catchment, ensuring a more realistic representation of runoff generation, and thus more accurate identification of erosion-prone areas.

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The hydrodynamic model was extended to include sediment transport and online morphological changes by applying Partheniades, (1965) and Krone, (1962) equations (P-K) to a soil layer of spatially distributed thickness. Model calibration was performed against cumulative inflow data as well as expected time of concentration and peak discharge at the reservoir inlet. Sediment yield calibration was based on previously established sediment rating equations and site measurements at the reservoir. Outputs include sediment flux, sediment yield, erosion and deposition maps to identify sediment sources and deposition zones.

Results & Conclusions

The model successfully reproduced the sediment dynamics associated with the selected flash flood event, providing key insights into sediment yield and erosion-prone areas. The total simulated sediment yield estimated at 1.9E+08 kg (147,846 m³), closely matching estimates found using the sediment rating equations (simulated-to-measured ratio of 0.92) and showing erosion rates and patterns (see Figure 2) comparable to Ijam and Tarawneh (2012), who used the USLE model.

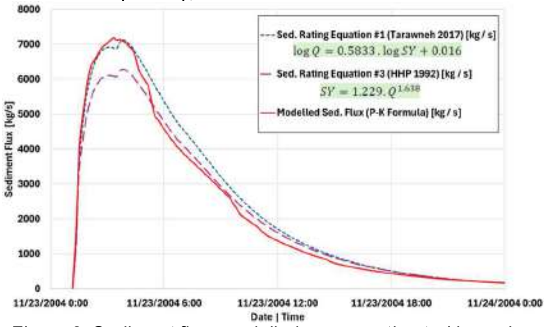

Figure 2. Sediment flux: modelled versus estimated by various sediment rating curves of the area.

Table 1. Sediment yield results: modelled results versus sediment rating curves estimations.

Year	Sediment Yield [kg]
Estimated (Tarawneh, 2017)	2.077E+08
Estimated (HHP, 1992)	1.892E+08
Modelled (P-K Equation)	1.922E+08

Sediment sources were investigated and quantified between overland flow and in-channel erosion process contributions. Overland flow mobilized 5.15E+07 kg (39,615 m³) of sediment, while in-channel erosion accounted for 1.407E+08 kg (108,231 m³). Erosion depth mapping identified the northern and western sub-basins as the most erosion-prone (15–30 tons/ha), while eastern and central sub-basins exhibited lower erosion rates (<3 tons/ha), influenced by the terrain slope, localized rainfall intensity, urbanization and land cover, and hydrodynamic forces.

While limited data availability was a major challenge, this work highlights the ability of Delft3D-FM to simulate complex sediment transport behaviours. Furthermore, the promising results support the use of Partheniades & Krone equations for soil erosion and reinforce the role of physically based models in capturing flash flood-driven sediment dynamics in arid regions.

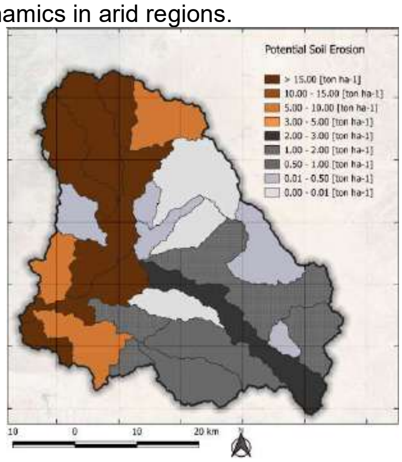

Figure 3. Potential soil erosion rates simulated for the wadi flash flood event dated 22/11/2004

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Cross-boundary sediment challenges in the Mekong River Basin

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Keywords — Reservoir sedimentation, sand mining, sediment budget, Mekong

Introduction

Numerous studies and reports have documented that sediment flows in the mainstream of the Mekong River have reduced dramatically over the past decades. For example, near the border between Thailand, China and Laos, sediment load have decreased from about 85 Mt/yr to 10.8 Mt/yr (MRC, 2021). This means a reduction of the current sediment contribution from the Upper Mekong Basin to 16% of the sediment load in the Lower Mekong Basin (LMB) as compared to about 55% historically (i.e., before direct human impacts) (Ta et al., 2002). Similar trends in decreasing sediment loads have been observed in the lower reaches of the Mekong River. The strong reduction in sediment loads have resulted in undesired impacts along the river corridor with respect to fish and agricultural productivity, riverbank stability, coastal erosion, and to some extent, issues with navigation.

Sediment management in de Mekong River is a typical cross-boundary challenge that requires cross-boundary solutions. The MRC aims to transition from the current reactive planning practice to a proactive regional planning (PRP) approach to facilitate sustainable development in the basin. To achieve this goal, a strategic study was performed to review existing information about the sediment loads and management, and to identify cross-boundary enabling activities to reduce the sediment-related issues in the Mekong River Basin, with a focus on two main causes: reservoir sedimentation and sediment mining.

Hydropower reservoirs

Sediment storage in reservoirs predominantly operated for hydropower generation is considered the main cause for the reduction in sediment load in the mainstream of the Mekong River. Over the past few decades, a large number of hydropower dams have been constructed in the Mekong Basin, and more dams are under construction or planned (Figure 1). In the LMB, based on information from 2023, the number of hydropower dams built, under construction or planned is 132. By 2040, the hydropower in the LMB is estimated to generate more than 30,000 MW.

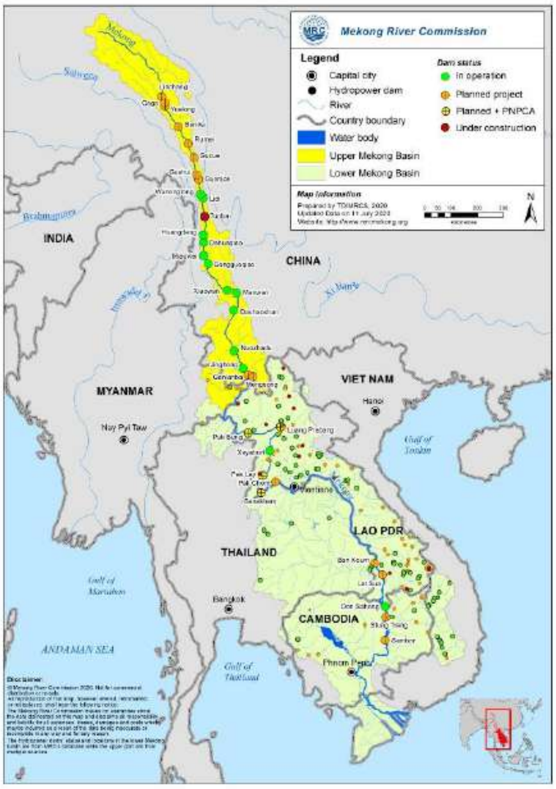

Figure 1. Hydropower dams in the Upper and Lower Mekong Basin. (Hydropower (mrcmekong.org))

As more dams in both the tributary and main stream of the Mekong River are being constructed, the sediment reaching the Vietnamese Delta may be reduced by 96% by 2050. Most of the hydropower reservoirs are (being) realised in the tributaries, sediment is often intercepted before even reaching the Mekong River. And currently, the only dam in the mainstream Mekong River equipped to pass sediment is the Xayaburi Dam in Laos, through sediment flushing (Cook, 2020).

Sand mining

In the LMB, another cause for sediment depletion is sand mining for land filling and construction purposes. In addition, sand mining in parts of the Mekong River in Cambodia is considered necessary to reduce flood risks in that country. However, sand mining also causes local riverbank erosion. There have been many reports, especially in the Vietnamese Mekong Delta, describing riverbanks collapsing after sand mining had occurred in the direct area.

Unfortunately, sand mining activities in the region are not fully documented (with substantial illegal mining likely occurring) and are not properly planned (i.e., permitted and monitored) and managed.

Since the 1990s, the Mekong River, especially in Cambodia and Viet Nam, has seen the development of large-scale sand mining operations. These sand mining operations are still ongoing and have reached a magnitude that is unsustainable for the amount of sediment that is being transported by the Mekong River on a yearly basis: annually an estimated 55 Mt of sand is being extracted from the LMB (Bravard et al., 2013). Other estimates of sand mining in the Mekong Delta are 33 to 55 million m³/year (Deltares, 2023). This sand mining is an order of magnitude larger than estimated sand load to the Mekong Delta, which is clearly not a sustainable situation.

Proposed enabling activities

In order to alleviate the negative impacts of sediment storage in hydropower reservoirs and sand removal by sand mining, a set of cross-boundary enabling activities were proposed to MRC:

- Planned and future hydropower dams need to be designed to enable sediment passage, for example by flushing, taking into account their position within the MRB.
- Coordination of sediment management by hydropower dam operators, in particular in cascades of dams and in the mainstream of the Mekong River. Solving a sediment problem at one location should not result in a (new) sediment problem further downstream. This requires sediment monitoring and cross-boundary data sharing among operators.
- Development, coordination and management of sustainable sand mining strategies. Stop sand mining at unsuitable locations within the active mainstream, and use alternative sand sources within the channel belt (Figure 2).

Conclusions

To counter the sediment issues that the Mekong Basin is facing, the challenges related to sediment storage in hydropower reservoirs and sand removal by sand mining need to be countered, among others with cross-boundary solutions. Special interest should be given to the East bank tributaries of Lao PDR, and the 3S basin in Cambodia, as these are currently the main sources of sediment for the mainstream Mekong River.

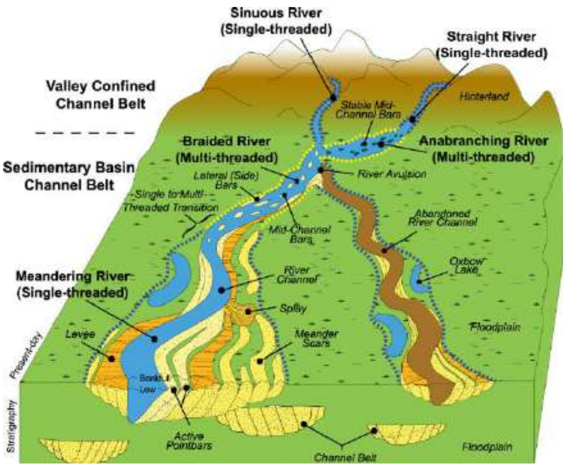

Figure 2. Schematic illustration of channel belt extent, including active and abandoned river channels and its associated levees, bars, and overbank landforms (Nyberg, et al., 2023)

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Migrating subaqueous dunes capture clay flocs

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Keywords — flocculation, subaqueous dunes, laboratory experiments

Introduction

Recent research highlights the abundance of floccule (flocs) in rivers (Nicholas, A. & Walling , 1996; Bungartz & Wanner, 2004; Lamb et al, 2020; Fetweis, 2008) formed by aggregation of clay particles with organic matter (Droppo, 2024; Dyer, 1989; Winterwerp, 2002; Mietta et al., 2009; Lasereva & Parfenova, 2023; Safar et al., 2022; Deng et al., 2019). These flocs affect the transport and the eventual fate of clay. Flocs exhibit distinct behaviour from the unflocculated sedimentary counterparts: they can deform and break, and have higher settling velocities (Lamb et al, 2020), which may in turn cause flocs to deposit and possibly interact with the riverbed (Lamb et al, 2020; Winterwerp et al., 2021; Baas et al., 2016)

Methods

Here, we conducted systematic experiments in an annular laboratory flume (Figure 1a, b) to identify the mechanisms by which flocs and bedforms interact. Different amounts of flocculant and various shear stress conditions (0.3 and 0.5 N/m^2) were applied, and the resulting floc characteristics and bedform geometry were measured. Bedform geometry was measured with an acoustic depth profiler (Figure 1c), and floc size was measured in a settling column (Figure 1d).

Results and Discussion

Under lower shear conditions, the flocs were larger, and transport rates were lower than under high shear conditions. However, under both shear conditions, flocs were transported via saltation and in suspension, and they became integrated within the sediment bed via deposition and burial in the lee of a dune, either as single flocs, clusters, or strings (Figure 2a). Deposition occurred predominantly on the leeward side of the dune, revealing distinct stratigraphy patterns (Figure 2a). The presence of flocs had a negligible impact on the actual geometry of the bedforms.

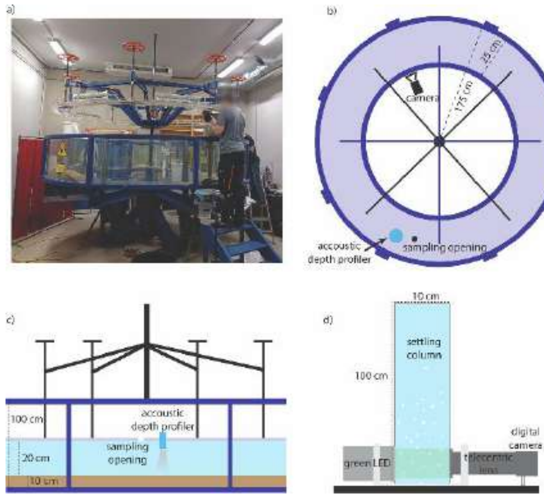

Figure 1. A picture (a), schematised top-view (b) and schematised side view (c) of the annular flume. d Side-view of the settling column setup. Subfigure (b–d) are not to scale for visualisation purposes. From de Lange et al. (2024).

The interaction of clay with the bed is summarised in Figure 2b. The variability in shear stress due to the geometrical complexity of the bed allows for the trapping of flocs. Floc transport occurs over the dune stoss, where shear stresses are larger, while floc deposition is concentrated in areas with low shear stresses (dune trough). At the top of the dune, where shear stresses are greatest, the fate of flocs is determined as flocs are either resuspended or trapped in the lee.

Conclusion and Implications

This investigation highlights the active role of flocculated clay particles in sediment transport in riverine systems, contrary to the general assumption that clay particles behave passively as wash load. This finding has the potential to affect sediment transport rates of fines, contaminants, and entangled microplastics (Ongley et al., 1992, Milligan & Loring, 1997; Laursen et al., 2022; Andersen et al., 2021; Yan et al., 2021) and could have far-reaching impacts on the interpretation of mud deposits in the sedimentary rock record

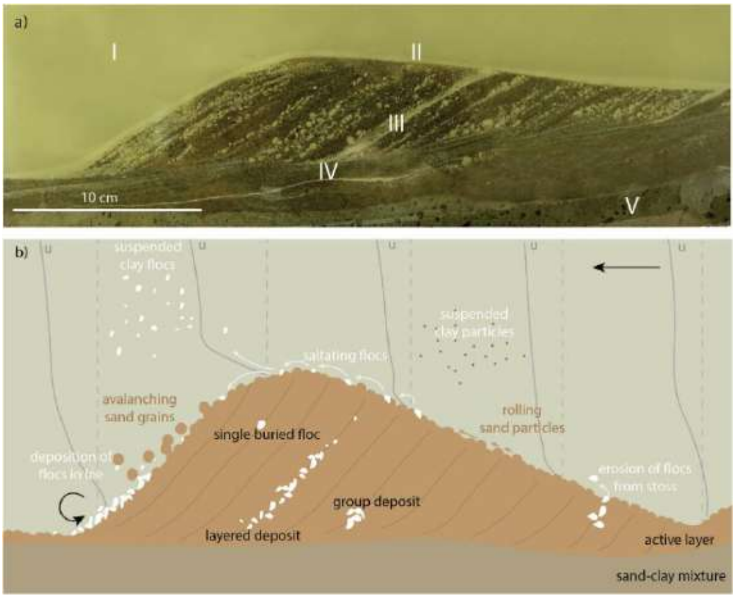

Figure 2. a Capturing of flocs in a bedform, in which five regimes are indicated, I: suspension, II: recent deposition, III: drapes within a dune, IV: drapes below the active surface (remnant), V: homogeneously mixed conditions (initial experiment conditions). The image is taken seconds after the flow has halted. In this time a depositions layer of flocs has formed on the dunes. The image is slightly adjusted to reduce reflections. b Schematic of the suspended and bed load transport of clay particles and flocs, and the subsequent trapping in the sediment bed. Velocity profiles (u indicates the flow velocity, dotted line indicates zero m s^{-1}) are schematised based on the measurements in Kirca et al. (2020). Image taken from de Lange et al. (2024).

(Schieber et al., 2007). For modelling and predicting mud transport in river systems a comprehensive understanding of the transport mechanisms of clay flocs is essential and should be considered (van Kessel et al., 2011; van Rijn et al, 2018)

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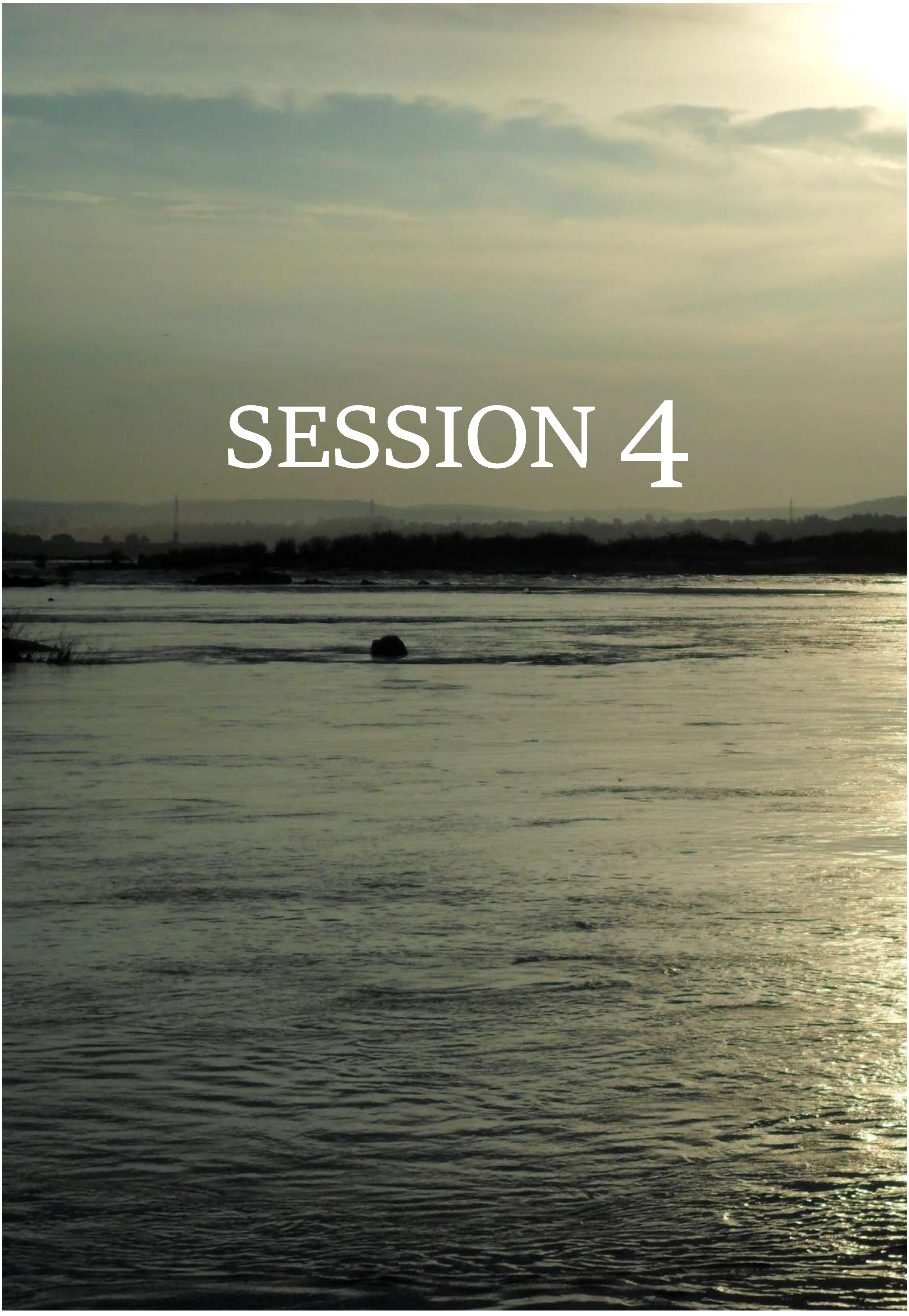
SESSION 4

Catching the Physics in Your Model: A Case Study of Steegse Haven

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Keywords — Steegse Haven, Computational Grids, Data Sources, Modelling Approach

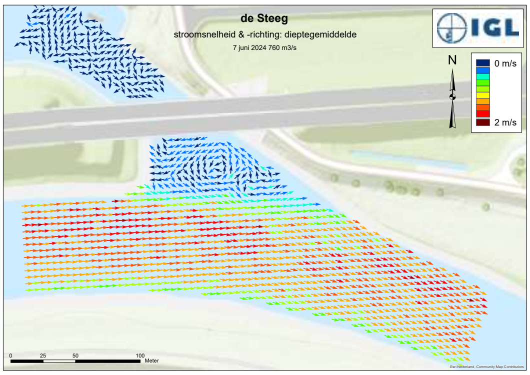

Figure 1: Flow fields near the harbour entrance

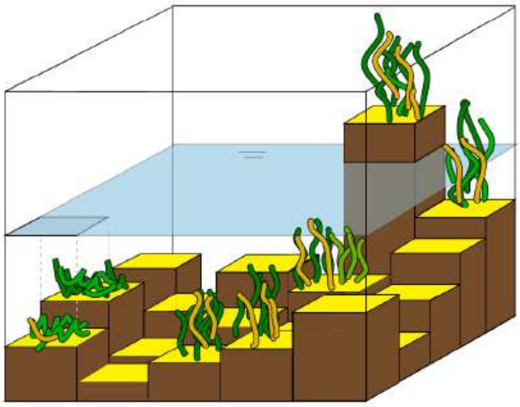

Figure 2: A computational cell with high resoltuion information

Introduction

The Steegse Haven is a small harbour situated along the river IJssel, where sediment accumulation occurs near the entrance due to a reduction in flow velocity. This results in a navigational bottleneck within the main channel. The challenge is to develop an optimised harbour design that prevents sediment deposition at both the harbour entrance and within the navigational channel. To address this challenge, a modelling study was conducted, which was validated by two measurement campaigns undertaken by Rijkswaterstaat (RWS) focusing on flow fields based on ADCP-measurements (Figure 1).

Modelling studies are indispensable tools for testing these type of mitigation measures and forecasting the impacts of changes within such a system. Numerous physics-based modelling techniques strive to simulate flow with the highest possible accuracy; however, there are different types of accuracy to consider. These include the mathematical precision of the computational methods used within the model's core, as well as the model's ability to replicate real-world measurements. Ideally, these types of accuracy would align perfectly. However, in addition to the fundamental decisions made within the computational core, accuracy is also influenced by factors such as the availability of precise input data (e.g., boundary conditions and bathymetry) and model-specific choices, such as domain selection and grid size. In addition, for any modelling study, it is crucial to effectively manage the available data to ensure optimal use, select the most appropriate model settings, and construct an adequate computational grid.

For this study, a modelling tool was used that is relatively unfamiliar for RWS. We used the 2D-depth-averaged, subgrid-based model, 3Di 3Di Documentation (2025). This model incorporates a regular grid structure while integrating high-resolution data in the computation. This significantly enhances the ability to capture bathymetry-driven flow effects (Figure 2) Volp et al. (2013), Casulli, v. (2008).

All this considered, this RWS project near the Steegse Haven provides a prime example to demonstrate the significance of several critical aspects in modelling studies (I) correct domain definition, (II) determination of an adequate computational grid, (III) assessment of the effect of the optimised harbour design, and (IV) the advantages of employing a subgrid-based computational method in this type of application. This case is particularly well-suited for such an analysis due to the strong bathymetry-driven circulation at the harbour entrance, ar-

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eas where groins significantly influence flow dynamics, and the bathymetric adaptation incorporated into the design.

The Data and the Model

RWS offers a wealth of open-source data, including bathymetry, land use maps, water levels and discharge data. The bathymetry is available at various resolutions. We combined different data sets, which resulted in a bathymetric data set, that was used in this project with a resolution $0.5m \times 0.5m$. Water level and derived discharge measurements were employed to define the model's boundary conditions. The open-source data were also used for the calibration of the roughness and validation process, in conjunction with the flow field measurements. The proposed optimised harbour design consists of a bathymetric modification at the harbour entrance and the installation of a narrow wall.

Capturing the Physics

Various physics-based models utilise different computational grids. Bomers et al. (2019) provides an overview of some of these methods and highlights the different challenges related to grid dependencies. The study discusses the differences between regular grids, unstructured grids, and curvilinear grids. In studies concerning grid techniques and their related accuracies, grid convergence studies generally demonstrate mathematical accuracy based on simplified flow domains. However, an essential factor in modelling flow behaviour is accurately capturing the physics governed by the correct bathymetry.

This case study will demonstrate the effect of accurately capturing bathymetry by changing the methods used to handle the bathymetric data. We will highlight the consequences when the bathymtry is not taken into account accurately (Figure 3) and when physical processes cannot be appropriately represented in the computational grid.

Conclusions

In conclusion, this study underscores the critical importance of capturing the correct physical scales within the computational grid. By utilising the highest available quality data for the domain of interest, we can focus on the relevant physical length scales that are essential for the application. In this case study, the primary objective was to accurately replicate the flow patterns near the harbour entrance, which necessitated the selection of an appropriately sized grid. A grid sensitivity analysis, while maintaining consistent base data on bathymetry and roughness, enabled the identification of the correct physical length scales.

Since the computational grid was explicitly designed to capture the relevant physics rather than simply base data such as bathymetry, the implementation of the proposed measure was straightforward. We believe that this enhances the reliability of the outcome.

The integration of various open data sources from RWS was invaluable in constructing, calibrating, and validating the model. This comprehensive and data-driven approach has proven effective, providing a reliable and robust solution for the application at hand. The subgrid-approach made it easy to adapt the model to the optimised harbour design and conduct the study to its effect.

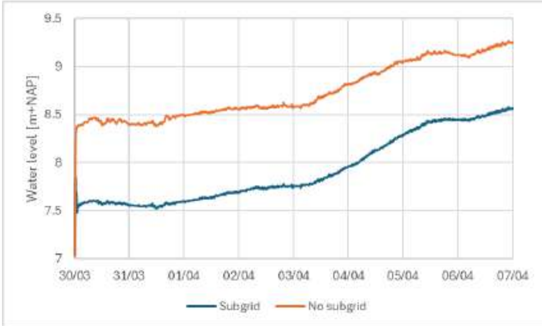

Figure 3: Water levels near upstream discharge boundary. Differences result from varying handling of bathymetry information.

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Unveiling the implications of model schematisation on dike breach flow and dike breach growth in large scale fluvial flood models

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Keywords — Flood modelling, Dike breach discharge, Dike breach growth

Introduction

Since 2017, the Netherlands adopted a new multi-layer risk-based flood safety assessment. This means that, besides decreasing flood probability (layer 1), policymakers should consider a sustainable layout of areas (layer 2) and crisis management (layer 3). Although the focus is still mainly on decreasing flood probability (strengthening dikes), Van den Berg, Westerhof and Huting advocate for an integral area assessment (*Havermans*, 2024). Next to the assessment of primary flood defenses, alternative measures in the river channel and floodplain may allow the same safety levels as strengthening dikes by assessing at the impact of a flood. Reliable 2D flood models and detailed flood simulations are needed to carry out such an area assessment.

Large floods from the Rhine and Meuse branches have not happened in The Netherlands since 1925, which makes it hard to validate flood models. Engineers face the difficulty of making sure that the models produce accurate results with limited resources, using the data and the scientific knowledge that is available and making effective use of the available computing power, time and money. This forces scientists and engineers to make choices in the schematisation of their flood model, which is a constant trade-off between time, detail and accuracy. It is therefore very important that we understand the consequences of our modelling choices and the sensitivity of the used model instrumentarium to these choices. The goal of this research was to unveil the implications of different schematisation possibilities for the computation of dike breach flow and water distribution in fluvial flood models. For this, a comparative analyses between models with different schematisations is used.

Flood modelling in D-HYDRO

As computational power and technical possibilities constantly advance, models are updated, and newer models are developed. A prime example of this, is the recently developed hydrodynamic modelling package, D-HYDRO. This package, now widely used among engineering companies and Water Boards, has significantly increased the possible schematisation choices compared to Delft-FLS and SOBEK1D2D. The current flood-risk assessment calculations on which the dike standard are based are primarily done with Deflt-FLS and Sobek calculations. However, by using D-HYDRO, different results are achieved as opposed to those from older software (*Schippers*, 2023) and it is of critical importance to understand these differences.

Breach flow and river schematisation

The hydrodynamic principles of Delft-FLS and D-HYDRO are largely the same, however, the computation of dike breach flow is largely different between both. Delft-FLS uses a simple weir equation, while D-HYDRO uses the 2D-shallow water equations. This makes the calculation of breach flow more accurate but also more sensitive to the schematisation of the river and the hinterland. The calculation accounts for friction around the breach, velocity gradients and streamlines on the river. In D-HYDRO, significant differences in breach discharge can be found at locations with similar water levels but different flow directions, flow velocities, bottom slope or channel width. In general, D-HYDRO will compute much lower breach discharges than Delft-FLS. This raises the question of how to best schematise the river in your fluvial flood model. We will present different cases that illustrate these differences and the implications for breach flow and flood extent.

Breach growth

The erosion caused by the flow through the breach causes the dike breach to grow. This process is complex to accurately consider in

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flood modelling. The current standard in the Netherlands is the Verheij-vdKnaap equation, which was developed in 2003. It is implemented in D-HYDRO. However, since then other models have been developed and computation of flow velocity in the breach has made large steps forward. The Verheij-vdKnaap equation does not consider underlying developments in flow velocities, flow height and upstream energy level in breach calculation. This makes the final breach width insensitive to the moment of breaching, which hides the possible devastating effect that a breakthrough before peak water level can have. Using the Verheij-vdKnaap equation in D-HYDRO limits the computed breach width and can significantly underestimate the actual breach width. The alternative breach growth equations shown in this research are proven to better relate breach growth to hydraulic conditions computed by the model. It raises the question if this equation is still the best way to describe breach growth. We will present alternative breach growth equations and apply them in flood models of the Waal.

Conclusions

This research has unveiled the implications of breach flow computation in D-HYDRO on breach discharge as opposed to Delft-FLS. It has identified prominent influencing factors in breach flow computation, showing that D-HYDRO computes much lower breach discharges than Delft-FLS. Alternative river schematisations are unveiled to have significant effects that can vastly overestimate breach discharge.

Next, to breach flow computation, this research has revealed flaws in the Verheij-vdKnaap equation for breach growth. It has shown that this approach can underestimate breach width and does not reflect computed hydraulic conditions. Other breach growth equations show a better representation of hydraulic conditions. When the Verheij-vdKnaap equation is used, breach width is mainly independent of breach moment. This hides the possible devastating effect that a breakthrough before peak water level can have. The proposed alternative growth equations are sensitive to breach moment.

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The effect of climate change on stage-discharge boundary conditions in interconnected river delta (sub)models

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Keywords — Boundary Conditions, Hydrodynamics, Stage Discharge

Introduction

Climate change impacts river deltas world-wide, now and in the future. To study impacts and mitigate effects, hydrodynamic models are often used. Developing these models poses challenges to its developers: the boundaries of these models should be chosen such that the model generates accurate predictions within the domain of interest. This is a fundamental, but difficult choice (Jakeman et al., 2006). As deltas are often interconnected networks of rivers and canals both bifurcating and confluencing, creating backwater curves, system dynamics quickly become complex. Choosing suitable boundaries is therefore not straightforward: modelling only part of a delta (i.e. using a submodel) might not capture important feedback mechanisms, increasing uncertainty due to boundary conditions (Berends et al., 2018), which can travel far into the model (Domeneghetti et al., 2013). Contrary: increasing the domain increases computational expenses. Finding a balance is up to the developer. This research investigates to what extent hydrodynamics in such complex networks can be modelled in parts by addressing the accuracy of boundary conditions of such submodels.

Method

To address this research question, three one-dimensional models of the Dutch Rhine, Meuse and the Rhine-Meuse-Estuary are merged, in order to create a combined model (Figure 1). By combining the submodels, the (former) downstream boundary conditions of the Rhine and Meuse submodels (Hardinxveld/Krimpen ad Lek and Keizersveer, respectively) are replaced by internal nodes where the hydrodynamic conditions are solved explictly. The combined model is then forced with different combinations of stationary boundary conditions to compute the hydrodynamic conditions within the river system. In all cases, the Rhine discharge is varied between 1000 and 18000 m³/s with a 1000 m³/s interval. Additionally, the discharges of 500 and 750 m³/s are considered to cover periods of low flow. For

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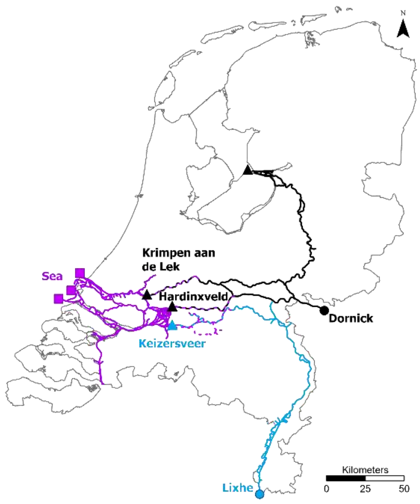

Figure 1. Overview of the Dutch river delta. Each color represents a submodel. Black: Rhine, Blue: Meuse, Purple: Rhine-Meuse-Estuary.

the upstream discharge of the Meuse and the downstream sea level, different scenarios are considered (Table 1). The Qh-relation at Lake Ijssel is kept equal in all scenarios. Lateral inflows and extraction are neglected. All possible combinations of boundary conditions have been evaluated, leading to 240 simulations. Using the outcome of these stationary computations, stage-discharge relationships are derived at the location of the downstream ends of the submodels: Hardinxveld and Krimpen a/d Lek (Rhine submodel) and Keizersveer (Meuse submodel).

Results

Figure 2 shows that on the Waal, both the downstream sea level and Meuse discharge can strongly affect the water levels at Hardinxveld.

Table 1. Stationary boundary conditions in the combined model, which have been varied independently to create 240 scenarios.

Boundary	Conditions
Rhine	500, 750, 1000-18000 in steps of 1000 m³/s
Lake Ijssel	Qh-relation as in submodel
Meuse	30 (low), 300 (ref), 3000 m³/s
Sea Level	-1.00 (low), 0.45 (ref), 1.50 (high) and 5.10 (surge) +mNAP

As the discharge on the Waal increases, the water levels at Hardinxveld converge; showing that they become discharge driven, reducing the impact of the downstream boundary conditions except for extreme sea level.

At Krimpen ad Lek, the downstream conditions also impact the water levels strongly. However, contrary to the conditions on the Waal, the actual discharge on the Lek is too small to supress the backwater curve created by the downstream conditions. Therefore, the water levels in the different scenarios do not converge to the same water level, even with increasing upstream discharge.

The water levels on both of these branches are affected more by the downstream sea level than the discharge of the confluencing Meuse. This is due to the fact that the considered Meuse discharges are small compared to the Rhine discharge and lead to smaller water level increases compared to sea level rise in the order of meters. The effect of this ratio is seen when evaluating the stage-discharge relation at Keizersveer. Figure 2c shows the water level at Keizersveer as a function of the Rhine discharge at Lobith. Here, it becomes clear that the effect of the discharge on the Rhine is in the same order of magnitude as the effects of sea level or even Meuse discharge.

Further analysis of the hydrodynamic simulations shows that the effects of the boundary conditions lead to water level differences exceeding 5 cm up to 60 km into the submodel. In the extreme case of a storm surge at sea, these differences even propagate upstream of the Pannerdensche Kop bifurcation possibly affecting the discharge distribution.

Conclusion

This study quantifies the importance of defining suitable boundary conditions when modelling only part of an interconnected delta. The ratio between upstream (river) discharge, the downstream base level (sea) and the discharge of a confluencing river can strongly affect the water levels within an interconnected river delta. Especially in studies considering rivers with a small discharge compared to the downstream confluencing tributaries or sea level (i.e. drought studies), the latter conditions strongly determine water levels in the river, as internal feedback leads to backwater curves propagating far upstream. For increasing discharge, the effects of downstream conditions decrease as water levels become discharge driven. In studies regarding large scale effects where all these factors are uncertain and changing (e.g. climate change), one should put extensive focus on defining appropriate boundary conditions for a submodel, or prefer using a combined model.

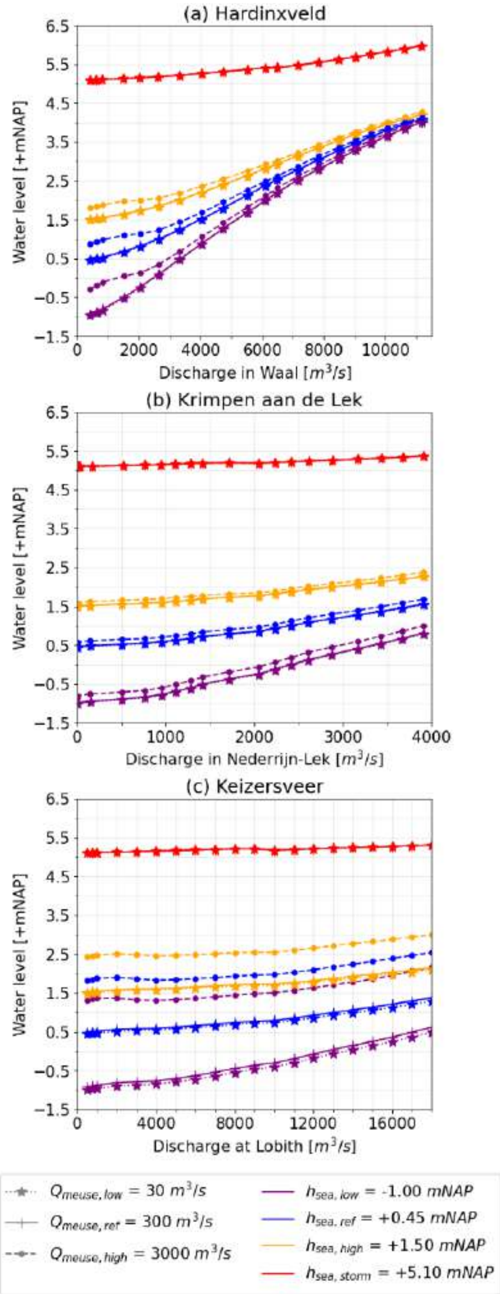

Figure 2. Stage-discharge relationships derived using the combined model.

Aknowledgement

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Sensitivity Analysis of Side Channel Dimensions on Crossflow Dynamics in the Waal

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Keywords — River Restoration, Side Channels, Sensitivity Analysis, Large-Scale

Introduction

The construction of side channels is advocated and implemented as a nature-based adaptation measure along major lowland rivers in the Netherlands, such as the Waal. Their main desirable effects are reductions in peak water levels, counteraction of main channel river bed incision and overall improvements of the ecological state along the river by creating diverse habitats.

However, at side-channel inlets and outlets, altered water flow dynamics can induce cross current flows that can threaten vessel maneuverability. The River Waal is connecting industrial areas in the Netherlands, Germany and Switzerland, and therefore of major importance for inland shipping. Any disruption in this transport route is likely to have significant economic consequences. The current conservative legal limit for crossflows is 0.15 m/s, at the edge of the navigation channel for side channel discharges exceeding 50 m^3/s (*Rijkswaterstaat*, 2024).

This study aims to determine how the large-scale implementation of side channels with varying geometries affects exceedances of critical crossflows in the Waal River under different discharge conditions.

Methods

RiverScape, a tool for rule-based positioning and parametrization of fluvial adaptation measures developed by *Straatsma and Kleinhans* (2018), was used to implement side channels with varying geometries along the Waal River between Pannerden and Gorinchem. The side-channel bathymetry followed a trapezoidal shape with maximum widths from 7.5 m to 75 m, while maximum channel depth remained constant at 2.5 m below water levels that are exceeded 363 days per year (Table1). Hydrodynamic simulations were conducted using Delft3D FM. The exact model domain was analog to the study of *Straatsma et al.* (2019).

For the preliminary analysis, a stationary bankfull Waal discharge of 2250 m^3/s (return period < 1 year) and a high flow discharge of 5296 m^3/s (ca. 2-year return period) were selected. The resulting depth-averaged flow velocities have been transferred into meaningful main channel cross-current velocities relevant for shipping defined in this study at a distance of 90 m from the main channel center line (visualized in Figure 1).

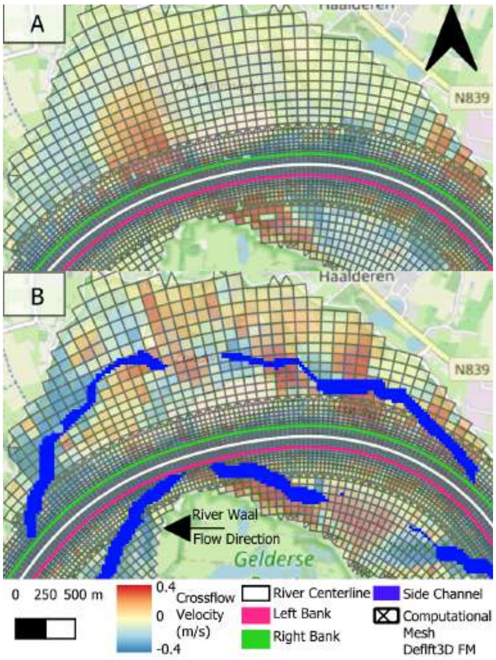

Figure 1: Crossflow velocities at Bemmelse Waard. A: Reference situation without side channel implementation. B: Scenario with side channels of 75 m width. Q 5296 m^3/s. Positive crossflow velocities indicate flow toward the right bank looking downstream.

Results

The model results show that the legal crossflow velocity limit of 0.15 m/s is exceeded at multiple locations along the river for all of the side channel configurations, including the reference scenario, i.e. the situation without implemented side channels (Table 1). The number of legal crossflow exceedances along the Waal River increases for larger channel widths (Table 1). This trend is amplified for higher

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discharge conditions of 5296 m^3/s compared to 2250 m^3/s (Table 1). However, exceptions to this general trend can be observed, such as between side channel configurations with widths of 30 m and 45 m on the left bank at a discharge of 2250 m^3/s, where the number of legal crossflow exceedances decreased from 11 to 9. The causes of this deviation require further investigation. In addition to the increase in the number of legal crossflow exceedances from 37 to 64 (across both the left and right banks) when comparing the reference scenario to the implementation of 75-meter-wide side channels at a discharge of 2250 m^3/s (Table 1), the magnitude of crossflow exceedances also locally increased in the 75-meter-wide side channel scenario compared to the reference situation (Figure 2). However, the median absolute crossflow magnitude shows a decreasing trend with increasing channel width for Q 2250 m^3/s (Figure 3). This trend will be discussed and compared to other discharge scenarios in future analyses.

Table 1: Number of legal crossflow exceedances along Waal River across different scenarios

Side Channel width (m)	Q 2250 m^3/s Left bank	Channel center	Right bank	Q 5296 m^3/s Left bank	Channel center	Right bank
Ref.	7	3	30	39	35	84
7.5	7	4	30	37	35	88
15	7	4	30	40	37	85
30	11	3	34	49	43	88
45	9	5	36	55	53	92
60	14	6	44	57	58	105
75	14	10	50	57	62	111

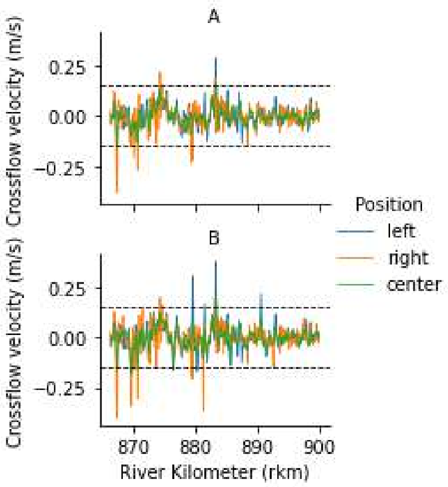

Figure 2: Longitudinal crossflow velocity profiles between river kilometer 870 (upstream) and 900 (downstream) at left and right channel bank and river center for Q 2250 m^3/s. A: Reference situation. B: Side channel scenario 75 m width. Dashed lines: legal crossflow velocity threshold of 0.15 m/s.

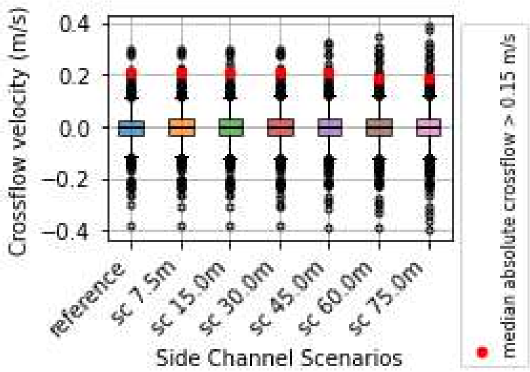

Figure 3: Crossflow velocities at left and right bank for various side channel dimensions for Q 2250 m^3/s. Red mark: Median absolute crossflow velocity $> 0.15 m/s$.

Future Work

Our preliminary results indicated that larger side channel widths led to an increase in legal crossflow exceedances. This underlines the importance to evaluate the implications for navigability when designing side channel dimensions. Further analyses will be conducted for additional discharges, including low flow conditions, to better understand the effect of side channels on navigation. Ultimately, the findings can help guide the selection of potential nature-based fluvial adaptation measures for river management and support the long-term and large-scale analysis of the measures' impact on flood hazard reduction and biodiversity enhancement, which will be the focus of our future research.

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SESSION 5

Sediment continuity: (mis)understandings and (mis)management in the 18th to early 20th century

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Keywords — Sediment continuity, morphological change, meandering river channel, managing morphodynamics

Problem

Two core concepts of geomorphology are continuity of flow and continuity of sediment. Development of the concept of flow continuity already began in the late 16th century with Galileo. For sediment continuity we generally refer to Exner (1925), who formulated it as a one-dimensional differential equation. As a meteorologist, Exner worked on atmospheric flow continuity. He likely introduced his equation without ado because of his familiarity with it.

We might ask the naïve question why it took three centuries to apply the principle of continuity to other substances, but a more interesting question is how the concept of sediment continuity developed, and what layers of meaning are attached to it. This also avoids the common, mistaken notion that concepts like this can be attributed to single brilliant minds.

This paper focuses on the theorization of erosion and siltation of the riverbed, specifically on a misconception that lives on in modern lay writing and among students. The dominant model of river flow in the eighteenth century held that rivers flow faster there where they are deeper. Theoreticians and practitioners reasoned that faster flow would lead to erosion, which inspired river 'normalization'. This caused issues around river incision and bifurcation stability that continue until today (Kleinhans 2023). Today we often see undergraduate students overgeneralize like this: where flow is faster, erosion will take place.

We show that sediment continuity was understood in several forms, decades before Exner, by experts involved in large-scale dredging and scale experiments with moving sediment but was contested into the 20th century by others. Here, we present a few examples of the historic evidence for these points.

Erosion as a function of depth?

An influential 1720 discussion of rivers by 's Gravesande, a Leiden professor who taught Newtonian mechanics, presents rivers as the result of scouring flow, which hollows stones to form a channel winding around uneroded obstacles before debouching into the sea. Following Italian engineers, he thought that the erosion, proportional to flow velocity, progressively pushes sand towards the sea as more sediment was picked up, and suspension and settling are balanced for only one flow velocity. Faster flow would cause net erosion and slower flow net sedimentation.

This view of sediment transport holds inconsistencies. On the one hand, there is only one velocity at which corrosion and settling are balanced, but on the other hand there is supply of sediment from upstream, which is pushed downstream. This should lead to increasing turbidity along the river, but here 's Gravesande contradicts himself by asserting that such turbid water lays down as much sand as it raises.

Such misconceptions were common and are also behind Cruquius's development of depth contours on his maps (van Besouw 2024) and in possible solutions to river 'decay' by localized siltation (e.g. Bolstra 1754). Siltation was thought to increase flood levels, induce ice dams, hinder navigation and unbalance the division of flow at river bifurcations. Large-scale dredging being not feasible yet, Bolstra and many others proposed to increase channel depth by decreasing overbank flow, shorten the groynes, removing irregularities in the riverbank, narrowing the river where it is wider, eradicating floodplain vegetation and modifying bifurcation shapes.

Do rivers even transport sand?

Causes for siltation were not entirely clear. Many experts believed sediment transport occurred only localized. The thalweg was seen as 'channel' whereas inner-bend bars and shoals at bifurcations were seen as unwanted effects of local sedimentation.

This may seem strange from a present-day perspective, informed by theory and numerical river models based on sediment continuity, but there was plenty of evidence. For example, in many engineering works the river did not have a continuous alluviated sediment bed but also flowed over outcropping, strongly cohesive substrates. Furthermore, no sand transport was measured. Measurements and methods were conducted and shared worldwide in the second half of the 19th century in view of increasing navigation. Lely and Fijnje conducted measurements and concluded that only mud was suspended while sand was rarely found in transport. Only when large-scale dredging works began, practitioners noted the dynamic response of the riverbed by sediment transport. Not everyone agreed. Stevin (early 17th century), Lulofs (mid 18th century), Lyell (mid 19th century) and others took for granted that sediment, eroded in the mountains, built up river deltas and filled coastal lagoons. However, geology-oriented works were barely cited by river engineering-oriented works. We speculate that they avoided the theological implications of the long timescales involved in delta formation.

Conceptions of ‘sediment continuity’

Fargue-Dioque (second half of 19th century) developed laws and a method for designing riverbed and riverbank continuity aimed at removing irregularities that led to local sedimentation (1868, also see Hager 2003). This strongly influenced the ‘normalization’ plans in the Netherlands and Germany (e.g. Lely refers to it). Fargue aimed for navigability improvements in the Garonne and the Gironde. The main idea is to train/regularize the river into a single, continuous channel with mild meanders such that riverbed erosion occurred in the outer bends without the sedimentation problems of sharp bends and islands. A key assumption by Fargue is continuous sediment motion. In fact, the purpose of his design method is that the motion becomes regular so that no shallowing occurs in inner bends and no erosion in outer bends. This essentially accounts for two-dimensional sediment continuity, demonstrating a strong historic link between developments of continuity concepts and river meandering concepts. Fargue observed such general sediment motion because he conducted, possibly the first, experiments: an unscaled analogue model with flow and sediment transport (Hager 2003).
Since then, Reynolds did scale experiments for navigation problems in the Mersey estuary (the first with scale considerations. He did not cite Fargue, whom he probably from international conferences on navigation that the Dutch also attended. Reynolds described the motion of sediment as drift on two length scales: that of bars and bends, and that of the river from source to sink. Reynolds outlined the two conditions under which riverbed change may occur, namely a spatial gradient in flow velocity, or a transition between a sandy riverbed and bedrock. Differences in flow direction near the riverbed, such as in riverbends, may cause local scour in the outer bend and siltation in the inner bend at the local scale. For the large scale Reynolds explains, with reference to Charles Lyell, that such sediment drift occurs from the source of the river until it reaches the ocean or lake where it extends a delta.
While the multiple causes of river meandering remain under debate until today, the picture of multi-scale sediment drift painted by Reynolds essentially poses in words what is captured in Exner’s equation. Moreover, the order in the reasoning is very similar, though Exner does not cite Reynolds: both start with the minimum flow velocity threshold for the motion of sediment and then proceed with explaining the continuity and the effect of a change in velocity. It was in the air by then: e.g., Gilbert conducted a set of experiments on sediment transport that is still used, cites Fargue and is cited by Exner.
In conclusion, we argue that the concept of sediment continuity already became established in the second half of the 19th century by many practitioners involved in laboratory scale experimentation, in dredging and in river regularization, well before Exner wrote it down in the form of a differential equation. Earlier conceptions contributed to the present ‘regularized’ state of rivers, and to continued riverbed erosion and static bends conducive to ecosystem deterioration.

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Bottlenecks for the restoration of tidal vegetations in heavily modified river deltas

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Keywords — Ecological restoration, Tidal nature, Sedges

Introduction

Ecological restoration in tidal rivers, as required by the Water Framework Directive, is one of the challenges for water management. The present ecological status of tidal rivers in The Netherlands is insufficient (Knoben et al., 2024). One of the targets for restoration is recovery of the once abundant clubrush vegetations, that have been decimated due to major hydromorphological changes in the water system. Despite restoration efforts in the past, the area covered by clubrushes remains very small (Honcoop et al., 2023). In this study we investigated bottlenecks for the reestablishment of clubrush species. To ameliorate the effectiveness of tidal restoration projects, field experiments were conducted to investigate key factors inhibiting the establishment and development of clubrush species (Liefveld et al., 2025).

We addressed the following research questions:

1. Is the establishment of clubrushes limited by the availability of seeds?
2. Are conditions suitable for germination, development and expansion of clubrush plants?
3. Is grazing by waterbirds a limiting factor for the establishment and/or growth of clubrushes?

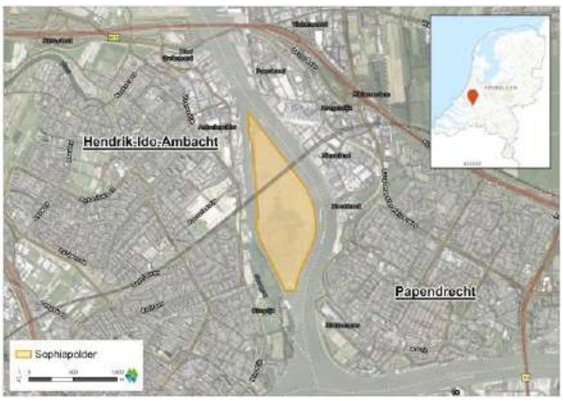

Figure 1. Study area, the Sophiapolder, in tidal riverbranch 'de Noord'.

Methods

The research was carried out over a period of four years (2020-2023) in the Sophiapolder, a newly restored, freshwater tidal area on an island (77 ha) in the tidal riverbranch 'de Noord' (Fig. 1). After restoring the tidal regime in 2011, it appeared that, unlike expectations, clubrush establishment did not occur on the tidal flats in this polder.

Seed banks

Soil samples (diameter, depth) were taken at 5 locations in the Sophiapolder and 1 in existing clubrush vegetation in the nearby Noordwaard as a control site. After sieving, all propagules were collected and identified for each sample.

Local conditions

An in situ germination experiment was carried out to test if local conditions in the polder were suitable for germination of clubrush seeds. Four different species (*Schoenoplectus triqueter, Bolboschoenus maritimus, Schoenoplectus tabernaemontani and Schoenoplectus lacustris*) were sown in twelve plots in 1x1m exclosures, to protect seedlings from herbivores. Additionally, seedlings were raised under controlled conditions and transplanted to the exclosures.

Herbivory

To study the impact of herbivores on vegetation development, we installed ten large exclosures (4 by 6 m), to eliminate the effects of grazing by geese and other water birds (Fig. 2). Near each exclosure a control plot was situated. Vegetation cover and species abundance together with silt sedimentation were monitored yearly in September/October from 2020 (T0) to 2023 (T3).

Figure 2. Large exclosure with vegetation development.

Results

The soil samples showed no viable seeds were present in the upper sediment of Sophiapolder. By contrast, they were found abundantly in the Noordwaard samples (Fig. 3).

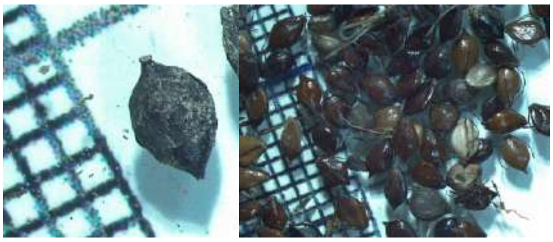

Figure 3. Left: only one clubrush seed (Schoenoplectus spec.) was found in the Sophiapolder while multiple viable seeds were found in the Noordwaard (right).

In five of the small exclosures seedlings of *Schoenoplectus triqueter* appeared from seeds that were sown. However, in only two exclosures the seedlings survived and developed to full-grown plants within four weeks. Seeds of the other three species did not germinate in the field, but they did so under controlled conditions. *Bolboschoenus* seedlings, were transplanted in exclosures and developed successfully into multi-stem plants (20-80% vegetation cover) in five months' time. *Schoenoplectus triqueter transplants* developed poorly when growing together with *Bolboschoenus maritimus,* but did very well (80% vegetation cover) in absence of other species.
Because of the generally very low percentage germination no further statistical analyses were deemed appropriate.

Figure 4. Within three months seedlings form Bolboschoenus maritimus developed to cover the entire (small) exclosure.

There was a striking difference in natural vegetation development between the large exclosures and unprotected control sites (Fig. 5), indicating strong impact of herbivores. In addition, no seedlings emerged from seeds sown outside the exclosures. Offshoots of plants growing inside exclosures that emerged outside of them showed clear signs of grazing.

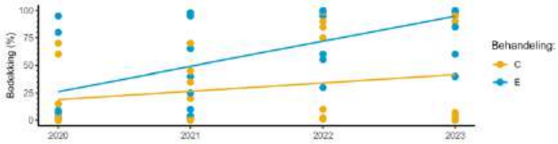

Figure 5. Total vegetation cover over time in the large exclosures and plots. Treatments: C= control, E=exclosure.

Conclusions

The absence of a seed bank seems to be an obstacle to the colonisation of the tidal flat by clubrush vegetation. Considering the nearest potential seed sources are located relatively long distance, the seed availability (research question 1) seems to be a major bottleneck.
We showed that germination and development of clubrushes can occur, indicating a suitable environment for the development of rushes exists in the Sophiapolder (research question 2). More specifically, clubrush plants develop well in the absence of herbivores and dense surrounding vegetation at more elevated zones in the tidal gradient.
Grazing by herbivorous waterbirds, in particular geese, was shown to be an important limiting factor for the establishment of vegetation with clubrush (research question 3).
On the long term clubrush vegetations may only persist under sufficiently high hydro- and morphodynamic conditions: Even without grazing, rushes will possibly disappear in time due to vegetation succession in combination with sedimentation as has been observed in the vegetation patches. This succession is a natural process. In a sufficiently large and varied area with more room for morpho- and hydrodynamics, suitable habitats for rushes will remain present in varying places around these waters.

This study offers insight in the potential for restoration of tidal wetlands and provides practical guidelines management.

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Modelling tidal channel evolution under the influence of tide and river discharge

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Keywords — Morphodynamics, Tide, Current

Introduction

A tidal park has been designed in the Nieuwe Maas in Rotterdam, a unique nature park influenced by tide and current. The tidal park is connected to a side channel (Zuiddiepje) of the Nieuwe Maas (Fig. 1). In collaboration with the municipality of Rotterdam, Svašek Hydraulics investigated the morphological development of the tidal park using a narrow down approach based on three different methods, with increasing detail:

- Equilibrium depth
- Segmented river model
- Numerical (FINEL) model

Figure 1. Overview of the designed tidal park (black lines) as an extension of the Eiland van Brienenoord.

Method

The morphological development of the tidal park has been studied using flow simulations with the Rhine-Meuse Delta (RMD) D-HYDRO model. In these simulations, hydrodynamic conditions representative for the park's morphological development were applied. For this study, two hydrodynamic conditions were selected:

- Average spring tide with median river discharge (2200 m³/s at Lobith): Spring tide is a representative condition in assessing the equilibrium depth in the tidal park, as this condition leads to relatively high flow velocities and also occurs frequently enough throughout the year.
- Spring-neap tidal cycle with median river discharge: Average spring tide alone is not representative of annual morphological changes. By using a spring-neap tidal cycle, morphological changes over multiple years can be determined in a structured and robust manner. This condition is used for the morphological development with the segmented river model and the numerical model.

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Equilibrium depth

The equilibrium depth is the depth to which the bed level will change in the long term, based on the highest flow velocities during spring tide. It is defined as the depth at which the flow velocity equals the critical flow velocity. The equilibrium depth is determined based on the Shields formula (Shields, 1936) for the stability of granular material. Supplemented with the dimensionless grain size found by Van Rijn (Van Rijn, 1984), the critical flow velocity for initiation of motion can be determined. The resulting equilibrium depth compared to the actual designed depth determines the potential erosion or sedimentation in the tidal park. This indicates areas which are prone to significant morphological change and their equilibrium state. However, the timescale of morphological development is not included in this method.

Segmented river model

Sediment transport in the segmented river model is calculated through cross-sections with the transport formula of Engelund-Hansen (Engelund & Hansen, 1967), which takes into account the flow velocity, depth, hydraulic roughness (0.02 m) and sediment grain size (200 µm). As hydrodynamic input, the D-HYDRO model simulation of the spring-neap tidal cycle was used.

By examining differences in sediment transport across the cross-sections, the model determines the volume of sedimentation/erosion for each cell (difference in transport multiplied by the timestep). The volumes for each timestep are summed to obtain the total morphological development over one spring-neap tidal cycle. The calculated volumes are converted into bed level changes by dividing the volume by the surface area of the cell.

To simulate morphological development over time, the model runs multiple loops in which the morphological changes for one spring-neap tidal cycle are calculated. Between loops, the computed bed level changes are applied to the different cross-sections using the "upwind" method. The core principle of this method is that bed level changes occur in the downstream direction. After the bed adjustment between loops, the flow velocity in the cross-sections is scaled with the new water depth for the next loop to ensure the discharge remains constant.

Numerical (FINEL) model

A detailed 2-dimensional numerical model of the tidal channel was set up to obtain a more reliable assessment of the timescale and spatially varying morphological developments. The morphological FINEL model (Svašek Hydraulics, 2025) was implemented as a nested model within the D-HYDRO model. This approach was chosen to simulate only the morphology of the tidal park and the Zuiddiepje, without including the entire RMD system.

The spring-neap tidal cycle from the D-HYDRO model was used as the hydrodynamic input. This cycle was repeated multiple times to simulate a longer period. To model 10 years of morphological development without having to compute 10 years of hydrodynamics, a morphological acceleration factor (morfac) is applied. This morfac multiplies the calculated erosion and sedimentation in the simulation, effectively accelerating these processes.

In the simulations with the FINEL model, a variable morfac is used. Since morphological development is expected to be greater at the beginning of the simulation, a smaller morfac (6.5) is applied initially. After the first year, the morfac is doubled (13) for years 2 and 3. For years 4 through 10, a morfac of 26 is used, meaning that a single hydrodynamic simulation of one spring-neap tide cycle (approximately 14 days) corresponds to one year of morphological development.

Supplementary to the segmented river model, FINEL simulates the spatially varying morphodynamics. Moreover, physics of suspended sediment load are included. In the segmented river model it is assumed that all sediment settles in the downstream segment, while in the FINEL model the behavior of suspended load is included in the model. Bed protection is also included in the FINEL model, resulting in scour around the bed protection.

Results

In Figure 2 the result of the bed level development is shown after 10 years, determined by FINEL. At the NCR days, we will present the results of the equilibrium depth, the segmented river model and the FINEL model and their differences and limitations.

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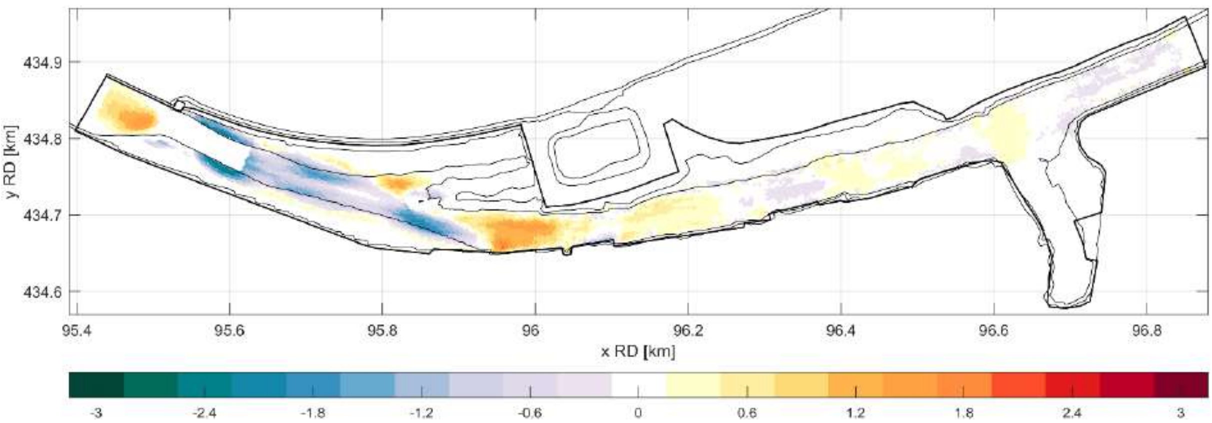

Figure 2. Bed level change (m) after 10 years in the tidal park and Zuiddiepje calculated with FINEL. Blue colors indicate erosion, red colors indicate sedimentation.

Forecasting and decision support for estuarine saltwater intrusion in the Rhine-Meuse Delta using machine learning

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Keywords — salt intrusion, chlorosity, machine learning

Introduction

Estuarine saltwater intrusion in the Rhine-Meuse delta presents significant hydrological and environmental challenges. Freshwater saltwater dynamics are further complicated by human interventions and climate change impacts, such as droughts, storm surges, and rising sea levels. Over recent years, saltwater intrusion events have become more frequent and severe, particularly during the summer droughts of 2018, 2020, and 2022, which have disrupted the freshwater availability for drinking, agriculture, and ecosystems. This escalating issue underscores the urgent need for accurate, real-time predictive models that forecast chloride concentrations (Cl) and the duration of saltwater intrusion (Huismans et al., 2019), which are essential tools for water managers and stakeholders to mitigate impacts and ensure freshwater supply in the region.

To address this challenges, traditional physical based and conceptual models have been used for predicting saltwater intrusion in the Rhine-Meuse delta. However, models such as the one dimensional (1D) hydraulic model SOBEK (Deltares, 2019) fail to predict Cl as it cannot fully capture the complexity of saltwater intrusion dynamics, while the three-dimensional (3D) hydrodynamic model RMM3D (Van der Kaaij et al., 2022) provides more detailed insights but is computationally intensive and not suitable for real-time operational use. The two dimensional vertical (2DV) model IMSIDE (Biemond et al., 2025) was developed to bridge the gap between 1D and 3D models but still lacks sufficient accuracy for operational uses. Consequently, there is a growing interest in data-driven, machine learning-based models, which have shown promise in offering accurate, real-time forecasts by capturing the complex, non-linear relationships within saltwater dynamics (Wullems et al., 2023).

The aim of this research is to explore the potential of machine learning-based models to (i) forecast daily Cl (mg/L) at multiple key locations in the Rhine-Meuse delta and (ii) assist water managers in real-time forecasting, early-warning, and decision support to mitigate saltwater intrusion events. The ultimate goal is to develop a modelling toolbox with a user-friendly graphical interface.

Forecasting chloride concentration

We applied Long Short-Term Memory (LSTM) models to predict Cl at multiple key locations in the Rhine-Meuse delta. LSTMs, a type of recurrent neural network, have been shown to effectively capture temporal dependencies and non-linear patterns in time-series data, making them ideal for forecasting saltwater intrusion events. Specifically, we applied LSTM models to forecast daily Cl at five key locations: two in the northern part, experiencing forward intrusion (Krimpen aan den IJssel and Kinderdijk), and three in the southern part, affected by backward intrusion (Beerenplaat, Bernisse/Zuidland, and Middelharnis Spui).

To develop the forecasting models, we analysed the characteristics of the study area and its water management practices, identifying relevant input variables. These included daily water level, discharge, wind speed and direction, and evaporation data. Data availability was also carefully considered, ensuring the variables selected were accessible for both model training and operational uses. We then set up an ensemble of 10 LSTM models to forecast both daily maximum and mean Cl, with lead times ranging from one to seven days, at the five locations. The model ensemble was trained using data from 2008 to 2018, tested on data from 2019 to 2020, and validated with data from 2021 to 2022.

Figure 1 shows the forecast results of daily Cl at a 1-day lead time for two locations, Kinderdijk (northern part) and Bernisse/Zuidland (southern part), during the validation period. The models successfully predicted daily Cl and the timing of peak concentrations. However, there was a tendency to underestimate the peak heights, particularly as the lead time increased, which indicates a need for further refinement of the model's performance at longer forecasting horizons.

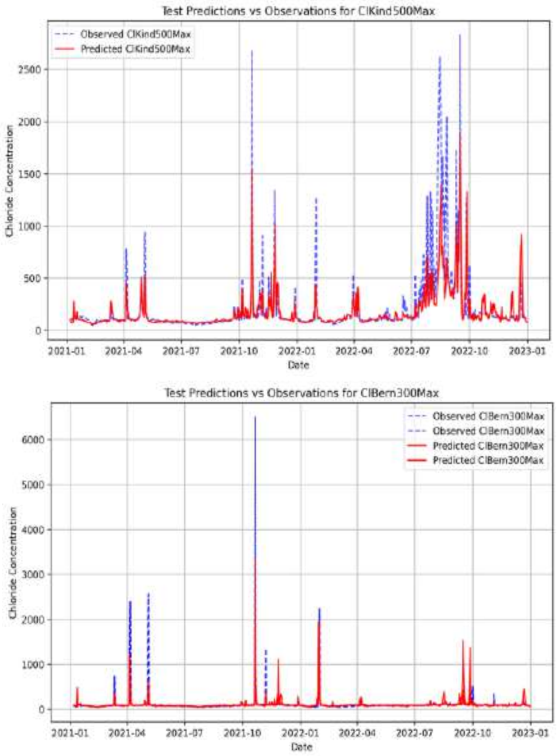

Figure 1. Forecast daily Cl timeseries at a 1-day lead time for Kinderdijk (upper graph) and Bernisse (lower graph) during the validation period (2021-2022).

Decision-support tool

Saltwater intrusion in the Rhine-Meuse delta can typically be mitigated by using freshwater from the rivers to push saltwater back toward the sea. By incorporating daily discharge data from controllable infrastructures into the model as input, the LSTM model ensemble can serve as an exploratory decision-support tool through scenario simulations. The five infrastructures include the Hagestein weir, Haringvliet sluices, Volkerak sluices, Prince Bernard locks, and Princess Irene Lock. By adjusting these discharge input variables and analysing their impacts on the resulting Cl values, we can evaluate the effectiveness of different mitigation measures for salt intrusion events.

Figure 2 presents the graphical user interface (GUI) of the decision-support tool, which enables users to explore various intervention strategies and assess their impact on chloride concentrations at the five locations. The model's strong performance, combined with its ability to simulate different scenarios, underscores its potential as an effective decision-support tool for water managers. The tool provides real-time actionable insights, assisting water managers in making informed decisions to mitigate the effects of saltwater intrusion and protect the region's freshwater resources.

Figure 2. Graphical user interface of the decision support tool

In summary, this research demonstrates the potential of machine learning, specifically LSTM models, to forecast chloride concentrations and assist in managing saltwater intrusion in the Rhine-Meuse delta. The development of a user-friendly decision-support tool further enhances its practical applicability, offering a promising assistance for real-time forecasting, early warnings, and the evaluation of mitigation strategies to safeguard freshwater availability in the delta.

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SESSION 6

Groene Rivier Well, a nature based design connecting water safety, groundwater levels, biodiversity and land use

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Keywords — Nature based solution, climate-robust design, 'Water en Bodem sturend'

Introduction

In the project 'Groene River Well', river widening, dike reinforcement and stream restoration are combined. The dike reinforcement and river widening form the basis for a plan to redesign the floodplains around Well, in which water management, agriculture and nature are restored.

The project area Well is characterized by the terraced landscape of the Maas. The village of Well forms a narrow stretch in the Maas, the current riverbed narrows from 1300 m to only 300 m (figure 1). A proposed new 210 m wide bridge in the motorway N270 makes an inflow opening possible to a green river. This restores the width of the former riverbed and substantially lowers the water level during high water (with ~17 cm).

In the design of this Groene Rivier Well, an optimization has been found between high water safety, water management, land use and spatial quality. This abstract briefly describes the design principles used to design this Groene Rivier Well. In these principles river engineering, spatial design, hydrology and ecology are working together to find the optimal solution.

Method

One of the main design challenges is to design a climate-robust water system in which peak rainfall and high river discharges are drained, while water is retained during periods of drought. To realize such a robust system, it is necessary to lower the ground levels (to create sufficient space for the objective high-water safety) and to dampen the draining watercourses, which raises the groundwater level (to retain water and prevent droughts). Lowering the ground levels also contributes to the potential of nature development and increase of biodiversity.

Principle 1: Follow the hierarchy of the landscape.

Based on the principle of 'water en bodem sturend', the DNA of the landscape forms the 'blueprint' for the design. The height, location and shape of the original gully-shaped depressions in the low terrace determine the size and scale of the lowering of the floodplain. Research into the structure of the subsoil (BAAC, 2025) has shown that there are various old gully patterns in the low terrace. It was decided to use these patterns as a guideline for the design.

Water management plays a crucial role in the design of the Groene Rivier. One of the objectives was to restore the seepage system characteristic for the Maas terraces.

Principle 2: Make a climate-robust water system.

The project area is being redesigned to better cope with climate change; various measures have been planned for this purpose. The Groene Rivier is designed as an isolated open water channel which will be filled by seepage. Around this channel the ground levels will be lowered. In the extent of the ground level lowering, an optimum was sought between (1) the river-related flood capacity during peak discharges (reaching the ~17 cm water level decline), (2) maintaining the groundwater levels by damping draining watercourses, (3) the suitability of the area for nature development and increase of biodiversity and (4) for agricultural use. Besides those four, also the way the floodplains can be managed (sediment and vegetation management) was taken into account.

Principle 3: Connect agriculture and nature.

In the area of the Groene Rivier, water levels and ground levels are the guiding principles in the design. In the Groene Rivier, four land types have been distinguished based on ground level and hydrological conditions: from the open water of the open water channel, to marshland, wet grassland, dry grassland and crop fields.

Principle 4: Increase biodiversity

The area becomes wetter under 'normal' water management conditions and by removing the nutrient-rich top layer over a large part of the

Groene Rivier, a good starting position for nature development is created. A gradient of open water, reed marsh and herb-rich grassland will be developed.

Conclusion

The design of Groene Rivier Well forms a solution for several important challenges. It forms an adaptive design with regard to floods and droughts, transforming agriculture and increasing biodiversity. By applying the design principles, a climate-robust, nature based design of the Groene Rivier is created in which river engineering, water management, ecology and spatial planning strongly interact..

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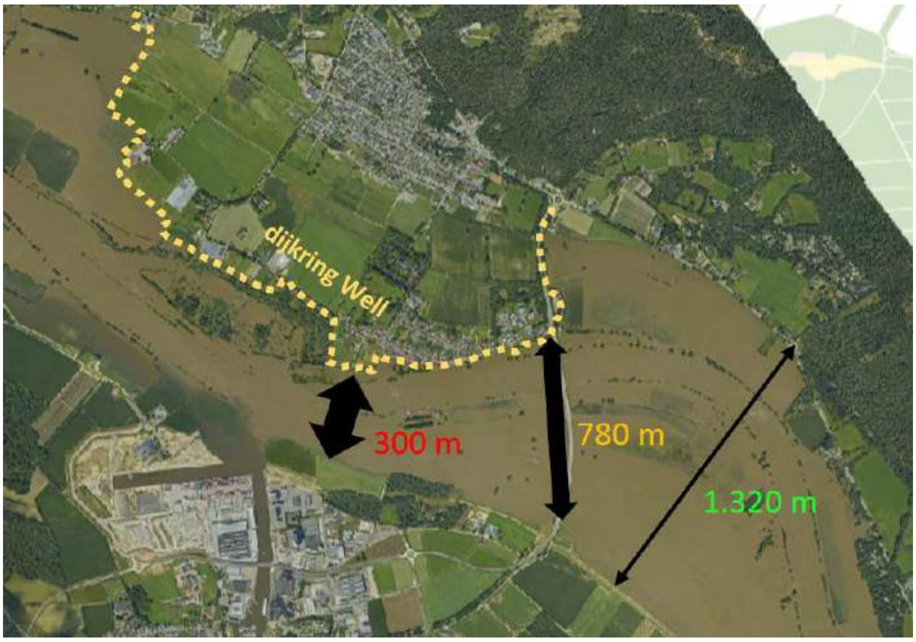

Figure 1: Current situation around Well during extreme discharges

Figure 2: Preliminary design Groene Rivier Well

Knowledge-related challenges in Dutch river innovation

Exploring barriers to knowledge management in Self Supporting River Systems

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Keywords: Transdisciplinarity, Knowledge Management, Innovation

Introduction

Complex knowledge from different stakeholders is vital to solve increasingly complex societal challenges (Stock & Burton, 2011). However, stakeholders involved in Self Supporting River Systems (SSRS, 2025), experience that integration and utilization of such knowledge is challenging. To start solving such barriers, different stakeholders need to understand each other's knowledge explicitly, preventing potential biases, cherry picking, and misinterpretation, to facilitate efficient and transparent transdisciplinary knowledge processes (Nonaka and Takeuchi., 1995; Derksen., 2014). When combining knowledge among stakeholders, barriers can arise due to differences in understanding, and valuation of knowledge deriving from differing perceptions, goals and workways (Böcher and Krott., 2016; Spaapen and van Drooge., 2011; Derksen., 2014; de Vries et al., 2024). E.g., scientists use knowledge to describe and explain the world, policymakers to influence development, and companies to earn and solve practical problems, all implying different criteria and valuations for knowledge (Böcher and Krött., 2016; Derksen, 2014). Additionally, knowledge can be disseminated in sub-optimal ways, possibly also due to different preferred disseminationstructures (Muhonenet al.,2018; Benneworth and Olmos-Penuela., 2018; Spaapen and van Drooge., 2011). As such, the innovative capacity of knowledge depends significantly on politics, established structures and rules, funding, and partnership patterns (Ahmed et al, 2023; Nonaka and Takeuchi., 1995). For innovation capacity of SSRS to be improved, there is a need to understand barriers to knowledge uptake.

Method

To better understand how knowledge processes for innovation in sustainable river management can be improved, this study explores barriers in Knowledge uptake. Perspectives are taken from knowledge theories like knowledge management (KM), to identify barriers to knowledge flow and knowledge integration(KI), to conceptualize the flow of knowledge between knowledge developers and users, see figure 1 (Nonaka and Kono, 1998; Böcher and Krott, 2016). In this research, we first assess the experiences of experts from universities, knowledge institutes, RWS, and engineering companies, to explore experienced barriers and enablers in knowledge processes. We have interviewed university researchers (17), researchers in knowledge institutes (5), innovation and knowledge experts in RWS (4), and representatives from engineering companies (3), all working in river-management or related disciplines between sept-dec 2024. The interviews specifically considered the familiarity with current knowledge uptake and innovation practices, experiences with current practice and barriers to successful knowledge uptake for innovation. These were analysed to understand the main barriers for current practices.

Results

Currently, SSRS aims to facilitate knowledge integration between 4 types of stakeholders: universities and knowledge institutes who develop innovative ideas, companies which develop ideas and implement innovations, and RWS which employs knowledge institutes and companies to develop knowledge, and companies to physically implement changes, see Fig. 1.

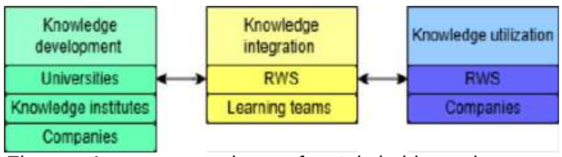

Figure 1: an overview of stakeholders in knowledge processes for Dutch river innovation in relation to the KI model.

Knowledge for innovation is currently integrated in the SSRS in three main ways: 1. reporting: academic knowledge is disseminated to policymakers and companies in reports, 2: through informal dissemination, usually key experts from different stakeholder groups have short lines, 3: innovation cards about every innovation currently undertaken are updated by involved stakeholders so everyone who is interested knows the state of things. Table 1 summarizes the main barriers in the knowledge process for innovation.

Table 1: Barriers for innovation from a knowledge perspective (preliminary results)

Barrier	Description
1.Current knowledge uptake structure is not working	Knowledge integration lacks structure and occurs ad hoc through projects or key individuals. Available tools like innovation cards are doubted and too dependent on regular updates
2.Limited visibility and involvement universities	University researchers were unaware of the learning teams and remained confused about the work processes after reviewing the website.
3. Limited uptake and visibility of knowledge within RWS	There is no central coordinator, leading to an ad-hoc process, while the size of RWS and high stakes in Dutch rivers create risk aversion and limited contact.
4. limits to free knowledge-flows and lack of upscaling in private sector.	Regular contracts alongside open learning spaces create a client-contractor dynamic, hindering true partnerships. Long-term contracts can stifle innovation if new solutions emerge mid-term.
5. Too few people feel responsibility and ownership of knowledge and innovations	Assigning managers of companies/government departments as knowledge owners is ineffective as they are often too busy, and acting as intermediaries slows down knowledge transfer, especially when they have other responsibilities. Ownership of knowledge is limitedly felt among knowledge institutes and companies.
6. Financial flows do not encourage innovation	Funding uncertainty hinders innovation, as contractors and institutes prefer upfront payments while RWS controls budget allocation, and other stakeholders invest limitedly. Contracts often fail to reward efficiency, incentivizing traditional methods over innovation.

Discussion/conclusions

Learning spaces have strong potential for innovation but are not fully utilized. Implementing solutions like stakeholder-driven innovation roadmaps, enabling rather than managing collaboration, and clearer communication can enhance their effectiveness. Accepting that some innovations may fail would reduce performance pressure and encourage experimentation. A central contact point for innovation dissemination could improve knowledge sharing, while process innovations in financial flows and contracts could better support new ideas. During the continuation of this study, KM and KI will be employed to unpack processes that lead to knowledge production and utilization for innovation in Dutch river management, to further unpack barriers identified in this study, as well as enablers and provide advice for overcoming them.

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Balanced distribution of low discharges requires large-scale measures on the Waal

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Keywords — Low discharges, Rhine, Room for the River 2.0

The IJssel River branch will continue to receive less fresh water in the future. This negatively impacts freshwater availability in northern Netherlands. In preparatory studies for the Room for the River 2.0 program, measures are being explored to maintain a balanced distribution of low discharges across the Rhine branches. Preliminary results indicate that large-scale measures at the Waal branch are the most viable option to achieve this. An advantage of this measure is that the control range of the weir at the river bifurcation will increase at low discharges.

River bed erosion in policy

The Rhine is the most important source of fresh water for the Netherlands. Uneven riverbed erosion in the Rhine branches causes a changing distribution over Rhine branches (Waal, IJssel and Nederrijn) at low discharges. As a consequence, the IJssel now receives approximately 30 m³/s less than it did 45 years ago at the same low river discharge of 1000 m³/s (Quartel, in prep.). Additionally, the Nederrijn-Lek does not receive the agreed 30 m³/s when the river discharge at Lobith falls below 1300 m³/s. These changes negatively impact the IJsselmeer as a freshwater source, shipping on the IJssel, and efforts to combat salinization in the Northern Netherlands. As a result, the Delta Programme Fresh Water (DPZW) has defined a target for a more balanced discharge distribution across the river branches.

The provisional target on the discharge distribution, as outlined by DPZW, specifies that at a discharge of 1300 m³/s at Lobith, the IJssel should receive at least 285 m³/s (as derived from the 2nd Water Management Memorandum, 1984), while the Nederrijn should receive 30 m³/s. To meet these targets, an increase of approximately 55 m³/s compared to the present situation is required for the IJssel at a discharge of 1300 m³/s. This goal is now incorporated into the policy objectives of Room for the River 2.0 (RvR 2.0).

The policy objective is as follows: "Ensure a sufficiently stable and manageable river summer bed position that contributes to the restoration of natural river dynamics and guarantees optimal navigability and water distribution across the Netherlands during low river discharges." A separate policy objective has been defined for high water, focusing on achieving adequate capacity to accommodate higher river discharges. Research is currently ongoing to determine the desired distribution of high-water discharges across the Rhine branches in the long term, as well as the necessary control ranges at bifurcation points.

Exploring river measures

In line with the first policy objective, this study explores how the desired discharge distribution at the bifurcation points at low river discharges can be achieved. This involves calculating various measures, assessing their risks, costs, and impacts on river functions. The calculations rely on 1D and 2D hydraulic models of the Rhine branches (SOBEK schematization version 'j24_6-v1a1', and D-Flow FM version 'rijn-beno19_6-v1b'). A sensitivity study is conducted with the 1D model to explore measure dimension, location and length. The 2D model gives more detailed insight in effectivity of potential river measures. Preliminary results are already available.

These results indicate that the desired discharge distribution is achievable (Asselman et al., 2025; Gensen et al., 2025). However, achieving this goal will require large-scale interventions on the Waal, potentially supplemented by measures on the Upper Ijssel branch. Figure 1 gives insight in the additional gain of fresh water towards IJssel for different measures as a function of total (Upper) Rhine discharge.

One proposed measure is the narrowing of the Waal's summer bed by 30 meters over a stretch of 50 kilometers through a multi-channel concept (e.g., longitudinal dams parallel to the main channel). A multi-channel concept primarily aims to reduce river bed erosion by widening the riverbed and slowing flow rates at discharges with large morphologic activity. With low discharge – with low sediment transport rates – the main channel can be narrowed. The narrowing results in an increase in waterlevel and therefore a change in discharge distribution in favor of the Pannerdensch Canal (and IJssel). Despite the reduction in Waal-discharges, the end result is an increase of waterlevel and therefor water depth for navigation. Results furthermore indicate that local interventions at the bifurcation point itself and measures on the Pannerdensch Canal are likely to be ineffective. It is already clear that the measures on the Waal will extend the control range of the Nederrijn weir (Driel) on water distribution over the Rhine branches, which is an explicit goal for future water management. Further specifications of these interventions are being explored in a follow-up study.

Next steps

In the coming months, the low water measures will be evaluated in conjunction with other policy objectives of Room for the River 2.0 for high-water scenarios. It is likely that the exploratory results will include a multi-channel concept for the Waal and an expansion of the control range for both high and low discharges.

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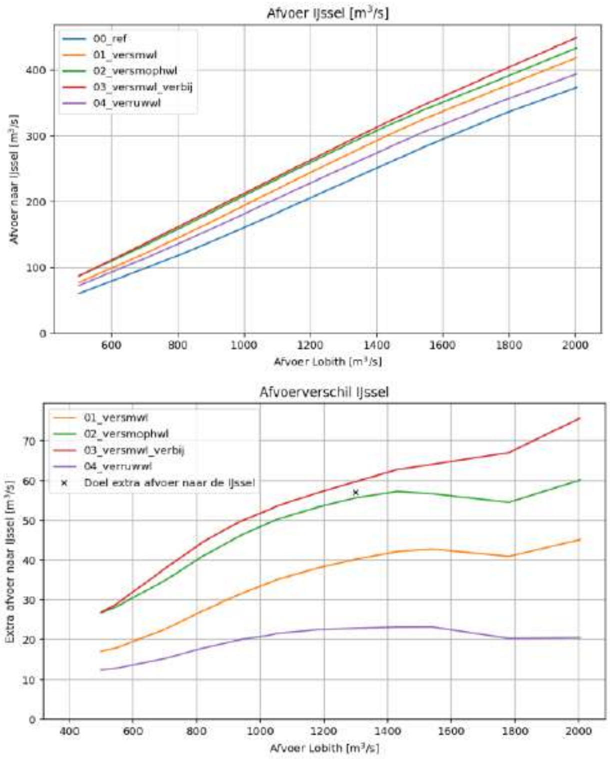

Figure 1. Preliminary results (based on the 2D model): Discharge (upper panel) and discharge difference (lower panel) towards IJssel river branch as function of Upper Rhine discharge for different river measures: 1- narrowing the Waal branch with 30 m over 50 km, 2- narrowing the Waal and heightening the river bed with 20 cm over 50 km, 3- narrowing Waal over 50 km and widening IJssel river branch over 10km with 15 m, 4- increasing Waal river bends roughness in two patches of approximately 1 – 1.5 km.

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Projected climate-change impacts on the flow partitioning in the bifurcation region in the upper Rhine delta

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Keywords — Climate Change, Climate Scenarios, River Bifurcations, Flow Partitioning

Introduction

In engineered river systems such as the Dutch Rhine, bifurcation dynamics play a crucial role in providing flood safety, freshwater supply, and inland navigation. While regulation measures in the past caused bed erosion (Ylla Arbós et al., 2021) and peak discharges may have caused changes in flow partitioning (Chowdhury et al., 2023) at the bifurcation points, climate change is expected to further alter hydrological patterns, impacting sediment transport and increasing bed erosion (Ylla Arbós et al., 2023) as well as affecting flow partitioning again.

The objective of this study is to investigate the effects of climate change on the Dutch Rhine bifurcation system over the next 150 years, focusing on hydrograph variations, sea level rise, and the influence of past engineering interventions. Understanding these dynamics is critical for future river management and adaptation strategies.

Methods

We have developed a one-dimensional numerical model to simulate flow partitioning and bed level change over a 540 km domain of the Rhine River. The domain of interest extends from Bonn (Germany, river km 640) to its downstream boundaries in the Waal (at Vuren, Netherlands), the Nederrijn-Lek (at Schoonhoven, Netherlands), and the IJssel (Keteldiep, Netherlands). As such, the model includes the Pannerdense Kop and IJsselkop bifurcations.

The model is informed by a two-dimensional model to account for sediment partitioning at the bifurcations and has been calibrated against measured data on flow partitioning and order of magnitude and sign of channel bed erosion rates. It is verified against water levels at four stations in the different branches. Climate change scenarios, including different hydrograph change projections (Buitink et al., 2023; Van Verseveld et al., 2024) and sea level rise projections (Van Dorland et al., 2023), were incorporated based on the KNMI'23 climate scenarios. The model simulates the bifurcation response in these scenarios, providing information on trends in discharge redistribution at the bifurcations, sediment flux, and channel bed erosion and deposition.

Results

Our projections indicate that while past human interventions continue to influence flow partitioning in the near term, climate change effects will become increasingly significant from 2060 onward.

In the reference scenario, the Waal-to-Lobith discharge ratio increases gradually, while the IJssel-to-Lobith discharge ratio declines, reflecting ongoing channel adjustments. Under climate change scenarios, hydrograph alterations lead to a further increase of the Waal-to-Lobith discharge ratio (Figure 1) and a coarsening of sediment flux arriving at the bifurcations.

By 2150, the dominant Waal branch is projected to experience a 5–8% increase in discharge, while the IJssel branch may see reductions of up to 30% during low-flow conditions. These trends result from intensified erosion in the bifurcation region due to sediment flux coarsening, which yields an increased mismatch between sediment supply and sediment transport capacities immediately downstream of the bifurcations.

Sea level rise has a counteracting effect on these hydrograph-induced changes, slightly increasing IJssel discharge by allowing backwater effects to propagate upstream. However, the impact of hydrograph modifications outweighs that of sea level rise in most scenarios. The bifurcation system response is largely driven by shifts in medium water discharges rather than extreme peak flows, indicating a gradual but persistent transformation of flow partitioning.

Conclusions

This study highlights the evolving role of climate change in shaping the Dutch Rhine bi-

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furcation system. While past engineering interventions have dictated historical and current flow patterns, their influence will decrease as climate-driven changes accelerate.

Climate-related hydrograph changes, rather than sea level rise, emerge as the dominant factor affecting the flow distribution at Pannerdense Kop and IJsselkop.

Our findings underscore the necessity of water management strategies to address changing hydrological conditions. Future policies must explicitly consider sediment flux coarsening and erosion dynamics to mitigate the long-term impact of climate change on the river bifurcations in the upper Rhine delta. By integrating these insights into planning efforts, policymakers and engineers can ensure the resilience of the Dutch Rhine delta against future climated-related hydrograph changes.

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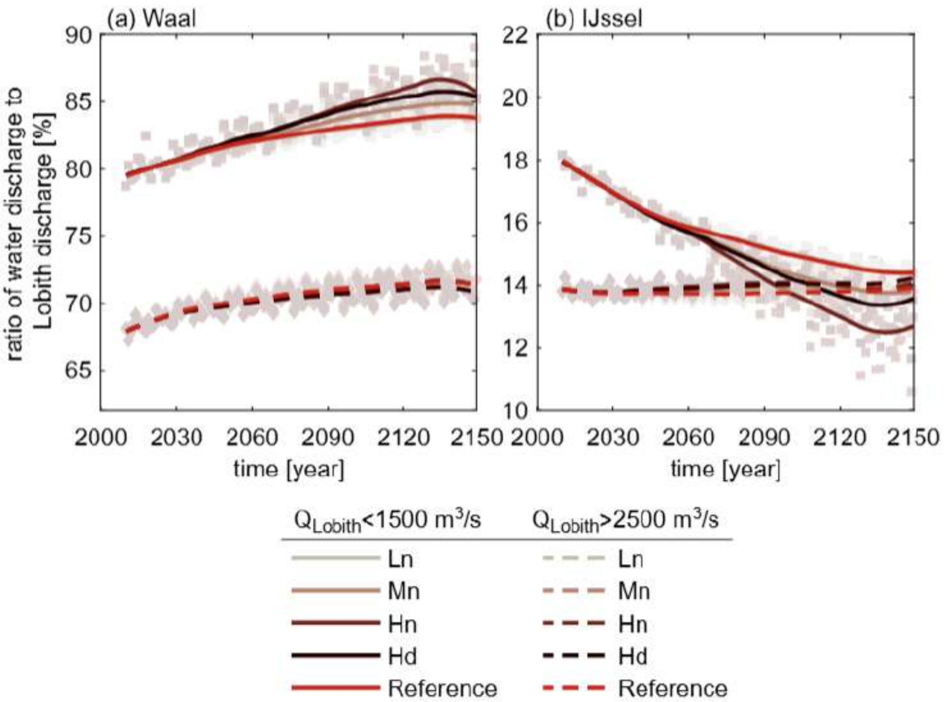

Figure 1: Waal-to-Lobith (left column) and IJssel-to-Lobith (right column) discharge ratios as a function of time, for low, middle and high (L,M,H) and dry and wet (d and n) hydrograph scenarios (Buitink et al., 2023) for high (i.e., open Driel-weir) and low (i.e., closed Driel-weir) Lobith discharges.

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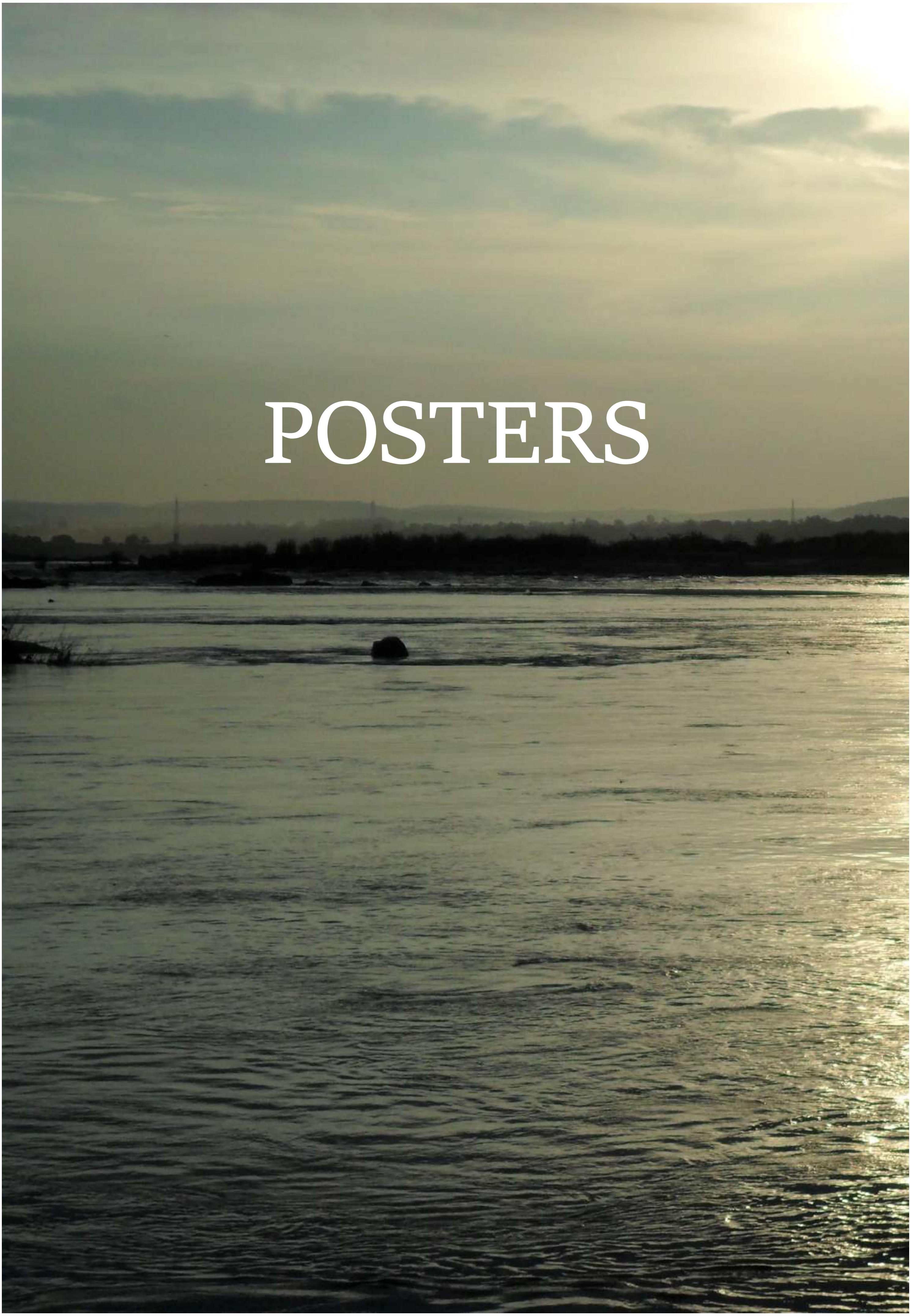

Discussing alternative fast dike breach flood models

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Keywords — Machine learning, conceptual model, flood modelling, real-time flood forecasting

Introduction

Dike breaches can have severe consequences due to the population centres that are often present in the hinterland. Therefore, it is vital to obtain insight in flood consequences. This knowledge can aid in setting up evacuation plans, and help design flood protection measures. Additionally, the uncertain nature of dike breach events means that authorities are interested in a range of scenarios that allow for making informed decisions.

Physics-based hydrodynamic models are often the tool of choice to simulate a flood event, including those after dike breaches. The main downside is the large computational time, prohibiting scenario analysis during time-sensitive emergencies. Therefore, alternative modelling techniques have been developed with the aim of decreasing computation times, while maintaining a reasonable accuracy. We will discuss two of such model types: (1) conceptual models and (2) machine learning models.

Conceptual models

Conceptual models do not contain equations of the physical processes that dictate the flow of water. They can be based on simplified rule sets derived from empirical relationships or from static inputs, such as elevation maps. Examples of conceptual models include the Rapid Flood Spreading Methods (distributing flood volumes across impact zones, delimited by ground depressions and raised structures, e.g. L'Homme et al., 2008); the planar models (extending water levels horizontally across a topography, e.g. Nobre et al., 2011); and cellular automata (local interaction between cells using simple transport rules, e.g. Jamali et al., 2019).

Machine learning models

Machine learning models are models relying on historical or simulated data to determine relationships between the variables of interest. A common form of machine learning models are neural networks. They are created through a process of training, in which known input-output pairs are repeatedly shown to the neural network. The model gradually adapts its internal structure to have its own output match the desired output as closely as possible.

An important part of the usability of machine learning models is how well they function in flood scenarios that were not included in the training. This ability is called generalization, and recent developments have shown that new techniques are increasingly able to be broadly applied. For example, machine learning dike breach flood models have been generalized to changing river discharge waves (Besseling et al., 2024) as well as different breach locations (Bentivoglio et al., 2023).

Discussion

Conceptual models and machine learning models both aim for a fast insight in the output of a computationally expensive model. The way they approach and reach this goal is different per method. Here, we discuss these differences for the aspects of computation time, set-up (time and data requirements) and model accuracy, which form a trade-off (Figure 1).

In general, machine learning models have very short computational times after the training, in the order of seconds. Conceptual models are somewhat slower, with computation times in the order of minutes. Still, both models would allow for obtaining model results during time-sensitive situations. These could include emergency scenarios, when decision makers need to address uncertainties during extreme events, as well as serious-gaming scenarios, when decision makers, the public or students need to obtain insight into the effects of certain flood safety measures on the flood consequences.

Regarding the set-up of the two model types, the machine learning models demand high computational resources and high data availability for the training process. In order to obtain a generalized machine learning model, some studies train the model using various computer-generated landscapes that resemble but do not represent real locations (e.g. Bentivoglio et al., 2023). This achieves impressive performance, but applying such models to real locations can result in less accurate performance due to properties of the

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real location not being reflected well enough in the training dataset. Therefore, recent studies have included fine-tuning simulations in the training, in which one simulation of the real location is included in the training data set (Bentivoglio et al., 2025). This requires a hydrodynamic model of the study area to be available. However, the field of machine learning has significantly advanced in the past years, and efficient training data set creation for such models is still improving. In the coming years, it is likely that machine learning models could reach accurate simulations for unseen locations without the need for such fine-tuning simulations.

Conceptual models require less input data than their machine learning counterparts and need no training before they can run. Because the DEM is often the only input, conceptual models can already be applied to any location without fine-tuning simulations. However, conceptual models such as the Rapid Flood Spreading Methods or the planar models have limitations to the application for dike breaches. First of all, extrapolating water levels horizontally from the flooding source may work well for river valleys in which rising river water levels are the cause of the flood, but this does not work for flat delta regions with point-source flooding such as dike breaches. Extrapolating river water levels into even lower-lying areas behind the dikes would lead to unreasonably large inundation extents. Additionally, the flood propagation from the breach into the low-lying hinterland cannot be simulated due to the level pool assumption; i.e. a filling/spilling scheme that starts filling from the lowest point. Therefore, many conceptual models are limited to giving an estimate of the final inundation extent. Future developments of conceptual models should aim to include a time-stepped approach, that resolves the flood propagation from the breach towards this lowest point, possibly using a topography-velocity relationship. It may be that this relationship will require a fine-tuning simulation for each real location. This challenge is subject of current research by the authors.

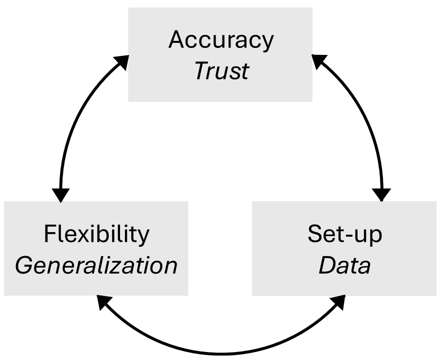

Figure 1. Trade-off for modellers and decision makers with respect to surrogate modelling in water management.

Finally, machine learning models seem to outperform conceptual models with regards to model accuracy. Recently, advancements in machine learning models have been focused on teaching the neural networks about the underlying physical processes of flood dynamics. As a result, these models have been able to accurately capture flow around bridge piers and large dike breach floods, for example. Important variables such as flood depth and inundation extents can both be accurately simulated. Conceptual models do not contain these physical descriptions of flood dynamics, and are therefore limited in their ability to accurately simulate the details of flood events. They are more suitable to reflect the general flood patterns and inundation extents throughout the flood event, with less accuracy on the flood water depths simulated.

Conclusion

After fast developments in the field of surrogate modelling, machine learning models seem to outperform conceptual models in the accuracy and simulation time aspects, though they require more complicated set-up processes and are more difficult for modellers to thoroughly understand. This raises the interesting question of which degree of accuracy modellers or decision makers would require before they accept the use of machine learning models or other surrogates in decision making (trade-off in Figure 1). Future developments of surrogate models will need to incorporate communication with decision makers and practitioners, in order to facilitate the adoption of these techniques in operational or educational water management.

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Benthic macroinvertebrate diversity in the Geul River, Netherlands in relation to large woody debris (LWD) and fluvial features

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Keywords — benthic macroinvertebrates, large woody debris (LWD), channel bed material, Geul River

Introduction

Benthic macroinvertebrates are commonly used as an indicator of ecosystem health. They serve multiple roles in the ecosystem by processing decaying organic matter, thus facilitating decomposition. Moreover, they present an important food source for fish and aquatic birds. In the adult stage of their life cycle, insects also become an important link in the food chains of terrestrial ecosystems (LAWA, 2024).

Large woody debris (LWD) is defined as any piece of dead wood (at least) partially submerged in the channel, that has diameter > 0.1 m and length > 1 m (Gippel et al., 1996). LWD serves to increase the pool to riffle ratio and overall channel heterogeneity (Hilderbrand et al., 1997), provides invertebrates with a source of food and shelter, and forms structures altering local flow patterns (Brouwer et al., 2020). This feature can provide macroinvertebrates with refuge during high flows (Baker et al., 2016). Historically, intense management of river channels has involved straightening and channelisation including the removal of LWD. Recently however, LWD has been recognized as an integral component of stream ecosystem health and numerous studies have been made linking LWD reintroduction to an increase in freshwater biodiversity, including the diversity of benthic macroinvertebrate species (Hilderbrand et al., 1997; Peeters et al., 2006; Thompson et al., 2017).

The overarching research goal is to provide a cross-sectional survey of the species composition of benthic macroinvertebrates in the Geul River. Site-specific LWD content as well as hydrological and geomorphic characteristics will be used as secondary variables to determine the relevance of these stream characteristics for invertebrate diversity. The study is focused on the macroinvertebrate populations in the middle section of the Geul River within the Netherlands, using primary data collected from an approximately 1.2 km reach of the river downstream of the Belgian border (Fig. 1).

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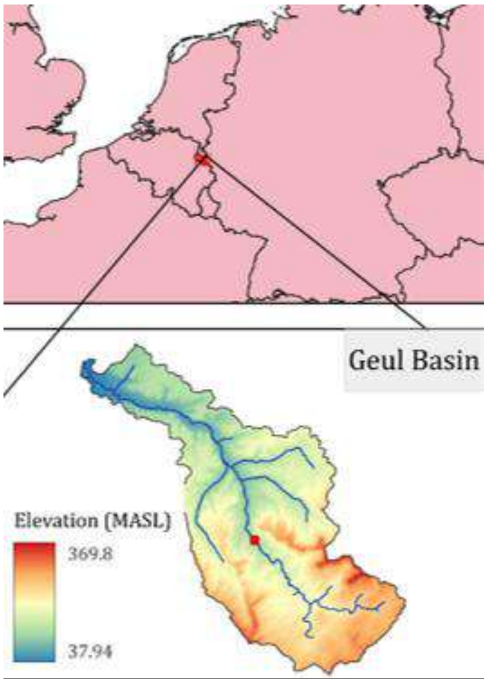

Figure 1. The Geul basin, showing the study site for field sampling.

Methods

Data was collected during two discrete sampling events: 20th-22nd September 2024, and 17th-19th October 2024. Samples were collected at 10 LWD sites and 9 control sites. At each site, three samples were taken in 1 m intervals, with three additional replication samples collected to account for different conditions between the two sampling events. Therefore, a total of 60 samples was collected. Samples were collected using a D-frame dip net with a 500-*um* mesh size (Tubić et al., 2024), according to a standardized method outlined in Fig. 2.

Each specimen was identified down to the lowest possible taxonomic level using a dissecting microscope (Bon Bonzemo, 2018; Smith et al., 2019; Fig. 3). Aggregations to Genus and Family were used most frequently, due to the trade-off between taxonomic detail and accuracy, as well as technical feasibility (Jones, 2008).

Figure 2. Illustrative flowchart of key data collection procedures; photograph b) sourced from Wadable Streams: Rapid Bioassessment Protocols (RBP) (n.d.).

Results

A total of 31 macroinvertebrate taxa was identified across all sampling sites. 30 of these were found at LWD sites, and 18 at control sites. On average, there were 146 individuals present in a LWD sample, as opposed to 82 in a control sample. The total number of *Ephemeroptera, Plecoptera* and *Trichoptera* taxa, most used as water quality indicators, was 10 and 6 at LWD and control sites. respectively, both amounting to 33% of total species diversity. The most common macroinvertebrate, and the only present in all samples, was *Gammaridae*. Simpson's Dominance Index at both LWD and control sites revealed a high dominance of all samples by *Gammaridae* (Table 1). Diversity t-test did not reveal a statistically significant difference between LWD and control samples. A statistically significant difference in species diversity was observed between pools and riffles ($p = 0.016$).

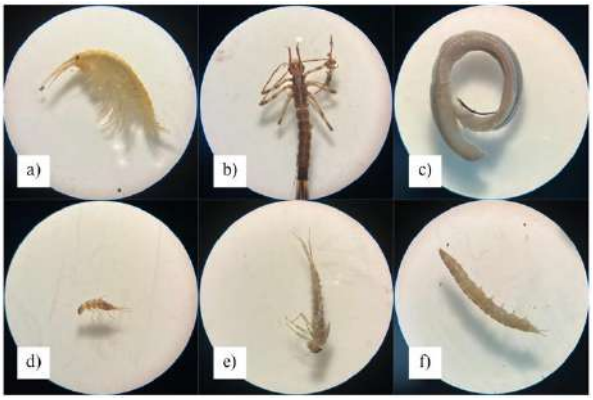

Figure 3: Examples of identified macroinvertebrates: a) Gammaridae), b) Calopterygidae, c) Hirundinidae, d) Perlidae, e) Baetidae, f) Pediciidae.

Table 1: Alpha diversity indices classified according to presence and absence of LWD, pools and riffles.

α Diversity	LWD	Control	Pool	Riffle
Taxa	30	18	26	27
Individuals	146	82	220	143
Dominance Index	0.83	0.78	0.60	0.44
Simpson Diversity Index	0.17	0.22	0.40	0.56
Shannon Index	0.63	0.72	1.30	1.78
Evenness Index	0.06	0.12	0.14	0.21

Conclusions

No significant effect of LWD presence on macroinvertebrate diversity was found. High *Gammaridae* dominance caused low diversity indices. There was significant difference between pool and riffle species diversity, in agreement with published literature (Baker et al., 2016).

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Automating sediment budgets with channel recognition

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Keywords — Sediment, Channel recognition, Western Scheldt

Introduction

Sediment budgeting is a means of quantifying sediment stocks and fluxes within a drainage basin (*Reid and Dunne*, 1996). In tidal basins and estuaries, the stocks to be quantified may be defined in terms of morphological units such as shoals and tidal flats. However, current methods rely on expert evaluation to identify suitable division units and delineate their boundaries (*e.g. Elias et al.*, 2023), which is problematic in dynamic systems.

Recent advances in the automated detection of landscape features have the potential to increase automation in sediment budgeting, potentially providing a reproducible and dynamic method for identifying relevant morphological units. The current work aims to achieve this using TopoTide (*Sonke et al.*, 2022; *Sonke*, 2024), a toolbox for the automatic detection of channel networks in tidal basins.

Two methods

The budgeting methods discussed here both rely on regularly collected bathymetries of the study area. The study area is divided into subunits, and the bathymetries are used to compute changes in sediment volume in those subunits over time. Coupled with records of sediment extraction and dredging and dumping activities, as well as published estimates of sediment fluxes in and out of the estuary, this may be used to deduce sediment fluxes between the subunits of the estuary. The difference between existing methods and our approach is in the way the estuary is subdivided.

The current method for creating a sediment budget uses manual morphological subdivision, as in *Elias et al.* (2023). Here, the Western Scheldt estuary is divided into units, termed *macrocells* (Fig. 1, top-left), each comprising a system with an ebb and flood channel, which are believed to be fairly consistent over time (*Wang et al.*, 2001). Some of the macrocells are further divided into main and secondary channel areas. Although this division is based on units with coherent sediment transport behaviour, the boundaries of the macrocells cut through the bars in the estuary, which are the actual sediment stocks (or sinks). Additionally, a single set of macrocell boundaries is used throughout the timeseries.

An automated method

The new method breaks up the study area into units that can reasonably be regarded as separate sediment stocks in between channels. We use automated channel recognition on each bathymetry, then use (some of) the detected channels as bar boundaries along which we subdivide the landscape. TopoTide detects channel paths by identifying the path of steepest descent between adjacent saddles in the landscape. It also assigns each channel a significance value, δ, such that the main ebb channel has the highest significance (*Sonke et al.*, 2022).

Case study: The Western Scheldt

The recent Western Scheldt estuary morphodynamics are recorded in 48 bathymetries, taken every 1-2 years from 1995 to 2023. Here we use only the three highest-significance channels from each year of the dataset to subdivide the landscape.

By merging these simple channel networks across the entire time series, we get a more complex network that reveals the major bars in the estuary (Fig. 1, top-right). We use these as fixed boundaries for the major bars to analyse all time steps, thus we can be sure that any volume changes we observe are due to sedimentation or erosion of the bar surface, and not changes in area due to channel migration.

This division also yields thousands of ”channel slivers” - tiny areas formed by the intersection of the same migrating channel at different points in time. Each of these slivers will have been part of the channel bed during at least part of the period covered by the dataset. This provides some initial identification of channel

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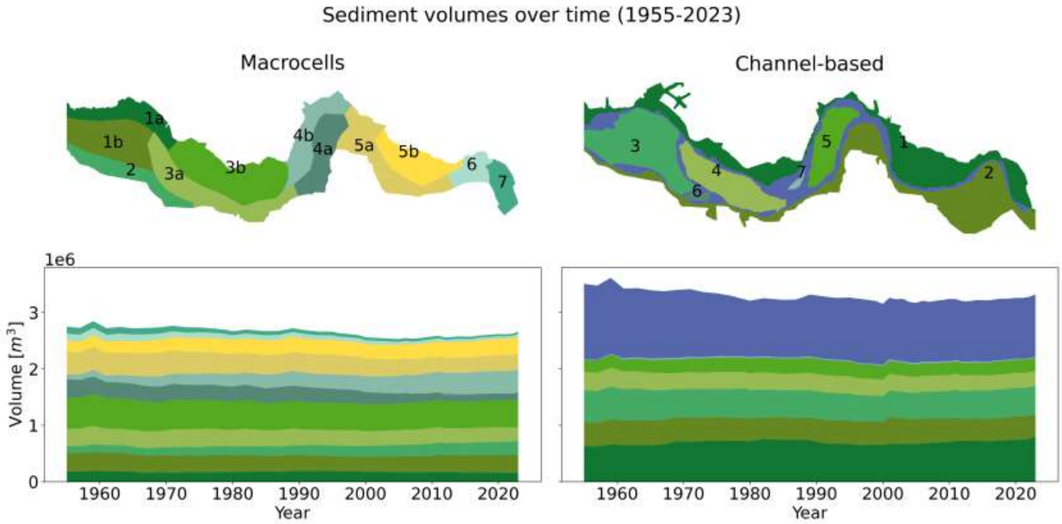

Figure 1: Subdivision of the Western Scheldt by the manual and automated method (top row) and the volume change over time in the resulting polygons (bottom row). The colours of the ribbons and polygons correspond.

areas (shown in blue in Fig. 1) based purely on the data, narrowing down the areas we would expect to be most dynamic.

A comparison of the two subdivision approaches (Fig. 1, top row) reveals a key difference - while the macrocells approach divides the estuary along two axes (along-flow and cross-flow), the channel-based approach divides it only in one (along-flow), picking out more elongated shapes, including the entire north and south bank of the estuary.

The methods pick up different dynamics. In the early 2000s, a sharp increase is observed in the south bank (polygon 2) in the channel-based approach, which is entirely absent from the macrocells analysis. This change likely occurred in the Saeftinghe salt marshes, near the south-eastern edge of the estuary. This area was deliberately excluded from the macrocells and deliberately included in the channel based approach.

Secondly, in the 1980s and 1990s, changes are visible in macrocell 3b which in the channel-based analysis are seen in the channel polygon (blue). These are due to the large channel migration visible in that area (roughly at the centre of the estuary).

Next steps

The next step in this study will be to trace the changes identified in the Western Scheldt case study. An attempt will be made to relate each of these changes to observed morphological changes (channel migration, avulsion, deepening; bar aggradation and degradation) and to known events (dredging and dumping, sediment extraction, artificial channel deepening). The results of these will be used to infer how sediment flows within the estuary.

Conclusion

Sediment budgeting by automated recognition of morphological features picks up morphodynamics missed by static subdivision.

Acknowledgements

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Describing and modeling river dune unsteadiness

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Keywords — Finite amplitude dunes, River discharge, upper stage plane bed

Introduction

Describing and predicting the longitudinal extent, amplitudes and shapes of riverine dunes as a function of transport stage (induced e.g. by the river discharge) has been subject to a multitude of experimental (Venditti et al., 2016), highly idealized (Colombini and Stocchino, 2008) and more complex (Duran Vinent et al., 2019, Van der Sande et al., 2025) model studies. However, the temporal variability and unsteadiness (Bradley and Venditti, 2019 – see Figure 1) of riverine dune characteristics as a function of transport stage has received less attention in the idealized modelling literature (De Lange et al. 2025 (in preparation)).

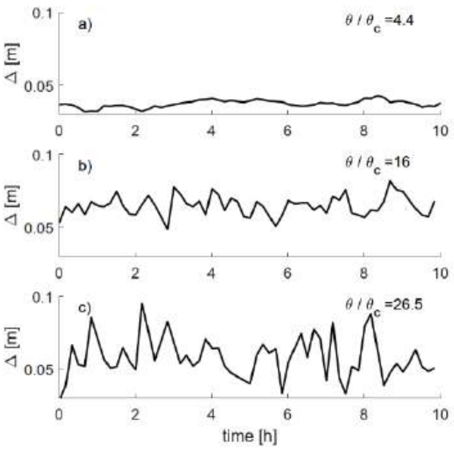

Figure 1. Dune height (vertical axis) in time (horizontal axis) for the three controlled flume experiments of Bradley and Venditti (2019). Between the flume experiments, the flume discharge and thus the transport stage was varied. The ratio of the bed shear stress and the critical shear stress is indicated.

This temporal variability is however important to understand, because to characterize dune properties in the field (e.g. to estimate the hydraulic roughness of rivers), usually a snapshot of the dune field is taken, which is then assumed to characterize the dune field over larger time scales. At high transport stages, where dune unsteadiness is observed to be large, such a temporal generalization of the dune properties may be unwarranted.

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Methods and outlook

The projected contribution of this postdoctoral work - which is in the starting phase – is twofold. Firstly, a set of controlled flume experiments will be conducted, with a focus on describing dune characteristics as a function of transport stage.

Figure 2. Flume setup at the Water and Sediment Lab at Wageningen University.

Secondly, an idealized, time - dependent morphodynamic model that allows for simulating the evolution of a dune field as a function of varying riverine discharge will be developed. The purpose of the model is to help understand the dune characteristics, with a focus on unsteadiness in terms of (yet to be determined) parameters and variables. As a first attempt, we will develop a spatially spectral dune model based on sigma coordinates and with periodic boundary conditions - with degrees of idealization and parametrizations taken from very simple, semi-analytical models (Kroy et al., 2002) to highly complex models (Duran Vinent et al., 2019, Van der Sande et al., 2025).

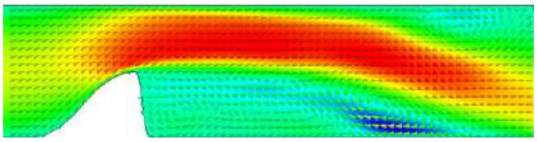

Figure 3. Preliminary idealized morphostatic model of non-hydrostatic flow over a river dune. Red is rightward flow, blue is leftward flow.

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A high-resolution paleoflood record of the Meuse, using advanced age-depth modelling

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Keywords — Sedimentary proxies, Paleohydrology, End-member analysis

Introduction
Recent extreme precipitation events in northwest Europe highlight the increasing flood vulnerability of river catchments to climate change (Kreienkamp et al., 2021). While extreme weather events are expected to become more frequent with warming, the response of flood regimes remains uncertain (IPCC, 2021). Monitored discharge records rarely exceed 100 years in length and severely lack in the recording of extreme events. These are necessary for reliable risk assessments, and to infer potential flood regime changes due to climate change. Paleoflood records derived from sedimentary proxies and dendrochronological information can provide valuable insights into extreme event occurrences and flood regime changes.

Method
This study examines a residual channel fill from the river Meuse, near Maasband in Limburg. The fill was sampled at 1-4 cm resolution. The samples were analysed for grain size distribution. These distributions were unmixed using end-member modelling (Paterson & Heslop, 2015). The two coarsest end-members (EM3 and EM4) were considered as indicative for flood magnitude (cf. Toonen et al, 2015). The finer end-members represent suspended and wash load fractions, which are assumed to show limited variation across different flood magnitudes. The flood chronology was established using radiocarbon dating and Bayesian non-linear age-depth modelling, incorporating sedimentary parameters (EM3+EM4) as an indicator for accumulation rates. This advanced age-depth method yields more realistic age-depth modelling results with a reduced uncertainty (Minderhoud et al., 2016), compared to a traditional linear age-depth model.

Grain-size results
The modes of the different end members are (EM1-4): 32 µm (fine silt), 53 µm (coarse silt), 210 µm (fine sand), and 595 µm (coarse sand), respectively. Three depositional phases are distinguished in the end-member abundances (Fig. 1). The first phase (350-407 cm) reflects the initial abandonment stage of the channel with frequent bed load deposition. Next, the contribution of coarse end members decreases between 154-350 cm, and most likely reflects a fluvio-lacustrine environment. The coarsening in the last phase (84-154 cm) reflects enhanced energetic conditions, possibly caused by channel relocation, an intensification of the flood regime or the shallowing of the infill.

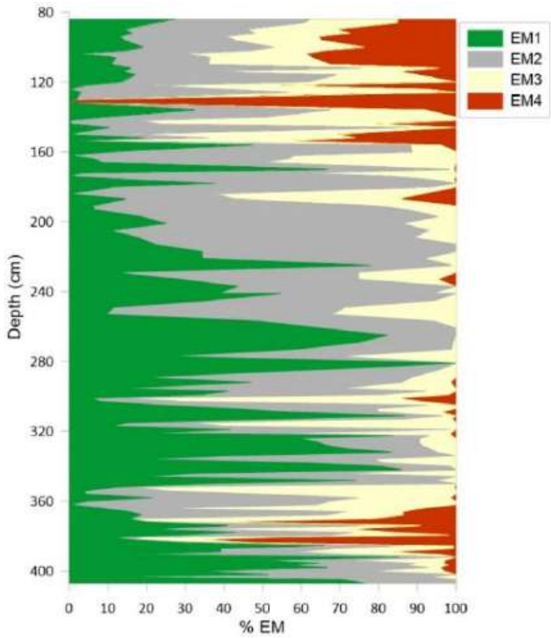

Figure 1. Cumulative end-member abundances, reflecting grain-size variability with depth in the Maasband residual channel.

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Non-linear age-depth modelling

The non-linear age-depth model incorporates grain-size data to modulate sedimentation rates. Larger grain sizes thus result in higher sedimentation rates (Fig. 2). Compared to a linear model, a calculated time increment (Eq. 1) determines the estimated sedimentation rate for each sample (Minderhoud et al., 2016). The substantial age differences between the linear and non-linear model of up to 90 years, underscore the need for more realistic age-depth models, particularly for accurately pinpointing the age of extreme events and their correlation with climate proxy data.

$$\Delta t_i = GS\_param_i^x D_i \times \frac{T_N}{\sum_{j=1}^{N} GS\_param_j^x D_j} \qquad (1)$$

Equation 1. Δt_i is the time increment for sample i, calculated using the grain-size parameter (GS_{Param} = EM3+EM4) raised to exponent x and multiplied by sediment thickness D_i. Exponent x is optimized by regression, minimizing the difference between modelled ages and independently radiocarbon-dated layers. N is the total number of samples and T_N is the time duration of the interval.

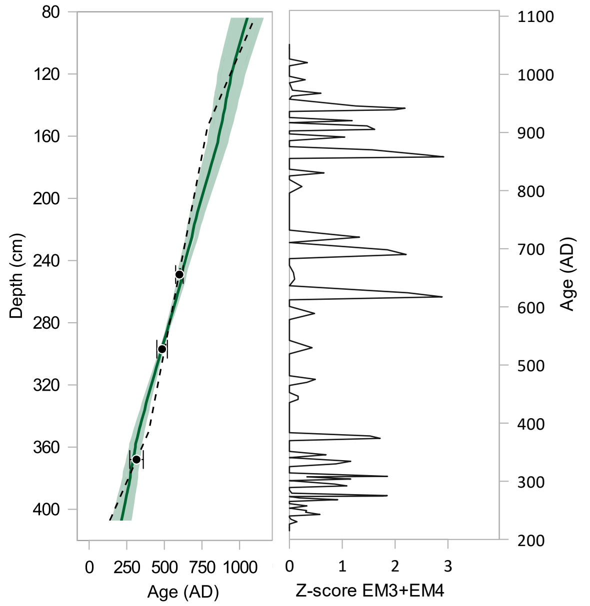

Figure 2. left: Non-linear age depth model (green), with the uncertainty range in light geen, based on sedimentology and radiocarbon dating (black dots, with ±1σ uncertainty) compared with a linear age-depth model, dashed line (U-sequence OxCal (Ramsey, 2009). Right: The Maasband flood record based on normalized EM3+EM4 values.

Flood chronology

Using the ages of the non-linear model and flood magnitudes based on normalized (z-score) EM3+EM4 values results in a flood chronology for the Maasband residual channel. Flood magnitudes peak between 200-400, 600-750, and 850-1000 AD (Fig.2). Strikingly, this covers both warm and cold phases. The Late Roman Period is a relatively cold period in Europe (refs. in Toonen et al., 2025). The second phase, from 600 to 750 AD, is also identified as a cold period in western and central Europe. This phase coincides with increased sediment fluxes of the Meuse (Toonen et al., 2025) and flood activity in the Rhine catchment (Toonen et al., 2015). The final phase, from 900 to 1000 AD is a generally warm period, the Medieval Climate Optimum. The floods in this period correspond with other Meuse flood records.

Outlook

To further refine the age-depth model, a tree-ring chronology from in-situ trees near Stevensweert (~20 km downstream) will be used to better constrain the timing of specific extreme events that induced major hydrological stress in the Meuse valley. These results contribute to the understanding of Late Roman to Medieval flooding and demonstrate how the Meuse flood regime has changed in response to past climate variability. This is increasingly relevant in the context of predicted climate change impacts. This high-resolution approach enables comparison of the flood record to NAO, solar, volcanic and regional climate records, as well as other river flood records, providing a broader perspective on the climatic drivers of extreme flooding.

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Public Perception of Erosion and Flooding along the Geul River, Limburg (NL)

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Keywords — Public perception, nature based solutions, flooding, channel bank erosion, Geul River

Introduction

Research that explores public perception of river management prioritises largely engineered and navigable rivers targeted by the Room for River projects such as the Waal, Rhine, or Meuse (Verbrugge and Van Den Born, 2018; Van Heel and Van Den Born, 2020; Buijs, 2009). Few studies have examined smaller Dutch rivers not utilized for navigation, including the Geul River. The Geul River's position within an 'erosion-sensitive' landscape in South Limburg that is susceptible to increasing precipitation intensity, calls for urgent academic attention. Research should strive to understand how current and proposed nature-based solutions (NBS) which aim to mitigate further damage inflicted by a changing climate are perceived and accepted by local populations in the Geul valley. Thus, there remains a gap in understanding public perception and support for NBS within various watersheds in the Netherlands (Turkelbloom et al., 2021).

Since the July 2021 floods that heavily affected the Geul valley, it is possible that perspectives on expected damage and support for river management approaches have changed. Belief of expected damage is found to be influenced by memories of near floods, meaning people who reside in the heavily flooded urban centres in 2021, such as Valkenburg and Gulpen, may exhibit a unique urgency and perception towards addressing erosion and water retention strategies in the Geul valley (O'Neill et al., 2016; Van Heel and Van Den Born, 2020; Strijker and Kok, 2022). Hence, an investigation into the specific social factors and interconnections that influence perceptions of residents along the Geul remains to be studied and understood to ultimately inform successful integrated river management projects (Van Heel and Van Den Born, 2020).

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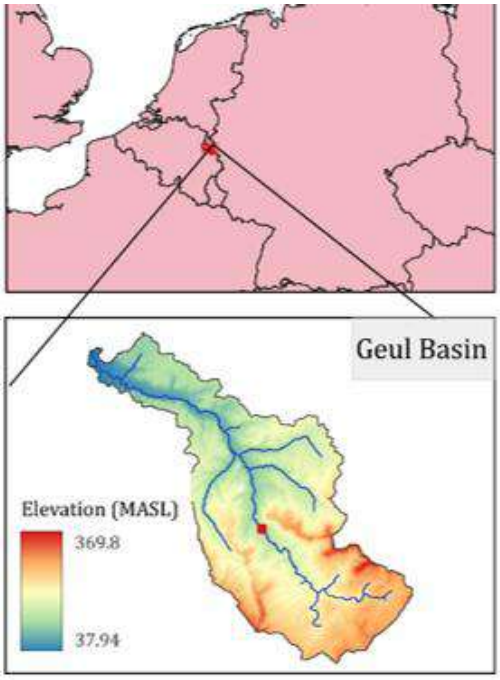

Figure 1. The Geul basin study site for erosion analysis and survey collection.

Methods

The focus of this study includes the results from a survey (online and in-person) and supporting interviews that measure respondents' awareness of erosion and flooding in the Geul and evaluate how selected independent variable groups influence support for river management approaches. To collect survey responses both online and in target areas such as populated urban centers, convenience sampling was employed. Posters with QR codes (Figure 2) linked to the online survey on Google Forms were distributed along the river and in towns in the Dutch catchment of the Geul. Answers to the survey statements of each variable group were measured on a Likert scale (1= strongly disagree and 5 = strongly agree) to allow for quantitative analysis as demonstrated in river perception studies (Verbrugge and Van Den Born, 2018; Buijs, 2009) and statistically analysed.
The study assesses the erosion and flood regime using a combination of standard GIS

methods and publicly available data on water levels in the Geul from Limburg Waterschap (P.F. Hudson, personal communication, January, 2025; Waterschap Limburg, n.d.e.). Using GIS and satellite imagery, a supporting visualisation of the Geul's erosional patterns and recent geomorphological history aims to describe the main issues and changes with which stakeholders are afflicted.

Figure 2. QR poster utilised for online survey collection.

Results

Survey respondents generally perceive flooding and bank erosion to be increasing in the Geul in recent years. Perceptions on erosion and its impact on hydrology and geomorphology are highly variable in relation to calculated rates. Spearman correlation and Kruskal Wallis tests indicate that spatial variables, including residence within the Geul valley, residence next to a river or interaction with different sections of the Geul, significantly influence perceived safety from flooding and satisfaction with flood management. Support for government funding and implementation of NBS in the Geul is high among survey respondents. Climate change awareness and support for NBS share a positive relationship.

Conclusions

The influence of socio-economic factors is contextually specific and are often mediated by geographical characteristics (O'Neill et al., 2016). Understanding drivers of support for various river management solutions in the Geul is increasingly salient within a context of climate change and perceived increase of flooding.

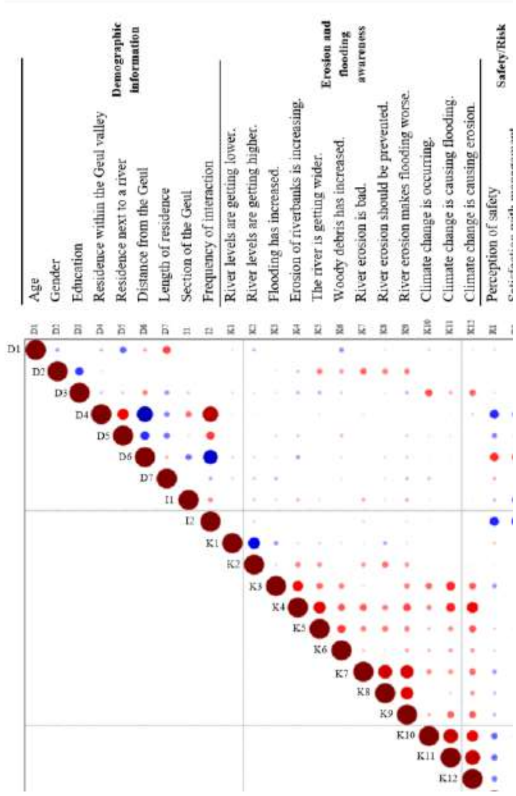

Figure 3. Spearman rho correlation matrix for analysed demographic and dependent variables. Made in Paleontological Statistics Software Package 4.17.

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Impact of Groyne Lowering on Groyne Field Bathymetry

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Keywords — groyne fields, groyne lowering, spatio-temporal variations

Introduction

Groynes are commonly found in lowland rivers, where they help maintain a navigable main channel depth and prevent bank erosion. The areas between them, the groyne fields, mainly consist of sediments. The morphodynamics of groyne fields have been studied through laboratory experiments (Yossef & De Vriend, 2010) and numerical models (McCoy et al., 2008; Constantinescu et al., 2009). However, these controlled experiments do not capture the spatial variability observed in natural settings. Based on field measurements Ten Brinke et al. (2004) hypothesized that groyne fields gradually erode under the influence of shipping, while substantial sedimentation occurs during floods. Our objective is to provide a more thorough understanding of the natural variability in groyne field bed level changes with the ultimate purpose to assess the potential and efficacy of groyne field nourishments. To this end, we first establish a baseline representing the natural variability in groyne field bed level changes. Additionally, understanding the factors that govern this baseline is essential.

Methodology

To determine the bed level changes of 40 groyne fields in three sections along the Waal River, we use multibeam data of 2018 and 2021 as an example (Figures 1a-b). Section 1 is located on the right (northern) bank in a large outer bend and features non-lowered groynes. Section 2 sits on the left (southern) bank in a reach with smaller bends, where the groynes are lowered. Section 3 is positioned on the right bank just downstream of section 2, also with lowered groynes. In sections 2 and 3, the groynes were lowered by 1.5-2 meters between 2008 and 2010. We define a groyne field as the area between two consecutive groynes, the normal line between their tips and the vegetation line (Figure 1c). Bed level changes are normalized by the groyne field areas for direct comparison of sedimentation rates.

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Preliminary Results

Figure 2 presents the measured bed level changes for the three sections. For sections 2 and 3, the erosion rates reach up to almost 15 cm/year, which is about 10-15 times larger than section 1 with non-lowered groynes. For reference, the erosional trend in the main channel is about 1-2 cm/year (Chowdhury et al., 2023). The differences in erosion rates between the lowered and non-lowered reaches can be attributed to the fact that lowered groynes are submerged more often (approximately 10% and 40% of the time for non-lowered and lowered groynes, respectively). For fields with lowered groynes, this increased submergence leads to higher flow velocities for a longer duration, resulting in increased erosion. Similar observations were made by Busnelli et al. (2011) who considered the initial response of groyne fields to groyne lowering. Interestingly, the rates of bed level change differ significantly between the different fields with lowered groynes. We hypothesize that the large variation between the bed level changes of fields with lowered groynes is dominated by two factors: secondary flow effects in river bends and the differences in navigation specifications (e.g., vessel dimensions, draught, distance to groyne field) between the left and right bank of the river.

Future Work

Continued research will evaluate our hypothesis regarding the influence of secondary flow in river bends and the navigation specifications on the sedimentation rates. Furthermore, we will investigate the spatio-temporal variations within groyne fields by identifying dominant morphological features, such as representative bed profiles and deposition patterns of groyne fields. To better understand large-scale temporal changes, we will analyze LIDAR data of bed level in emerged parts of the groyne fields before and after the major river interventions, creating a time series of measured bed level changes. The integration of these analyses will offer a more comprehensive understanding of the spatio-temporal variations observed in groyne fields along the Waal River.

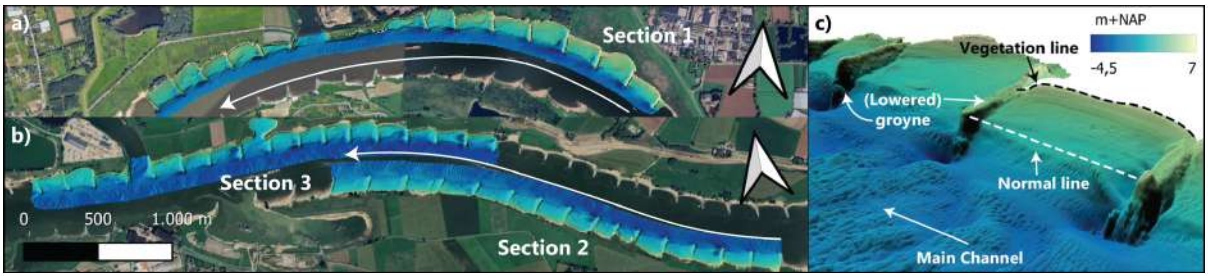

Figure 1: a) Section 1 near Gendt (rkms 877-881) and b) section 2 near Winssen (rkms 894-897) and section 3 near Dodewaard (rkms 896-899). The main channel flows from right to left. c) Close-up of some groyne fields. A distinction can be made between lowered and not yet lowered groynes. The vertical scale is exaggerated with a factor 7.

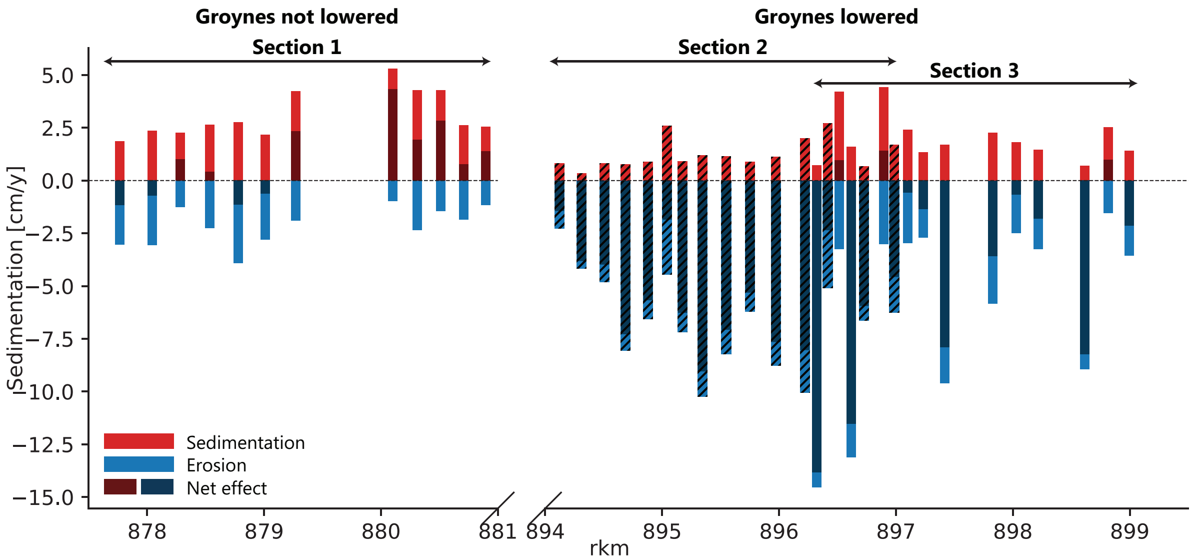

Figure 2: Measured bed level change rates between January 2018 and July 2021 for the three different sections. The lighter bars represent the amount of sedimentation and erosion present per groyne field, whereas the darker bars represent their combined net effect. The bars for section 2 (left bank) are marked to distinguish them from section 3 (right bank).

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Simulated Study of the interaction between horizontal flow structure and suspended sediment transport in partially vegetated channel

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Keywords — horizontal eddy viscosity model, vegetated flow, suspended sediment transport

Introduction

The presence of instream and riparian vegetation significantly affects the flow field of rivers, which in turn impacts sediment transport (Vargas-Luna et al., 2016, Calvani et al., 2023). Few studies, however, have investigated the interaction between horizontal flow structure and suspended sediment transport. Hamidifar (2019) conducted a flume experiment investigating the flow field structure in a half-vegetated channel configuration and found strong horizontal vortices. Other experimental works observed the strong transverse sediment transport process along the interface area between vegetation and open channel (Box et al., 2018; Xu et al., 2022). As for numerical simulations, few studies focus on the reproduction of the physical processes between the partially channel vegetated flow and suspended solids. The present simulation studies mainly focus on the small-scale large eddy simulation model, which has not been applied in practice (Wang et al. 2021). This study focuses on the effect of horizontal viscosity models on the simulation of suspended solid transport in a partly vegetated channel in the most applied Reynolds-averaged Navier-Stokes model. Three viscosity models: the constant model, the Elder model, and the Hybrid viscosity model are applied to reproduce an experimental work selected from the literature.

Methodology

Sharpe's (2003) experimental work on suspended sediment transport in half-vegetated flows is selected for validation in this study. Experiments were conducted in a straight flume made of smooth concrete with 12 m in length, 0.76 m in width and a constant slope. Vegetation was represented as emerged 1 cm-diameters rigid cylinders. The whole vegetated area was set as a staggered pattern covering 11 m in length and 38 cm in width located on the left side of the flume starting from the upstream. Rough Nomad matting was applied at the bottom of the vegetated section to capture sediment deposition. Four 0.306 m-long measurement sections were designed to capture the deposition inside vegetation patterns.

For each case, the upstream discharge remained constant, and a relatively uniform flow was established. The transverse streamwise velocity distribution was measured at the cross-section 7 m from the upstream boundary. Then, the sediment material was fed as a line source with a constant rate of 1.73 g s^{-1} from the water surface via a 0.38 m conveyor belt. The line source was located at the open channel side of the 1 m cross-section from the upstream, with 2 hours input duration.

As for the viscosity models, the Elder model and the Hybrid model are considered. Van Prooijen et al. (2005) proposed that, when the water depth is regarded as the characteristic length scale and friction velocity is regarded as the velocity scale, the eddy viscosity can be calculated by the Elder formulation:

$$\nu_{t,E} = \alpha \sqrt{c_f}\, uh \tag{1}$$

where α is a constant of the order of 0.1, u is depth averaged velocity and h is the water depth at the calculated location, and bed friction coefficient c_f is calculated as:

$$\frac{1}{\sqrt{c_f}} = \frac{1}{\kappa}\left(\ln\left(\mathrm{Re}\sqrt{c_f}\right) + 1.0\right) \tag{2}$$

Recently, Truong and Uijttewaal (2022) proposed a hybrid eddy viscosity model considering the impact by the bottom turbulence, the presence of vegetation and the

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occurrence of the large horizontal coherent flow structures in the partially vegetated channel:

$$\nu_{t.H} = \begin{cases} \alpha\sqrt{c_f}\,uh_m + \frac{h_m}{h} h_r^2 \beta^2 \delta^2 \left|\frac{du}{dy}\right| (outside) \\ \alpha\sqrt{c_f}\,uh_m + \frac{1}{8} C_t^{-2} C_d D u + \frac{h_m}{h} h_r^2 \beta^2 \delta^2 \left|\frac{du}{dy}\right| (inside) \end{cases}$$

(3)

In which h_m is mean water depth: $h_m = 0.5*(h_c + h_v)$, which is equal to h in this study , h_c is the water depth in the open channel region; h_v is the water depth inside vegetation region; h_r is the water depth ratio: $h_r = h_v / h_c$, which equal to 1 here; β is a proportionality constant depending on the transition slope, which is 0.0625 in this study; δ is the mixing length, which is 0.28 m calculated based on $y_{5\%}$ and $y_{95\%}$ in this study; C_t is a constant of proportionality which depends on the shape of the streamwise velocity profile; C_D is the drag coefficient of a single stem, both C_t and C_D are equal to 1 theoretically. The 2DH model is established in Delft 3D in this study. The grid size is set as 1cm*1cm, and the time step is set as 0.001 minutes. The upstream boundary conditions are set as constant discharge, and the downstream boundary condition is set as water level. The Baptist approach is used to represent the effects of vegetation. Based on the experimental data, the bottom roughness is set as a manning coefficient of 0.021 in the vegetated area and 0.0145 in the open channel area for the cement mixture bottom. The stable flow condition is first established, and then the sediment is added evenly via 38 subdivided discharge cells at the corresponding cross-sections. Sediment is fed at a very high concentration (45.53kg m^{-3}) with a small discharge (1cm^3 s^{-1}) in each computational cell to neglected the effect of the excess input discharge on the main flow. Sediment transport processes are simulated using the 2DH advection-diffusion equations, in which sediment settling velocity is set as 20 mm/s, which corresponds to a grain size of 0.2 mm.

Preliminary results

For all cases with the three viscosity models, the flow field results are analyzed by comparing the water depth and velocity distribution with measurements to assess the performance of the viscosity models in replicating the flow structure. Preliminary results indicate that, in terms of velocity distribution, vortex development is observed only in the Elder model results (Figure 1b). Conversely, the hybrid model does not exhibit turbulent structures as the transverse hydraulic dynamics is supposed to be represented by the modelled turbulent viscosity (Figure 1a).

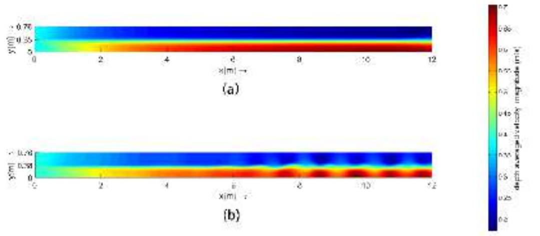

Figure 1 Velocity distribution in Baptist vegetated models in which the horizontal background eddy viscosity is set as (a) Hybrid model;(b) Elder model

Successively, for sediment transport, the final sediment deposition distribution and transverse deposition profiles at each measurement section are analysed and compared with measurement data. Preliminary results indicate that all three viscosity models underestimate sediment deposition, which may be due to the simplified representation of vortex flow structures and also, the simplification of the 2DH model in representing the 3D sediment transport process.

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The influence of riverine wetlands on flood and drought mitigation: a case study for the Aa, the Netherlands

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Keywords — Wetlands, SWAT+ modelling, Hydrology

Introduction

Due to a changing climate, there will be more extreme weather, influencing the discharge in river systems. Large discharges can cause flooding, while small discharges, due to longer dry periods, can cause droughts (IPCC, 2023). Proper water management in rivers, like the implementation of Nature based Solutions (NbS) can reduce the impacts of these natural hazards while at the same time providing environmental, economic, and social benefits (Nelson et al., 2020). There is a wide range of NbS possibilities, with riverine wetland creation or restoration being one of them. Riverine wetlands have been proven to be effective in reducing flood risks and droughts (IPCC, 2023; Y. Wu et al., 2023), however there is still a lot unknown on the functioning of these NbS regarding flood as well as drought reduction as there are many factors, like for example size, location and vegetation that influence the functioning of wetlands (Mohamed et al., 2012; Ogawa & Male, 1990; Tang et al., 2020). Therefore, it is necessary to look further into the hydrological functioning of wetlands.

The objective of this research is to investigate if a wetland is a suitable solution for flood and drought reduction in the Aa catchment, the Netherlands and to provide a recommendation on how to adapt for climate change based on the results of this thesis. In this "suitable solution" can be defined as a solution providing flood and drought mitigation for the Aa river for the current and future climate taking climate change into consideration.

To reach this aim four research questions were set up:

1. *What riverine wetland type(s) can be implemented best in the Aa and how to model these wetland types in SWAT+?*
2. *How can suitable locations for wetland creation or restoration in the Aa be defined?*
3. *What is the influence of riverine wetlands on flood mitigation in the Aa in the current and future climate?*
4. *What is the influence of riverine wetlands on drought mitigation in the Aa in the current and future climate?*

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Methods

Case Study

For this research a case-study is selected namely the Aa river basin in the Netherlands (Figure 1), which is part of the LIFE-IP project which explores coupling opportunities, like nature development, recreation, drought and flooding, for making streams climate-proof (Kennisportaal Klimaatadaptatie, n.d.). The Aa experienced floods and droughts over the years. This indicates a need for change in this area. Due to the multifunctionality of NbS, a wetland might be a suitable option to tackle these problems and find coupling opportunities.

Figure 1: Study area of the Aa (North-Brabant, the Netherlands)

Literature study

The type and location of a wetland can have a large influence on the functioning of riverine wetlands. To choose a suitable wetland type and location in the Aa a literature study will be performed combined with some unstructured interviews with experts. For the location this will result in areas physically suitable for wetlands and a criteria list, which will be used to determine the best location from the suitable areas. For the different wetland types there will be looked into historically present wetlands in the Aa basin, but also into wetlands in comparable landscapes. By doing some further literature research there will be looked into how to model the found wetland types in SWAT+, which will be used to model the hydrological effects of implementing a wetland which will be based on the key performance indicators (KPIs) in Table 1.

Table 1: Key performance indicators for measuring the hydrological effect

Hazard	**KPIs**
Flood	Peak flow, Rise-time, Lag-time between precipitation and flood peak, Duration, and Flood volume
Drought	Surface water availability

SWAT+ Model

SWAT+ is a widely used hydrologic model and has been applied in many watersheds across the globe for simulating river flows with application to land use and climate change, soil erosion, crop yields and water quality in river basins (Bieger et al., 2017) and therefore will also be used in this study to answer research question 3 and 4. In this model first the current situation will be modelled. Based on the results of research question 1 and 2, different wetland types will be implemented in the model at different locations. In these different models, different meteorological inputs will be used to model the influence of the wetland in the current as well in a possible future climate, using the KNMI23 climate scenarios.

Expected Results

It is expected that many riverine wetland types can be implemented in the Aa basin. The largest difference will be in forested or non-forested wetlands (Decleer et al., 2016). It is expected that the forested wetland retains the water longer than non-forested wetlands and therefore might have a better flood mitigating function than wetlands without trees.

Wetlands develop and exist in wet areas. This means when restoring or creating a new wetland the area should have a specific soil wetness (Decleer et al., 2016). Next to this physical demand for wetland restoration or creation, a list of criteria will be set up, which will include for example the available size, upstream location, and ownership of the area.

Looking into flood mitigation it is expected that the implementation of a wetland in the Aa basin, will reduce discharge peaks upstream, which is also found in the research of Loucks (1989) (**Error! Reference source not found.**). However, to which extend, will also be dependent on the type and location of the implemented area.

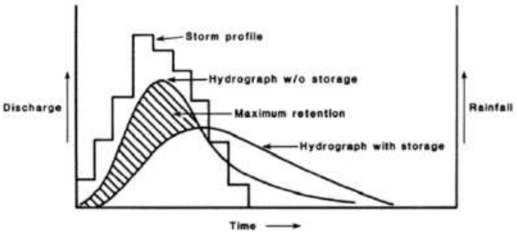

Figure 2: Expected hydrograph with wetland, adapted from Loucks (1989)

Also, for drought mitigation it is expected that it will positively effects droughts. In the wetland water will infiltrate and will be released in dry periods in the form of baseflow also found by Wu et al. (2023), which also reduces extremes in low discharges. Also, to which extent droughts will be mitigated by wetlands, will be dependent on the type and location of the implemented area. As more extreme weather is expected in the future, it is expected wetlands can also contribute to flood and drought mitigation in the future climate.

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Acoustic observation of suspended sediment in the hyperturbid Ems Estuary

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Keywords — Field work, ADCP, Acoustic inversion

Introduction

Quantification of sediment fluxes is essential for managing estuaries, tidal rivers, and coastal regions. The estimation of sediment fluxes primarily relies on observations of suspended sediment concentration (SSC), especially in hyperturbid environments. Acoustic measurements using an Acoustic Doppler Current Profiler (ADCP) offer a non-intrusive method to simultaneously obtain velocity and concentration data, which has been applied to various river systems Sassi et al. (2012); Haught et al. (2017). While many studies suggest that the acoustic calibration to SSC is time-dependent, the extent of this dependency remains unclear. This study presents acoustic observations from the Ems Estuary, highlighting temporal variations in calibration coefficients.

1. Research area and method

Data were collected in the Emder Fahrwasser, a section of the Ems Estuary located along the Dutch-German border, where a highly concentrated benthic suspension is more likely to develop in the water column close to the bed. Boat surveys were conducted using a framed ADCP system (Fig. 1). The frame was equipped with a downward-looking ADCP, four Verderflex pumps, and plastic tubes. During measurements, the boats remained clamped to an anchored buoy while the frame was gradually lowered toward the bed. It hovered approximately 2 meters above the bottom for several minutes, allowing for velocity and backscatter measurements and four samples collecting within the near-bed layer. Based on the sonar equation, the calibration method is adapted for high concentrations by considering temporally varied but vertically constant acoustic parameters. The addition of a temporal component in the calibration process is applied using a sinusoidal function.

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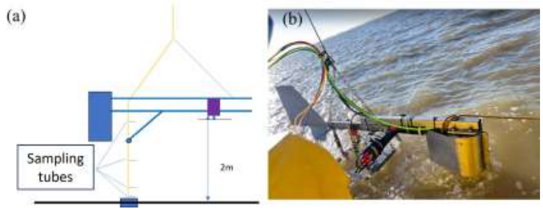

Figure 1: Conceptual structure and picture in fieldwork of the framed ADCP

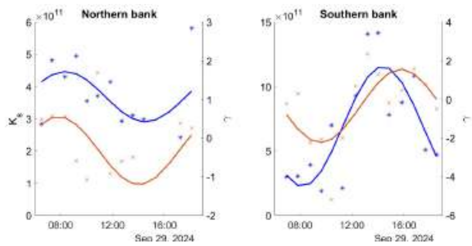

Figure 2: Tidal fitting of calibration coefficients.

2. Results and conclusions

The first and fourth water samples are used for calibration. The addition of the temporal component to the calibration process of acoustic parameters K_s and γ was achieved with the sinusoidal function in Fig 2, based on the data from the Ems Estuary. The tidal fitted K_s and γ exhibit a similar tidal phase, though a lag remains between them. The sinusoidal signal in the calibration coefficients may be attributed to the backscatter sensitivity K_s and to γ, which represent the acoustic properties in the sediment particles.

The measured acoustic backscatter profiles from the ADCP were converted into suspended sediment mass concentrations using both sinusoidal function calibration and an average value with empirically derived constant coefficients. The remaining two samples from the middle water column were used for validation. The results are presented in Fig 3. The Pearson correlation coefficient R indicates the goodness of fit. The time-dependent function yields a significantly more realistic profile compared to the constant calibration coefficients.

Acknowledgments

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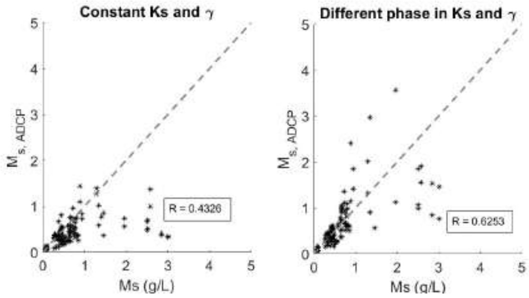

Figure 3: Validation of the ADCP estimated mass concentra-tion M_s of the samples at mid-depth.

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Trend monitoring, the basis for a healthy and clean upper river system

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Keywords — Trend monitoring, water quality/quantity, riverbed

Introduction

Rijkswaterstaat is responsible for the design, construction, management and maintenance of the Netherlands' primary infrastructure facilities. This also includes the main water system and main waterways, such as the North Sea, the IJsselmeer and the river Rhine.

An important task to meet this responsibility of Rijkswaterstaat is to collect data for the knowledge of the water management situation of the country ("Waterstaatkundige toestand van het land", MWTL) (Besluit Rijkswaterstaat January 14, 1971). This concerns long-term series of data and consist of a physical (since ± 1800), chemical (since 1952) and biological program (since 1989 – salt water and 1992 – fresh water). In addition, Rijkswaterstaat regularly collects data of the position of the waterbed of the main rivers and canals and of the large waters.

In this case, the area of interest is the upper river area, upstream of Keizersveer. This area consists of river branches of the Meuse and the Rhine. An important characteristic is that the area is not affected by the tide. High water levels are caused by high water discharge.

Method

Within the upper river area Rijkswaterstaat is responsible for collecting data of the following monitoring networks:

- Phytobenthos
- Aquatic macroinvertebrates
- Fish
- Birds
- Ecotopes
- High water measurements (water quantity)
- Position of the riverbed
- Water quantity stations ("Landelijk Meetnet Water", LMW)

The data is collected in diverse ways adjusted on the specific characteristics of the area. We will explain these methods on the poster.

After collection the Rijkswaterstaat Laboratory (or through outsourcing) analyses the samples of phytobenthos and macroinvertebrates.

The collected data is made available and is used for further analyses. Trends are calculated for the various monitoring networks to determine the condition of the upper river area.

Conclusion

Different types of information and associated monitoring is needed for the management of a healthy and clean upper river system. Being able to accurately assess all this information starts with insight into long-term developments in the chemical, biological and physical state of the area. These long-term series of basic data provide us not only with insight into how the upper river area has been functioning in the past and how it is functioning right now. This data also gives us the tools to assess which measures we can implement for a healthy and clean system in the future.

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Sorting out flood sediments: the role of grain shape in overbank deposition

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Keywords — Sedimentology, fluvial geomorphology, morphodynamics

Introduction

The last decades have shown an increase in the frequency and magnitude of floods (Blöschl et al. 2020). The intensification of flood regimes will likely enhance rivers' capacity to erode and transport sediment. Sedimentary properties, such as texture, porosity and geochemistry are crucial factors that affect the economic and ecologic values of overbank zones. Moreover, understanding of sediment fluxes and pathways is also key in predicting the distribution of adhesive heavy metal contaminants, microplastics and forever PFAS chemicals. Yet, modelled estimates of sediment transport and overbank deposition are notoriously inaccurate. A recent experimental study of bed load transport suggested up to a factor 5 attributable to the shape of particles (Deal et al., 2023).

Here we show that the shape of sand grains is probably also a critically overlooked factor in suspended sediment transport. Its effects are observed from lateral-distance sorting in overbank deposits from different catchments. We used hydraulic modelling to further test our initial observations and to explore the magnitude of changes in sediment transport that are potentially caused by grain shape.

Methods

Fresh overbank deposits were gathered immediately after floodwater receded: for the Meuse, Geul and Roer in summer 2021, and for the IJssel and the Overijsselse Vecht in winter 2024. A total of 199 samples was collected mainly along lateral transects to investigate the trends in grain shape properties. Digital Image Analysis (DIA), measured at the Sedimentary Laboratory at the VU Amsterdam, was used to gather information about the aspect ratio (Eq. 1) of individual grains between 20-1600 μm.

$$(1)\quad aspect\ ratio = \left(\frac{min.\ Feret\ diameter}{max.\ Feret\ diameter}\right)$$

To further test the plausibility of shape-based sediment sorting, fall velocity calculations were performed using different shape parameters (cf. Ferguson and Church, 2004). The effect on suspended sediment concentrations was calculated using Rouse profiles, using varying shape characteristics while keeping flow depth, slope and reference sediment at constant values (Rouse, 1938).

Results

Our results demonstrate that for all studied catchments comparable trends in the mean aspect ratio of the sand fraction could be observed. In general, coarser particles had more elongated shapes compared to smaller-sized particles at similar locations. Notably, the aspect ratio of similarly-sized particles declines when the distance to the active river channel increases (Fig. 1). Sample transects along highly variable topography, such as point-bar relief indicate that elevation affects sediment sorting. The topographic highs demonstrated significantly higher aspect ratios and increased coarseness compared to low-lying areas (Fig. 2), suggesting deposition to been limited to peak flow conditions with maximum transport capacity.

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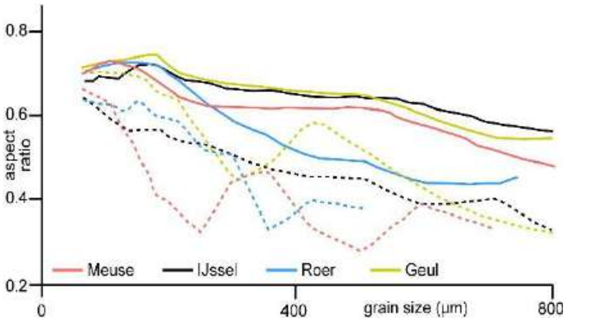

Figure 1: Changes in grain shape versus grain size, plotted for different rivers and grouped for proximal sample locations (solid line) and distal sample locations (dashed).

Explorative hydraulic modelling on the effect of grain shape suggests an increase in fall velocities for the fine sand fraction (Fig. 3 – upper frame). Likewise, the Rouse profiles (Fig. 3 – lower frame) demonstrate that the concentration of suspended fine sands increases for in-channel transport when particles have a higher aspect ratio.

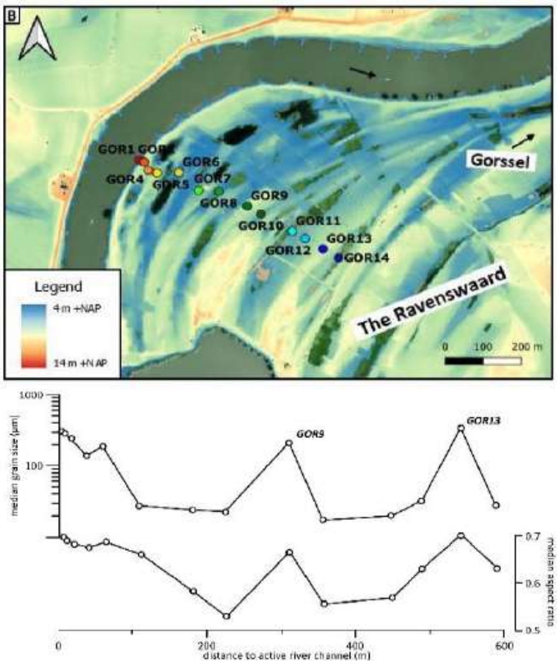

Figure 2: Sample transect over point-bar morphology of the IJssel at the Ravenswaard near Gorssel (Reijmers, 2025) – the coloured dots are indicative for an increasing distance. The median grain size and aspect ratio are plotted versus distance to the active river channel.

Conclusions

The combination of field measurements after recent flood events and explorative testing using hydraulic models indicates that selective sorting based on shape is a significant factor in fluvial transport. The more elongate shape of particularly larger sand grains causes an enhanced buoyancy, and susceptibility to turbulence, that enables such grains to travel further from its source compared to their spherical cousins.

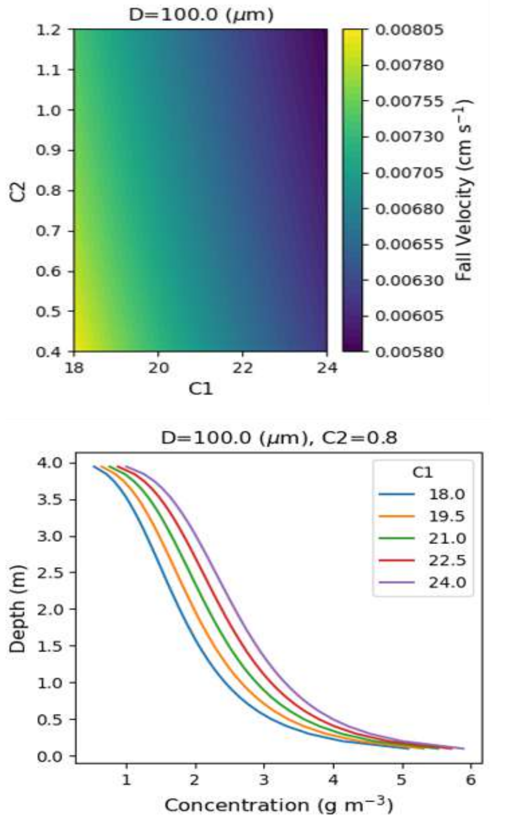

Figure 3: Conceptual testing of the effects of grain shape (example shown for 100 µm particles) on fall velocities (upper frame) and sediment concentration (lower frame). C1 is a constant in Ferguson in Church (2004), to represent grain elongation (C1=18 represent a sphere). C2 represents a constant asymptotic value of the drag coefficient (C2=0.4 represents a sphere).

Similar trends in shape-based sorting are observed for different catchments, despite variations in settings that may affect the results, such as valley morphology, flood conditions and sediment mineralogy. This implies that there is an overall driving physical mechanism determining the observed pattern, which is likely universally applicable, at least to low-gradient alluvial systems.

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Climate Change Adaptation through Interventions in a River Bifurcation Region

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Keywords — river bifurcation, interventions, river response, numerical modelling

Introduction

The Rhine River system has been shaped by human interventions for centuries, making it one of the most engineered river networks in Europe. Issues such as ongoing channel bed incision and changes in hydrograph due to climate change (*Arbos et al.*, 2023) are anticipated to significantly affect future river functions, including flood safety, freshwater supply, and inland shipping. In recent decades, large-scale projects such as "Room for the River," the installation of longitudinal training walls, and sediment nourishments have helped preserve the Rhine's functionality.

At the Pannerdense Kop bifurcation, where the Dutch upper Rhine divides flow and sediment between the Waal and the Pannerden Canal, a gradual change in flow division between the branches is observed (*Chowdhury et al.*, 2023). This change appears to be linked to a series of peak flow events in the 1990s, which resulted in sediment deposition in one bifurcate, setting off a slow shift in flow partitioning ever since. More recently, *Blom et al.* (2024) proposed that the extreme flows in the 1990s might have pushed the system toward a tipping point and an emerging alternative equilibrium state.

Ensuring the anticipated flow partitioning is crucial not only for maintaining water supply and navigability during low-flow periods but also for controlling flood risk during peak events.

Objective and Method

This study aims to evaluate various interventions intended to maintain the desired flow partitioning and mitigate channel bed erosion over extended time scales (50–150 years). While earlier research has examined interventions such as floodplain lowering and sediment nourishment outside the context of a bifurcation, focused on modeling the bifurcation area without interventions, or studied climate change scenarios without morphological feedback, this study concentrates on both interventions and climate change adaptation within the Pannerdense Kop bifurcation region in a morphological context.

We will investigate two methods for evaluating the effectiveness of combining conventional engineering measures with (nature-based) solutions: (1) a one-dimensional modeling approach, and (2) a hybrid one/two-dimensional modeling approach. In the hybrid method, the boundary conditions for the two-dimensional domain of the bifurcation are dynamically connected to the one-dimensional model sections representing the river branches. This study will determine whether such dynamic coupling can accurately represent lateral flow exchanges between the main channel and the floodplain, as well as sediment transport and bed evolution processes within the bifurcation region, all while maintaining the computational efficiency typical of one-dimensional models for the larger system.

Expected Results

We expect that the effectiveness of interventions is significantly different in the presence of a bifurcation compared to single-channel conditions, with the specific design and location of interventions playing a crucial role. This analysis will provide insights into the relative effectiveness of a range of intervention strategies under various climate change scenarios, informing the development of adaptive management plans that enhance the long-term resilience of the Rhine River system.

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Rivierwerken: a soil-based approach for floodplain restoration and dike reinforcement

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Keywords — Sustainable river management, soil-based programming, river restoration, dike reinforcement

Introduction

Rivers have historically served as vital lifelines for human societies, supporting a multitude of functions including water safety, shipping, nature conservation, water quality, freshwater availability, living, working, and recreation. However, over the centuries, the spatial extent of major rivers has steadily decreased. Rivers used to meander freely through landscapes, with channels silting up and shifting, and adjacent areas experiencing regular flooding. The 19th century marked a significant shift with large-scale river normalization projects aimed at improving navigation and flood safety.

In the Dutch context, floodplains have accumulated silt over the centuries due to frequent flood events and the narrowing of space caused by dikes. Consequently, floodplain restoration in the Netherlands necessitates excavation. Additionally, approximately 1400 km of dikes in the Netherlands require reinforcement by 2050 to meet safety standards. Linking soil supply from nature restoration projects with the demand for dike strengthening presents a logical and sustainable approach to river management. This soil-based approach offers sustainable materials for local use, potentially leading to cost savings, reductions in CO_2 footprint, and minimized environmental impact. The *Rivierwerken* (River Works) project, which concluded at the end of 2024, focused on this innovative approach.

Methods

Rivierwerken was structured into three work packages: 1) Sustainable Resource Extraction, 2) Circular Material Use, and 3) Soil-Based Programming. Led by HAN University of Applied Sciences, the consortium comprised 20 partners from public, private, and knowledge sectors, including two ministries (Infrastructure, and Agriculture and Nature), a nature management agency (Staatsbosbeheer), three waterboards (Limburg, Rijn en IJssel, and Rivierenland), two provinces (Limburg and Gelderland), two foundations (Smart Rivers and EcoShape), three additional knowledge institutions (Deltares, TU Delft, and Van Hall Larenstein), and a multidisciplinary group of private companies (Fugro, Van Oord, K3 Delta, Netics, Aveco de Bondt, Witteveen+Bos, and Arcadis) covering both consultancy and contractor roles.

Results

Output WP1: Sustainable Resource Extraction

- A tool is developed for estimating soil volume extracted in nature development projects based on riverscape characteristics, validated with an expert-based system approach (Figure 1).
- Opportunities for local sediment replenishments to counter riverbed erosion are identified.
- Designs for nature restoration projects that follow the DNA of the river.

Output WP2: Circular Material Use

- A comprehensive review of soil treatment techniques.
- An experimental case study and desk study on improvement of mechanical properties by mixing different clay types.
- Compositional effects and suitability for dikes are examined.
- Soil-based dike design methodologies are developed.

Output WP3: Soil-Based Programming

- A methodology for an integrated approach to soil management is formulated.
- Existing tools for soil management are evaluated.
- A new tool to match soil supply with demand is developed (Figure 2).

These findings offer valuable insights and tools for technical managers, designers, risk managers, as well as project and operational managers involved in dike and floodplain management. This contributes to a more sustainable approach to river management.

Conclusion

The *Rivierwerken* project has demonstrated the potential for integrating soil-based programming into sustainable river management practices. By linking soil supply from nature restoration projects with the demand for dike reinforcement, this approach not only provides locally sourced sustainable materials but also offers significant cost savings and environmental benefits. The tools and methodologies developed through this project will support the ongoing efforts to enhance floodplain restoration and dike safety in the Netherlands, contributing to a resilient and sustainable riverine landscape.

Acknowledgements

This project was conducted with the support of all the partners mentioned, and not solely by HAN University of Applied Sciences. This research has been funded by Regieorgaan SIA, project nr. RAAK.PUB09.018.

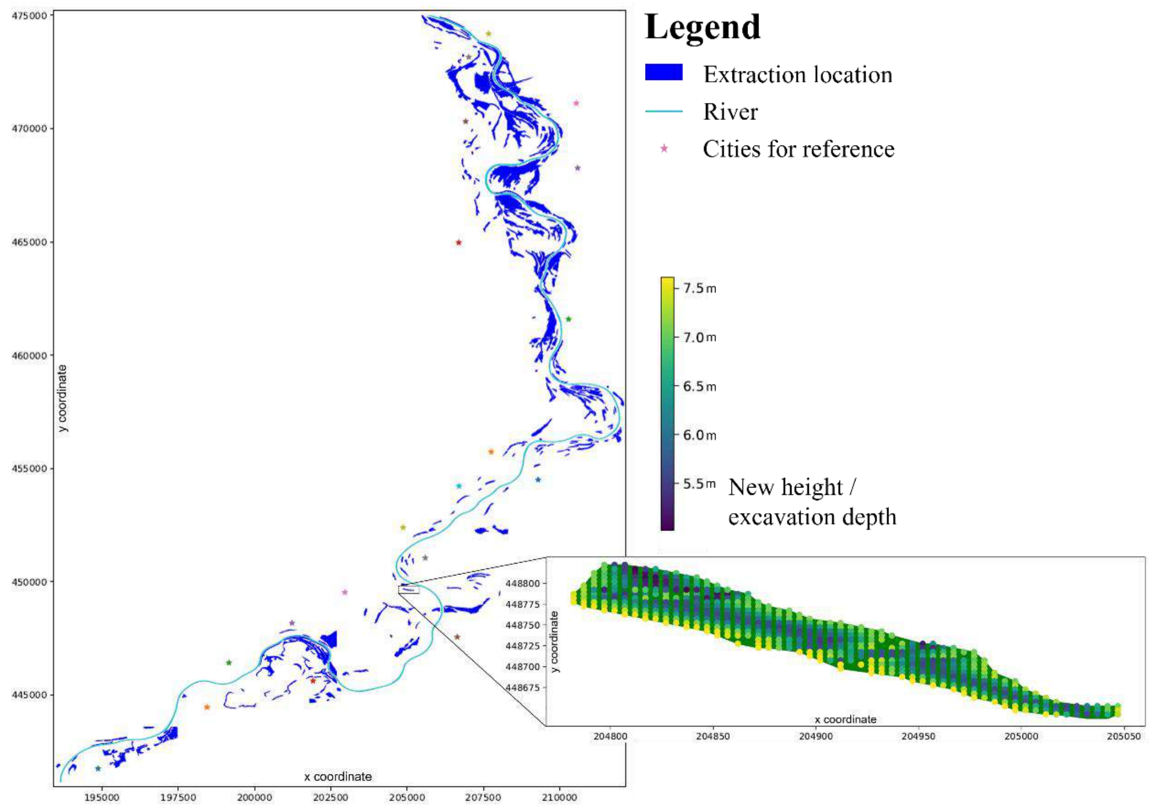

Figure 1. Example of tool output for the case of the IJssel river

Figure 2. Screenshot of the tool developed in WP3

Serious game design to reveal delta ENIGMAs for shifting to more flexible and adaptive flood risk management

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Keywords — combined flood protection, learning, transdisciplinary collaboration, policy-making

Introduction

ΔENIGMA is a national research infrastructure with various work packages (WP) studying the water and sediment dynamics for nature-based, flexible, and adaptive flood risk management in the Dutch Delta's river-estuary-coast continuum. WP6 joins efforts between TUDelft, Wageningen, Twente, and Deltares Labs to study and facilitate interactions bridging related knowledge-communication-action gaps. The WP6 designs various tools, such as serious games, using digital and physical interfaces to facilitate collaborations between societal and academic actors while joining efforts within, across, and beyond WPs. Collaborative interactions are considered productive when achieving individual, group, and societal learning about the problem and proposed solutions, the norms and values behind, and the necessary (collective) action f (Barth et al., 2023). This paper presents the TU Delft Game Lab+'s prototype, developed with ΔENIGMA WP2 and TU Delft Serious Game Design students (Kontaxopoulou et al., 2024).

Collaborative design framework for productive interactions

Serious games simulate climate adaptation scenarios that are otherwise difficult to experience and are increasingly used to facilitate productive interactions that inspire sustainable collective actions. When well-designed, games change attitudes toward the problem or solution, increase related knowledge, and allow practicing necessary skills. However, effective games must balance complexity, learning goals, and enjoyment. To address this design dilemma, we used established collaborative frameworks (Kip et al., 2025) and bring together considerations for designing interactive games for learning (Jaccard et al., 2021), collaboration, and policy-decision-making processes (Djenontin & Meadow, 2018). We follow the **Figure 1** framework by involving relevant stakeholders as informants or co-designers at different stages according to the value they can get and give from their involvement (De Jans et al., 2017).

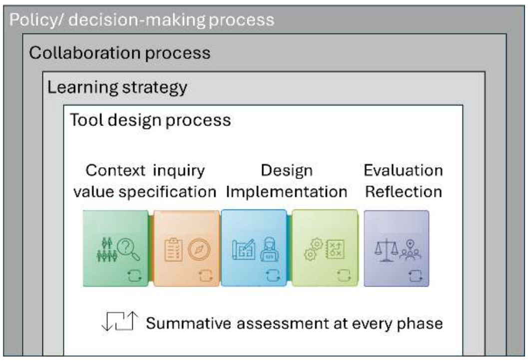

Figure 1. Collaborative design framework for productive interactions. (Adapted from Kip et al., 2025).

Preliminary prototype and results

Inspired by WP2 research in the Dutch Schelde estuary, brainstorming sessions between the (co-authoring) team led to the following game elements:

Game context

Delta communities and management actors have historically chosen a flood protection approach that reclaims land for development via hard or soft measures such as dikes, sand nourishment, or coastal wetlands. The short-term benefits of delta flood safety kept wetlands dry for developing urban, agricultural, and industrial activities, leading to economic prosperity. This protection approach has increased delta communities' development and flood exposure in the long term. A closed protection approach has also led to the degradation of delta ecosystems and land subsidence, ultimately increasing the flood risk. In turn, short-term effects in the long run are reduced by an inability to reverse past choices. However, in the past, the delta land flooded at high levels; the free water and sediment dynamics allowed sediment and vegetation that contributed to flood protection. The free dynamics enriched soils, supported diverse ecosystems, and improved water quality. Today's rising sea threatens the delta's sustainability. Combining dikes with wetlands that can flood strategically can enhance flood safety and nature.

Policy-making value specification

A combined approach requires space from land that may already be developed for implementation. Moreover, management actors should make collective management agreements, such as continuously assessing the development and flood maintenance needs. The benefits of land use changes for combined flood protection may take years to decades to become visible as ecological benefits. Economic gains required additional efforts, such as creating recreation and tourism opportunities. Altogether, there is a need to communicate to all generations how the management of the past contributed to the undesired effects of today. A sustainable future requires collective action and considering the benefits and challenges.

Learning goals

The serious game to design aims at:
(1) Learning about the role of water-sediment dynamics in the short and long-term sustainability,
(2) Showcasing the benefits and challenges of combining protection and
(3) Fostering collective reflection and responsibility on past management to enable flexible and adaptive futures.

Target audience and game setting

Intended players are last-year high school students. The game serves as an icebreaker for discussions on flood protection agreements among (future) managers or experts. We expect the game to be played in educational and collaboration activities, science days, or museum visits at the location. Initially paper-based, the game may move online for broader reach or integrate elements of other interactive tools. Playing the whole game should take a limited time.

Game Outline

Four players own each region in the delta game board (**Figure 2**). Each region has different land uses represented by tokens related to four interests (villages, agriculture, nature, and industry). Players work collaboratively to achieve flood safety, ecosystem value, and economic prosperity for the region to ensure a future-proof delta. Players make protection choices in three rounds, representing the past, present, and future. Protection choices are doing nothing, building a dike, or a dike with a wetland, each represented with Lego pieces on the board. Some options are locked out depending on the protection choices. A scorecard determines the area tokens and flood protection in the short term.

Figure 2. Tabletop board and game elements impressions as prototyped by Kontaxopoulou (2024).

After making choices in the past and current rounds, a flood event may take some tokens away from each region according to its protection level. In the future and last round, players realize and discuss the long-term scorecard of their decisions. Every round, players learn of the choice effects through interactive stories.

Feedback & next steps

Game design students suggested enhancing engagement, interactivity, and interconnectedness of effects. Next is to validate the prototype context, choices, and expected use with academics, educators, policymakers, and professionals.

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Experimental study on flow patterns and turbulence in a tight sinuous open-channel

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Keywords — Bank erosion, secondary flow, impinging flow

Introduction

Flow-driven bank erosion is an important process in the causing of bank retreat in alluvial rivers (*Zhao et al.*, 2022), and better quantification could help water managers design channels and control floods. Quantifying flow-driven erosion can done by a form of the excess shear stress formula for which bank shear stress is needed (*Partheniades*, 1965), however, the distribution of bank shear stress is difficult to predict due to secondary flow patterns that develop in open channel bends (*Termini*, 2015; *Hu and Yu*, 2023). This study presents the results of a flume experiment conducted in a sinuous open channel with a rapidly changing radius of curvature and a radius of curvature to width (R/B) ratio of 0.87 at the bend apex, see Figure 1. Acoustic Doppler velocimetry (ADV) measurements were conducted across cross-sections for two different water depths, keeping the average velocity constant. This ADV data was used to map (secondary) flow patterns, calculate the strength of secondary flow cells and determine the Turbulent Kinetic Energy (TKE) and Reynolds shear stress acting on the bank.

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Figure 1: Diagram of the flume set-up.

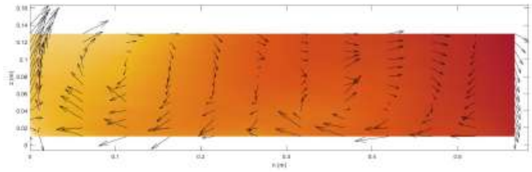

Figure 2: The measured cross-section at the start of the bending section for a water depth of 0.16 m.

Results

The results show that the high-velocity core followed the inner bank, while a large secondary flow cell developed on one side of the channel and remained there, see Figure 2. The flow was impinging on the outer bank after the bend apex, where the TKE and Reynolds shear stress were lower than before the bend apex, where flow separation occurred, see Figure 3. This flow pattern deviates from the classical (secondary) flow pattern observed in bends with a low R/B ratio ($R/B < 3$), characterized by a centre-region cell and an outer bank cell and predicted by parameter β developed by *Li* (2022).

Discussion & conclusion

The difference between the classical flow pattern and the pattern observed in this study is because the flow pattern lagged behind the rapidly changing radius of curvature and prevented the flow patterns from fully adapting to the channel geometry, this also caused the flow to impinge on the outer bank after the bend apex. Literature indicates that maximum flow-driven bank erosion typically occurs at the outer bank after the bend apex, in this case where the flow was impinging and with relatively low TKE and Reynolds shear stress acting on the bank which implies that bank erosion cannot be predicted solely based on Reynolds shear stress or TKE under the conditions created in this study. Flow-driven bank erosion in tight sinuous channels might be caused by the impinging flow (IM) which was quantified by the following formula: $\rho\overline{uv}$, see Figure 4. To test this further research is needed where a part of the bank has to be replaced by movable particles.

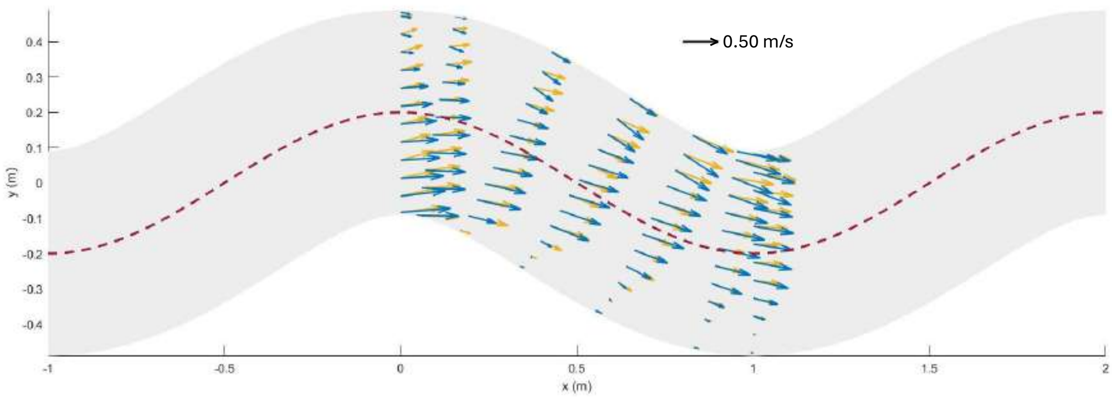

Figure 3: Top view of the sinuous section with the velocity vectors of the water flowing 2 cm from the bottom (orange) and at the water flowing 3 cm below the water surface (blue) for a water depth of 0.16 m. The gray area represents the channel and the red dotted line is the centreline.

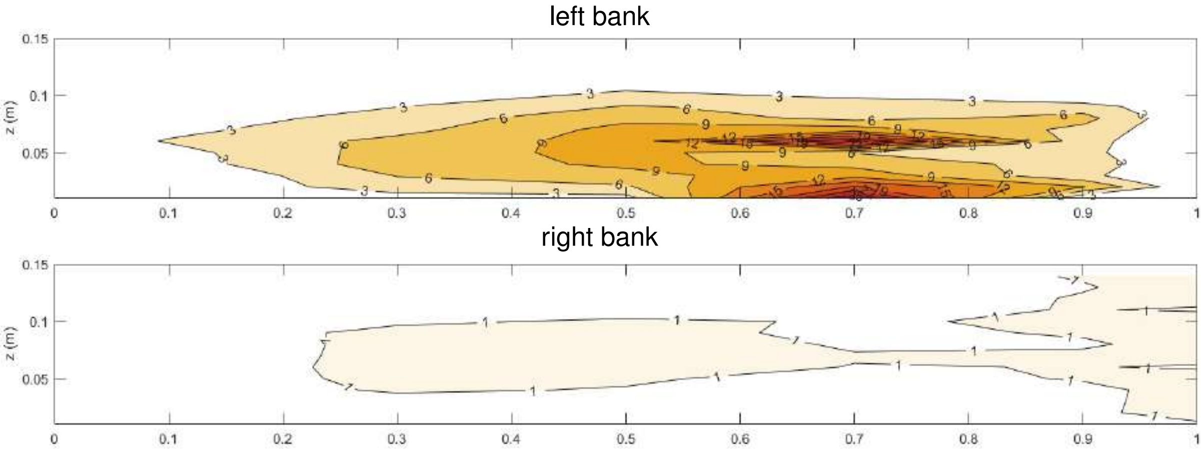

Figure 4: The impinging flow (IM) measured next to the left and right bank along the length of the channel for a water depth of 0.16 m. At the locations were IM was pointing away from the bank the value was set to 0.

Acknowledgements

This are the results of a MSc thesis conducted at Wageningen University & Research under supervision of Ton Hoitink and Nick Wallerstein. The flume experiment was done in collaboration with Niguse Abate.

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Delta-ENIGMA: an update from its first year of operation

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Keywords — delta, biogeomorphology, rivers, estuaries, dunes, observatory, climate adaptation

Introduction

Deltas and coastal plains are facing growing risks from the adverse effects of human activities and climate change, including sea-level rise. Deltas are shaped by physical forces, human interventions and physical-ecological relations. Understanding biogeomorphology — how natural forces and organisms shape these landscapes — is key to predicting the future of deltas. The Delta-ENIGMA project aims at bringing biogeomorphology research in the Netherlands to the next level, by providing a unique research infrastructure to understand how organisms, currents, waves, wind and sediment load together shape the delta landscape, including during extreme events.

Delta-ENIGMA is a 10-year NWO-funded Large Scale Research Infrastructure (LSRI) project, in which a consortium of seven Dutch institutions of NCK and NCR closely collaborate. The Delta-ENIGMA project develops a delta-scale observation network of bio-morphological processes, using state-of-the art equipment (e.g. 3D laser scanners, submerged flow and sediment monitoring, multibeam echosounders), over a 10-year period at fixed number of key-site transects across rivers, estuaries and beach-dune systems. Doing so, Delta-ENIGMA will establish the Dutch delta as a Super Site for bio-geomorphological field measurements focusing on data collection during extreme events to capture slow trends and sudden disruptions.

Methods

Delta-ENIGMA comprises 8 Work Packages that will establish the following (Figure 1):

- A long-term observation network measuring the slow and cumulative processes during normal conditions in rivers (WP1), estuaries (WP2), beaches and dunes (WP3), as well as during extreme events (WP4).
- Upgraded and new laboratory facilities to study events and conditions that are presently unobservable in the field (WP5), but may become realistic under climate change.
- A productive knowledge interaction facility (PROD) boosting interactions between experts, policymakers and delta managers (WP6).
- A coherent open database by bringing all produced sensor data into one infrastructure supporting researchers with a wealth of data for own or shared needs (WP7). Project governance (WP8).

To maximize societal impact, scientists and stakeholders will collaborate to identify strategies for implementing adaptive measures. Over the 10-year period, a comprehensive open database will accumulate results, serving as the foundation for conceptualizing delta processes, developing novel models, and validating them. The institute retrieves and processes data from sensors, adds documentation and metadata, then transfers it to Yoda platform for sharing. Yoda is Utrecht University's institutional repository for storing, publishing, and sharing research data. Effective data management is crucial, to ensure data is structured, accessible, and reusable.

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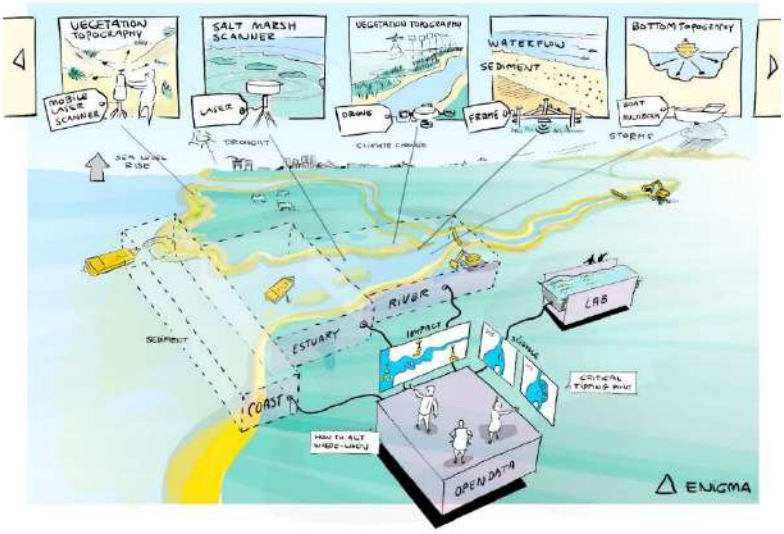
Figure-1 Conceptual visualization of Delta-ENIGMA



Results

In 2024-the first year of the project, Delta-ENIGMA successfully achieved several keys tasks and objectives. Effective collaboration among partners and open communication facilitated the integration of expert knowledge. WP1-WP3 identified the following field monitoring stations:

- WP1-river: Dodewaard, Vuren, Rotterdam and Hoek van Holland
- WP2-estuary: Zuidgors and Waarden, both in the Western Scheldt
- WP3-beaches and dunes: Sand Motor (nourishment), Egmond aan Zee (recreational beach) and Castricum (dynamic dune management)

Besides that, WP4-events acquired the appropriate equipment for storm events and extreme conditions, e.g. AQUADOPP, turbidity logger, ADCP's, wave recorders, multispectral drone etc.. Various teams, involving MSc students, are being set-up to go out into the field when an extreme event is imminent.

WP5-laboratory facilities made progress with equipment procurement and with the designing of wind tunnel, mesocosm lab and the complex BioLiveFlumes lab.

WP6- PROD facility successfully designed the roadmap for 4 labs (IDlab-Deltares, Wanderlab-WUR, Serious Gaming Lab- TUD and the Design Lab- UT).

WP7-ICT designed a roadmap for the data management infrastructure. iRODS in combination with Yoda is chosen for the federated data environment.

Prospects

Looking forward into 2025, we plan the following tasks to achieve:

- 75% of equipment has been purchased, validated and installed
- All collected data are integrated into WP7-ICT
- PhD proposals have been initiated
- The construction of new flumes has started.

Delta-ENIGMA provides instruments and facilities, but does not involve the further data analysis and research. We therefore encourage researchers from NCK and NCR partners, as well as externally, to come up with new research ideas and submitting proposals that make use of Delta-ENIGMA's facilities and data.

Physics-Informed River Discharge Estimates Throughout a Tidal Cycle Based on ADCP Transect Data

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Keywords — ADCP, River Discharge, Tidal Junction

Introduction

Acoustic Doppler Current Profilers (ADCP) are widely used to measure flow in open water. They are often mounted on a moving vessel and accompanied by a GPS, allowing the collection of spatially correlated flow profiles. This makes it possible to capture the flow dynamics of a specific transect, such as the cross-section of a channel. The resulting flow fields can be used to infer river discharge or tidal amplitudes (*Simpson*, 2001).

Due to the high measuring frequency of an ADCP, the resulting data also contains turbulence that can be found at a small scale. However, for most applications of ADCP measurements in geophysical fluid mechanics the Reynolds-averaged flows (without turbulence) are important. The turbulence is often removed by using an average of repeated transects. This approach, however, fails when investigating a tidally influenced region as the Reynolds-averaged flow is expected to differ for each moment in time due to this tidal influence.

This research builds on the work done by *Jongbloed et al.* (2025). He describes a physics-informed approach to estimate the Reynolds-averaged flow from raw ADCP-measurements. The approach is based on assumptions regarding temporal changes and spatial uniformity. Therefore this approach uses a combination of tidal projection methods based on tidal constituents (*Carrillo et al.*, 2005; *Münchow et al.*, 2000) and a spatial mesh-based method (*Vermeulen et al.*, 2014). The resulting model is regularized using physical laws. By applying different weights to each law the model can be steered into a realistic solution.

This research attempts to apply this approach to two channels in a tidal junction in the Ganges-Brahmaputra-Meghna Delta. This area is of interest due to the size of the system and channels. It leads to complex flow patterns for each transect that could change throughout a tidal regime. Up to now there is no standardized approach for the selection of the constituents for the tidal projection, spatial resolution of the used mesh and the regularization weights (*Jongbloed et al.*, 2025).

The objective of this research is to develop and apply a robust modelling approach to make accurate predictions of discharge in a tidal river using the model described above.

Method

The model described above is called 'adcptools' and was developed by *Vermeulen et al.* (2014) and further developed by *Jongbloed et al.* (2025). The model was applied to ADCP-transect measurements collected in two channels of the Ganges-Brahmaputra-Meghna Delta. The measurements were collected at the end of the monsoon period. This means that the discharge and the turbulence of the water in both channels are around their peak. For each channel two vessel-mounted ADCP tracks were selected, where each track was sampled eight times (Fig. 1).

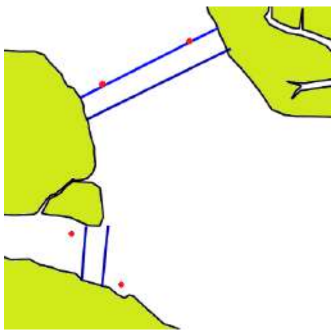

Figure 1: Top down representation of the study area. The blue lines indicate the area where the meshes were place. The red points indicate location of moored ADCP measurements

These measurements were projected on a mesh and consequently fitted by a tidal model. The tidal model is described by:

$$u(t) = u_0 + \sum_i A_i cos(\omega_i t - \phi_i) \quad (1)$$

In this equation u is the resulting flow velocity and u_0 is the non-tidal component. Depending on the number of selected constituents (e.g. M2, M4 & M6) more components are added. A_i represents the amplitude of constituent i,

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ω_i the period and ϕ_i the phase-shift.
After setting up the framework of the model, the resolution of the grid, the considered tidal constituents and the regularization weights were tweaked to find the best performing model. The model performance was tested against moored ADCP-measurements (Fig. 1, red dots) that were collected throughout the full sampling campaign. The temporal pattern described by the model based on the transect should be similar to the moored ADCP measurements. Additionally, the discharge between two consecutive transects was compared. Based on the conservation of mass the discharge though both transect is expected to be the same.

Results

The first impression of the results show that fitting the model for tidal constituents M2 and M4 with a coarse grid size and high regularization weights forcing uniformity in the flow could have some promising results (Fig. 2). It shows that the fitted model represents the transect and the moored measurements closely.

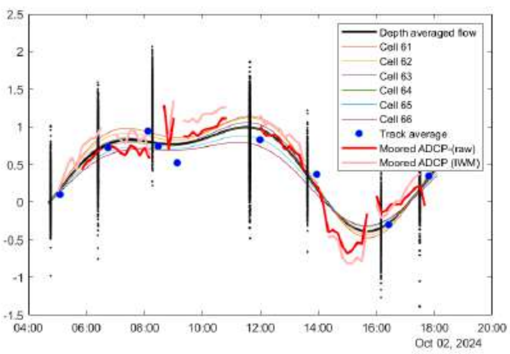

Figure 2: Comparison of the fitted model (black line) with raw input data (black dots) and moored ADCP measurements (red line). The blue dots indicate the mean of the raw input data of a single track made by the moving vessel.

With a finer spatial resolution or in a more dynamic channel, the model fit seems to be poorer and the fitted model and the moored ADCP measurements diverge more. Additional tuning of the weights has to be conducted to investigate if a model in these circumstances can still produce realistic results.

Acknowledgements

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Facing Floods: a stakeholder river management game

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Keywords — Serious game, stakeholder management, river engineering

Introduction

River management projects involve multiple stakeholders with different interests, priorities, and constraints. As these stakeholders could have conflicting perspectives, river management entails complex decision-making processes. While technical expertise is essential, students in higher education should also develop an understanding of the societal impacts of engineering interventions. Integrating such skills into engineering curricula is crucial. One effective method is the use of serious games, which simulate and simplify the real-world complexities (*Kriz*, 2003). These games provide a safe space for students to explore practical challenges without facing real-world consequences (*Freese et al.*, 2020). Serious games are also proven to enhance the learning outcomes and increase motivation, even in professional contexts (*Bekebrede and Champlin*, 2022).
We developed *Facing Floods*, a game designed for students in higher education to simulate the challenges of river management projects. Players take on the roles of stakeholders, each with specific goals, needs, and budgets. Through discussion and negotiation, they must balance individual objectives with the shared responsibility of effective river management.

Setting

Facing Floods takes place in Bendegom, an idealized town in the Dutch countryside, through which the Tulla River flows. The town is protected by dikes, but a recent alarming report shows the flood water level has risen by 10 cm. Hence, the current dike height no longer meets the required safety standards. Rijkswaterstaat hires a consultant to develop a plan for decreasing this risk, while aiming to balance the interests of multiple local stakeholders. These stakeholders will collaborate in drafting the plan through negotiation, working toward a solution that addresses their individual goals and needs.

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Stakeholders, criteria, and playing

The game features five stakeholders: Rijkswaterstaat, concerned on reducing the risk of flooding; the Municipality, aiming to increase housing; the navigation sector, interested on improving the river navigability; farmers, seeking for more more agricultural land; nature conservationists, fighting to enhance the ecological status of that region. The game is set on the floodplains (Fig. 1). Two-thirds of the floodplains are occupied by agricultural (brown) and natural areas (pink). Farmers and nature conservationists use these areas for their goals and no intervention can be placed there without their consent. The green area has no owner and is open for all stakeholders to implement their measures. The area behind the dikes (black lines) is split between the town (gray) and the farmers (brown).

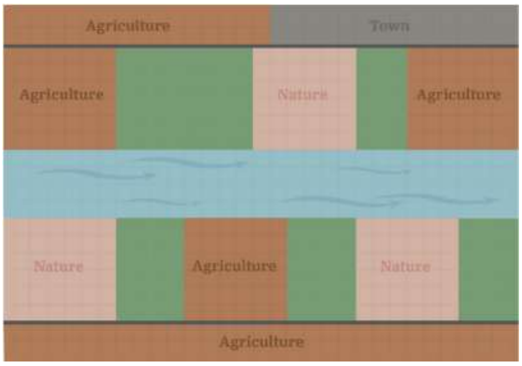

Figure 1: Map of Bendegom.

Figure 2: Bendegom dashboard of all criteria.

Five criteria are used to assess the performance of the river and the floodplains: flooding safety, quality of urban life, nature value, agricultural yield, and navigability. Each criterion has a score ranging from -10 to 10, which changes based on the measures implemented. These scores are tracked and displayed on the Bendegom dashboard (Fig. 2). Each stakeholder has a budget to propose one or more measures (Fig. 3).

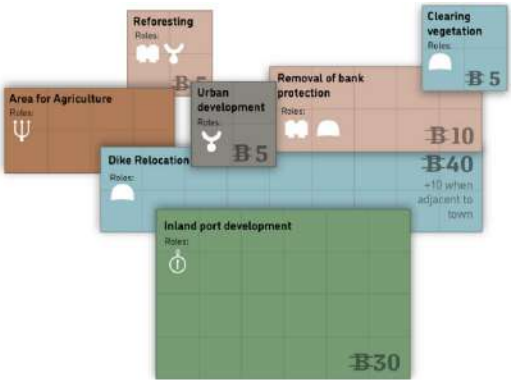

Figure 3: Examples of possible river measures.

A facilitator is needed to introduce the story, explain the game and the rules, and lead the debriefing at the end of it.
The game begins with each stakeholder presenting their proposal to the consultant, who reviews them and facilitates discussion and negotiation. Once a shared plan is agreed upon, the consultant implements it by placing the selected measures on the map and updating the criteria scores. This concludes the first round.
The game is designed to be played in two or three rounds. At the end of every round, a “News event” is introduced to highlight specific societal issues or emphasize a particular criterion, adding new challenges to the decision-making process. Four events are proposed: a sudden increase in citizens, underscoring the housing shortages; a governmental law to promote self-sufficiency in food production, addressing the need for more agricultural yield; an increased demand for inland navigation, pushing for improved shipping connections; a governmental law to promote nature-based solutions for increasing the safety against flooding. The event card can be chosen at random or selected to guide the game towards a specific direction. Each event introduces requirements for certain criteria scores. If stakeholders fail to meet these requirements, they face penalty fines (Fig. 4).

Debriefing and discussion

At the end of the final round, players reflect on their experiences and draw connections between the game and real-world challenges. It

Figure 4: Example of a ”News event” card.

is important to analyze the emotions, strategies, and interactions with other players. They should consider how they communicated, why they made certain decisions, and whether the game is representative of real-life negotiations. Test sessions of the game showed that students understood the relevance of stakeholder management in river engineering and that negotiation is required when taking multiple objectives into account.

Acknowledgements

The game material is available on Edusources.
This project has benefited from the Education Innovation project *STREAMS* of the Faculty of Civil Engineering and Geosciences of TU Delft and the collaboration with TU Delft Gamelab.
The authors thank Laura Maria Stancanelli for funding acquisition and project initiation; Erik Mosselman for designing the original workshop that laid the foundation for the development of the serious game, and for valuable reviews, feedback, and suggestions; Ralph Schielen for valuable reviews, feedback, and suggestions; Michelle Rudolph for conceiving and outlining the first draft of the game, and for the useful conversations and suggestions provided during the course of action.

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Is the New Waterway self-deepening?

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Keywords — Sediment transport, Estuaries

Introduction

Fluvial and marine sediment supply, in combination with the hydrodynamic conditions, determine an estuaries ability to keep up with sea level rise. While the fluvial sediment supply is declining globally as a result of upstream dam construction and land use changes (Walling & Fang, 2003; Dunn et al., 2019), the marine supply is less well investigated. Hou et al. (2024) find a global increase in coastal SSC near river deltas, but at the same time point out that the actual sediment supply depends on the capability to retain the supplied sediment. The latter depends on multiple factors and is, although little investigated, likely to be affected by human interventions.

An example of a heavily engineered estuary is the Rhine-Meuse Estuary (RME). The RME (Figure 1) has an history of human interventions including branch cut-off, channel deepening and confining channels. Although port basins are regularly dredged, indicating a supply of sediment, Niesten et al. (2024) found that the New Waterway is exporting sediment under average hydrodynamic conditions. Moreover, the channel depth has increased over the past years. This suggests that the New Waterway is a self-eroding channel, with important consequences for its ability to retain sediment and keep up with sea level rise. Therefore, this study aims to (i) determine if the New Waterway is indeed eroding and (ii) determine how recent interventions have changed the sediment dynamics and related sedimentation and erosion in the New Waterway.

Study area

The RME is fed by three upstream rivers: the Waal, Meuse and Lek. Water is discharged into the North Sea via the New Waterway in the north and the Haringvliet in the south. The Southern Haringvliet was closed off from the North Sea in 1970 by a complex of sluices, which has greatly affected the water levels (Vellinga et al., 2014), tidal currents and sedimentation and erosion in the cross-cutting branches (Huismans et al., 2021). Under average discharge conditions, a net discharge of about 220 m^3/s reaches the North Sea via the Southern Haringvliet branch, while the Northern New Waterway discharges about 1400 m^3/s (Cox et al., 2021). During periods of low river discharge, the Haringvliet sluices are fully closed, and

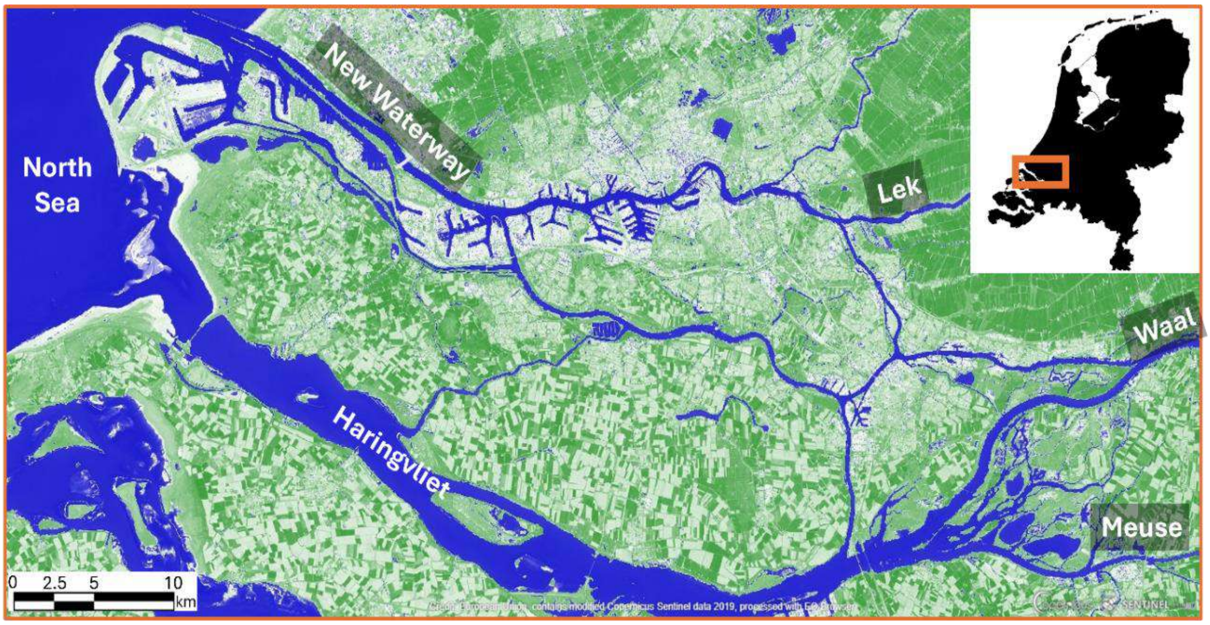

Figure 1. Overview of study area. Image source: Copernicus 2019

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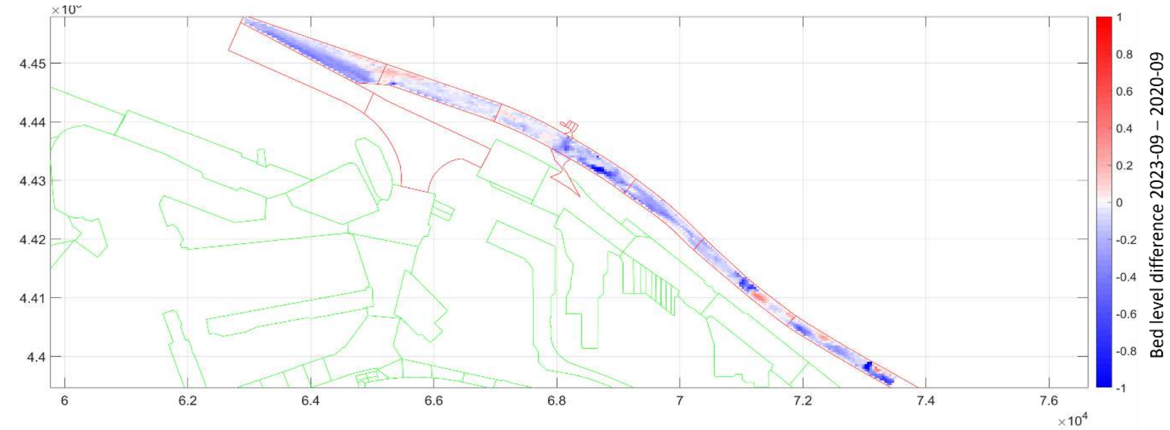

Figure 2. Bed level difference (September 2023 – September 2020) of the downstream stretch of the New Waterway. The channel was artificially deepened in 2018.

all river discharge leaves the system via the New Waterway. The tidal regime in the New Waterway is predominantly semi-diurnal and flood-dominant. Tidal ranges vary between 2.0 m (spring tide) and 1.2 m (neap tide), under average conditions (De Nijs, 2012).

Two human interventions are especially relevant in the context of this study. Firstly, an offshore port expansion (Maasvlakte 2) was realized between 2008 and 2011, with possible consequences for tidal hydrodynamics at the seaward boundary of the New Waterway, controlling residual bed shear stress at the channel entrance. Secondly, the New Waterway has been deepened considerably during the past decades, leading to a very deep and almost prismatic channel without floodplains or intertidal area. The most recent deepening took place in 2018-2019, decreasing the New Waterway's average bed level from 14.50 to 16.20 m below MSL.

Data

Bed level measurements of the New Waterway and its mouth area (Maasmond) were made available by Rijkswaterstaat, the Dutch governmental organization for public works and water management. The data consist of a combination of regular bed surveys with a frequency of approximately once per month, and project-related bed surveys with an irregular frequency and spatial coverage. Altogether, the bed level data cover the period 2000 - 2023.
Furthermore, dredging volumes in both the channel and adjacent port basins were provided for the same period on a weekly basis.

Preliminary results and outlook

The New Waterway was artificially deepened in 2018. Data show a further bed level decrease in the period 2019 - 2023 (Figure 2), while dredging in the channel is near-zero. Thus, the channel bed is indeed eroding. A first analysis of average channel bed levels suggest that the New Waterway was already eroding in the period 2007 – 2018, albeit at a slower rate. To verify the effect of the artificial channel deepening and port expansion on the bed level trend, we will further analyse the spatially varying bed level trend from the period 2000 – 2007 and infer erosion rates for the three periods (I) before the port expansion in 2008, (II) between the port expansion and channel deepening in 2018 and (III) after the deepening. The study will continue with an exploration of mechanistical explanations for the observed channel erosion.

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Development of a dashboard for management of saltwater intrusion in the Haringvliet Estuary

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Keywords — saltwater management, estuarine dynamics, bathymetric depressions, dashboard development

Introduction

The Netherlands has a long history of large-scale water management to protect its low-lying and densely populated regions from flooding. The North Sea flood of 1953, known as the "Watersnoodramp," claimed the lives of 1836 people and highlighted the need for enhanced safety measures (Duiveman & Jensen, 2025). A large-scale flood protection was initiated in response to this disaster (Delta Works). A key part of the project involved closing the Haringvliet Estuary (1970) to reduce the shoreline length. The Haringvliet is a North Sea estuary located in South Holland in the mouth of the Rhine-Meuse Estuary (Figure 1a and c). By cutting off the natural connectivity with the sea, the Haringvliet Estuary was later turned into a freshwater lake, increasing freshwater availability but being detrimental for ecology (Figure 1b).

In 2000, the Dutch government introduced the Kierbesluit, a policy to partially open the Haringvliet floodgates during flood tides. This initiative aims to restore fish migration while maintaining flood protection and freshwater supply. However, the controlled reintroduction of saltwater has created a complex interaction between fresh and saltwater within the system, mainly due to the bathymetric depressions generated by the scouring activity of the flowing water from the time the estuary was open and by the extraction of sand for the construction of the gates (Figure 1d). When the floodgates are opened during flood tide, saltwater tends to enter the Haringvliet and settle in the deep zones due to the difference in density compared to freshwater (Figure 2). During the closure of the floodgates, under conditions of low flow rates from the river and unfavourable winds, wind-driven currents can spread the saltwater that is trapped in the depressions throughout the system (Kranenburg et al., 2023). This is undesirable as it may reach the freshwater intakes at the Middelharnis-Spui line (Figure 1d). Understanding how the saltwater spreads into the Haringvliet Estuary and under what conditions can be flushed from the bathymetric depressions is imperative for the proper management of the estuary.

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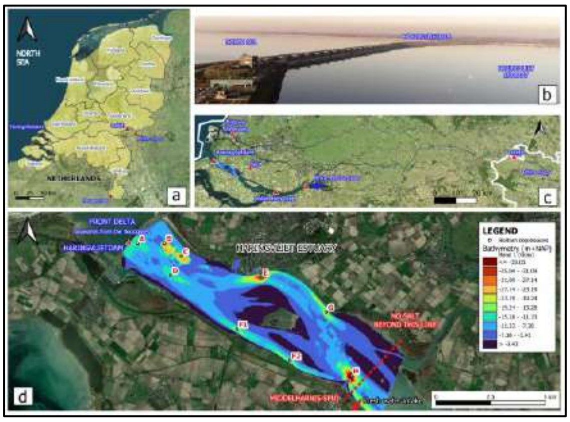

Figure 1. (a) Regional map of the Netherlands highlighting the Haringvliet Estuary in South Holland; (b) Photograph of the Haringvliet Dam; (c) The Rhine-Meuse River system and key locations such as Lobith, where the Rhine River enters the country, Nieuwe Waterweg, Hollandsch Diep, and Spui channels; (d) Detailed bathymetric map highlighting the bottom depressions and key features including the Middelharnis-Spui boundary, which marks the limit beyond which saltwater intrusion is restricted.

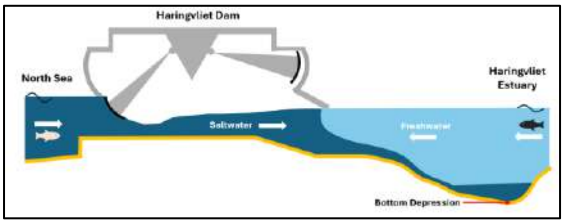

Figure 2. Saltwater intrusion through the Haringvliet Dam highlights saltwater inflow and saltwater accumulation in bottom depressions. Adapted from Jacobs et al., (2003).

Design Problem

In the Haringvliet Estuary, management protocols depend on predefined gate operation strategies to control saltwater intrusion. These protocols have uncertainties that can affect their effectiveness. The uncertainties arise from variations in input parameters, parameterisations of physical processes, and simplifications in model configuration. Moreover, the high computational cost of running a 3D model (Svašek Hydraulics, 2023) to test different input combinations limits the ability to explore and compare multiple scenarios efficiently. An analytical model has been developed by Svašek Hydraulics (2024) to reduce the computation time, however, it still needs further refinement to capture local physical dynamics and spatial variability, such as the differing flushing efficiencies observed between bottom depressions. Furthermore, stakeholders lack an interactive tool to execute scenarios and identify threats, making the evaluation of different management strategies and the recognition of potential outcomes challenging.

Main objective

This project aims to design a dashboard for saltwater management in the Haringvliet Estuary, which integrates fast analytical models for the prediction of saltwater intrusion and to support better decision-making.

Methodology

The methodology of this project is structured around three key stages, each corresponding to a core research question.

Sensitivity and Uncertainty Analysis

The initial phase identifies and quantifies sources of uncertainty within existing saltwater management protocols. Sensitivity analysis is first conducted using the Morris method (Morris, 1991), which functions as a screening tool to detect the most influential variables. Following the identification of key variables, the Sobol method (Sobol, 1990) is applied to quantitatively assess how these variables and their interactions contribute to output variability.

Analytical Model Refinement

After the sensitivity and uncertainty analysis, we will enhance the process-based functions of the analytical model with focus on the variables that generate the greatest uncertainties. For example, the initial assumptions in the analytical model consider uniform velocity and uniform salinity concentration within each bottom depression when calculating the mixing processes. However, this does not reflect real-world conditions. In reality, flushing mechanisms vary due to local factors such as geometry, salinity gradients, and the depression position within the system (Debler & Armfield, 1997; Kranenburg et al., 2023). Assuming homogeneous conditions oversimplifies the problem. Also the model configuration relies on defining spatial zones around bottom depressions, which are connected through threshold sills and saltwater transport pathways. Currently, the model treats each sill as a fixed value (uniform depth), which lacks a physical representation. Incorporating detailed bathymetric information (in the model configuration of the analytical model) allows the definition of sill geometry using measurable physical features such as slope, shape and roughness. Debler & Armfield (1997) indicated the importance of the start and end of the bottom depression (slope), which can accelerate or delay the flushing mechanism. The flow over sills can alter mixing rates and influence how far saltwater intrudes into the estuary.

Dashboard Development and Scenario Evaluation

In the final stage, the analytical model will be integrated into a dashboard. The dashboard interface will allow stakeholders to simulate and compare saltwater management strategies by adjusting input data such as available discharge (linked to the Rhine River), salinity concentration (seawards from the floodgates), and inlet volume (floodgate operation). The platform also will present uncertainty visualization of the strategies, allowing users to assess the reliability of each scenario using key performance indicators such as flushing efficiency and the extent of saltwater intrusion.

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Institutional influences on transitions in water management

A comparison between Dutch and Flemish river management plans

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Keywords: policy innovation, institutional change, NbS

Introduction

To support the transition to integrated, nature-based river-basin management, institutions supporting such strategies and practices need to be established while existing institutions hindering the transition need to be gradually broken down and replaced (Fig. 1). Institutions play a vital role in transitions since they are the rules which determine the range of acceptable behaviour in society and how interactions are organised (North, 1990). This study draws lessons from the influence of different institutional frameworks in transitions towards nature-based river management by comparing institutional developments in the Dutch *"Room for the River"* programme and the Flemish "*Plan Sigma"*.

Methods

Room for the River (RvR) in the Netherlands and the Sigma Plan in Flanders were established to protect against flooding from major rivers by integrating ecology and living environments with water safety programs (Hartgers et al., 2015; De Jonge et al., 2022). These programs showcase efforts towards institutional change. Since the two programs are organized differently, they have led to distinct institutional consequences, offering valuable insights. In this research we study how the institutional arrangements of the two programs contribute in different ways and with different speeds to nature-based river management transition. To this end we studied: policy documents (4 RVR, 3 Sigma), Research reports (2RVR, 1 Sigma), scholarly articles (2 RVR, 2 Sigma), and conducted interviews with water-management scholars (2) and a landscape-architect.

Institutions exist in a multi-layered nested hierarchy of rules: *Operational rules* (more rules that determine daily actions), *Collective Choice rules* (rules for selecting operational rules) *Constitutional rules* (rules for selecting collective-choice rules) (Ostrom, 2005). This hierarchy illustrates how different institutions influence each other and is used to categorize institutions in this study to allow for more detailed analysis and understanding of their influence on transitions.

Figure 1: The X curve of transitions representing building up new institutions and breaking down old ones (Hebinck et al., 2022), combined with the three institutional levels at which change may take place (Ostrom, 2005)

Results

Room for the River

Due to high water levels in the 90's, allowing room for rivers became a basis for the high-water protection programmes in the 2000's (Rijkswaterstaat, 2000). This was formalized in law with a core planning decision by the parliament in 2007, combining water protection, ecological recovery, and spatial quality in a flexible and participative manner (Busscher et al., 2017). The rise and formalization of this new norm is a great example of a new *constitutional institution,* moving a transition into the stabilisation phase, see fig 1 (Rotmans et al., 2000). The *collective choice institutions* based on this included how the new rules would be implemented, which was through programmes with specific structures: the room for the river programme, but for example also the Meuse works programme. These programs were governed by a programme directorate and executed through cooperation of Rijkswaterstaat, municipalities, engineering companies and regional water boards, partially informed through local participation (Rijkswaterstaat, 2000). Changing operational institutions included public participation, public-private partnerships and technical ways of working (De Jonge et al., 2022).

Plan Sigma

Plan Sigma had a similar motivation to the "Room for the River" initiative. It was designed to prevent flooding while enhancing spatial quality and nature around the Scheldt River and its tributaries (De Vlaamse Waterweg, nd). Initiated in Belgium in 1977, Plan Sigma is an integrated water management program that has evolved to better protect Flanders from flooding while balancing with ecological and landscape objectives. By integrally embedding this approach in the departments of mobility and public works this represents a *constitutional shift* (Meire et al., 1995; 2014). Instead of adhering to an absolute safety standard, the plan applies a risk-based approach. In the 1970s, space was allocated for the estuary, diverging from the traditional approach of large-scale hydraulic engineering projects, both examples of *collective choice institutions*. The plan is implemented through a broad collaboration of government agencies, experts, and societal actors, making it a multi-stakeholder approach that also marked an *operational institutional shift* (Van Lierde et al., 2013).

Discussion/ Conclusions

The main difference between the two programs that Plan Sigma was integrated in existing power structures, while for Room for the River new structures were installed backed up by law (*Planologische Kern Beslissing*), instantly setting up constitutional institutions and moving the transition into stabilisation. The consequences were that Room for the River attained its goals quickly, successfully, and within budget because no barring institutions needed to be broken down for the programme direction to implement innovative ideas (De Jonge., 2022). In Plan Sigma it took a lot longer to attain similar results, since old, contending institutions, required breaking down before the new integrated approaches could be implemented. On the turn side, while lauded and copied worldwide, when Room for the River was finished, and the governing bodies disbanded, the new institutions established were gone, cut off from funding and official organisations. And since it had been separately organized, very little was internalised in the department of infrastructure and public works, where old, hard-infrastructure focussed institutions still reigned (WNF, nd; Busscher et al., 2017). The breaking down part of the X curve (fig.1), never occurred. Plan Sigma, which slowly but steadily built new institutions, while breaking down old ones, has fully internalised the integral, nature and area based, participative workways, moving on the X curve in classic fashion from experimentation to institutionalisation to stabilisation, developing institutions on the relevant levels, see fig 1. This demonstrates how important the breaking down of old institutions and internalization of new institutions in existing power structures is when aiming to support transitions.

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Assessing alternative discharge distributions at the Dutch Rhine Bifurcations to address climate change impacts by 2100

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Keywords — Dutch Rhine system, discharge distribution, climate change, river functions, performance indicators

Introduction

Climate change poses significant challenges to river systems. For the river Rhine, this means that the discharge variability is changing through more frequent and lower flows in the summer and more extreme discharge peaks in the winter (Buitink et al., 2023). This inevitably impacts functions humans allocated to rivers over the past century.

In case of the Dutch Rhine system, river branches are heavily engineered through the construction of hydraulic structures to support multiple functions including providing conveyance capacity (i.e. flood safety), fresh water supply and navigation, as the Rhine is one of Europe major waterways. However, often these interventions were carried out with focussing on one specific river function in mind.

All these human interventions, together with some high discharge events have also contributed to alterations in the river's discharge (distribution) over the two bifurcations in the Netherlands.

To understand how climate change affects future river functions in relation to each other, we aimed at defining performance indicators for each river function and to use these in a Multi Criteria Analysis to investigate the effects of climate change in the Dutch Rhine at a system scale. Additionally, we used this framework to compare alternative discharge distributions and large scale river widening measures to adapt for climate change.

Performance indicators

Based on literature research, performance indicators have been found to assess the performance of the total river system.

The *conveyance capacity* of the river is based on the increase in maximum water level along the length of one river branch.

Fresh water supply has been quantified based on the low flows with the corresponding return period.

Contributions to habitat have been quantified based on the area of the floodplain and the dynamics in the floodplains which is the difference between the 5% and 95% water levels.

Navigation suitability in different scenarios is quantified as the maximum number of days per year on which the critical navigation depths (2.8m for the Waal and Nederrijn/Lek, 2.5m for the IJssel) are not exceeded.

Performance under future conditions

We studied the various effects of climate change by use of the SOBEK 1D model of the Dutch Rhine branches. This model is forced by different upstream Rhine discharges, representing possible future hydraulic conditions based on the KNMI'24 scenarios (Buitink et al., 2023).

First, the model is forced with an increased design discharge (18.000 m^3/s) to study the effects of climate change on the performance indicator for conveyance capacity. Second, the model is run with a multitude of discharge timeseries representing a variety of climate ensembles covering 30 years developed by Buitink et al. (2023). The future hydraulic conditions in each of the river branches were then evaluated on the identified performance indicators and the scenarios are compared in an equally ranked Multi Criteria Analysis.

Additionally, the impact of possible future interventions on the rivers' performance is assessed. We chose to assess the impact of two different scenarios for allocating the increase in design discharge from 16.000 to 18.000 m^3/s in line with the advise from ENW (2024). In this study, we considered two scenarios where the additional 2.000 m^3/s is divided 80%-20% and 60%-40% over de Waal and IJssel respectively. This has been implemented in the model by a adapting the main channel roughness over a stretch of 1 kilometres upstream of the bifurcation points until the desired discharge distribution is reached.

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To compensate for the additional discharge on the IJssel in the 80-20 and 60-40 scenarios, three large scale measures have been implemented (dike relocation, floodplain excavation, main channel xcavation) in the model and the results are compared throughout the performance indicators and the MCA.

Results

The MCA (Table 1, top section) shows that the river functions overall all score worse for a future climate compared to current climate. Analysis of the individual performance indicators show that the performance of the river functions conveyance capacity, water supply and transportation decrease. However, the function habitat shows to improve for wetter scenarios. This might be due to the definition of the performance indicator.

The MCA (Table 1, middle section) also shows that in a context of a future climate with large increase in emissions and a drier climate, an alteration in the discharge distribution is beneficial for the conveyance and the habitat of the river. Both considered scenarios show an improvement, where the 60-40 scenario scores best.

Furthermore, to compensate for the increase in discharge on the IJssel in the 60-40 scenario, large scale dike relocation measures show mainly improvements for the conveyance of the river, whereas the other performance indicators remain equal or show little improvement (Table 1, bottom section).

Conclusion

We developed a novel framework to assess the overall performance of a river system by scoring the performance of individual river functions using different performance indicators and an MCA. Although the application of an MCA is subjective, it still provides a good indication of the overall trend. This framework is then used to assess the impact of different climate change scenarios on the performance of the Dutch Rhine system. We found that in general, climate change reduces the overall performance, but might enhance individual river functions. Furthermore, we found that by altering the discharge distribution during design discharges over the Waal and IJssel, the overall system performance might be increased. The framework also suffices in assessing the impact of river interventions to compensate for the altered discharge distribution.

Table 1. MCA performance river functions in climate scenarios. A lower score is better. Nomenclature for the climate scenarios is in line with KNMI (2023).

Scenario	**Conveyance**	**Water supply**	**Habitat**	**Transportation**	**Sum**
Current system under future change					
Current	1	1	5	1	**8**
2100Md	2.5	3.5	4	3.5	**13.5**
2100Mn	2.5	2	2	2	**8.5**
2100Hd	4.5	5	3	5	**17.5**
2100Hn	4.5	3.5	1	3.5	**12.5**
Impact of different discharge scenarios					
Current	1	1	4	1	**7**
2100Hd	4	3	3	2.5	**12.5**
2100Hd 80-20	3	3	2	4	**12**
2100Hd 60-40	2	3	1	2.5	**8.5**
Impact of river widening interventions					
Reference	**1**	1	4	1	**7**
2100Hd 60-40	5	3.5	3	3	**14.5**
Dike relocation	4	3.5	1	3	**11.5**
Floodplain excavation	3	3.5	2	3	**11.5**
Main channel excavation	2	3.5	5	5	**15.5**

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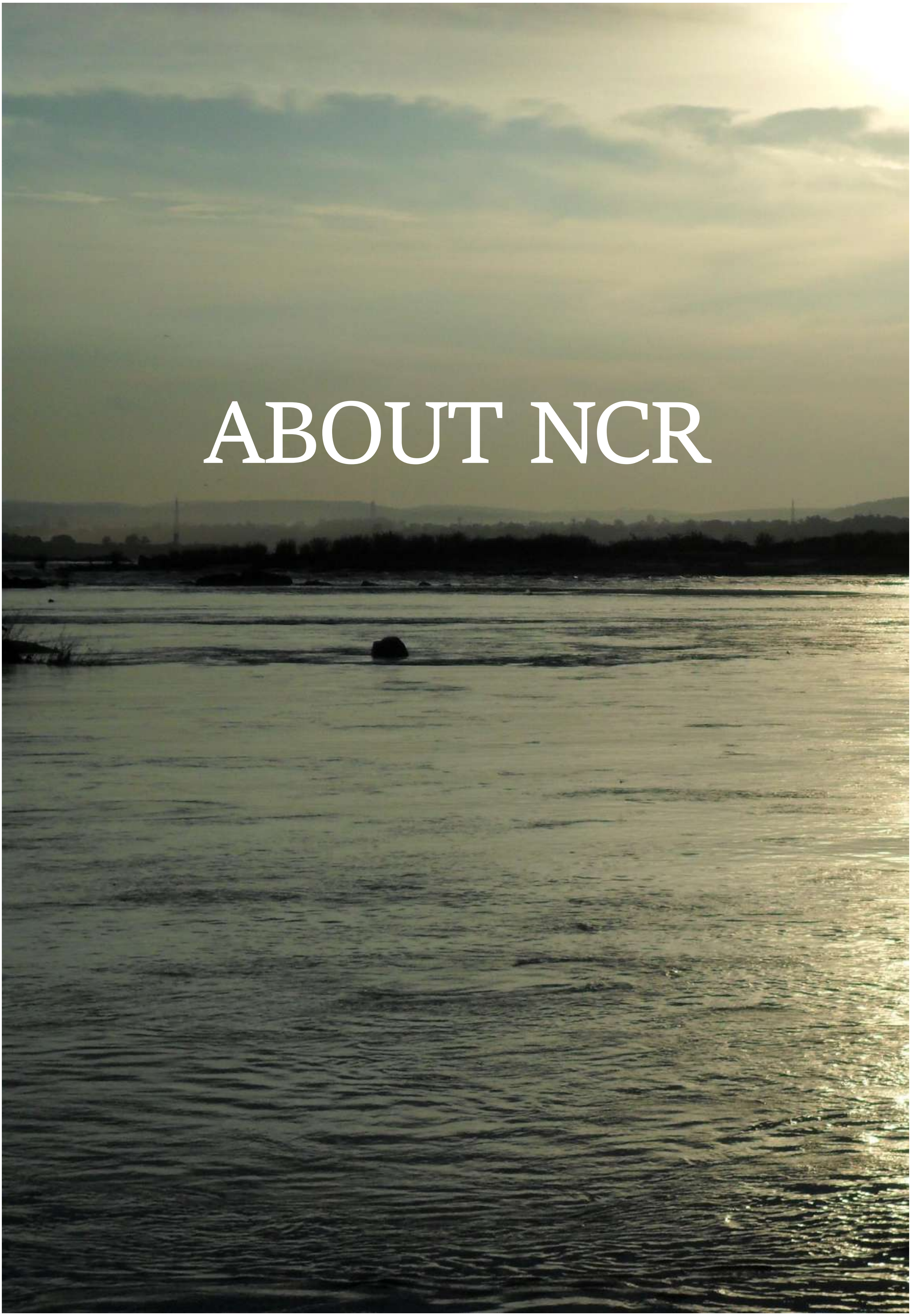
ABOUT NCR



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') 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 beter 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 the 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 practiced 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 Organization

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 Supervisory Board (SB) and Programme Committee (PC); monitors 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.
- **Programme 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), Deltares, Universiteit Twente (UT), Radboud Universiteit Nijmegen (RUN), Universiteit Utrecht (UU), Technische Universiteit Delft (TUD), Wageningen University & Research (WUR), Leiden University College (LUC), Vrije Universiteit Amsterdam (VU) and IHE Delft.
Each partner contributes in-kind and/or in-cash to realise the annual programme.

Table 1: The composition of NCR Boards in 2025. Persons marked with * are chairpersons.

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