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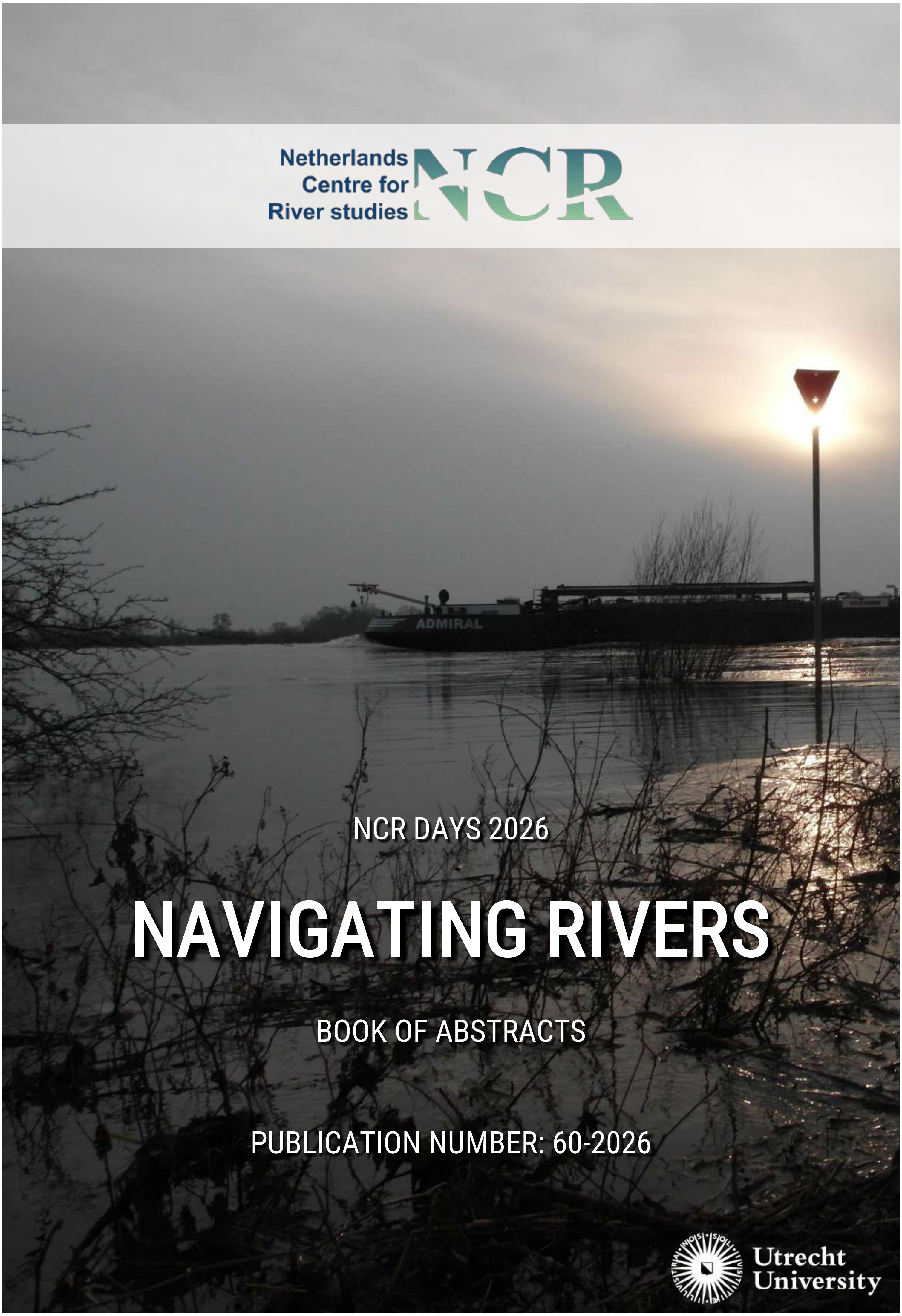

NCR DAYS 2026

NAVIGATING RIVERS

BOOK OF ABSTRACTS

PUBLICATION NUMBER: 60-2026

Utrecht
University

NCR DAYS 2026

Navigating Rivers

Menno Straatsma, Kim Cohen, Marcel van der Perk,
Maarten Kleinhans, Hans Middelkoop

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Haskoning
Enhancing Society Together

Organising partner:

Utrecht University

Conference venue

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Cite as: Straatsma, M.W., Cohen, K.M., van der Perk, M. Kleinhans, M.G., Middelkoop, H. (2026), *Navigating Rivers: NCR DAYS 2026 Proceedings*. Netherlands Centre for River Studies publication 60-2026

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Preface

Welcome to the 28th edition of the NCR DAYS! On April 16 and 17 2026, the annual conference of the Netherlands Centre for River studies (NCR) will take place in Utrecht. Entitled 'Navigating rivers', this conference addresses how to navigate the multifaceted landscape of rivers.

This edition presents two days with poster and oral presentations in five thematic sessions: (1) Solution space for decision making, (2) Flow dynamics, (3) Morphodynamics at multiple scales, (4) Advances in flood risk management, and (5) Modern and unforgettable issues. The after-lunch programme features a choice of activities, being a lab tour to the Metronome, a visit to the UU library map room with historic river maps and a discussion on the legal lessons we can draw from the Room for the River 1 project.

Three keynote lectures navigate the fluvial landscape from their own unique perspective. Firstly, prof. mr. Marleen van Rijswick - professor of European and Dutch Water Law and the director of the Utrecht University Centre for Water, Oceans and Sustainability Law - will go into depth regarding the untapped capacity and solution space within the legal framework. Secondly, Dr Ignacio Peralta-Maraver from Universidad de Granada (Spain), who is an eco-physiologist studying freshwater ecosystems, takes over together with prof dr Wilco Verberk who is professor of Functional Ecology from the Radboud University (NL). They will address the functional ecology of rivers. Starting at the substrate boundary layers they scale up and out to habitat heterogeneity at the landscape scale. Thirdly, prof. dr. Rebecca Hodge from Durham University (UK) takes the perspective of the fluvial geomorphologist. She adds cohesion to the substrate and investigates how that affects gravel entrainment.

With 32 poster presentations, 22 oral presentations and 3 keynote lectures, the 28th edition of the NCR DAYS has a full and exciting programme. We hope you will enjoy the conference and look forward to seeing you all in Utrecht!

The local organizing committee
Menno Straatsma, Kim Cohen, Marcel van der Perk, Maarten Kleinhans and Hans Middelkoop

Utrecht, April 2026

Conference details

Organising partner

The organizing partner of the 2026 edition of the NCR DAYS is Utrecht Univerity, specifically the Department of Physical Geography of the Faculty of Geosciences.

Venues

The conference will take place at the Utrecht Science Park, formally known as 'De Uithof' (Figure 1). The registration and poster sessions will be on the first floor of the Minneart building, Leuvenlaan 4, 3584 CE Utrecht. The main entrance is at the south side of the building. Lectures will be given, just around the corner in Koningsberger, lecture hall ATLAS. Additional information: https://www.uu.nl/minnaertgebouw

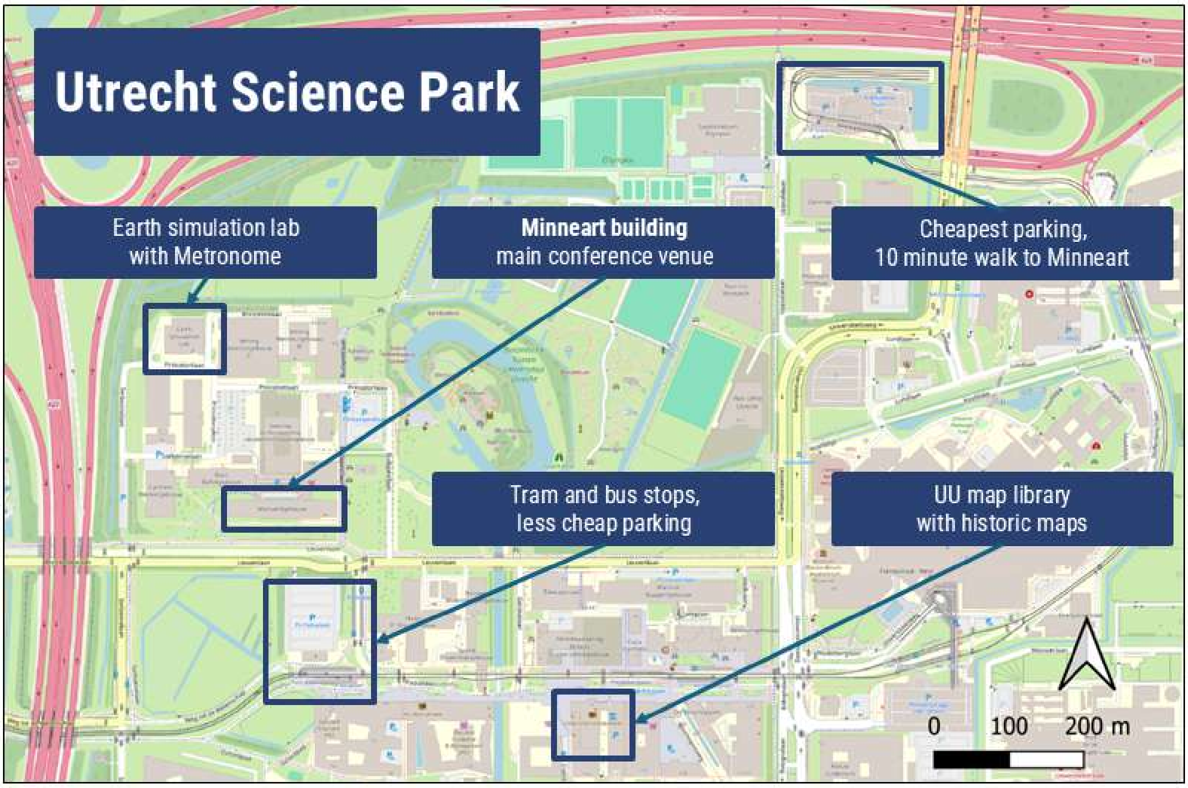


Figure 1: Conference venue at the Utrecht Science Park. The main location is the Minneart building. Map credits: Openstreetmap and contributors.

Local organising committee (LOC)

The LOC consists of five members: Menno Straatsma, Kim Cohen, Marcel van der Perk, Maarten Kleinhans and Hans Middelkoop

PROGRAMME

Programme NCR days 2026

	Day 1 - Thursday April 16 2026	
	08:45 - 09:15	Registration, welcome and coffee
	09:15 - 09:30	Opening of the 28th edition of the NCR days
	09:30 - 10:20	**Marleen van Rijswick | Keynote lecture I** *Navigating rivers: untapped capacity and solution space within the legal framework*
	10:20 - 10:40	**Poster pitches**
	10:40 - 11:10	Coffee break & poster session
Session 1	**Solution space for decision making**	
	11:10 - 12:25	**Valeria di Fant** *Pathways for transformational climate adaptation for Integrated River Management in the Netherlands* **Borjana Bogatinoska** *Revisiting the forgotten Randmeer: multifunctional flood end drought resilience modelling for the Noordoostpolder region* **Thorvald Rorink** *HWBP Vierwaarden – The potential of Serious Gaming in river engineering: benefits and challenges* **Hendrik Havinga** *Impact of RVR2.0 on future Waal lay-out and navigation* **Yinghua Li** *New opportunities for experimental meandering rivers*
	12:25 - 12:50	Lunch
	12:50 - 13:50	Two options: (1) Legal lessons Room for the River, ATLAS (2) Lab tour Metronome
Session 2	**Flow dynamics**	
	14:00 - 15:15	**Frans Buschman** *Derivation of stage-discharge relations for Rhine and Meuse: reflection on the current practice* **Marthe Oldenhof** *Experimental investigation of the flow field in a scour hole in a river* **Hadeel Al-Zawaidah** *Microplastics under turbulence: quantifying the turbulent Prandtl–Schmidt number with multiphase PIV/PTV* **Chit Yan Toe** *Flow transition from open-to-closed channels in rivers: implications for plastic accumulation and ice jams* **Marieke de Lange** *Rewetting floodplains along the Rhine: Dutch case study of the EU MERLIN project*
	15:15 - 15:45	Coffee break & poster session
	15:45 - 16:35	**Wilco Verberk & Ignacio Peralta Maraver | Keynote lecture II** *Functional ecology of rivers: from substrate boundary layers to habitat heterogeneity at the landscape scale*
	16:35 - 18:30	Drinks & bites & poster session
	17:00 - 19:00	Optional river walk, guided by Kim Cohen: Kromme Rijn to City Centre, ends at restaurant
	17:00 - 18:30	**NCR board meeting: Room Minnaert 0.18**
	19:00 - 21:30	Conference dinner @ "De Utrechter" and pubquiz by YNCR

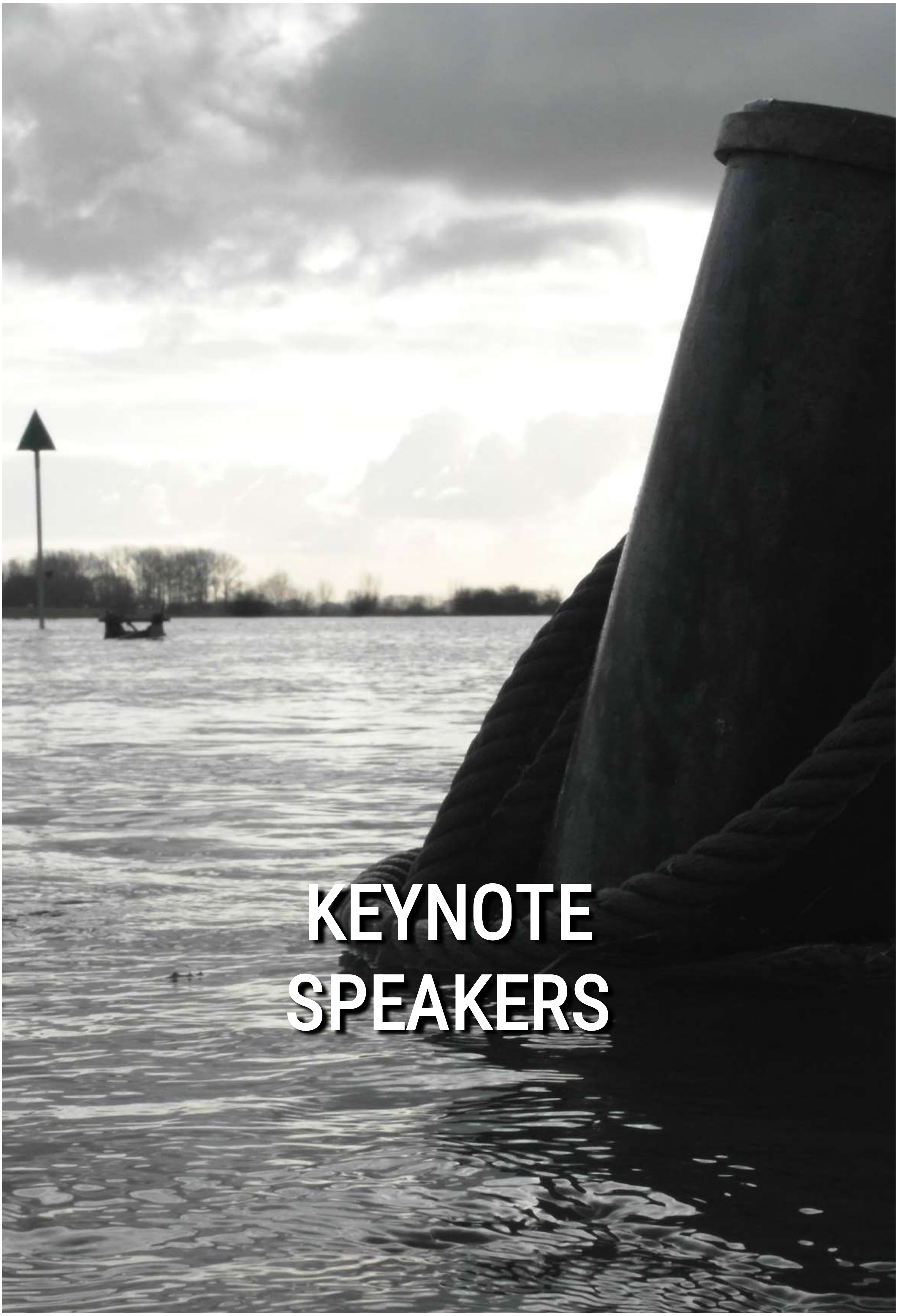
Day 2 - Friday April 17 2026

	09:00 - 09:30	Registration, welcome and coffee
	09:30 - 10:20	**Rebecca Hodge | Keynote lecture III** *The impact of cohesive materials on gravel entrainment*
	10:20 - 10:40	Poster pitches
	10:40 - 11:10	Coffee break & poster session
Session 3	**Morphodynamics at multiple scales**	
	11:10 - 12:25	**Niek Collot d'Escury** *Quantifying topographic river confinement worldwide* **Pepijn van Denderen** *Arresting bed degradation in the Waal river: intervention strategies* **Matthijs Gensen** *Towards a manageable and stable riverbed for the Meuse* **Debora van Dieren** *The morphological response to peak flows at the Pannerdense Kop* **Maarten Bakker** *Satellite-based monitoring of riverbed evolution and reservoir storage capacity*
	12:25 - 13:00	Lunch
	13:00 - 14:00	Two options: (1) Visit to UU library map room with historic river maps, (2) or lab tour Metronome
Session 4	**Advances in flood risk management**	
	14:00 - 15:00	**Brecht Schielen & Meike Oppelaar** *Reducing storm surges in the IJssel-Vecht Delta using Tesla valve shaped islands* **Victor Chavarrias** *Physical origin of water-level oscillations in the Meuse model near river kilometer 203* **Tim Winkels** *From sedimentary structures to channel-belt architecture: effects on 3D groundwater flow for dike safety analysis* **Leon Besseling** *Fast spatiotemporal flood modelling after a dike breach*
	15:00 - 15:30	Coffee break & poster session
Session 5	**Modern and unforgettable issues**	
	15:30 - 16:15	**Eveline van der Deijl** *Wave-reducing capacity of fascine screens* **Rutger Siemes** *Tidal propagation into rivers influenced by salt intrusion* **Roy Frings** *A forgotten disaster: the 1926 Meuse flood*
	16:15 - 16:30	Closing of the 28th edition of the NCR days
	16:30 - 18:00	Drinks & bites

Posters presentations Thursday April 16th

Anouk Boon	*Silting and permeability in the Common Meuse river bed*
Astrid Bout	*Unique data available from monitoring longitudinal training walls in the Waal river*
Patit Chotemankongsin	*What are the modelled hydrological impacts of wetland restoration in lowland river systems?*
Ali Fakhri	*Managing river bank protection by groynes in straight and meandering river reaches in Iraq*
Bas Gradussen	*Investigating the relationship between sedimentation hotspots and normal width variations*
Robert Groenewege	*Evaluation of a flexible groyne in comparison with a traditional groyne*
Lieke Lokin	*Constructing water depth maps: comparison of bedform statistics and shoals*
Tobias Nootenboom	*Long-term development of lowland rivers Rivers2Morrow - a research program*
Pauline van Adrichem	*Expected ice loads on hydraulic structures in the Maas in a scenario of decreased AMOC strength*
Bas van Leeuwen	*Modelling salt intrusion response to the tidal park Feijenoord in the Nieuwe Maas using a refined 3D hydrodynamic model*
Erik Verhagen	*Finding opportunities for flexible vegetation management in the Biesbosch*
Luc Visser	*Using environmental DNA to inform rehabilitation practices for rheophilic fish in the river Meuse, the Netherlands*
Nathan Visser	*Analytical and numerical assessment of lateral exchange effects induced by porous longitudinal training dams*
Joris Weel	*Turbulence-Particle Interactions as possible mechanism behind Dune Height Bimodality at Large Transport Stages*
Niels Welsch	*Using scenario discovery to identify system deficiencies in a river delta affected by deeply uncertain climate change*
Kelsey Wentling	*Advancing recognitional justice in integrated river basin management through stakeholder analysis*

Posters presentations Friday April 17th	
Jitse Bijlmakers	*Rivers and rhinos: linking river flow alteration to habitat quality for endangered floodplain herbivores*
Anouk Bomers	*SNAPFLOOD: Stochastic Neural network Approach to forecast river FLOOD probabilities in real-time*
Smriti Dutta	*Delta-ENIGMA: advancing biogeomorphology research in deltas through observation and experimentation*
Jiaqi Liu	*Numerical study of suspended sediment dynamics in a free surface flow constructed Wetland in Norway*
Jacobus Meuwissen	*Spatial variation in the composition of recent deposits of fine sediments along the Rhine River*
Irene Mulder	*Exploring spatio-temporal river water temperature patterns in Dutch small and large rivers*
Joe Nicholas	*Tributary mouth widening effects on hydro- and morphodynamics in small, sand bed rivers*
Eise Nota	*Reoccurring quasi-steady states in experimental estuaries*
Noortje Oosterhof	*Linking microplastic deposition to sediment deposition: a field study*
Julius Overhoff	*Shifts toward drier-associated terrestrial plant species along the Waal River between 1993 to 2023*
Lars Paternotte	*Hydro- and morphodynamic LES modelling of scour holes in rivers*
Kees Sloff	*The science behind Room for the River 2.0's bed erosion control measures*
Maartje Supèr	*Exploring measure possibilities within Room for the River 2.0 for the IJssel River near Steenderen, The Netherlands*
Wouter van der Niet	*To aggrade or to erode: side channels alongside longitudinal training walls*
Marcel van der Perk	*Tracing the source and fate of suspended matter in the Dutch Rhine branches*
Tim van Kampen	*Visual analysis explains extrapolation uncertainty of calibration methods in rivers*
Marijn Wolf	*Balancing accuracy and efficiency in centennial-scale 2D morphodynamic river modelling*



KEYNOTE SPEAKERS

Functional Ecology of Rivers: from substrate boundary layers to habitat heterogeneity at the landscape scale

Wilco C. E. P. Verberk[a*], Joshua D. Climo[a], Ignacio Peralta-Maraver[b]
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Keywords —climate change, oxygen, low summer discharge, benthic macroinvertebrates, hyporheic zone, river management

Spatial and temporal scales

Rivers harbour biological communities which operate at a range of spatial scales: from protists and invertebrates living between sediment grains to fishes and birds making a living across the whole catchment of a river, spanning across countries (Fig. 1; Peralta-Maraver et al. 2018; Malmqvuist, 2002). Interannual, seasonal and daily changes add a layer of temporal variability, which needs to be integrated with the spatial dimension for understanding how riverine ecosystems function. Rivers receive, transport, and transform energy, nutrients, and pollutants from their catchments, making them both highly productive and highly sensitive to environmental impacts. Consequently, riverine ecosystems and the species they support are increasingly threatened by human stressors. Here, we present a broad overview of river ecology highlighting key principles and how anthropogenic stressors affect river biota and ecosystem functioning.

The flow, temperature and oxygen nexus

Breathing underwater is challenging owing to the much slower rates of oxygen diffusion in water than in air. Additionally, there is ~20-30 times less oxygen dissolved in water. Consequently, ventilating gills takes much more effort than breathing via lungs. Like all ectotherms, demand for oxygen in fish and invertebrates increases steeply with warming. Thus, in warm waters, it becomes increasingly difficult to meet oxygen demand. Hence, we see a clear synergistic effect of heat stress and deoxygenation (Verberk et al., 2016). Flow helps here as this alleviates the costs of ventilating gills and the water movement enhances aeration, increasing oxygen levels. For example, in the Common Meuse, summer flows are frequently too low, exacerbating oxygen stress. Indeed, despite improved water quality in the Meuse (lower phosphate loading, improved oxygenation), invertebrate communities deteriorated, likely because of lower flows in the summer.

Shear stress, flow and grain size

Shear stress, flow and grain size are important interacting components of the microhabitat of riverine invertebrates, linking ecology closely with the field of morphology. The shear stress experienced can vary dramatically across small spatial scales (due to variation in depth, flow and substrate dimensions), allowing animals to choose their preferred conditions. Animals have various adaptations (claws, suckers, hooks, streamlined body shape, behavioural; Malmqvuist, 2002) to deal with high shear stress and the position they occupy reflects a balance between the benefits of flow (feeding, respiration), and the disadvantages (dislodging, abrasion).

The hyporheic zone

The riverbed imposes many challenges for the animals living there: high, abrasive flow, sudden desiccation or predation. thermal stress and high-flow disturbance. These can be avoided by entering the hyporheic zone; i.e. the water-saturated sediments beneath and alongside the active river channel Although not readily visible, the hyporheic zone is estimated to have a global surface area of up to 662,041,000 km^2 (four times the area of the Pacific Ocean; Battin et al., 2016). This is because the zone extends subsurface beyond the actual river channel.

The hyporheic zone hosts a diverse array of organisms, from microscopic protists to macro-invertebrates (Fig 1B&C). In addition, many benthic invertebrates temporarily use the hyporheic during early developmental stages (Robertson et al., 2000). The habitat quality of the hyporheic depends critically on the sediment grain size distribution and its permeability, governing flow and oxygen conditions. Colmation (interstitial clogging) can degrade the quality, shifting the community from large-bodied taxa to numerous small-bodied organisms as oxygen and nutrient constraints intensify (Peralta-Maraver et al., 2018).

Functionally, hyporheic communities operate as a bioreactor, processing dissolved and particulate organic matter and degrading a wide range of organic contaminants (Stamm et al., 2016). This capacity emerges from the combined effects of long pore-water residence times and microbial consortia. Invertebrates and protists modulate these processes through grazing and sediment reworking (Fig 1B).

The transversal dimension

Along the transversal gradient, from the main channel to the outer floodplains, the variation in flow and inundation generates a mosaic of distinct habitats and sediments, supporting diverse assemblages of macrophytes, invertebrates, and fish. In addition to this spatial heterogeneity, temporal variation in discharge governs exchange between channel and floodplain, sustaining productivity and life-history strategies (i.e. the flood pulse concept; Junk et al., 1989).

Protected and endangered riverine species collectively require habitats spanning the entire hydrodynamic gradient and habitats of intermediate dynamics are disproportionately important (de Nooij et al., 2006). Thus, river management, including side-channel construction, should re-establish the full gradient; side channels with restricted inflow often stagnate during low summer flows, reducing connectivity, habitat diversity, and overall ecological value.

Room for the rivers

Currently, the area remaining for riverine nature is approximately 30,000 ha, which is less than 7% of the total area of floodplains that rivers took up before large scale dyke construction in the 12th century. Thus, reserving more space both within and outside the embankments is a vital precondition for ecological restoration. Having more room also provides flexibility, making it easier to align nature development with other functions of the river such as high-water safety. Room for the river is necessary to recreate the mosaic of habitats which requires 1) space and 2) differences in elevation. Alleviating pressure on space creates flexibility in where succession can take place without resulting in substantially increased peak water levels. Recent large scale floodings teach us that if we do not provide the rivers the room it requires, it will take it for herself. So the choice we have is perhaps not how much room we give, but how we give the room.

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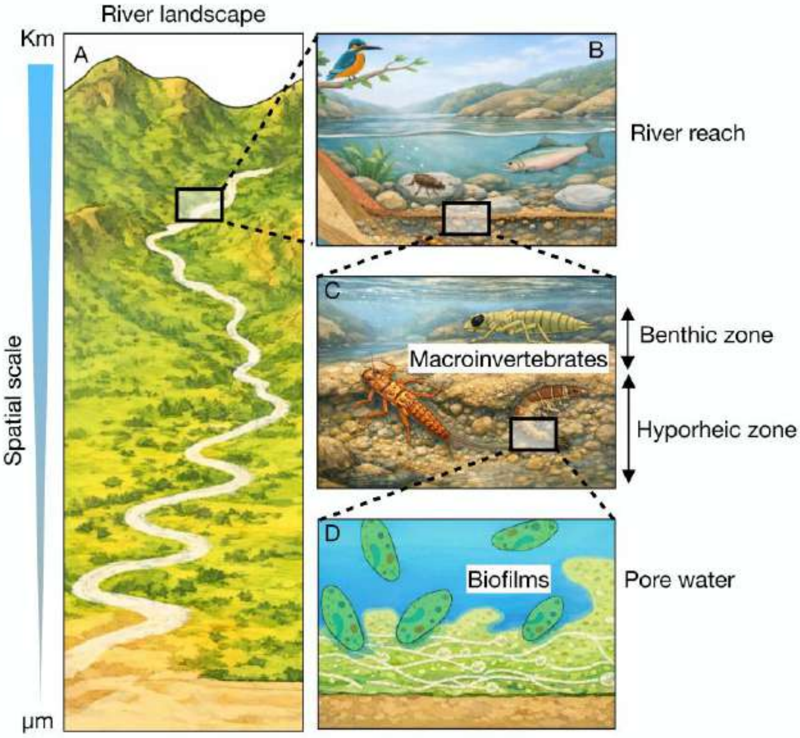

Figure 1. Hierarchical spatial organization of river ecosystems, spanning from the river landscape at the kilometre scale (A), to the river reach (B), the benthic and hyporheic zones inhabited by macroinvertebrates (C), and finally the pore-water environment at the micrometre scale, where biofilms and associated microorganisms develop (D). Across these nested spatial scales, rivers provide habitat for a wide diversity of organisms, including vertebrates, macroinvertebrates and microbial communities, whose interactions collectively shape ecosystem functioning.

The impact of cohesive materials on gravel entrainment

Rebecca A Hodge[a*], Elowyn M Yager[b], Hal Voepel[c], Danette Sitorus[a], David A Sear[c], Julian Leyland[c], David Whitfield[a], Andrew W Tranmer[b], Joel P L Johnson[d], Kevin Jensen[b], Sangki Lee[b], Timothy Richard[b], and Channing Syms[b]

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Keywords — gravel entrainment, clay and ice, critical shear stress

Introduction

Predicting bedload transport in gravel-bed rivers relies on estimates of critical shear stress (τ_c). However, our ability to predict τ_c is still such that predictions are only accurate to an order of magnitude (Phillips et al., 2022). One commonly occurring factor that is often overlooked, and which might contribute to poor predictions, is the presence of cohesive material within gravel beds. For example: clay is found in rivers draining agricultural catchments; biological cohesion is produced by commonly occurring caddisfly larvae, mussels, and biofilms; and ice can form in exposed beds or where rivers flow over permafrost.

Studies that have quantified the impact of cohesion have found that cohesive sediment can at least double τ_c. For example, Barzilai et al. (2012) measured bedload in an ephemeral gravel-bed channel (D_{50} = 17 mm) before and after there was the development of a clay/silt matrix in the bed, and found that matrix deposition doubled τ_c compared to clean bed conditions. Hodge et al. (2013) measured the force required to lift grains vertically from a gravel-bed river with a riffle-pool morphology (D_{50} = 18 to 42 mm). They found that some grains were in pockets lined with a visible clay matrix, termed mortaring. For pool exit grains without mortaring the mean lift force was 1.4 times the grain weight, whereas for those with mortaring the mean lift force was 3.9 times. Liébault et al. (2016) collected bedload data from a channel with high suspended sediment concentrations caused by erosion of the surrounding badlands. They calculated τ^*_c values for the gravel bedload (D_{50} = 8 mm) of 0.28 to 0.77, which is an order or magnitude larger than is commonly reported for gravel-bed rivers. They attributed this high value to a cohesion effect from the large quantities of clays and silts in the channel bed. Perret et al. (2018) conducted gravel-bed (D_{50} = 7 mm) flume experiments with additional cohesive and non-cohesive fine material and found that clogging of the bed with cohesive fines (cohesive glass powder) increased τ_c by up to 12%. This impact was similar to that of water-working a loose bed, which is notable as water-working has been invoked as the likely mechanism that causes observed temporal changes in τ_c (Masteller et al., 2019).

Yet, despite these observations, there is no systematic way in which cohesion is included in predictions of τ_c. Our aim is to assess whether cohesive non-biological material can be needs to be considered to produce accurate predictions of τ_c of individual grains, and if so, how.

Methods

To quantify the impact of non-biological cohesive material on gravel entrainment, we combine modelling with laboratory and field data. We use a force-balance grain entrainment model that calculates the total entrainment force (F_R) as a function of grain weight (F_g), the weight of overlying grains (F_s), the force of intergranular friction (F_d) and a new term that represents cohesion between grains (F_c). In the field and laboratory, we measure F_R. The laboratory experiments isolate the impact of varying clay and ice contents. For the field, we isolate cohesive effects by pairing datasets from seven sites that are similar apart from the presence/absence of cohesive material. We fit the entrainment model to the field and laboratory data by adjusting the distributions of either intergranular friction (for sites without cohesion, F_d) or the new cohesion parameter (for sites with cohesion, F_c).

Results

We first apply the entrainment model to a single grain size with varying relative protrusion (p/D), parameterised using a range of cohesion values we measured in the laboratory. Our results (Figure 1) show that the cohesion force F_c is

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large compared to the other components of the force-balance, especially when relative protrusion is low. For most tested values of cohesion, the individual cohesion force F_c is larger the total entrainment force F_R when there is no cohesion (F_{R0}), suggesting that cohesion is an important component of the force-balance. Our paired-site force-gauge field data (Figure 2) support this finding, showing that values of horizontal entrainment force normalised by grain weight (F_R/F_W) are systematically higher in the sites with cohesive material compared to those without. The presence of cohesive material increases the median value of F_R/F_W by 1.6 to 4.7 times. For the frozen lab beds, the difference in median F_R/F_W between the unfrozen bed and 10% frozen bed is 1.2 times, which is similar to the partially frozen field site. The 25% and 50% frozen lab beds have far larger values of F_R/F_W, with increases in median F_R/F_W of 96 and 490 times, respectively.

Finally, we use our field data to calibrate the entrainment model, and calculate critical shear stress. The calibrated model agrees well with field data, and we find that the cohesive materials found in our field settings increase median dimensionless τ_c by 1.7 to 9.9 times.

Conclusion

Cohesion from fine sediment and frozen pore water is a potentially important factor affecting critical shear stress in gravel bed rivers, even with relatively coarse grain sizes such as 25 to 50 mm. We have incorporated cohesive effects into a model for grain entrainment, and the model has been calibrated to provide a suitable fit to field data. Model results from all sites show that cohesive material can increase τ^*_c by up to an order of magnitude, and that the impact of cohesion was higher than the impact of variations in sediment grain size and protrusion between sites. We recommend that the impact of cohesive material on τ_c should be more widely considered.

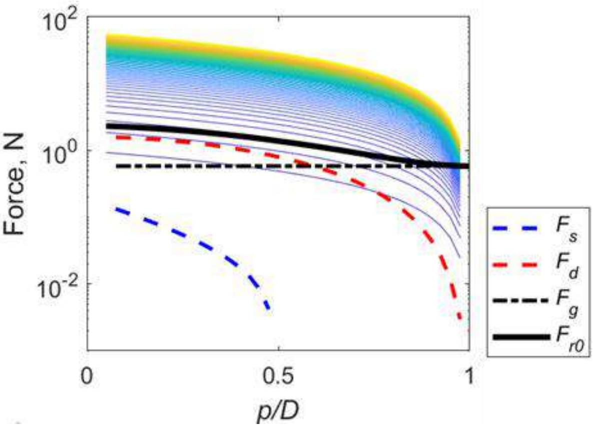

Figure 1. a and b) Components of F_R (F_s, F_g, F_d and F_c) as a function of relative protrusion (p/D) and cohesive force per unit area (C_F, N m^{-2}, blue through yellow lines). F_{R0} is total force with no cohesion.

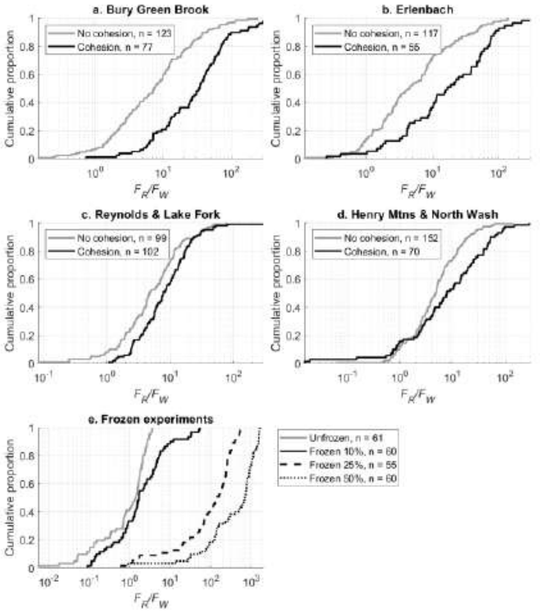

Figure 2. Measured distributions of F_R (resisting force) relative to F_W (grain weight). Grey lines show sites without cohesive material, and black lines show sites with cohesive material.

Acknowledgements

UK Natural Environment Research Council, grant numbers NE/K012304/1, NE/K013386/1 and US National Science Foundation grants EAR1921790 and EAR 0847799.

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SESSION 1

Pathways for transformational climate adaptation for Integrated River Management in the Netherlands

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Keywords — transformational climate adaptation, adaptation pathways, integrated river management

Introduction

As climate change grows in speed and impacts, incremental climate adaptation may not be sufficient anymore, and transformational adaptation is increasingly needed (IPCC, 2022). Nevertheless, transformational adaptation remains complex both conceptually and in practice, and adaptation action is largely incremental (Biesbroek et al., 2026; Berrang-Ford et al., 2021).

Adaptive pathways planning is a decision-making approach which enables long-term planning of climate adaptation under deep uncertainty by sequencing individual measures into so-called adaptation pathways (Haasnoot et al., 2013). The approach is well established both in the literature and in practice, with applications across sectors, levels of government and geographical areas (Haasnoot et al., 2024; Werners et al., 2022). The approach is well fit to operationalise planning of transformational climate adaptation, but has been criticised for favouring incremental adaptation over system-wide approaches (Bosomworth et al., 2017).

In this research, we bring together concepts and methodologies from the adaptation pathways, adaptation limits, visioning, and backcasting literature to evaluate two approaches for developing transformative adaptation pathways so to better include transformational adaptation in long-term decision-making. We test both approaches with the case of Integrated River Management (IRM) in the Netherlands, and compare the resulting pathways to assess the implications of each approach.

Case study

We apply the two approaches for developing transformative adaptation pathways to extreme river discharges in the Netherlands and more specifically in the Green Metropolitan Region of Arnhem and Nijmegen (GMR). In doing so, we focus particularly on the Dutch Rhine, including Waal and Ijssel. Future climate projections predict increases in peak discharges between now and 2100-2200, and further heightening may be caused by increase in protection upstream in Germany, the implementation of specific national Sea-Level Rise strategies, and change in discharge distribution between Ijssel and Waal (Buitnik et al., 2023; Haasnoot and Diermanse, 2022).

For one approach we zoom in to the GMR, a bottom-up collaboration between 17 municipalities in the Netherlands, including the area between Arnhem and Nijmegen. The contained regional scale allows to take into account the GMR 2120 vision, which includes consideration of both room for the river (RvdR) and other regional transitions (Volskamp et al., 2023a).

Two approaches

We apply and evaluate two approaches for developing adaptation pathways which are more transformative:

Adaptation thresholds and limits approach: in line with the ‘traditional’ adaptation pathways approach described in Haasnoot et al. (2013), we here propose to include transformational adaptation gradually within the pathways, as thresholds of incremental measures are approaching. Transformational adaptation is thus a response to the narrowing incremental solution space. The approach is tested here for IRM in the Netherlands.

Visioning approach: involves backcasting adaptation pathways starting from a transformational future vision, thus combining backcasting and visioning approaches (van der Voorn et al., 2012; Nalau and Cobb, 2022). Transformational adaptation is implemented out of a desire to do things differently, concretised in the formulation of future vision(s). The approach is tested here by backcasting adaptation pathways from the GMR 2120 vision, through a combination of vision document analysis and semi-structured interviews.

Results

Adaptation thresholds and limits

Long-term (2050-2200) climate adaptation to extreme river discharges along the Dutch Rhine can be achieved through either incremental or transformative adaptation pathways (Figure 1). An incremental pathway starts with dike heightening, followed RvdR measures outside of existing dikes and RvdR accommodation measures only when needed. Under a transformational adaptation pathways, RvdR accommodation measures are implemented right away, and are later complemented with RvdR measures outside of dikes and dike heightening when needed.

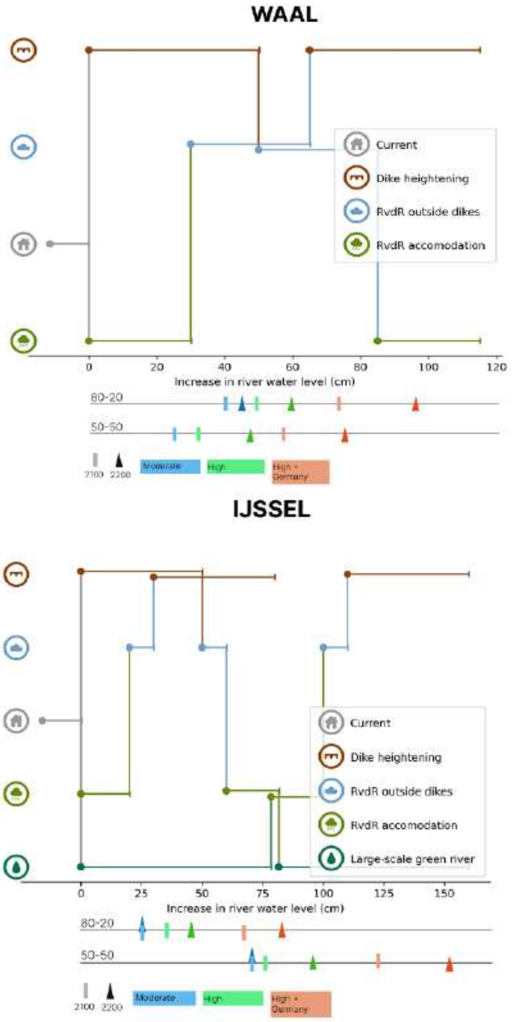

Figure 1. Adaptation pathways for the Waal (top) and Ijssel (bottom) under increasing water levels.

Vision-based

It was not possible to back-cast quantitative adaptation pathways for river flood risk management from the GMR2120 vision. Although the vision has clear system boundaries and scope, no explicit adaptation objectives were stated, and thus neither were adaptation metrics to asses in how far such objectives are maintained through time and growing climate impacts. Climate change and socio-economic scenarios were taken into account, but only qualitatively. Figure 2 showcases necessary adaptation measures for reaching the vision, which measures were considered for which locations, and how these may be sequenced through time. Although the resulting pathway cannot be quantified, or further specified, based on the existing vision, it does provide insights on what information should be included in a transformational future vision to ensure backcasting an adaptive plan is possible.

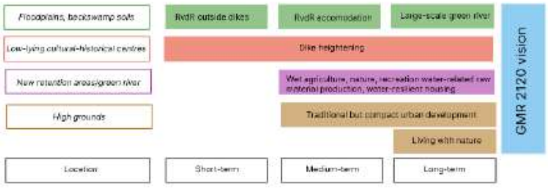

Figure 2. Adaptation pathways for the GMR, as backcasted from the GMR2120 vision.

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Revisiting The Forgotten Randmeer: Multifunctional Flood And Drought Resilience Modelling For The Noordoostpolder Region

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Keywords — Bordering Lake, Flood Risk Management, Climate Adaptation

Introduction

The Dutch delta is defined by engineered landscapes where reclaimed polders, lakes and rivers operate as a tightly managed hydraulic system. Peripheral lakes, or randmeren, were historically constructed to hydraulically decouple reclaimed land from adjacent higher grounds, reduce groundwater drawdown, and increase system buffering capacity (Van de Ven, 2004). The Noordoostpolder (NOP), reclaimed in the 1940s, remains a notable exception. Unlike later Flevoland polders, it was constructed without a randmeer along its eastern boundary.

From the late twentieth century onward, the idea of constructing a randmeer along the former Zuiderzee shoreline re-emerged in policy and technical studies. Hydraulic assessments conducted around 2000 focused primarily on extreme flood events and peak water level reduction. However, the project was never implemented and became informally known as the "Forgotten Randmeer".

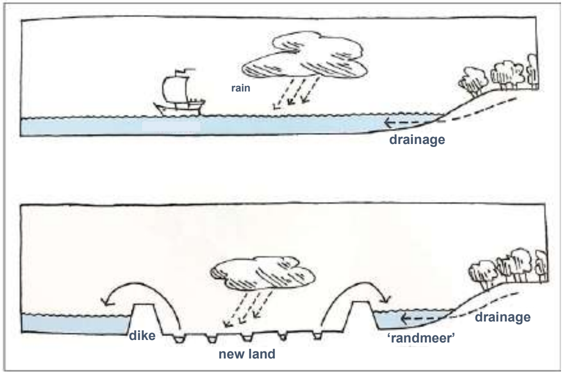

Figure 1. Schematic representation of the geohydrological function of the peripheral lakes as a replacement for the Zuiderzee. Source: Van Der Borden (2023)

Today, climate change has shifted the water management paradigm. The Netherlands faces increasing compound extremes, where prolonged drought is followed by intense rainfall and high river discharge. This duality requires integrated solutions that enhance both flood safety and freshwater resilience. Previous modelling efforts largely addressed flood safety under historical climate, while groundwater dynamics, drought buffering capacity and long-term system behaviour remain underexplored.

This research revisits the Forgotten Randmeer using an integrated modelling framework to evaluate its multifunctional potential under present and future climate conditions.

Method

Study Area

The study area covers the Vechtdelta–Zwarte Water–IJsselmeer transition zone, including the Overijsselse Vecht catchment, the Zwarte Water river corridor, Zwarte Meer, the Noordoostpolder drainage system and a conceptual randmeer corridor along the eastern NOP boundary.

This region forms a hydraulic junction where river discharge, lake water levels, wind setup and polder drainage interact. Adjacent Natura 2000 areas such as Weerribben-Wieden and Kuinderbos are sensitive to hydrological changes.

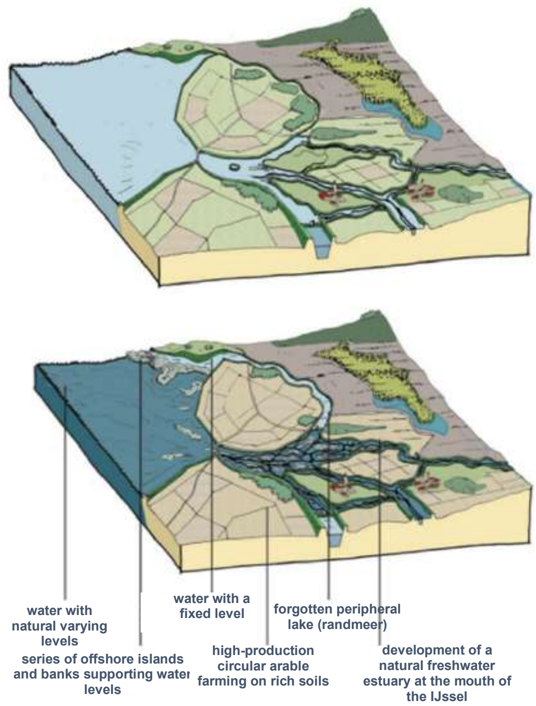

Figure 2. Schematization on the current situation (up) and the future situation with a bordering lake (down). Source: NL2120 map

Modelling Framework

An integrated modelling framework is planned to be developed combining:

1. **wflow**, a distributed hydrological model simulating precipitation, evapotranspiration, runoff generation, soil moisture and groundwater storage processes across the upstream catchments (Schellekens et al., 2020).
2. **SFINCS**, a two-dimensional hydrodynamic model resolving water levels and inundation patterns in rivers, lakes and floodplains (Leijnse et al., 2021).

The models are planned to be coupled offline. wflow generates discharge hydrographs and drought indicators, which serve as boundary conditions for SFINCS simulations.

A simplified reservoir or compartment representation is introduced to schematise the IJsselmeerboezem and the proposed randmeer, including hydraulic connections such as sluices and weirs

Scenario Design

Five scenarios will be analysed:

- Baseline without randmeer under present climate
- Baseline without randmeer under KNMI'23 future climate
- Randmeer with flood-optimised water level regime
- Randmeer with drought-optimised regime
- Randmeer with flexible seasonal peilbeheer strategy

Performance indicators would include:

- Peak water levels and inundation duration
- Frequency and intensity of hydraulic structure operation (e.g. Ramspolkering)
- Low-flow statistics and groundwater storage proxies
- Ecological littoral zone potential
- Trade-offs between flood safety and freshwater availability

Expected Results

The research is expected to quantify how a randmeer alters:

1. Peak water levels in the Zwarte Water corridor during compound flood events.
2. System storage and freshwater buffering capacity during prolonged drought.
3. Operational demands on hydraulic infrastructure.
4. Trade-offs between flood risk reduction and freshwater retention.

Preliminary conceptual analysis suggests that benefits are strongly dependent on water-level management strategy. A flood-optimised regime may reduce extreme water levels but limit drought storage capacity. Conversely, a drought-oriented regime may increase baseline water levels and reduce peak attenuation efficiency. A flexible seasonal regime may offer a compromise but requires adaptive operational rules.

Under future climate scenarios (2050 and 2100), increased discharge variability and longer drought periods may amplify both positive and negative effects. The modelling framework allows explicit quantification of these nonlinear trade-offs.

Conclusion

This research would provide a quantitative reassessment of the 'Forgotten Randmeer' under contemporary climate and water management conditions. By integrating distributed hydrology with two-dimensional hydrodynamics, it moves beyond earlier flood-only assessments and addresses drought resilience, groundwater dynamics and multifunctionality within a single framework.

The results will contribute to ongoing discussions within the IJsselmeer and Vechtdelta system regarding climate-resilient water system design. Beyond the specific case of the Noordoostpolder, the study offers a transferable methodology for evaluating hybrid and multifunctional flood risk management strategies in delta environments.

Acknowledgements

This research is conducted within the NWO Future Flood Risk Management programme and contributes to NL2120 objectives on climate-resilient landscape design.

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HWBP Vierwaarden – The potential of Serious Gaming in River Engineering: Benefits and Challenges

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Keywords — Serious Gaming, River Engineering, Decision Making

Introduction

The Vierwaarden project in Venlo-Noord, Velden, Grubbenvorst, Lottum, and Hertogbroek (Arcen) addresses dike reinforcement (in accordance with new standards), space for the Meuse (preservation of 20 hectares of winter bed), (river)nature restoration (75 hectares), and spatial development. The location of the area is shown in Figure 2. It is located just downstream of the hydraulic bottleneck of Venlo (Figure 1). In addition to preserving space in the winter bed, the project has the objective of achieving a net water level reduction of 5 cm near Venlo during highwater peak discharges of 4.118 m^3/s (flood risk of 1/3000th per year).

Project goals

The project objectives are achieved through a combination of dike reinforcement, dike setback, high-water channels, seepage channels, obstacle removal, lowering of floodplains and (river)nature restoration. The project is currently in the exploratory phase, in which dozens of combinations of individual interventions are possible throughout the project area. This brought significant challenges in identifying the best combination of interventions for the preferred alternative.

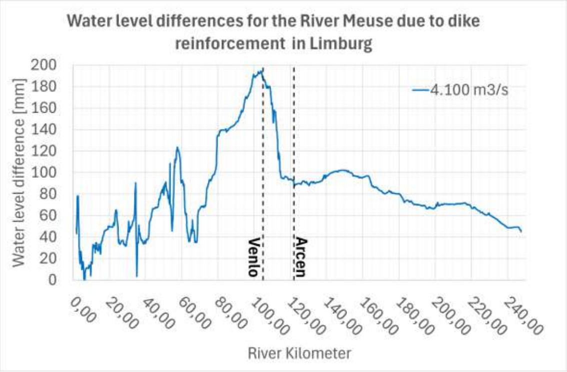

Figure 1: Water level increase in the future when the primary flood defences in Province Limburg along the River Meuse are reinforced at their current location. The highwater peak near Venlo is clearly visible.

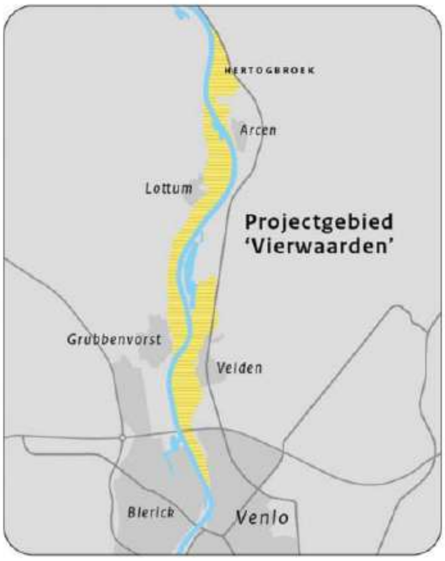

Figure 2: Location of the project area of Vierwaarden (in yellow) alongside the River Meuse (in blue). The project area spans between river kilometres 109 – 122.

Method

To select a preferred alternative, a 'Serious Game' board game was made, where for each individual intervention in every alternative the contribution to the project goals (and environmental effects) was evaluated on an individual basis. By tailoring with the contribution of individual interventions, an optimal combination could be chosen to achieve all project goals, which resulted in the final preferred alternative.

For most project goals, such as hectares of winter bed preservation or hectares of (river)nature restoration, determining the contribution of an individual intervention to all project goals could be done quite easily. However, the hydraulic effects of several interventions were intertwined due to (physical) overlap and backwater curves. It was too time-consuming to calculate the hydraulic effects of all possible combinations of interventions, so a 'block box method' was used, with each intervention being a block that can be combined with any other blocks to make a larger combination. By cleverly selecting combinations of interventions and the use of post-processing results, the number of calculations could be

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limited. The effects of the dike interventions were compared against a baseline scenario (reinforcing the dike at its current location). The effects of the floodplain interventions were compared against the most riverward version of the dike reinforcement. In Figure 3, the splitting of interventions for the area of Venlo-Noord is given.

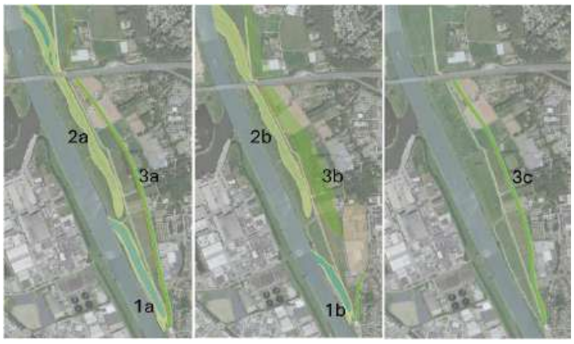

Figure 3: Example of splitting interventions near Venlo-Noord.

Results

The contribution of the individual interventions to the project goals (and to environmental effects) was incorporated into the Serious Game. The resulting Serious Game board game has been successfully employed at resident evenings for the local community and by the steering group. Using the Serious Game, it was possible to quickly funnel towards a few combinations of interventions that met all project objectives and had support from the parties involved. These combinations were then optimized and calculated in full. In the end, one of the combinations has been submitted for approval as concept-preferred alternative (VKA).

Benefits

The use of a Serious Game allowed for a greatly expanded project scope, with much more possible combinations of interventions than would be feasible in a traditional exploratory phase. The use of a block box method complemented the Serious Game very well, as determination of (hydraulic) effects of the expanded scope were achieved within a relatively short timeframe and with limited resources.

In addition, the use of a Serious Game has fostered understanding among the local community and the steering committee in a playful way. It created a will to cooperate between the parties involved and gave insight in the contrasts and relationships between the different project goals. Through this, the Serious Game captured key decisions to be made in the exploratory phase and illustrated the available means to achieve and optimize project goals.

Challenges

Although the Serious Game offered numerous advantages, it also presented certain limitations. Not all contributions to project goals could be attributed to one single intervention. Most notably, the hydraulic interaction between interventions means that if interventions had physical overlap, a combination of interventions must be used as one block in the block box method. For the sub-area of Grubbenvorst, this resulted in more than 15 additional calculations for combinations of several interventions, which greatly increased the number of calculations. Alternatively, a bandwidth consisting of the maximum and minimum combination could be used in such circumstances.

In addition to this, combined effects of two interventions are not additive when interventions lie parallel (or in proximity) to each other. To counter this, the final preferred alternative was recalculated in its entirety and compared with the sum of the individual interventions from the block box method. The resulting hydraulic error margin on the location of evaluation for the project goal (river kilometre 109) was approximately 1 mm (less than 2%), which was considered very good for the exploratory phase. Local differences were a few millimetres higher and can mostly be attributed to optimizations during the exploratory phase.

Conclusion

The Vierwaarden project used a Serious Game combined with a block box method to explore numerous dike reinforcement and river restoration options efficiently in the exploratory phase. This approach enhanced decision-making, community engagement, and cooperation, despite challenges in modeling complex hydraulic interactions and intervention overlaps. The used method is most beneficial when intervention effects are distinct. Small differences between interventions reduce the added value due to inherent uncertainties.

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Impact of RVR2.0 on future Waal lay-out and navigation

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Keywords — Room for the River 2.0, Flood protection, Longitudinal training dams, Inland navigation

Introduction

The Dutch spatial planning program Room for the River 1.0 (RVR1.0, 2006–2015) was designed to manage high water levels in the Rhine, Meuse, Waal, and IJssel rivers. Today the successor to the program is underway: Room for the River 2.0 (RVR2.0, preparation phase 2025-2029). RVR2.0 is investigating a wide range of measures to make the Dutch river system even safer, more ecological and more attractive than the goals of RVR1.0. More precisely: more water must be discharged safely (Rhine River outlook for 2100: from 18,000 to 20,000 m³/s), approximately 80,000 hectares of additional riverine nature must be created and spatial quality should be preserved as much as possible. Numerous studies on measures are being carried out within a consortium that includes the well-known Dutch research institutes and engineering firms.

These studies are based on the preconditions and wishes submitted by the various sectors. The overriding requirement to prevent ongoing bed degradation —particularly on the Waal River— is crucial. This is achieved by introducing a multi-channel system (including longitudinal training dams). This is also beneficial to inland navigation as it leads to larger navigation depth (sailing depth).
However, it is striking that the shipping sector focusses on preserving the actual quality of navigation, in terms of sailing depth and traffic handling. This in itself will be quite a challenge given the expected increasing occurrence of low discharges. The shipping sector does not point out developments in ship design and traffic handling that may very well be demanded in the next 75 years.

The author foresees major difficulties in finding integrated RVR2.0 solutions if no intervention is made in the navigational channel (which would need to be narrowed), potentially putting the quality of navigation under pressure. Furthermore it may be expected that navigation on the Rhine River will come under increasing pressure in the coming decades due to reduction in water supply from the Rhine catchment and longer periods of low discharges. These developments will have consequences for the types of vessels used and the way traffic is handled. It is the view of the author that the goals of RVR2.0 and future inland transport on the Waal River are served by a serious reduction of the main channel width (or ‘normal width’) by longitudinal training dams.

Reduction of the low water bed

By reducing this normal width in which the fairway is located more space is created in the riverbank (shore) zone. The solution with longitudinal training dams offers advantages for bed erosion (which is halted and may even be reversed), flood protection and ecology. However, this requires limiting the normal width. The recently built longitudinal training dams near Tiel (2016) have reduced the normal width by 30 m, from 260 m to 230 m (see figure 1).

Figure 1: Longitudinal training dam in the Waal River near city Tiel (photo F. Collas, Radboud University Nijmegen)

Narrower normal widths offer even more opportunities for measures in the low water bed and the shore zone to achieve greater flood level reductions and to increase the ecological potential. These possibilities have not been investigated within the scope of the current consortium. The author would like to see alternatives developed where the normal width is reduced much further, for example to about 100 metres, in order to assess the extent to which this would be beneficial for bed erosion, flood protection, navigation and ecology. This would probably come at the expense of the handling of shipping traffic, but would be favourable for the available sailing depth.

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Possible future navigation concepts

At present, the current functionality of inland navigation must be maintained (may not be harmed), also because of strict international agreements in the field of shipping, according to the Trans-European Transport Network (TEN-T) policy 2024. However, the question is whether these agreements can be upheld in the longer term, e.g. towards 2100. Inland navigation on the Rhine River will come under increasing pressure in the coming decades due to the expected reduction in water supply from the Rhine catchment and longer periods of low discharges. These developments will inevitably have consequences for the types of vessels used. A shift can be expected towards wider and/or longer vessels instead of the continued preference for deep sailing depth. It is also almost certain that alternative propulsion systems will be required, electric/ hydrogen, or fully electric. This also offers opportunities to consider different vessel concepts, for example autonomous barges with their own propulsion using small electric motors and small rudders. These barges could be coupled into long units that might be able to navigate autonomously (using AI). In the past, the RiverSnake concept was proposed (Smits et al, 2000), in which many barges are coupled longitudinally to form very long units (on the order of a kilometre or more) that can closely follow the river alignment, even in small, winding rivers (see figure 2).

Figure 2: The RiverSnake concept

Concluding remarks

The author foresees future pressure on the navigational channel width of the Waal River and thus on traffic handling, also to facilitate the RVR2.0 goals. A different ship design, autonomous navigation, the use of improved sensors and AI may make it possible to reduce vessel spacing maintaining a certain quality of traffic handling of inland navigation. This may lead to allowing a narrower fairway. However, a narrower navigational channel may offer fewer lanes for multi-lane traffic, but is the actual five-lane traffic still appropriate with increasingly frequent low discharges? It may be possible to switch to 3-lane traffic. This would, of course, require much more uniform vessel speeds and would lead to periods of congestion. However, with greater standardisation of inland navigation vessels, this may not pose a major problem.

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New opportunities for experimental meandering rivers

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Keywords — Meandering rivers, morphology, scale experiments

Introduction

Laboratory experiments of rivers have been conducted for decades, with most significant advancements in data collection, data processing, and analyses in the past 25 years (Leenman & Eaton, 2024). As opposed to field surveys of rivers, laboratory experiments allow for rapid development of river morphologies under controlled conditions, with possibilities for frequent and comprehensive measurements. For example, Van Dijk et al. (2012) succeeded in creating laboratory experiments of meandering rivers in the Eurotank facility at Utrecht University. Inspired by these and other experimental rivers, we are currently resuming efforts of recreating rivers in our laboratory facility, the Metronome (Kleinhans et al., 2017; www.uu.nl/metronome). We recently developed new methods for the Metronome that open up new possibilities in experimental river research (Nota et al., 2026a-b; also see our other abstract). The Metronome facility is included in the Delta ENIGMA infrastructure (https://delta-enigma.nl/), providing opportunities for broader collaborations. Here we present the preliminary results of our new experiments of meandering rivers, after which we will host a lab visit to the Metronome during the NCR Days.

Methods

The Metronome facility is a 20 by 3 m flume, which is mostly used for emulating tidal systems, such as estuaries, through periodic tilting (Kleinhans et al., 2017). For our river experiments, we set the flume on a fixed slope, with fixed river discharge from a transversely moving upstream river inlet, triggering the meandering bends in a bed of mobile sand (as in Van Dijk et al., 2012). Moreover, the river inlet is connected to a sediment feeder, adding sand to the upstream boundary at a continuous rate.

Our experimental rivers are processed with unprecedent accuracies and high relative alignment between various cameras and sensors. These are seven different overhead cameras, one gantry-mounted DSLR camera, and one gantry-mounted laserscanner system (Nota et al., 2026a). At set timesteps of 60 seconds, we collect overhead imagery to process into orthomosaic timelapses (Fig. 1), and at larger timesteps (~1.5 hours), we pause the experiment to conduct dry bed laserscans to process into Digital Elevation Models (DEMs), Fig 1). Furthermore, we apply Machine Learning to predict water depths from our overhead orthomosaics (Nota et al., 2026b), allowing for quantitative analyses on water depths at unprecedentedly dense timescales.

Results and discussion

Fig. 1 shows several timesteps of orthomosaics and a single DEM of the first experiment of meandering rivers that we have conducted. Similar to the experimental results of Van Dijk et al. (2012), we observe the development of meandering bends, triggered by the transverse movement of the river inlet, and after some time the development of chute cutoffs, which act as natural side channels.

Conclusions

We are conducting new experiments of meandering rivers in the Metronome laboratory flume, which are included in the Delta ENIGMA infrastructure project. We have state-of-the-art data processing methods that allow us to conduct quantitative analyses at unprecedented timescales and accuracies. During the NCR Days we will show more of our experimental results, as well as organize a lab visit to see a meandering river in the Metronome.

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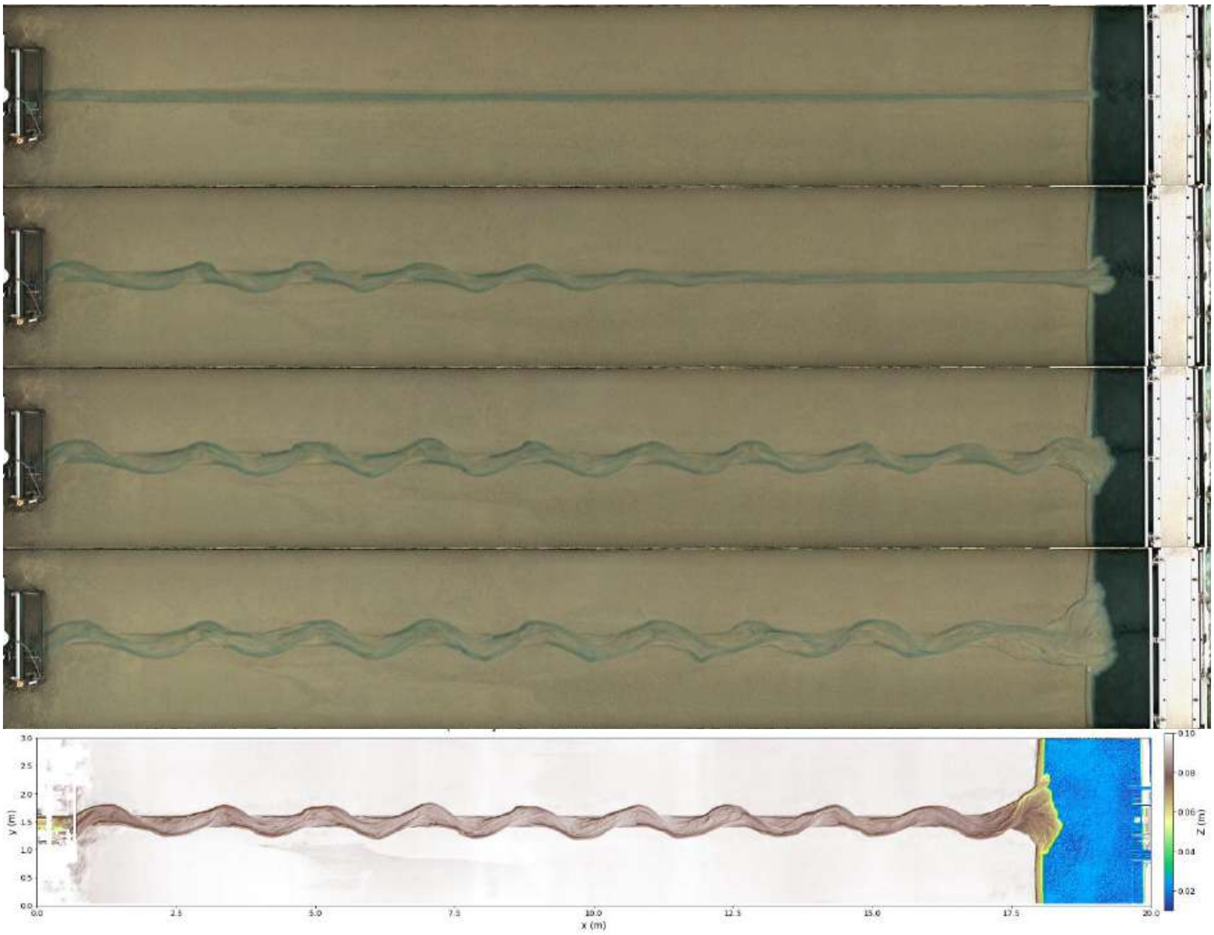
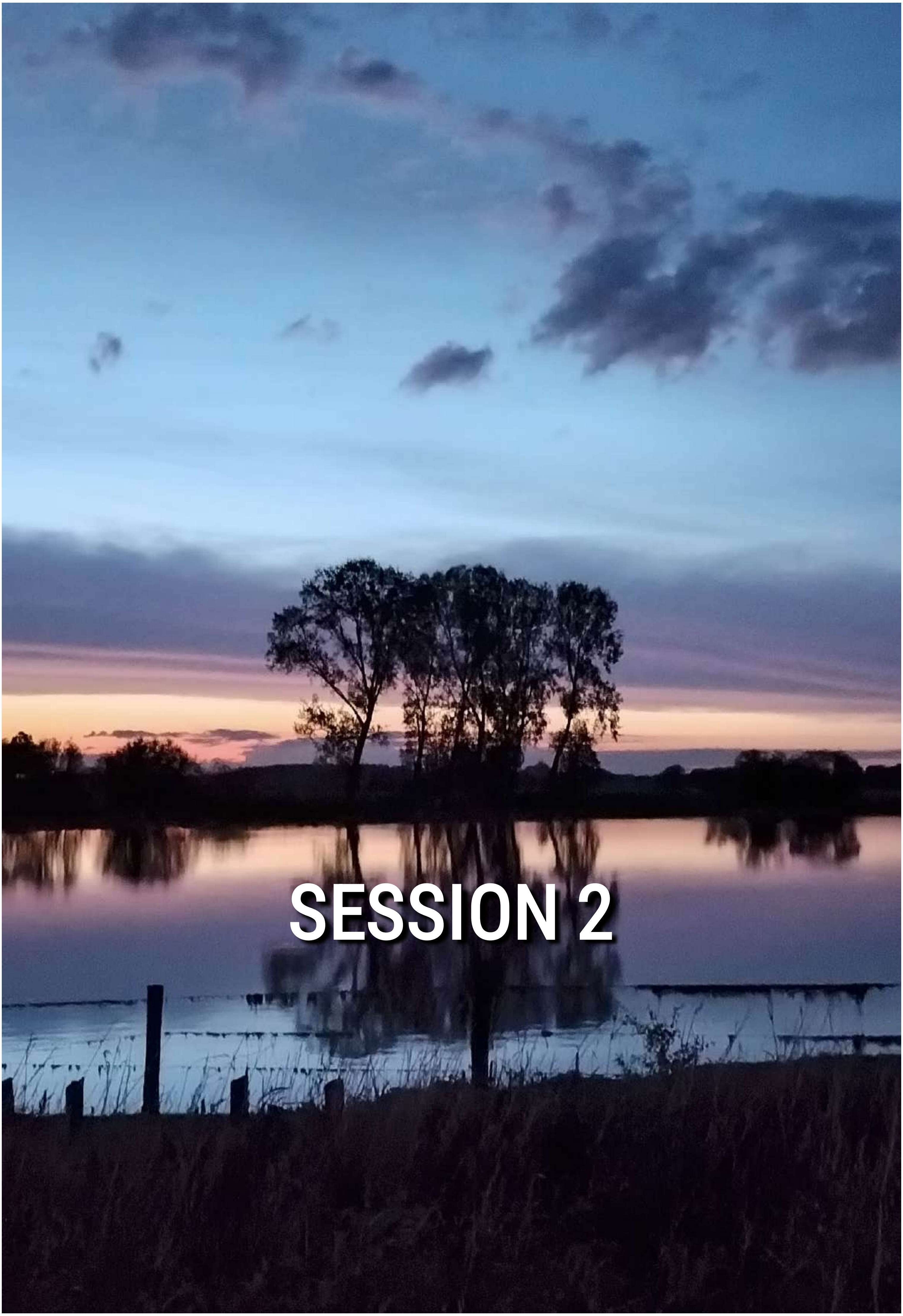


Figure 1. Illustrative orthomosaics and DEM from our first experiment of a meandering river in the Metronome facility, showing the onset of meander bends and the formation of chute cutoffs.



SESSION 2

Derivation of stage-discharge relations for Rhine and Meuse: reflection on the current practice

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Keywords — Rating curve, stationary, time dependent

Introduction

Rijkswaterstaat uses statistical models to determine river discharge from measured water levels. This is necessary because discharge cannot be continuously determined from flow velocity measurements in practice. A relation between discharge (Q) and water level (h) allows us to estimate discharge even when no flow velocity measurements are available. Such Qh-relations have been established at various locations in rivers managed by Rijkswaterstaat. The discharge data based on these relations are widely used.

We provided an overview of how these relations were derived for locations along the Rhine and Meuse rivers (Buschman et al., 2025). The aim was to combine both the theoretical background and the current practice of the derivations of the relations, such that it is readily available for users of discharge data. A second aim was contributing to a long-term vision on deriving and maintaining Qh- relations.

Theory

To calculate discharge based on water level, it is necessary to make two assumptions that simplify the mass and momentum equations to the point where the relation between water level and discharge can be solved directly. These assumptions are *stationarity* (discharge does not change with time) and *uniformity*. Uniformity implies that flow velocity, river width and discharge do not vary along the river, implying that water surface slope and bed level slope are equal. In practice, these assumptions are often violated.

It is possible to correct Qh-relations in order to include non-stationarity or non-uniformity introduced by, e.g. hysteresis, backwater effects and bed level changes. Hysteresis is the phenomenon that for a given water level the discharge may differ. An example is that the discharge is higher in the rising limb of a flood wave than in the falling limb. In the corrections, variables that change over time are often taken into account, such as the rate of change of the water level over time in the case of hysteresis.

Results

At some locations, the Qh-relation is straightforward, such as in the Rhine branches near Tiel, Hagestein, and Olst. At those locations, a Qh-relation with one width section is used. In other cases, for example in the Meuse at Eijsden and in the Rhine at Lobith, the effects of weir operation, bed erosion, and hysteresis are incorporated through (time dependent) corrections to the stationary Qh-relation. Such relations with corrections are generally referred to by Rijkswaterstaat as *Qf-relation*. For Lobith and the bifucations along the Rhine, the Qf-2018 (Svasek, 2019) are currently applied. Figure 1 presents the general steps for deriving and applying these Qf-relations.

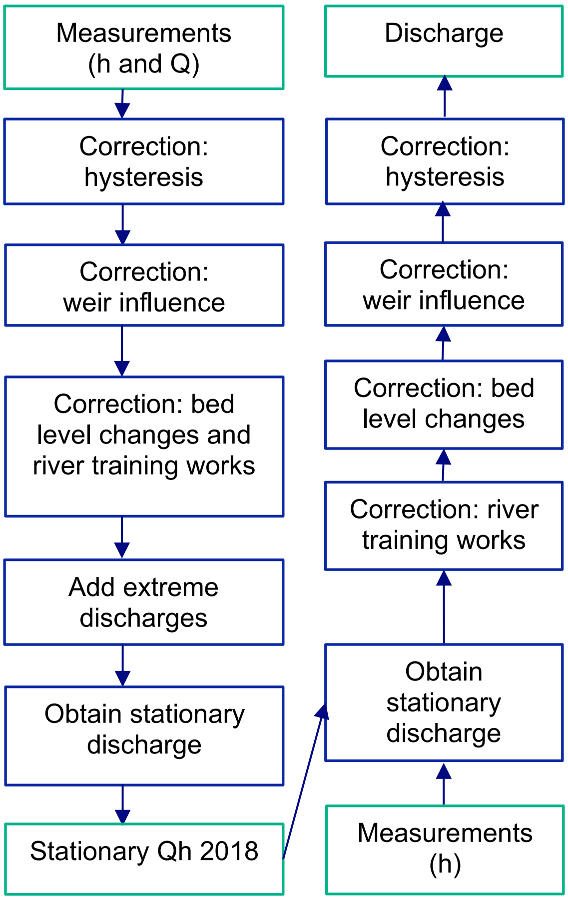

Figure 1. General steps involved in deriving the Qf-2018 relations for locations along the Rhine (left) and applying the

relation to obtain discharge from water level measurements (right)

A result of the Qf-relations for these Rhine locations is that they do not yield a consistent water balance (Beyer and Quartel, 2023; Gensen et al., 2022). Furthermore, the relations were partly determined using numerical models. In turn, those models are calibrated using discharge time series obtained from Qf-relations, which may result in circular reasoning.

For the Meuse the steps for deriving a relation (e.g. Rura-Arnhem, 2020) are similar to those in Figure 1, but differences in methodology occur. For example, in the derivation of the relations no correction for hysteresis and weir operation is applied in the Meuse, since the discharge variation in the Meuse can be large (it can even be negative for part of the day). Another difference is that no linear bed level correction is assumed for the Meuse, whereas such a correction is implemented for many Rhine locations.

Conclusion

The findings support the need for a long-term vision for renewing and maintaining the method to derive and apply Qh- and Qf-relations, putting the specific information and practical needs of Rijkswaterstaat central. These needs include validity across the full discharge range (including the extremes of which no or very limited measurements are available) and maintainability in the context of a changing river system. We noted that the number of people within Rijkswaterstaat who have expertise in deriving these relations is limited.

Considering the theory and current practice, we arrived at five main conclusions:

1) Currently, Qh- and Qf-relations are not validated, which means that the added value of the increased complexity (corrections) cannot be demonstrated, and the predictive value remains unknown.
2) There is a strong interdependence between the Qf-relation and the numerical model, making it difficult to draw a clear line between the ground-truth and the numerical model, and updating the Qf-relation is very labour-intensive.
3) There is no uniform approach to data validation, making the origin and uncertainty of the data underlying the Qf-relations unclear.
4) As for Eijsden and Borgharen-dorp in the Meuse no continuous discharge measurement is available. For these Qf-relations discharge is derived from other locations, which adds uncertainty.
5) The Qf-relations are highly complex and mutually inconsistent, which fragments operational knowledge of the relations and makes it difficult to understand how the method is applied in practice.

Acknowledgements

We are thankful for the contributions to this study by Lianita Suryawinata and Rolf van der Veen.

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Experimental investigation of the flow field in a scour hole in a river

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Keywords — scour holes, experiment, flow velocities

1. Introduction

Scour holes have been observed all around the world. Their significant depth and steep slope can pose a threat to nearby infrastructure. Barneveld et al. (2025) studied about 15 deep scour holes that formed during the summer flood in 2021 in the Meuse river. Their formation was attributed to a combination of a local narrowing resulting in high flow velocities locally, and strong morphological changes by means of the formation and migration of river dunes. This caused the top bed layer consisting of gravel to break. The underlaying fine sand got exposed to the flow and eroded quickly, resulting in the formation of deep scour holes.

The deepest scour hole reached a depth of 15 meters compared to the mean bed level. This hole threatened the stability of a ferry landing and was manually filled to stabilize the river bed. Nevertheless, the majority of the scour holes remained open after the flood. It is unknown how these scour holes evolve over time: whether they will function as a sediment trap and gradually fill or will suddenly grow in extent during a next flood.

As a first step to get a better understanding on the behaviour of existing scour holes, Oldenhof et al. (2026) studied the morphological evolution of eight scour holes in the Rhine delta. The scour holes in the upstream branches show a dynamic behaviour in which the dimensions of the scour holes vary with fluctuating discharges. The scour holes in the downstream branches are more stable over time. These scour holes are characterized by hardly erodible layers at the edges, e.g. clay and peat. It is know that the architecture of the bed surface plays an important role in the formation of these scour holes (Huismans et al., 2021).

As a next step, we want to elucidate the flow processes in the scour hole. We performed flume experiments in which flow velocity was measured in three dimensions with a Ubertone Acoustic Velocity Profiler in great detail. The main objective of these experiments is to analyse the difference in morphological evolution between scour holes located in a free movable bed consisting of uniform sand and scour holes which are fixed by a coarser toplayer. Moreover, we would like to relate the morphological changes to the observed flow field.

2. Method

The flume experiments were performed in a 17 m long, 1.65 m wide and 0.35 m high flume at the Technische Universität Wien in Vienna. At the center of the flume, a sand box was installed with a depth of 0.15 m. The box was filled with uniform sand with $d_{50} = 0.8$ mm. To create a fixed scour hole, on top of the sand a 5 mm thick layer of coarse gravel with grain sizes between 4-8 mm was placed.

We started the experiments with a predefined scour hole. The dimensions of the initial scour hole are based on field measurements (Oldenhof et al., 2026). In general, scour holes are twice as long as their width and their depth is approximately half of the water depth. This resulted in an initial scour hole with a length of 1.8 m, a width of 0.8, and a maximum depth of 0.08 m (see Fig. 1). We mimicked three different flow conditions, which were based on the critical velocity of the uniform sand allowing for bed transport (Table 1).

Figure 1. Experimental setup with a predefined scour hole in a fixed bed.

Table 1. Explanation of the three scenarios

Scenario	Upstream velocity (m/s)	Upstream water depth (m)
1	0.47	0.18
2	0.50	0.20
3	0.52	0.23

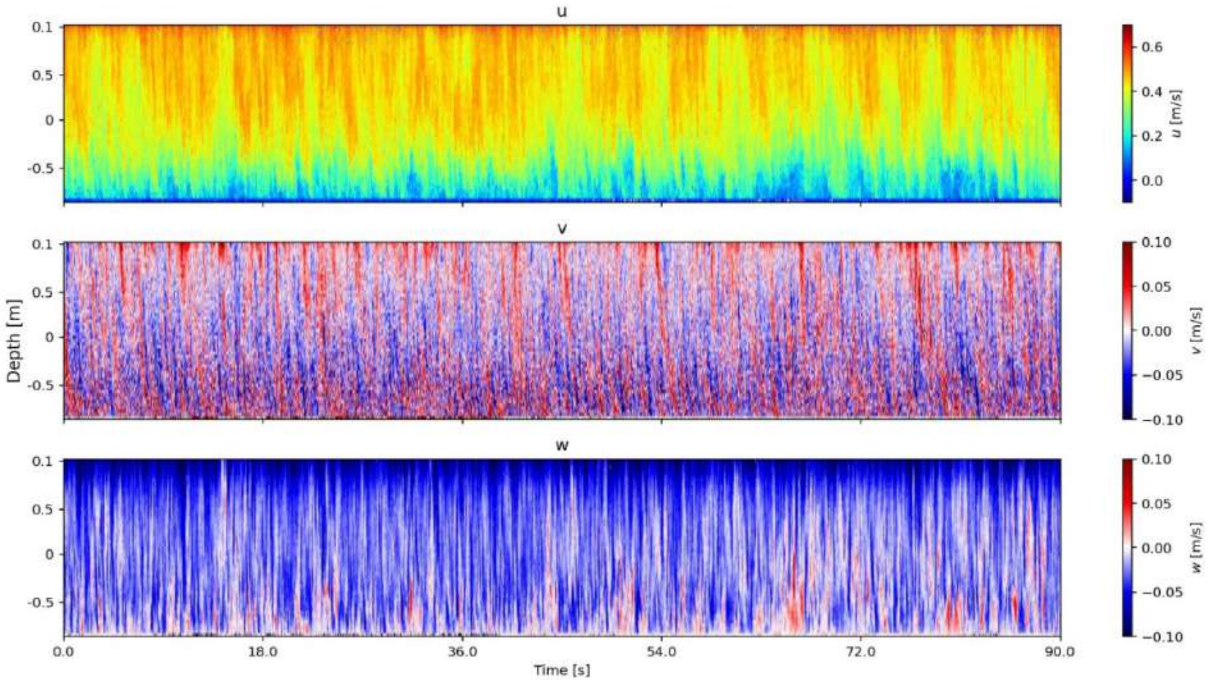

Figure 2. Measured flow velocities for scenario 1 with a fixed scour hole. The flow velocities are measured around the deepest point of the scour hole after 8 hours of simulation. Depth = 0 equals the average bed of the flume. The depth of the scour hole is represented by the negative depth values.

3. Results

The measured flow velocities in the scour hole reveal a highly intermittent and three-dimensional turbulent flow field. As an example, in Figure 2 the measured velocities in the longitudinal, transverse, and vertical direction, respectively *u, v,* and *w* ,for scenario 1 with a fixed bed are presented. These velocities are measured around the deepest point of the scour hole. The zero-depth line represents the edges of the scour hole. This is the average bed level of the fixed bed around the scour hole.

The average upstream velocity is 0.47 m/s and temporal peaks above 0.6 m/s are measured near the water surface. Near the bed the velocity becomes zero with some temporal, small negative velocity values in the u-component, suggesting standing water in the lower parts of the scour hole. The average flow field of the vertical direction is directed downwards, towards the deepest point of the scour hole. However, we observed some clear positive peaks. These positive vertical flow velocities are mainly observed in the scour hole but sometime cover the entire water column. This up and downward directed flow might reflect the existence of intermittent eddies. This hypothesis is strengthened by the temporal negative values in the u-component.

4. Outlook

A first analysis of the measured flow velocities reveals a strong three-dimensional character of the flow in a scour hole. Next steps are to further analyse the flow patters and relate these to the observed morphological changes. Furthermore, we are interested in how changes in scour hole geometry alter the flow velocity field. Insights in these phenomena help to get a good understanding on the evolution of scour holes which in return helps in developing sustainable strategies to manage these deep scour hole.

Acknowledgement

This work is part of the Perspectief research programme Future flood risk management technologies for rivers and coasts with project number P21-23. This programme is financed by Domain Applied and Engineering Sciences of the Dutch Research Council (NWO).

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Microplastics under turbulence: quantifying the turbulent Prandtl–Schmidt number with multiphase PIV/PTV

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Keywords — Microplastics, Turbulence, Prandtl–Schmidt number

Introduction

Rivers are increasingly recognised as dynamic transport pathways for microplastics from terrestrial environments to the oceans (Lebreton et al., 2017; van Emmerik & Schwarz, 2022). Understanding how microplastics are distributed throughout the water column is therefore essential for improving monitoring strategies and predictive transport models.

Materials vertical concentration profiles in rivers depend on the balance between gravitational settling and turbulent diffusion. This balance is commonly described through the turbulent Prandtl–Schmidt number,

$$\beta = \frac{\varepsilon_c}{\nu_t}, \tag{1}$$

where ε_c represents particle diffusivity and ν_t the eddy viscosity of the flow. Most modelling frameworks assume $\beta \approx 1$, following classical sediment transport theory (van Rijn, 1984). However, microplastics differ substantially from sediment particles in shape, density, and drag behaviour, which raises questions about the validity of this assumption (Cowger et al., 2021).

This study investigates how turbulence controls the vertical mixing of microplastics and evaluates how β varies across particle types and turbulent flow conditions.

Methods

A total of 23 non-buoyant microplastic types were tested, including spheres, pellets, fibres, and fragments (Fig. 1). Particles covered nominal diameters ranging between 0.5 and 5 mm and densities ranging from 1.03 to 1.45 $\mathrm{g\,cm^{-3}}$.

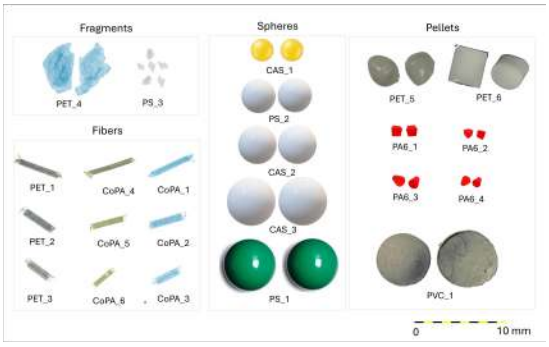

Figure 1: Overview of the microplastics examined in this study showing particle shapes and their corresponding nominal diameters and settling velocities.

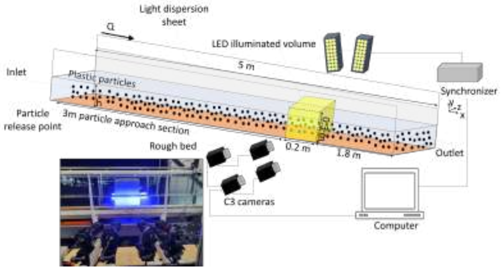

Figure 2: Experimental setup: flume configuration, particle release, and the PIV/PTV setups.

Experiments were conducted in a 5 m long recirculating laboratory flume at Wageningen University. Microplastic trajectories and flow velocities were measured simultaneously using a multiphase particle tracking and particle image velocimetry (PIV/PTV) system. Particles were introduced near the flume bed and tracked within an observation volume located approximately 3 m downstream from the inlet (Fig. 2).

Three turbulent open-channel flow conditions were tested (Table 1). These flows span a range of mean velocities and turbulence intensities typical of river environments.

From particle trajectories we estimated the vertical material diffusivity ε_c, while the turbulent eddy viscosity ν_t was derived from flow velocity fluctuations. The turbulent Prandtl–Schmidt number β was then calculated for each particle–flow combination.

Results

Across particle–flow combinations, β departs strongly from unity and varies systematically with depth. Median β values ranged from approximately 0.4 to 2.4, indicating that turbulence transfers momentum and mixes microplastics at different rates.

Multivariate analysis shows that hydrodynamic

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Table 1: Flow conditions tested in the flume.

ID	Q ($\mathrm{L\,s^{-1}}$)	h (m)	U ($\mathrm{m\,s^{-1}}$)	Re (-)	Fr (-)	u_* ($\mathrm{m\,s^{-1}}$)
F1	39.7	0.167	0.78	61452	0.62	0.077
F2	31.7	0.164	0.63	49513	0.51	0.057
F3	21.4	0.157	0.46	35725	0.38	0.038

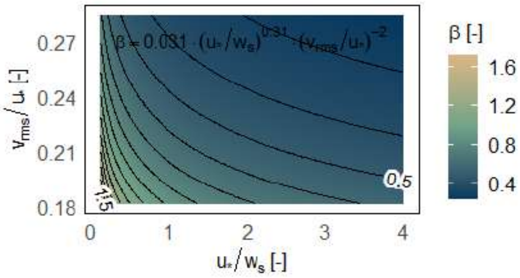

Figure 3: Empirical relationship linking the turbulent Prandtl–Schmidt number (β) to the shear-to-settling velocity ratio and the normalised turbulence intensity (v_{rms}/u_*), where R^2 = 0.812.

parameters dominate the behaviour of β. In particular, the shear-to-settling velocity ratio u_*/w_s and the normalised turbulence intensity (v_{rms}/u_*) explain most of the observed variability, while particle properties primarily influence transport indirectly through settling velocity.

Conclusion

Microplastics cannot be treated as passive tracers that mix at the same rate as turbulent momentum transfer. The turbulent Prandtl–Schmidt number β varies substantially depending on hydraulic conditions, with strong departures from the commonly assumed value of unity.

Our results demonstrate that the vertical mixing of microplastics is primarily governed by the balance between turbulent suspension capacity and particle settling, as well as the normalized turbulence intensity. The empirical relationship derived here provides a practical framework for estimating β from measurable hydraulic parameters and can improve vertically resolved predictions of microplastic transport in rivers.

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Flow transition from open-to-closed channels in rivers: implications for plastic accumulation and ice jams

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Keywords — plastic waste, ice jams, boundary layer turbulence

Introduction

Plastic waste results from human innovation, emerging from our development and use of synthetic materials called plastics. However, because of their long-lasting durability, plastics do not break down quickly and safely in the environment after the duration of intended use. This causes plastic waste to accumulate in the environment, threatening valuable ecosystems and human health (Thompson et al., 2024). Therefore, reducing and mitigating plastic pollution is an urgent priority.

Rivers are considered the main conveyor of plastic debris toward the ocean (Thompson et al., 2024). Once the plastic debris enters the ocean, it becomes more challenging to track and collect them due to a highly dynamic nature of the oceanic processes and wind transport (DiBenedetto, 2025). Hence, collecting macroplastic debris from the river will facilitate clean-up procedure before they reach the ocean.

On the other hand, mismanaged macroplastic debris also harms urban drainage system due to the accumulation at hydraulic structures. These debris accumulations affect the performance of hydraulic structures and result in additional flooding. Hence, understanding the accumulation process of plastic debris is crucial to better design hydraulic structures. It should be noted that ice-jams in rivers can cause similar problems to hydraulic structures.

To analyse the research problem, we subdivided the accumulation process into three subprocesses as shown in Fig. 1: (1) the overall stability of the accumulation layer, also called the carpet, (2) the flow response (e.g. mean flow velocity profile, boundary shear stresses) to the presence of the carpet, and (3) detailed analysis of hydrodynamic forces (lift and drag) acting on the individual particles located in different horizontal and vertical positions with respect to the carpet.

In this study, we are interested in how the particles are influenced by the flow transition induced by the debris carpet or ice jams within a turbulent flow, leading to the following research question: “How does the accumulation affect the hydrodynamic forces, drag and lift forces, acting on the individual particles in the vicinity of the transition point and underneath the layer?”

Research Methods

To better understand the flow physics in such a transition from an open channel to a closed channel, we employed Direct Numerical Simulation (DNS) coupled with the volume penalization technique. Different roughnesses of the top cover were studied with the combination of smooth bottom wall in this research.

To investigate the impact of such a flow transition on the hydrodynamics forces acting on the particles, using DNS method we simulated different scenarios in which a particle is positioned at different vertical and horizontal positions in the computational domain with respect to the carpet as shown in Fig. 2.

Results and Discussion

At the transition, the bottom shear stress forms a hump-shaped profile, and gradually approaches a constant value at the fully developed flow condition of the closed channel section. This hump-shaped shear stress profile is attributed to flow acceleration caused by the cross-sectional contraction, as well as the downward streamline deflection induced by the carpet geometry. As for the top carpet boundary, the shear stress at the transition is significantly large compared to the stress along the whole carpet, and it decreases to the constant value of fully developed flow condition.

Due to the asymmetric roughnesses at the top and bottom boundaries, the location of streamwise maximum velocity is found to be different from the location of zero shear stress. Therefore, the practical consequence of the rough top boundary can be seen in the river bed erosion under the debris accumulation or ice-jams.

Regarding the effect of the carpet on particle forces, a particle far upstream or downstream of the carpet shows a constant mean drag force and lift force, being independent of the hor-

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izontal position. A particle near the leading edge of the carpet experiences a relatively large downward force (or negative lift force) due to flow contraction at the transition point, therefore being very vulnerable to particle erosion. Moreover, due to flow separation at this location, the particle also experiences extreme fluctuation forces, which can also trigger the erosion. Vortex shedding, commonly occurring in flows past a sphere, is also observed around the emerged sphere far upstream of the carpet. However, the vortex shedding no longer occurs for the particle in the vicinity of the carpet, which leads to more unpredictable irregular force fluctuations.

Spheres located in the position of a fully developed flow underneath the carpet show smaller drag and lift forces, where the spheres of interest are shielded around the spheres of the carpet. Therefore, these shielded particles are less vulnerable to particle erosion compared to the particles at the flow transition.

Future Perspectives

The acquired knowledge in this study on flow transition and an asymmetric closed channel can be beneficial to not only collecting the floating debris accumulation but also mitigation of bed erosion in the channel. Lessons learned can be used for the role of driftwood and ice-covers with respect to the interactions with hydraulic infrastructures. Knowledge of the mixing process underneath the carpet will also enhance our understanding of the transport of nutrients and energy essential to riverine ecosystems.

Acknowledgements

This research was supported by NUFFIC and Rijkswaterstaat, and made use of computational resources of the DelftBlue supercomputer, provided by Delft High Performance Computing Centre, and the Dutch national e-infrastructure with the support of the SURF Cooperative grants.

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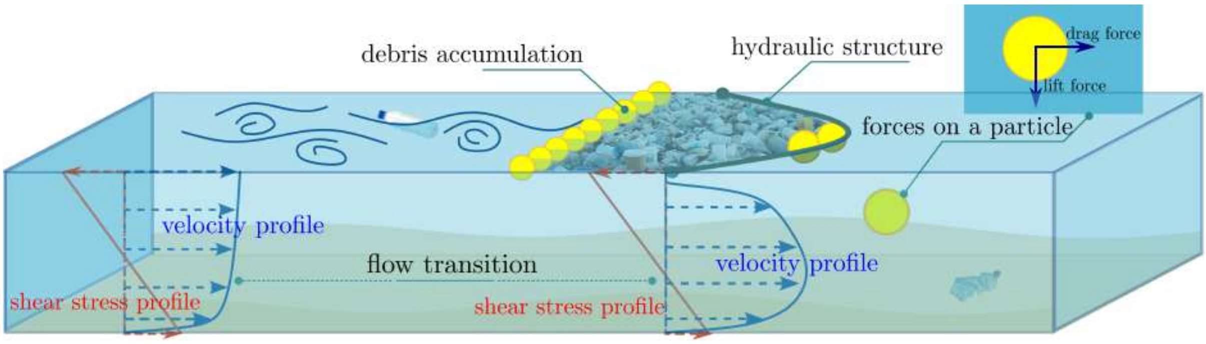

Figure 1: Three subprocesses of the debris accumulation at a hydraulic structure: (1) overall stability of the accumulation layer or the carpet, (2) flow response due to the presence of the accumulation layer, and (3) quantification of hydrodynamic forces action on the particle in different configurations with respect to the accumulation layer.

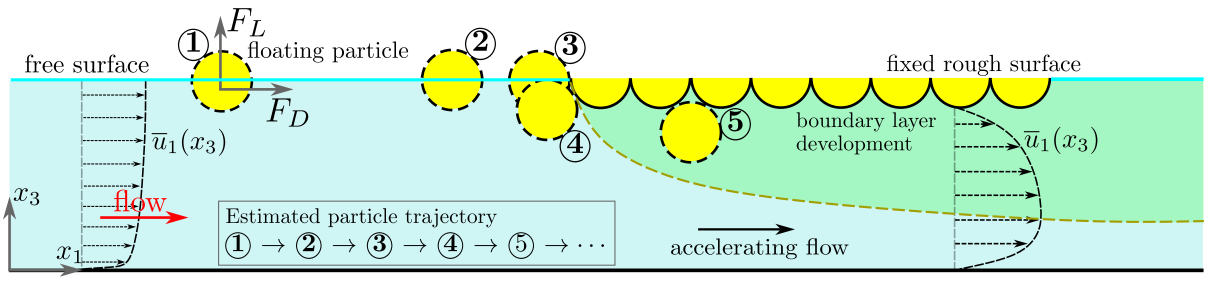

Figure 2: Conceptual sketch for a particle at different positions with respect to a floating carpet. A floating particle is considered to advect in the mean flow direction from position 1 to 5 through encountering a flow transition from the open to closed channel.

Rewetting floodplains along the Rhine: Dutch case study of the EU MERLIN project

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Keywords — floodplain reconnection, river ecosystem, nature-based solutions

Introduction

River ecosystems worldwide are biodiversity hotspots but are often at the same time heavily engineered systems for flood safety and navigation purposes, with impact on ecological functioning. Flooded floodplains in spring and summer are currently the missing link in Dutch river ecosystems (Kurstjens et al., 2020; Nijssen et al., 2021). Rijkswaterstaat and Deltares cooperated in the MERLIN case study aimed to rewet floodplains. MERLIN is a European research and innovation project with 47 partners across 16 countries, dedicated to improving freshwater restoration from isolated efforts to coordinated large-scale action (e.g. Buijse et al., 2026).

Approach

The selection of project areas resulted from an extensive inventory conducted by OBN and MERLIN across nearly all floodplains along the Dutch branches of the Rhine. Over 50 areas were assessed. Following intensive stakeholder consultations and multiple field visits, measures were ultimately identified for implementation in nine of these areas during the 2023–2026 period, with co-financing provided by MERLIN.

Results

Figure 1 shows the result of the floodplain inventory, with for each floodplain the potential for rewetting. In green are the floodplains that the MERLIN project co-financed. Most of the floodplains are unsuitable for rewetting, mainly due to technical and/or hydrological aspects of the floodplain. Other floodplains have potential in the long term. This is due to the time needed to involve stakeholders and build trust, which was longer than the EU project could offer. Another time-consuming aspect was the obligatory administration to formalize cooperations.

All MERLIN co-financed rewetted floodplains are described in a storymap: www.merlin-nederland.nl.

The MERLIN project also focused on the monitoring of the wider impact of nature-based solutions in the Dutch Rhine branches (cf. Penning et al., 2023). Initial monitoring results of the OBN study on hydrology, water quality, and ecology of rewetted floodplains indicate that rewetting in spring can indeed boost the production of algae and zooplankton (Nijssen et al., in prep.). Monitoring of the broader socio-economic benefits of rewetted floodplains proved to be more difficult, because the indicators that were developed within the MERLIN project did not match well with the available data from the Netherlands (Carvalho et al., 2022).

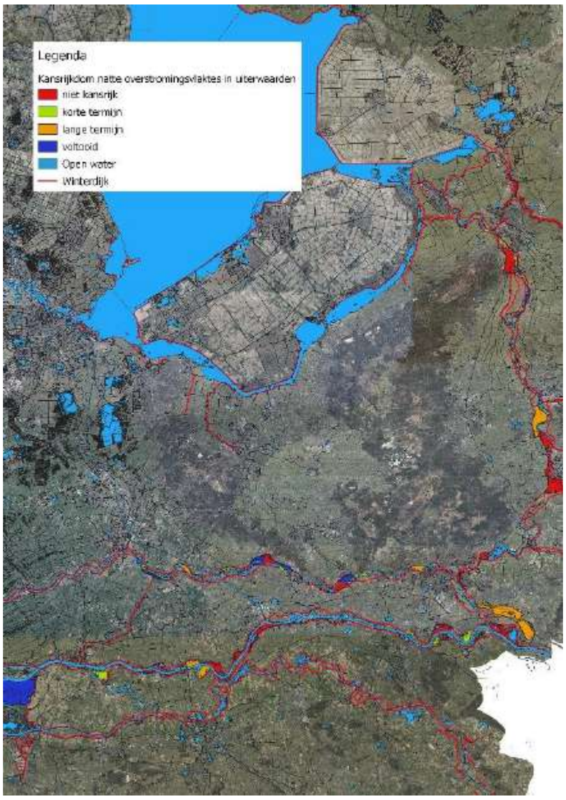

Figure 1. Map with floodplain potential for rewetting. Red = not possible; green = short term possibility; orange = long term possibility; dark blue = already rewetted; light blue = open water; red line = winter dyke.

Lessons learned

Our case study focused on rewetting floodplains, which is just one part of the river ecosystem. We extrapolated from our case study, combined with lessons from the Room for the River program, for general lessons learned for mainstreaming and upscaling nature-based solutions.

MERLIN demonstrated that technical feasibility is rarely the primary bottleneck. Instead, progress accelerated when three elements came together:

- System-level thinking: explicitly working at the landscape or basin scale.
- Stakeholder alignment: engaging stake-holders early and continuously through co-creation;
- Clear drivers: such as the Water Framework Directive or Natura 2000.

When these elements were present, projects moved faster and gained broader support. Where they were weak, even technically sound measures struggled to scale. The main takeaway is clear: nature-based solutions succeed when they are treated as socio-ecological system interventions, not just spatial measures.

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SESSION 3

Quantifying topographic river confinement worldwide

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Keywords — River confinement, Global, Unsupervised classification

Introduction

River confinement, the extent to which lateral channel movement is topographically restricted, is a fundamental control on river morphology (*Van den Berg*, 1995), governing lateral migration (*Parsapour-Moghaddam and Rennie*, 2018), sediment deposition (*Nanson and Croke*, 1992), and channel stability (*Cowie and Brierley*, 2008). Confinement exists on a continuum (*Brierley and Fryirs*, 2004), from freely migrating unconfined alluvial rivers (*Fryirs et al.*, 2016) to fully entrenched bedrock channels where migration is practically impossible, see Fig. 1 (*Nanson and Croke*, 1992). Existing classification schemes further complicate comparison, as they rely on differing metrics and arbitrary thresholds (*O'Brien et al.*, 2019; *Polvi et al.*, 2011) ill-suited for global-scale assessment. Recent advances in high-resolution satellite imagery and digital elevation models now make standardized, fully automated confinement mapping possible. Here, we quantify river confinement at the global scale and apply unsupervised statistical clustering (*Clubb et al.*, 2019) to identify characteristic confinement regimes, allowing classification boundaries to emerge naturally from the data rather than from subjective thresholds.

Methods

River confinement is quantified using global datasets of river centerlines from the Surface Water and Ocean Topography River Database (*Altenau et al.*, 2021) and topography from FABDEM (*Hawker et al.*, 2022). Confinement is evaluated bend by bend, as each represents a fundamental morphological unit controlling lateral channel migration. Two complementary metrics are used: the confinement ratio, defined as $C_r = \frac{W_v}{W_b}$ where valley width (W_v) is divided by channel width (W_b), and the confinement slope, defined as $C_s = \frac{H_c}{W_v}$ where H_c is the confinement height. To identify confinement regimes without imposing predefined thresholds, the resulting metrics are classified using an unsupervised Gaussian Mixture Model (GMM) clustering algorithm.

Results

The global distribution of confinement shows clear spatial patterns, with highly confined rivers concentrated in mountain belts such as the Himalaya and Andes and low confinement dominating large lowland basins such as the Amazon and West Siberian Basin (Fig. 2). Clustering of the confinement metrics identifies four physically distinct confinement classes. The majority of bends are classified as unconfined (60%), characterized by low confinement slopes and large valley widths relative to channel width. Symmetrical partial confinement accounts for approximately 10% of bends and represents systems where confining margins are present but do not directly abut the channel. Asymmetrical partial confinement forms a substantial fraction of the dataset (23%), reflecting rivers constrained on one side. Fully confined bends are comparatively rare, representing about 6% of the total and occurring primarily in high-relief mountainous terrain. Overall, approximately 88% of river bends experience some degree of topographic restriction within 50 channel widths. Confinement also shows systematic relationships with

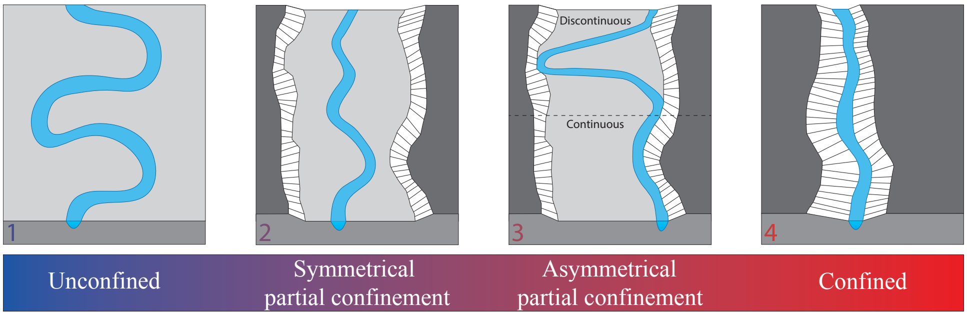

Figure 1: Four confinement classes range from unconfined (1) to confined (4), with symmetrical (2) and asymmetrical (3) partial confinement as intermediates. Class 3 is further divided into discontinuous (top) and continuous (bottom).

geomorphic setting: higher confinement values are generally associated with higher elevations, whereas the lowest confinement values are most common in wide lowland rivers. These results demonstrate that while confinement exists along a continuum, the clustering approach reveals a limited number of globally consistent confinement regimes.

Conclusion

This study demonstrates that river confinement can be quantified globally using a fully automated framework based on satellite-derived centerlines and digital elevation data. Confinement is widespread but organized into four distinct regimes identified through unsupervised clustering, providing a scalable basis for investigating how confinement influences river morphology, sediment dynamics, and landscape evolution.

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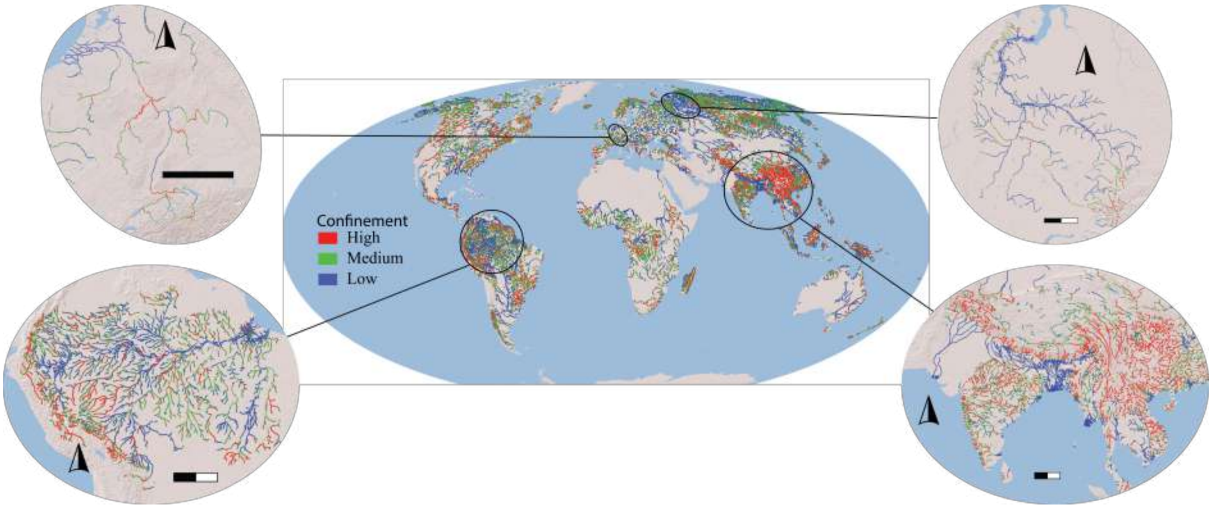

Figure 2: Global distribution of confinement ratio. Blue indicates low confinement, green intermediate, and red high confinement. Regional examples shown: Rhine (top left), Ob (top right), Amazon (bottom left), and India/Himalaya/Southeast Asia (bottom right). Scale bar intervals represent 250 km.

Arresting Bed Degradation in the Waal River: Intervention strategies

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Keywords — bed degradation, Multi-channel approach, sediment nourishment

Introduction

The upper Dutch Rhine branches show continuous bed degradation (1-2 cm/year) threatening multiple river functions. The bed degradation is a response to past sand mining, channel narrowing and straightening, which increased sediment transport capacity and created a sediment transport gradient that drives ongoing erosion (Figure 1). Room for the River 2.0 (RftR 2.0) aims to create a climate-resilient river system, supporting river functions. Arresting bed degradation is essential to prevent further deterioration of river functions. For the Waal River, two principal intervention strategies were investigated: (1) continuous sediment management and (2) a large-scale implementation of the multi-channel approach. While sediment nourishment counteracts ongoing erosion by supplying the deficit in the sediment balance, the multi-channel approach reduces sediment transport by diverting discharge from the main channel to a parallel side channel.

The objective of this abstract is to determine the effectiveness of both interventions in arresting bed degradation. We present the results of the intervention strategies evaluated with a quasi-3D morphodynamic model (Delft3D) in which the multi-channel approach is schematised as longitudinal training walls separating a side channel from the main channel.

Method

For RftR2.0, the existing DVR Delft3D model of the Rhine branches was updated with a more recent geometry and mixed-sediment in all model domains (Sloff et al. 2024). This model was calibrated such that the gradient in sediment transport and thereby the erosion rates reproduce observations. We use the model to evaluate three strategies to arrest the bed degradation in the Waal River: Do nothing, nourishment and the multi-channel approach.

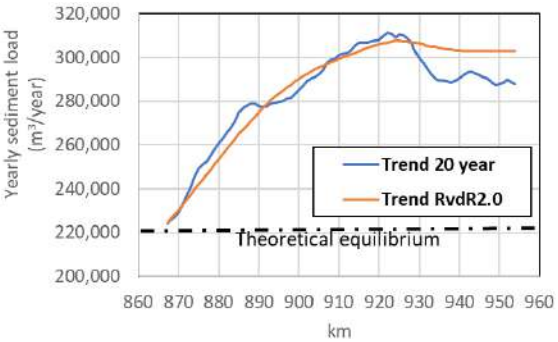

Figure 1 The long-term average yearly sediment load along the Waal River.

Nourishments

The annual repeating nourishment schemes are applied in the outer bend of eroding river sections. The nourishment material is similar to the local bed material preventing additional erosion (Czapiga et al. 2022), but the immobile (coarse) grain sizes are excluded to prevent armouring. Each year, the nourishment volume is limited to the amount eroded during that year, maintaining a constant bed level at the nourishment locations.

Multi-channel approach

A multi-channel approach divides the river into two separate channels: the main channel and a parallel side channel. The side channels widen the effective channel width during intermediate and high flows, reducing flow velocities and sediment transport rates. The goal is to create a gradual downstream reduction in flow velocity, eliminating the gradient in sediment transport. This requires progressive downstream enlargement of the side channels relative to the main channel: from 10% upstream to 50% downstream.

In addition, the main channel is narrowed to increase water levels increase during low-flow conditions by constructing the dam in the main channel about 40 m from the bank. This

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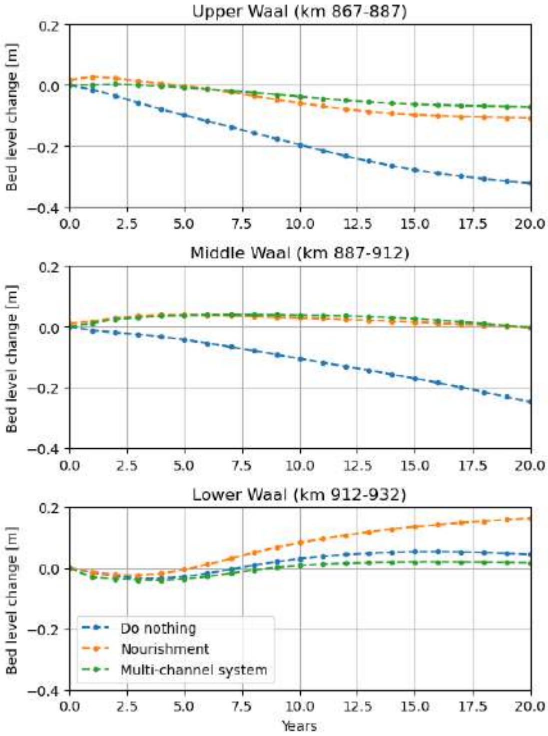

Figure 2 The computed bed-change for three strategies and averaged over the three domains.

achieves two objectives: maintaining adequate navigable depth and diverting additional discharge to the Pannerdensch Canal, stabilizing the low-flow discharge distribution between the Waal and Pannerdensch Canal.

Results

Figure 2 shows the average bed level change in three reaches of the Waal River. The interventions reduce erosion rates in the Upper Waal from 2 cm/year to 0.5 cm/year, approaching a constant bed-level after 10-15 years. The nourishment volume is variable and is similar to the sediment deficit of 150,000 m^3/yr. However, initially, the nourishment volume is much larger because the river needs to adjust to the added sediment.

Figure 3 shows that the multi-channel approach significantly reduces the gradient in sediment transport and shifts it downstream of the intervention reach. This reach should be extended further downstream. The design needs to be further improved by considering the local geometry and adjusting the main channel and side channel width accordingly.

Reflection

The main conclusion is that both nourishment and a multi-channel approach can arrest the bed erosion in the river Waal. The multi-channel approach has additional benefits beyond erosion control such as a water level increase at low flows, reduced flood levels and potential for ecological habitat creation.

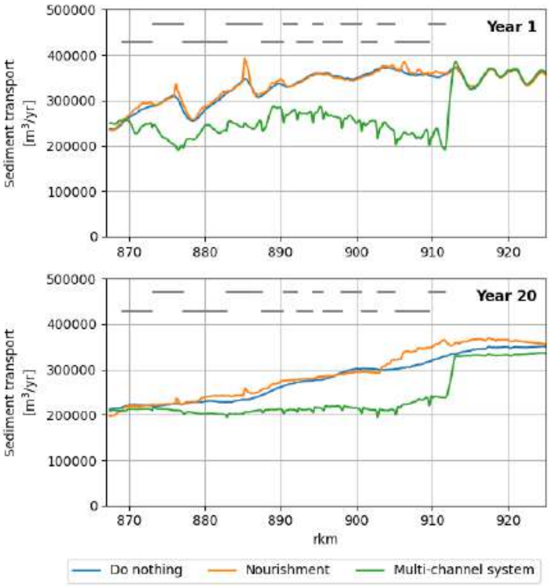

Figure 3 The computed sediment transport in year 1 and 20 for the three strategies with in grey the location of the side channels.

Main lessons on the multi-channel approach:

- The side channels need to increase in size in downstream direction to remove the sediment transport gradient and therefore will become very large (about half the main channel).
- Side channels must be implemented along the entire river branch. Partial implementation leaves non-widened sections with high transport capacity, resulting in localized intense erosion and bed degradation.
- The side channels shift the gradient in sediment transport further downstream. For a stable system, the multi-channel approach needs to be continued even past Zaltbommel.
- Attention should be paid to the spatial integration in the existing river geometry and with the surrounding side channels to mitigate local erosion and deposition.
- The increased bed dynamics can increase the maintenance need of the navigation channel and the side channels need to be maintained regularly to remain effective.

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Towards a manageable and stable riverbed for the Meuse

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Keywords — Room for the River 2.0, sediment balance

Introduction

The Meuse River shows ongoing bed degradation which threatens infrastructure and nature. During the 2021 flood deep scour holes formed unexpectedly. These scour holes were found to be the result of continuous erosion, tectonics and river widening which lowered water levels and increased bed shear stresses in bottlenecks (Barneveld et al., 2025b). The sediment balance of the Meuse shows an increase in sediment load from zero at the Belgian-Dutch border to 100,000 m^3/yr near Lith, the most downstream weir, representing the annual sediment deficit of the river (Figure 1).

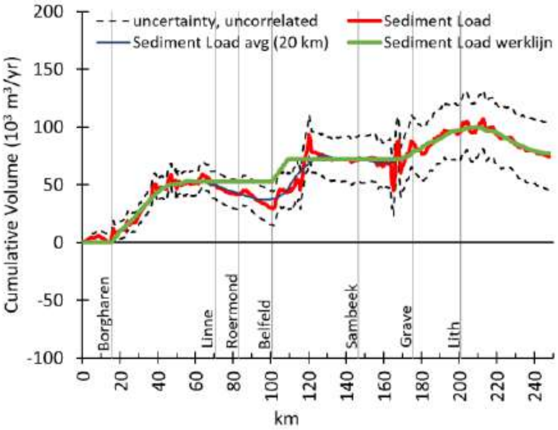

Figure 1 Estimated sediment transport volume along the Meuse River (based on (Barneveld et al., 2025a))

The Room for the River 2.0 program aims at establishing a stable and manageable bed level that contributes to the restoration of natural river dynamics and ensures good navigability. This implies, that the river authority needs to define a bed level that should be maintained: the “baseline riverbed level (BRL)”.

In this study, we evaluate four options for this BRL. The reference bed level is the estimated bed level in fifty years without a policy change. Variant 1 is the current bed level and is therefore the most feasible to construct, Variant 2 is the bed level that is most easy to maintain and Variant 3 is the bed level that restores ecological values of the river. Finally, we assess the efficitivity of several interventions to reach and maintain the bed level.

Assessment criteria

The four bed level variants were evaluated based on six main criteria:

- Feasibility: the effort required to achieve the desired bed level through human intervention.
- Manageability: the effort required to keep the bed level within an established bandwidth;
- High water safety, focussing on the change in high water levels;
- Navigability, focussing on the change in navigable water depth;
- Fresh-water availability, focusing on the discharge during low-flow conditions.
- Nature, including the available habitat, inundation frequency of the floodplains and connectivity.

Results

Figure 2 shows the difference in the average bed level within reaches of the Meuse. The reference bed level is compared to the current bed level and then the three variants are compared to the reference bed level.

Reference situation

Without intervention, the bed level in the Meuse River will continue to erode with a sediment deficit of about 100,000 m^3/yr. Most erosion occurs in the Common Meuse and this erosion will migrate downstream (Sloff, 2021). Within the Common Meuse, there is a high risk of new deep scour holes resulting in a large decrease of the average bed level (up to 2 m in total).

Variant 1: most feasible

The current bed level is maintained. This means that the yearly deficit of 100.00 m^3/yr needs to be compensated for by sediment nourishments. In addition, new scour holes are repaired which requires about 40.000 m^3/yr of sediment.

Variant 2: most manageable

In the Meuse river, the absolute bed level has a limited effect on sediment transport and therefore on the sediment deficit. A stable, but more manageable bed level cannot therefore be achieved by changing the bed level. However, in the scour hole reach of the Common Meuse, an addition of a protective top layer could prevent the development of new scour holes. About 1.5 m of alluvial sediment is needed to minimize this risk. This makes maintaining the bed level more manageable, but the annual deficit of about 100.000 m^3/yr remains.

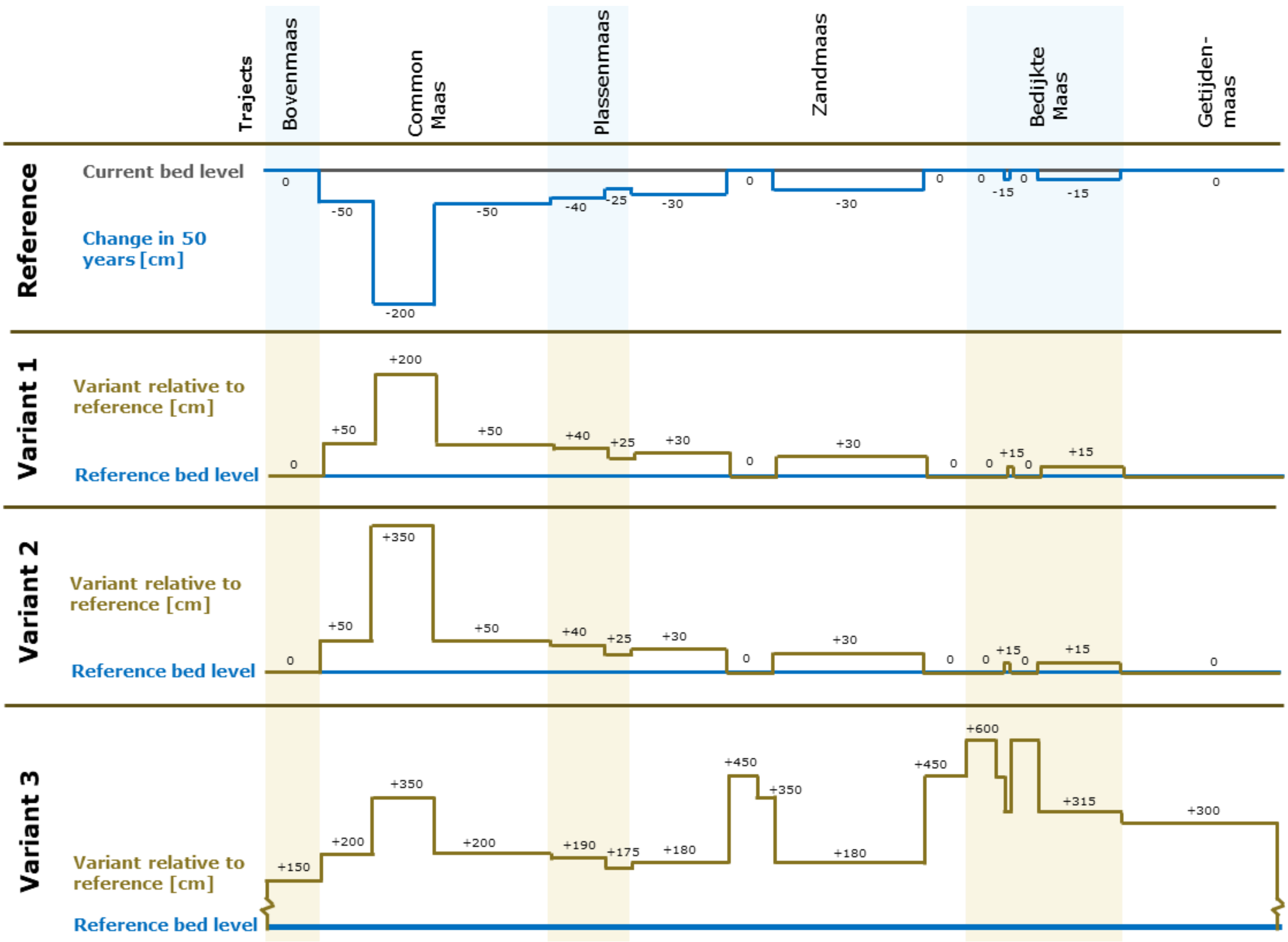

Figure 2 The reference bed level in 50 years relative to the current level. The bed level of the three variants relative to the reference level.

Variant 3: ecological restoration

An optimal bed level for all functions does not exist as the functions conflict with each other. Variant 3 therefore focusses solely on nature. The most direct link between nature and the bed level is through the inundation frequency of the floodplain. To achieve significantly higher frequencies, the required bed level increase is very large (up to 6 m). The larger inundation frequencies will reduce the sediment transport, but a deficit remains.

Interventions

There are several interventions that show potential to reduce the sediment deficit and to make maintaining the bed level more manageable:

Stop sediment extraction

Currently, sediment that is dredged for maintaining the main channel is extracted from the river. This dredged volume is estimated to be around 50,000 m^3/yr which is similar to the sediment deficit downstream of the Common Meuse. By reusing dredged sediment within the river, the deficit may be halved. Due to the large uncertainties in the sediment balance (Figure 1), it is recommended that this intervention be monitored and evaluated regularly after implementation.

Prevent scour holes Common Meuse

Increasing the top layer thickness in the reach where scour holes may develop or creating a fixed layer could prevent the development of scour holes during peak flows. This reduces the repair costs after such events. In addition, local widening can reduce the bed shear stress.

Conclusions

Maintaining the current bed level in the Meuse River seems to be the most feasible and manageable variant. Additional interventions are needed to reduce the yearly sediment deficit and the risk of scour holes.

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The morphological response to peak flows at the Pannerdense Kop

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Keywords — Morphology, bifurcation, peak flows

Introduction

The Pannerdense Kop is a key bifurcation in the engineered Dutch Rhine system where the Bovenrijn divides into the Waal and the Pannerden Canal. The discharge partitioning at the Pannerdense Kop is important for the Room for the River 2.0 programme, as it influences navigation, flood safety, and freshwater availability. Observations show that since the 1990s an increasing share of discharge is routed towards the Waal (Fig. 1), accompanied by a stronger erosional trend in the Waal than in the Pannerden Canal (Becker, 2021; Sloff, 2019; Chowdhury et al., 2023). A mechanism which may have caused this change is related to the peak flows in the 1990s, when the incoming sediment flux may have exceeded the transport capacity in the Pannerden Canal (Chowdhury et al., 2023; Blom et al., 2024). This stresses the importance of the morphological behaviour during peak flows. During peak flows, morphological adjustments around the bifurcation occur on multiple spatial scales, from dune dynamics affecting roughness (Julien et al., 2002; Frings & Kleinhans, 2008) to patterns related to floodplains, groynes, and bends (Ahrendt et al., 2022; Parker et al., 2011), yet existing knowledge is fragmented across individual processes and time periods. This research therefore provides a comprehensive multiscale analysis of morphological behaviour at the Pannerdense Kop by combining multiple field datasets with output from 1D and 2D morphodynamic models and systematically comparing their responses.

Methods

The analysis combines several field datasets with existing numerical models and literature. A 1D Sobek model (Chowdhury et al., in press) and a 2D Delft3D model (Sloff et al., 2024) were used to analyse their morphological response to peak flows. Field data were used to characterise bed level changes at three scales: small-scale dunes (<0.1 km), intermediate-scale patterns (0.1-1 km), and large-scale adjustments (kilometres). Model outcomes were evaluated against the observed responses at these scales.

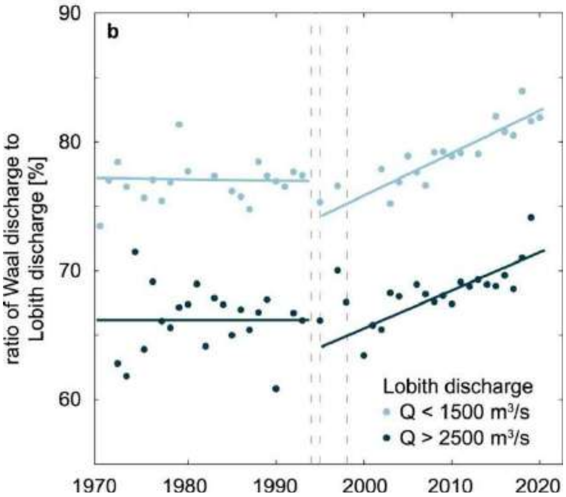

Figure 1. The discharge distribution at the Pannerdense Kop over the past decades. Since the 1990s, an increasing share of the discharge enters the Waal at the expense of the Pannerden Canal. (Blom et al., 2024)

Results

Data from field measurements show peak flow impacts on the small scale in the form of dunes. At an intermediate scale, patterns of erosion and deposition may be related to the local geometry (Fig. 2): deposition at the branch inlets, erosion at floodplain outflows, groyne-induced effects, and bend dynamics. Evidence of a large-scale erosion adjustment wave is found in only one historical dataset.

Both morphological models are limited in reproducing the impact of peak flows. Similar to the field data, the 2D model shows patterns of erosion and deposition related to the local geometry. Large-scale erosion waves were not observed in the model results.

Conclusion and recommendations

Peak flows induce morphological adjustments at <0.1 km and 0.1-1 km scales, and possibly also at the >1 km scale at the Pannerdense Kop. Of the two models examined, both models are limited in representing the morphological response to peak flows.

This research improves the understanding on the morphological response to peak flows at the Pannerdense Kop, and the possibilities and limitations of current morphological models.

Based on the outcomes of this research, it is recommended to measure the sediment distribution and sediment transport rates more at the Pannerdense Kop for a better understanding of the morphological system and for improvement of current morphological models. With regards to the current models, it is recommended to further examine the 1D model sediment distribution and to study the sensitivity to different peak flows in the 2D model.

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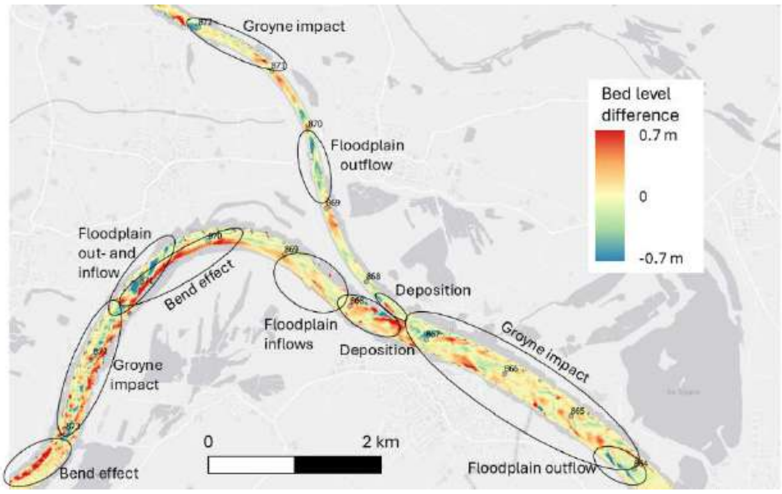

Figure 2. Bed level difference over the period October 2023 and January 2024 based on field measurements. A peak flow of 7550 m3/s occurred in December 2023. Intermediate-scale changes are visible and may be related to the river geometry.

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Satellite-based monitoring of riverbed evolution and reservoir storage capacity

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Keywords — satellite remote sensing, riverbed morphological change, reservoir sedimentation

Introduction

Dynamic alluvial river systems continuously adjust to simultaneously occurring changes in climate, basin land use and human interventions. Long-term monitoring is essential to understand and anticipate riverbed changes, guiding management practices and implement measures to ensure river system services, including flood conveyance, navigation, and hydropower exploitation.

Satellite-based earth observation is rapidly advancing, with continuous improvements in spatial and temporal resolution, the emergence of complementary sensor types, and enhanced data accessibility through cloud-based computational platforms (Donchyts et al., 2016; Gorelick et al., 2017). However, most satellite-based assessments remain limited to planform change detection, while quantifying below-water morphology and volumetric sediment redistribution remains challenging, particularly in sediment-laden and seasonally dynamic environments (e.g., Giri et al., 2021). We present an integrated framework developed by Bhattarai et. al (2026) that combines multiple satellite sensors and in-situ water-level measurements to reconstruct seasonally submerged bed topography and assess the morphological evolution in rivers and reservoirs.

Method

The employed methodology was built upon a framework developed by Giri et al. (2021), which quantified river planform changes at different water occurrence probabilities using multi-temporal optical satellite imagery. While that approach enabled systematic assessment of areal changes across hydrologic stages, it did not explicitly account for inter-annual hydrologic variability (water level distributions are implicitly assumed to be comparable and differences in water occurrence probability are directly attributed to erosion/sedimentation) and volumetric change. Multi-temporal optical and Synthetic Aperture Radar (SAR) imagery, and in-situ water level measurements are used to derive water occurrence probability and water surface elevation percentiles, while ICESat-2 ATL03 land photon data provide exposed bed elevations. These complementary datasets were integrated within a machine learning framework to estimate spatially continuous seasonally submerged bed topography. By comparing reconstructed bed topography across years, we quantify erosion–accretion patterns and volumetric changes, accounting for inter-annual hydrologic variability.

Lower Jamuna River (Bangladesh)

The monitored seasonal fluctuations of water levels the Lower Jamuna River reveal its highly dynamic nature with pronounced spatiotemporal variability in bed levels for the period 2019–2022 (Figure 1). Distinct zones of high-intensity erosion (red) and accretion (blue) are concentrated along actively migrating in-channel bars and eroding bars, reflecting lateral river bed changes. Annual net volumetric changes fluctuate substantially, with alternating periods of reach-scale erosion and deposition, indicating strong temporal variability in sediment transport dynamics. While localized reaches exhibit intense erosion during specific years (e.g., 2020–2021), other periods show compensating accretion (2021–2022), highlighting the transient and spatially heterogeneous nature of morphologic adjustment. In this way, advance processing and analysis of EO data facilitates a deeper understanding of channel evolution and bankline dynamics over extensive reaches of a large river system like Lower Jamuna.

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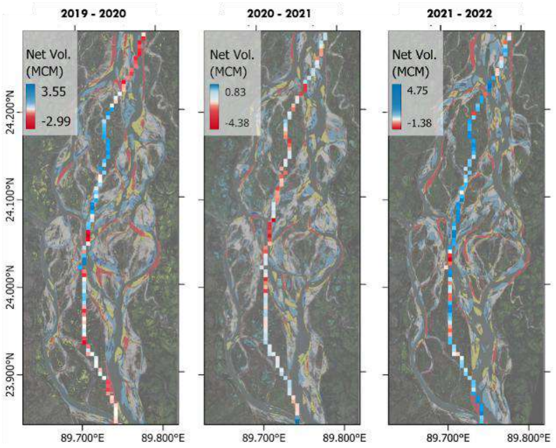
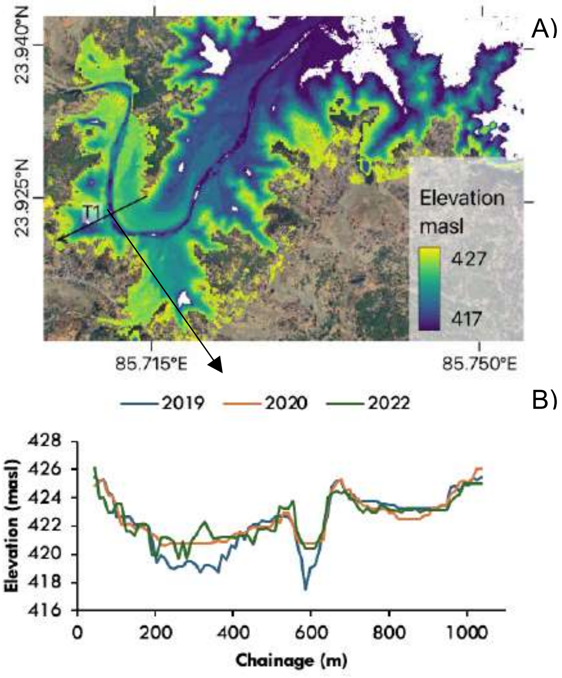


Figure 1. Morphological changes in the lower Jamuna River, adapted from Bhattarai et. al (2026).

Konar Reservoir (India)

The water levels in the Konar Reservoir are regulated over a depth of ~20 meters for water supply and hydropower generation purposes. Periodically submerged reservoir morphology is most extensive near the inlet of the reservoir (Figure 2A, B). Morphological changes here are limited, providing confidence in the used method and indicating that delta sedimentation is limited and not affecting the live storage volume of the reservoir (Figure 2C). Sediment may pass by the inlet and deposit in the permanently inundated part, the dead storage zone of this medium-size reservoir. While our method cannot quantify sediment accumulation within dead storage zones, it enables the temporal analysis of reservoir live storage capacity and how it may be impacted upon by sediment delivery processes from upstream catchments.



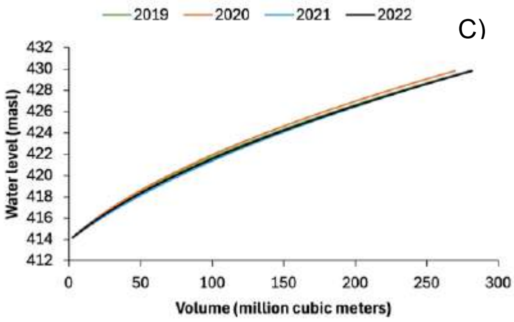


Figure 2. A) Konar reservoir topography, B) cross-sectional changes at transect T1 and C) volume-elevation curve.

Conclusions

Our case studies demonstrate the application of advanced satellite-based monitoring techniques and in-situ water level measurements for quantitative areal and volumetric assessments. This provides a consistent basis for the analysis of annual variability in riverbed morphology and the (long-term) response of river systems to direct and indirect human impacts. In future work, we seek further integration of water surface elevation data from Surface Water and Ocean Topography (SWOT), satellite or hydraulic modelling to facilitate fluvial research and river management applications, particularly in large-scale river systems in remote regions.

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SESSION 4

Reducing storm surges in the IJssel-Vecht Delta using Tesla valve shaped islands

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Keywords — Tesla valve, constructed islands, storm surges, flood risk reduction, nature-based solutions

Introduction

The Ketelmeer is a complex fluvio-lacustrine system shaped by the interaction of river dynamics, lake and wind processes, and human interventions. Influenced by the closure of the Ijsselmeer and constructed as a flood control area during the reclamation of Flevoland, the Ketelmeer now experiences unique flooding challenges while simultaneously facing degrading ecosystems (Lenselink, 2001). The region is highly vulnerable to flooding, particularly during north westerly storms. Wind drives huge volumes of water across the IJsselmeer and heightens water levels in the eastern part of the Ketelmeer and in the IJssel river near Kampen (Rijkswaterstaat, 2015; WMCN-Meren, 2024). To simultaneously reduce flood risk and provide co-benefits for ecological and other values in the area, innovative flood risk reduction strategies are being explored.

This study investigates the effectiveness of Tesla valve shaped (TVS) islands as a nature-based solution to mitigate storm-induced flooding in the Ketelmeer. This Tesla valve configuration, invented by Nikola Tesla (1856-1943), non-mechanically restricts fluid flow to one direction, while promoting flow to the other direction, thus slowing down the wind-driven waves from the lake side, while still allowing the throughflow of river discharge (Wiley and Huang, 2024). Experiments were conducted using the Metronome (see Fig. 1), a 20 by 3 meter tilting tidal flume in which the Ketelmeer was scaled using geometric, kinematic, and dynamic similarity (Heller, 2011). Storm surges were simulated by adjusting a weir at one end of the flume, while a range of storm surge conditions such as height, duration, number of peaks, and sea-level rise were investigated. Different island configurations were also tested, including different numbers, shapes, and spatial arrangements of the islands, to determine their varied effectiveness in reducing storm surge heights. Flow velocity patterns were analysed to assess potential impacts on sediment and pollutant transport.

Figure 1. Set up of the experiments in the Metronome.

Observations

The results show that TVS islands can significantly reduce storm-induced water levels and wave heights in the Ketelmeer and in the IJssel near Kampen across a wide range of storm surge scenarios (20%-50% water level reduction near Kampen – see Fig. 2). Island placement is critical: configurations with islands positioned closer to the lake entrance are more effective than evenly distributed layouts. Increasing the number of islands enhances wave reduction, but there is a threshold of effectiveness, which is reached at approximately four islands, beyond which additional benefits diminish (Fig. 3). No large-scale erosion or sedimentation patterns were observed, although localized scour occurred at island heads, which hint that maintenance may be required if these islands are implemented. The presence of islands alters flow patterns in the Ketelmeer, creating low-energy zones in their lee where pollutants such as arsenic, selenium, benzo(a)pyrene, and mercury may settle. These sheltered areas may also provide

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opportunities for nature development. The construction of hybrid islands (a mixture of a fixed base with sediment/vegetated areas) could therefore combine flood protection with ecological benefits and potential water quality improvement.

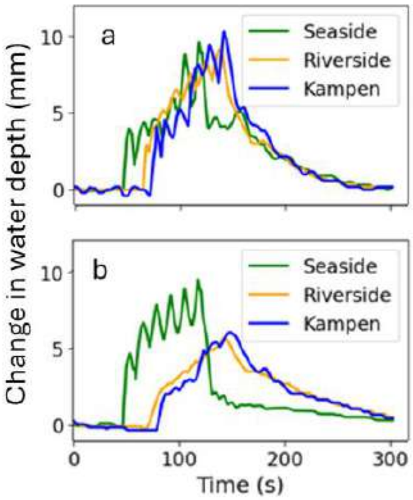

Figure 2. Change in water depth during a storm surge with multiple peaks with a) no islands in the Ketelmeer and b) three islands in the Ketelmeer

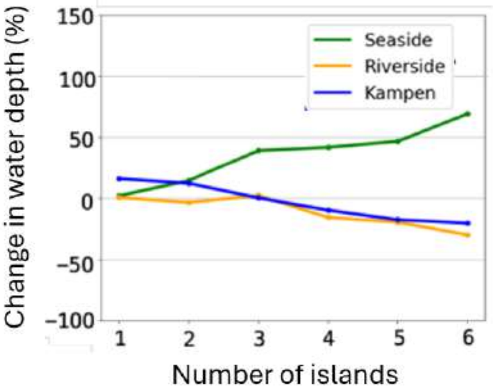

Figure 3. The percentage change in water depth of a storm surge against the number of islands put in the Ketelmeer, for different locations in the Ketelmeer.

Long-term maintenance of the TVS islands may give lower costs than that of strategies relying solely on dikes and pumps (Oerlemans et al., 2021). Moreover, TVS islands offer substantial co-benefits, including ecosystem restoration, improved water quality, and enhanced recreational opportunities, contributing to objectives under the European Water Framework Directive and Natura 2000 and in line with the PAGW goals to create new nature areas in this region.

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Physical origin of water-level oscillations in the Meuse model near river kilometer 203

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Keywords — Meuse River, Delft3D Flexible Mesh, Physical instability, Vortex shedding, Intervention assessment

Introduction

A two-dimensional Delft3D Flexible Mesh (a.k.a., D-HYDRO) simulation of the Meuse River shows persistent water-level oscillations near river kilometer 203 (downstream of the weir at Lith) for a discharge of approximately $4100\,\mathrm{m^3/s}$ at Maastricht. The oscillation amplitude is about $1\,\mathrm{cm}$. Although small given the model uncertainty, this is relevant for permit and intervention assessments where effects are often evaluated at millimeter scale. Numerical instability is usually the first suspect whenever the solution is unsteady. However, that is not the only source of unsteady behaviour. Physical instabilities are ubiquitous in nature and, in fact, stability is often the exception rather than the rule. The objective of this work is to determine whether the oscillation is numerical or physical.

Flow properties and diagnostics

Earlier investigations had already shown that the unsteady behaviour persists across hardware configurations and model variants. To isolate the mechanism, a reduced subdomain model was created around the unstable reach. This reduced model keeps the instability while allowing fast simulations and high-frequency output ($30\,\mathrm{s}$).

The flow in the reduced model was studied by analyzing the evolution of water level, velocity vectors (Figure 1), vorticity, stream function, flow direction, and a passive-decaying tracer pair (used to estimate water age and reveal recirculation dynamics, Figure 2). This revealed a dominant oscillation period of roughly $20\,\mathrm{min}$. A seiche (a standing wave that oscillates in an enclosed or partially enclosed body of water) was observed. The apparent envelope in the water level time series seen in the original simulation is explained by aliasing: sampling at $5\,\mathrm{min}$ is too coarse to properly capture the $20\,\mathrm{min}$ period. Visual analysis shows two counter-rotating ed-

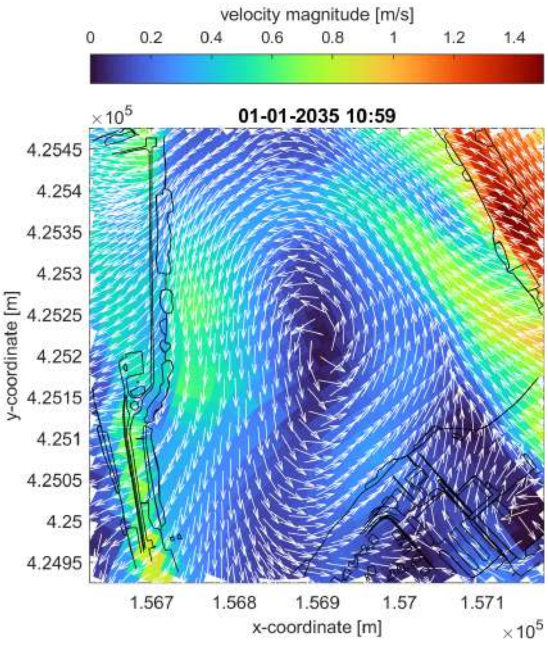

Figure 1: Snapshot of the velocity magnitude and vectors, showing the eddy on the left side of the main channel.

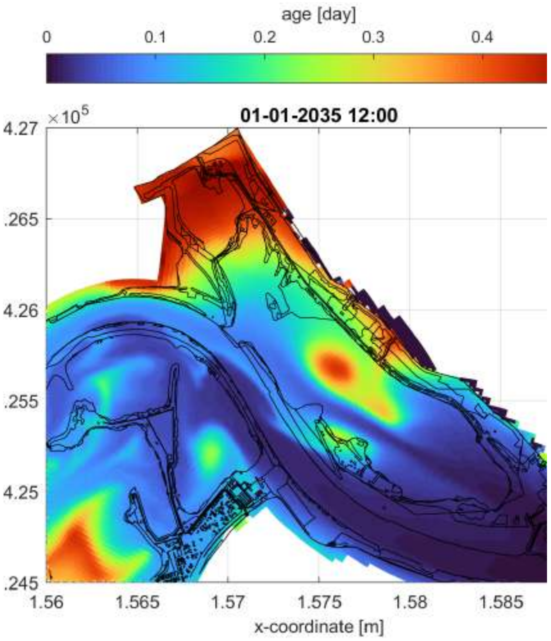

Figure 2: Snapshot of the age tracer, showing the two counter-rotating eddies as zones with high residence time at the left and right sides of the main channel.

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dies on both sides of the main channel, oscillating in antiphase. Their size and edge velocity are consistent with the observed period $(T \approx 2\pi R/U = 2\pi 100\,\mathrm{m}/0.5\,\mathrm{m/s} \approx 20\,\mathrm{min})$.

The eddy pair is consistent with vortex shedding at a sudden flow expansion and bend geometry, supported by deep local pools and relatively low friction that sustain recirculation. From instability theory, this behaviour can be interpreted as amplification of perturbations in the continuous flow (physical instability), as opposed to growth generated only by the discrete solver (numerical instability). In expansion-driven shallow jets, regime transitions are commonly organized with a jet Reynolds number $Re_b = BU/\nu$ and a friction-based stability number $S = C_\mathrm{f}B/(2h)$, where B is jet (channel) width, U velocity, ν kinematic viscosity, C_f friction coefficient, and h flow depth. For representative values in this reach, Re_b is very large and S is low, which places the system in the unstable domain expected for sustained large-scale eddy shedding.

Intervention experiment

While there is strong evidence for a physical instability mechanism, it is not possible to completely rule out numerical instability. To further test the hypothesis, an intervention experiment was performed by locally raising the bed in one floodplain zone to suppress one of the two main eddies. After this change, the periodic water-level signal disappeared (Figure 3). This direct cause-effect response strongly supports a physical instability mechanism, rather than a numerical instability in the solver.

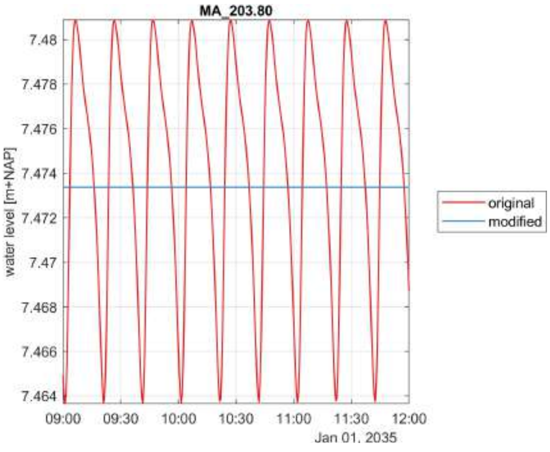

Figure 3: Time series of water level at the observation station `MA_203.80` in the reduced model, showing the disappearance of the oscillation after the intervention.

Implications for practice

For safety and permit assessments in physically unstable regimes, using only time-averaged levels can hide relevant peak behaviour. The maximum water level should be considered. Furthermore, interventions that alter the flow geometry can have a significant impact on the instability mechanism, which can lead to non-intuitive effects. For example, an intervention that suppresses one of the eddies could reduce the oscillation amplitude, but it could also increase the mean water level by reducing the flow capacity of the floodplain. Nevertheless, given the small amplitude of the oscillation and assuming a limited intervention that does not affect the instability mechanism, the mean water level is a good proxy for assessing the impact.

In finding the average or maximum, care must be taken to consider aliasing effects due to the sampling frequency. The closer the sampling frequency is to (a multiple of) the frequency of the oscillation, the larger are the aliasing effects and the longer should be the averaging period.

As a general advice, assuming oscillations with a period of maximum around $1\,\mathrm{h}$ and minimum around $10\,\mathrm{min}$, an averaging period of $5\,\mathrm{h}$ and sampling interval of $2\,\mathrm{min}$ would guarantee that the error is less than 5%.

Conclusions

The oscillation near Meuse river kilometer 203 is most plausibly a physical hydrodynamic instability caused by interacting eddies generated by local expansion/bend geometry, not a purely numerical artifact. This changes how uncertainty should be handled in assessments: diagnostics should distinguish physical from numerical oscillations first, then apply sampling and averaging strategies that are consistent with the identified mechanism.

From Sedimentary Structures to Channel-Belt Architecture: Effects on 3D Groundwater Flow for Dike Safety Analysis

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Keywords — Subsurface heterogeneity, groundwater modelling, Piping

Introduction

The subsurface of the Rhine-Meuse delta is notoriously heterogeneous, consisting of aquitard clays and peat that are dissected by sand bodies (i.e., channel belts) belonging to past fluvial systems (e.g., Berendsen & Stouthamer, 2000). Functioning as shallow-depth aquifers, these channel belts play a critical role in dike safety assessments (e.g., Winkels et al., 2021; Knaak, 2025). Their three-dimensional configuration within deltaic wedge, together with their internal architecture and small-scale sedimentary structures, govern groundwater flow through these shallow aquifers. Understanding *how* these various nested scales of subsurface heterogeneity affect three-dimensional groundwater flow is essential for developing *practical workflows* that incorporate these complex subsurface build-ups into dike safety assessments.

Current schematization techniques employ a probabilistic approach to generate subsurface scenarios for safety assessments, effectively reducing three-dimensional information to one- or two-dimensional representations (e.g., Hijma and Lam, 2015). This raises the question of whether such a reduction may obscure important three-dimensional heterogeneity effects on groundwater flow.

Here, we showcase piping - *the development of open conduits 'pipes' beneath dikes during flood periods* - as a clear example of a process in which the loss of three-dimensional information can cause important subsurface effects on groundwater flow to be overlooked.

Groundwater modelling approach

We deploy a three-dimensional groundwater modeling approach to investigate the impact of different types of subsurface heterogeneity on groundwater flow patterns from a river a towards a concentrated outflow point behind a dike.

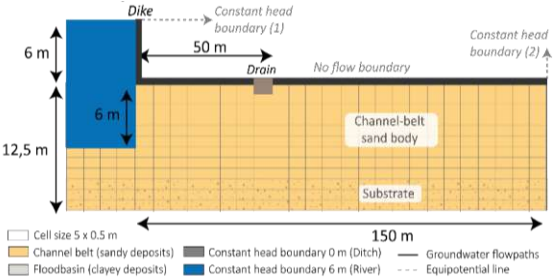

Figure 1. Groundwater Model Setup (cf. Dirkx et al., 2026)

The model domain is set up as a voxel-based framework (1mx1mx0.2m), with each voxel assigned a specific hydraulic conductivity that is systematically varied across different subsurface schematizations (see below).

Hydrological boundary conditions include two constant-head boundaries representing the river under elevated water levels (CH–6 m) and the ditch level (CH–0 m) representing managed water tables behind the dike (Fig. 1). The upper voxel layer has extremely low permeability (kh =10^{-33} m/day), effectively acting as a no-flow boundary. A drain with fixed conductance (100 m/day) is place at a fixed distance (50 m) from the constant river head (Fig. 1), creating a single a single outflow point, allowing simulation of the groundwater flow prior to pipe initiation.

All simulations are run in MODFLOW 6 as three-dimensional steady-state models (cf. Dirkx et al., 2026), yielding 3D groundwater flow paths towards the outflow point, which are tracked using MODPATH 7. When quantifying this three-dimensional flow, several key parameters were considered:

- **Well Discharge** – *The total flux leaving the domain through the outflow point.*
- **D_{min} / D_{max}** – *Minimum and maximum depth of flow paths.*
- ***Area*** – *The surface area through which water enters the model from the river*
- **Volume** – *The total subsurface volume through which water flows*
- **Darcian Flow Rates** – *The total flux divided by the vertical area of the model cell face.*

Subsurface schematizations

To assess the impact of the three-dimensional configuration of sandy channel belts and their internal architecture within a deltaic wedge, we fall back to a detailed reconstructions of a 6 km^2

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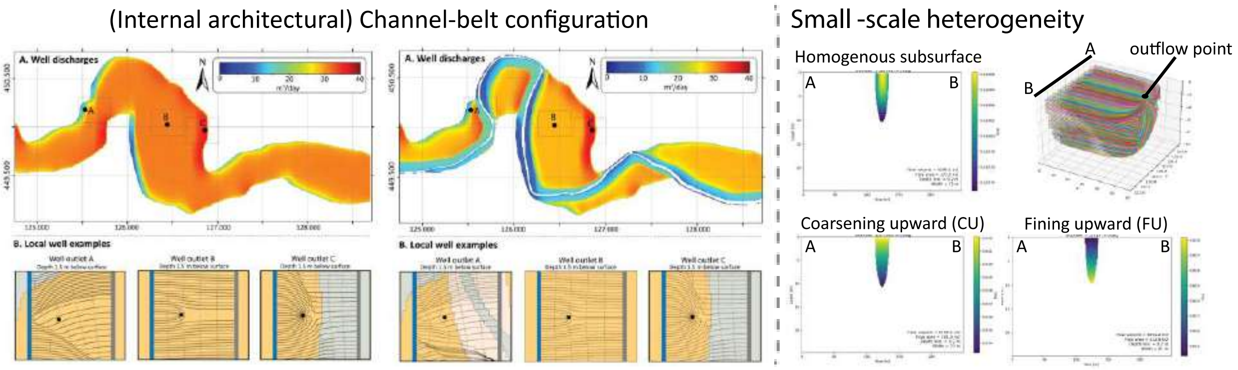

Figure 2. Impact of different forms of subsurface heterogeneity on three-dimensional groundwater flow patterns during the piping

deltaic sand body from the Stuivenberg Channel Belt in the central Dutch Rhine–Meuse Delta (Winkels et al., 2022). Individual internal architectural units were assigned a constant hydraulic conductivity based on their lithological composition and representative literature values (Dirkx, et al., 2026).

Small-scale sedimentary heterogeneity is schematized theoretically by simulating sedimentary sequences typically found within channel belts (i.e., FU and CU sequences) through adjustments of permeability within the voxel model. The resulting schematizations reflect varying degrees of FU and CU trends, enabling a systematic investigation of their impact on three-dimensional flow behaviour.

Results

Our simulations show that the local subsurface architecture of channel belts controls groundwater flow well beyond the local setting, shaping flow patterns across a wide area.

The greatest spatial variability in flow parameters occurs near the channel-belt margins (within ~50 m of the edge). Here, contrasts between permeable channel sands and less permeable flood-basin clays induce localized flow convergence or divergence via restricted infiltration or drainage (Fig. 2). Under divergent flow, restricted inflow from the river reduces total outflow (-50%), but the narrowed active flow area (max 10 m) concentrates flow, yielding high specific rates (~1.1 m/day). Under convergent flow, groundwater focuses toward the outflow due to impaired drainage, and high discharge (+25%) over a wide area (50 m) reduces specific rates (~0.2 m/day). Disconnection from the Pleistocene aquifer amplifies spatial patterns by increasing absolute differences, as groundwater can no longer flow through the continuous aquifer. The internal architecture of abandoned channels further modulates variability, with low-permeability units shaping the spatial expression of divergent and convergent flow.

Building on these macro-scale controls, local-scale simulations of FU and CU sequences show that even small contrasts in hydraulic conductivity strongly influence three-dimensional flow. A subtle fining-upward (FU) sequence shifts flow downward, increasing discharge to deeper layers by ~40%, whereas a slight coarsening-upward (CU) sequence concentrates flow in the upper layer (Fig. 2). In contrast, a homogeneous scenario distributes flow more evenly, highlighting the effect of vertical heterogeneity.

Implementation in Dike Safety Analysis

Our work shows that a 3D approach to subsurface schematization is crucial, revealing direct effects on groundwater flow missed by 1D approach. These insights form the basis for informed decisions on which aspects of subsurface heterogeneity to incorporate into dike safety assessments and we are actively collaborating with different stakeholders to determine how to apply them in practice.

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Fast spatiotemporal flood modelling after a dike breach

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Keywords — Levee breach, inundation, flood arrival time, conceptual model, surrogate model

Introduction

Dike breaches are events that can cause large economic damage and loss of life. It is of critical importance that these events are predicted and well-managed. A key component of developing disaster management plans is obtaining insight into flood characteristics, such as flood arrival times and water depths in the affected area. Numerical 2DH flood models are often used to obtain detailed spatial-temporal characteristics of a possible flood scenario. However, these models are computationally expensive, making it nearly impossible for them to aid decision making with the many uncertainties during an emergency situation (Leskens et al., 2014).

Surrogate models are cheaper-to-run versions of more complex models that reproduce or emulate the relevant output at an acceptable accuracy. Examples include data-driven models such as machine learning techniques, or conceptual approaches based on empirical relations and (often) filling and spilling rules, such as ‘bath-tub’ models.

In this work, we focus on conceptual surrogate models of dike breach floods using a Digital Elevation Model (DEM). These have been successfully applied for rivers exceeding their banks and inundating clearly bounded valley topographies. However, horizontally extrapolating river water levels can lead to large overestimations of the flood (Sanders et al., 2024), especially with point-sources like dike breaches in a flat delta-region. Another common approach is to fill from the lowest point, but this location can be far away from the flood source. Therefore, these conceptual models typically only provide the maximum inundation extent, not the flood propagation through time.

In this study, we present a fast conceptual flood model with new characteristics compared to existing methods: a single inflow location to simulate a dike breach and a time-stepping approach to model flood propagation. This allows the model to simulate water depths and arrival times for the duration of the flood.

Method

The model is based on a Digital Elevation Model (DEM) and requires a breach location and a breach discharge hydrograph as input. The model computes the Local Drainage Direction (LDD) by finding for each grid cell the steepest downward slope of its eight neighbouring cells. We assume that the flood will flow along this LDD away from the breach location. The elevation change between subsequent grid cells gives a slope in the direction of the flow, which together with breach discharge correlates with the propagation velocity of the flood front (Besseling et al., under review). Every time step, the distance that the flood travels along the LDD path is computed with the propagation velocity, leading to the flood arrival times.

The breach discharge that enters during a time step duration introduces a volume unit into the flooded domain. The volume unit is assigned to the path grid cells flooded during this time step, and spread across the topography using the principle of Height Above Nearest Drainage (HAND, Nobre et al., 2011) to compute the water depths.

In further time steps, the first volume unit propagates further along the path and floods a new section of grid cells. A new volume unit then enters the domain and floods those grid cells previously occupied by the first volume unit.

Preliminary results

We run the conceptual model for a dike breach along the German Rhine, near the village of Bislich upstream of the Dutch border. The conceptual model is forced with the breach discharge computed by a D-Hydro 1D-2D model of the study area.

Figure 1 compares the results of the conceptual model to the D-Hydro model. The flood arrival times are very well predicted (Figure 1a). The Critical Success Index (CSI) score measures the match between the inundation extents, with a CSI of 1 indicating perfect performance. The model achieves a score of around 0.8 in the first two days of the simulation (Figure 1b). The water depths show a Mean Absolute Error of 0.75 meters (Figure 1c), which is relatively high compared to the average D-Hydro water depth in the first two days of around 3 meters. We comment on this briefly in the next section.

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Finally, the computation time of the conceptual model is around 40 seconds for five days of simulation time, with a time step of one hour. On the same machine, the D-Hydro model computes for two days, so a speed-up factor of about 4000x is achieved. The simulation time of the conceptual model decreases to 20 seconds if a time step of 3 hours is used, while the performance remains very similar (Figure 1b-c).

Next steps

The current model is limited to the first section of the hinterland, where a raised highway limits further flooding. We are working on a spilling algorithm based on the broad-crested weir equation to advance the flood propagation beyond this boundary. Additionally, the D-Hydro model discharges water from the grid cells in the 2D embanked areas to adjacent 1D rivers via overtopping and via weirs, while also leaving higher remaining volumes in upstream sections. The conceptual model does not have these features, resulting in the high mean water depth errors. Improvements in the division of volumes across the hinterland could lead to a better water balance and improved water depth accuracy. Furthermore, the conceptual model is now still dependent on the breach outflow hydrograph from the D-Hydro model as input. Future work can couple the conceptual model to a fast outflow model (e.g. Besseling et al., 2025) to make a fast and fully independent modelling framework for probabilistic analysis of uncertainties shortly before or during dike breach floods.

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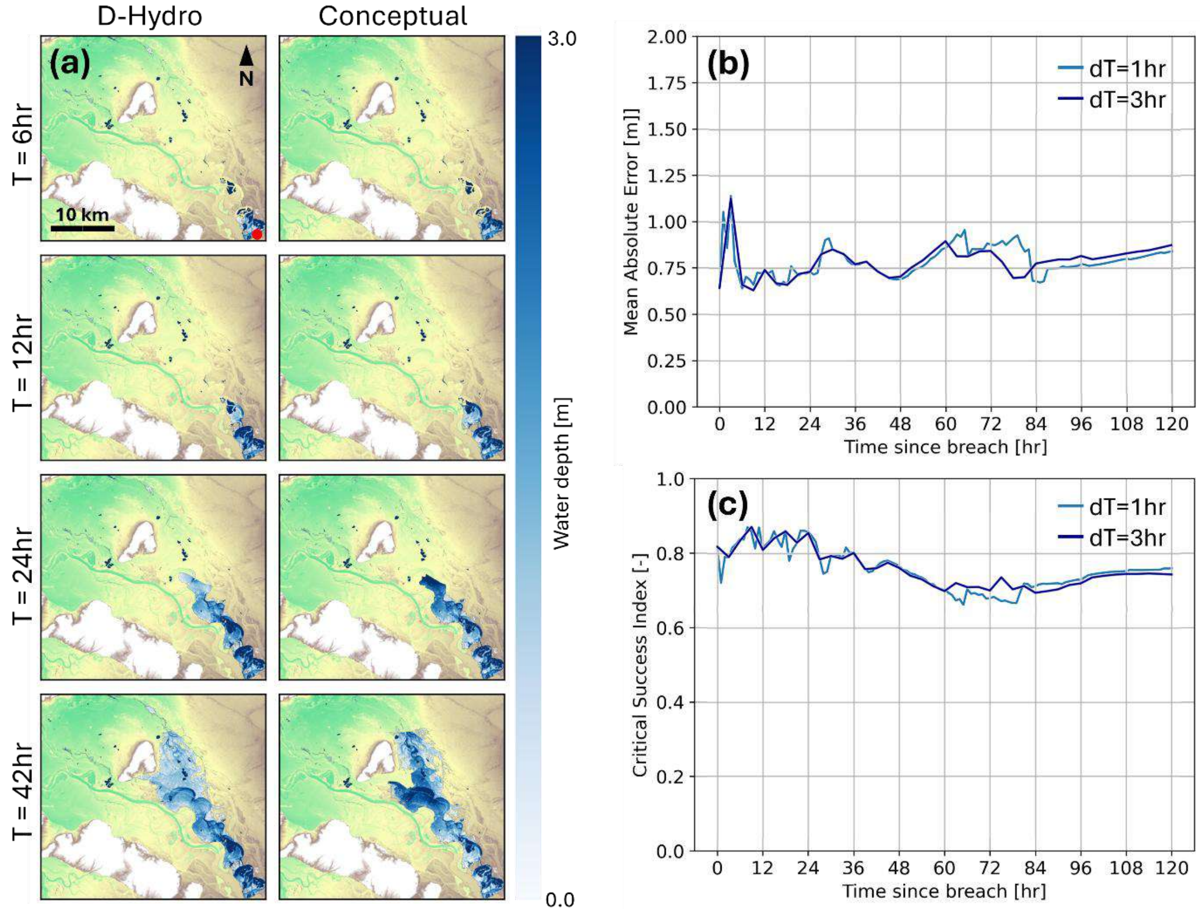
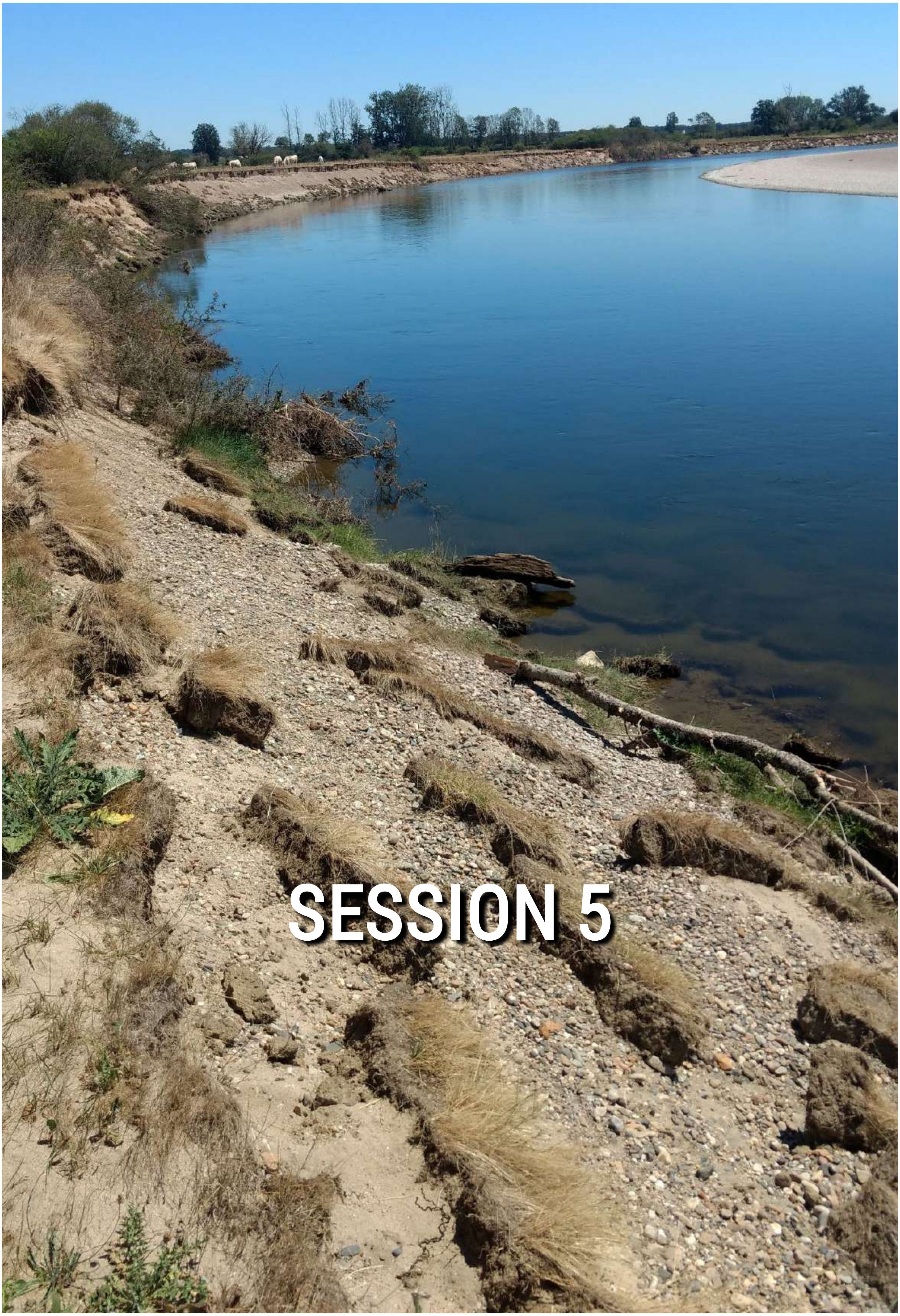


*Figure 1. **(a)** Comparison of D-Hydro and the conceptual DEM-based model simulated water depths of the flood spreading from the breach (at red dot) towards the north-west several time steps after the breach. **(b)** Mean Absolute Error (MAE) of water depth throughout the simulation for a time step of 1hr and 3hrs. **(c)** Critical Success Index (CSI) of inundation extent throughout the simulation for a time step of 1hr and 3hrs.*



SESSION 5

Wave-reducing capacity of fascine screens

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Keywords — Fascine screen, Brushwood, NbS, ship wave reduction, bank protection, laboratory

Introduction

Within the innovation team of Rijkswaterstaat, Strukton & Van Den Herik, and Deltares, research was conducted to assess whether brushwood screens can serve as an effective, nature-friendly measure to protect riverbanks against erosion caused by ship waves. The aim of this pilot is to determine, in a controlled lab environment, the wave-reducing capacity, including the influence of failure scenarios such as low filling degree and degradation.

In total four configurations (see Figure 1) were tested at full scale in the Delta Flume at Deltares:

- **Screen 1:** Robust screen, 1.80 m thick
- **Screen 2:** Regular screen 0.6 m thick
  Screen 3: Regular screen with a gap at the top, caused by degradation over time
- **Screen 4:** Regular screen with low filling degree, caused by buoyancy of the wood during construction

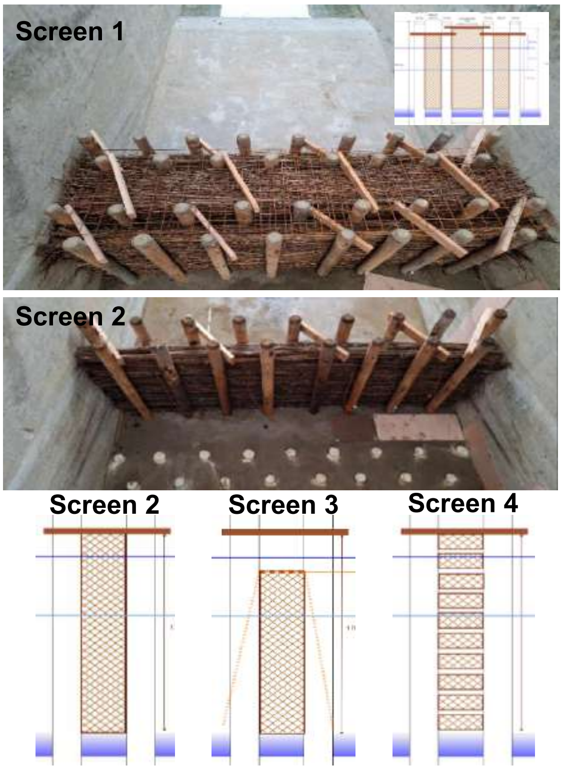

Figure 1 Four screen configurations tested in the Delta Flume

Laboratory test

For each screen, a set of thirteen wave tests was performed for two water levels: the design water level according to the GROW guidelines (Vos & Onderwater, 2025) for fascine screens within the Water Framework Directive (WFD), respectively 0.2 m below the top of the brushwood filling, and a water level 0.5 m lower.

Each water level was tested with five realistic ship-wave conditions consisting of combined primary and secondary waves. In addition, eight tests with regular, repeated individual primary and secondary waves were carried out. Their wave heights and periods were derived from the five realistic ship waves. All waves are based on the geometry and the main type of ship traffic (M6 and M8 ships) near Wilsum on the IJssel *(*BIVAS-webviewer, 2024*).*

Ship length primarily determines the primary-wave period, while ship speed influences the remaining wave characteristics. Waves were simulated using methods of Van der Hout et al. (2011), including a Bernoulli-based potential approach for primary waves, while secondary waves followed DIPRO and the Rock Manual. The resulting wave conditions span heights from 0.16 m to 0.90 m and periods from 1.7 s to 57 s, providing a broad range which also captures characteristics for other ship types. One simulated realistic wave shape is shown in Figure 2.

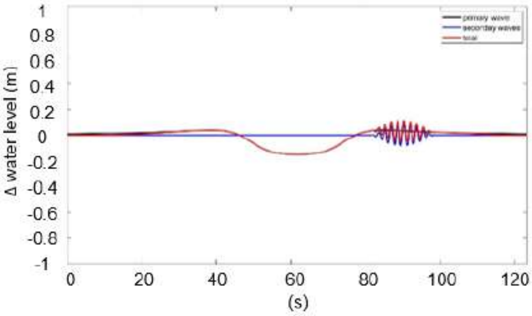

Figure 2 Realistic simulated ship wave (in red) build from a primary wave (black) and a set of secondary waves (blue)

The longest periods of the primary waves of these tests previously not been tested in the

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Delta Flume, making these tests pioneering and offering new insight into the facility's capabilities for future applications.

Results

Water level was measured along the flume, directly in front and directly after the screen. Wave transmission coefficients are determined both for the screen alone and for the combined effect of the screen and foreshore slope by dividing the wave height behind the screen with the wave height in front of the screen or the wave height at the start of the flume.

Figure 3 shows, for one realistic wave test, the water level measured in front of the screens (blue) and behind (green) the four screen configurations (robust, regular, degraded, and low-filling, from top to bottom). The results demonstrate that all screens reduce the height of both the primary and secondary waves.

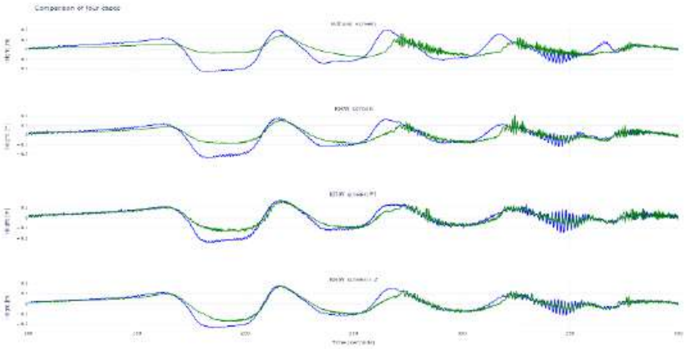

Figure 3 Measured water level in front (blue) and behind (green) the four screen configurations during a realistic wave signal at design water level

Figure 4 shows the wave-transmission coefficient (C_t) of the four screens at low water level as a function of wave period. All screens reduce wave energy, with the robust screen showing the greatest reduction (smallest transmission). However, as the wave period increases the effectiveness converges.

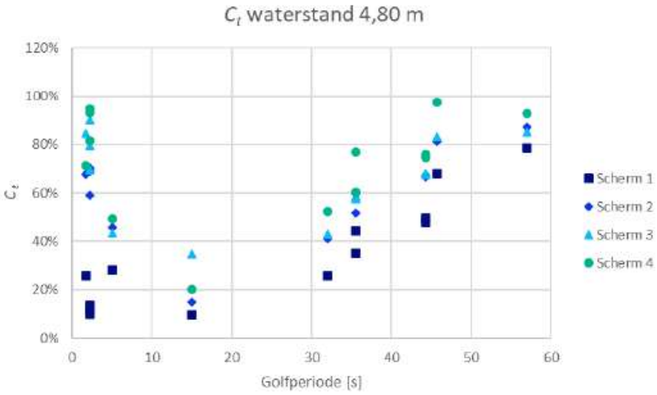

Figure 4 The wave transmission coefficient (C_t) for the four screens during low water level

The combined wave transmission coefficient of the screen and foreshore is shown in Figure 5. This figure shows for the longer wave periods coefficients over 100%, because for the long waves the increase in wave height on the foreshore by shoaling is larger than the wave reduction by the screen. The waves with periods between 15 and 30 seconds often shoal and break at the slope in front of the screen.

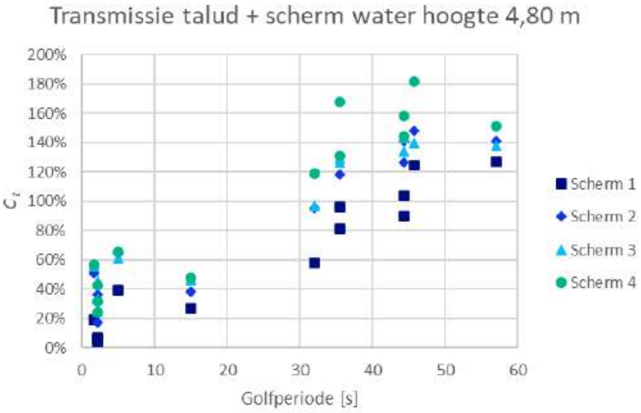

Figure 5 The wave transmission coefficient (C_t) for the four screens including foreshore slope during low water level

Conclusions

The tests show that brushwood screens can substantially reduce ship-induced waves, particularly the shorter secondary waves. The robust screen performs best, reducing wave heights by about 80% at design water level and 66% at lower water levels, significantly more than the regular screen. Wave reduction depends strongly on screen thickness and underwater filling degree. Long primary waves (>30 s) are only weakly reduced (7–21%) and are influenced more by foreshore slope and water depth than by screen design. The results further demonstrate the importance of proper filling during construction and proper maintenance, as insufficient infill can noticeably reduce the effectiveness for wave reduction. Ensuring a high underwater filling degree, even without a fully closed top, is essential for achieving optimal wave-reduction performance.

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Tidal propagation into rivers influenced by salt intrusion

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Keywords — Tidal propagation, Salt intrusion, Flood risk

Introduction

The propagation of tides into rivers is classically described as a balance between convergence-driven amplification and frictional damping (e.g., Savenije et al., 2008). In stratified estuaries, however, density gradients suppress turbulence, thereby reducing vertical mixing and altering effective bed friction (Geyer, 1993; Stacey et al., 1999). Vertical stratification can significantly alters tidal dynamics and has been shown to enhance tidal ranges (Winterwerp et al., 2009). Despite these insights, a systematic framework that quantifies how salinity-induced stratification influences tidal propagation into rivers is still lacking.

We investigate how salinity-induced stratification affects tidal water levels in rivers, and assess the adequacy of depth-averaged models to capture these effects. We address the following research questions: 1) How do salinity-induced density gradients influence tidal propagation? 2) Can physics-based parameterisations be used to improve depth-averaged model performance?

Method

The modelling software Delft3D Flexible Mesh (DFM; version 2025.01) is used. The tidal river is represented as a single channel of 250 km, a depth of 15m which slopes with 5x10^{-5} m/m. The model has a horizontal resolution of 100 m, uses 60 sigma-layers in the vertical and applies a uniform manning roughness of 0.03 $\mathrm{m}^{1/3}/s$.

At the upstream river boundary, a constant discharge q_r is applied and a background salinity of 0.1 PSU. At the river mouth, a S2 tidal range of A_0 and a salinity of 30 PSU are applied.

Configurations & cases

Three salinity-stratification classes are considered:

- well-mixed: q_r=0.06m^2/s, A_0= 3.2m
- partially-mixed: q_r=0.6 m^2/s, A_0=1.6m
- salt-wedge: q_r=3.0 m^2/s, A_0=0.8m

Moreover, various cases are considered: depth-varying cases with and without salinity (called *Base case* and *Fresh case*, respectively), and depth-averaged cases with diagnostically derived salinity fields (*Diag. salinity*) and effective roughness fields (*Diag. Roughness*).

Results

Results per stratification class show clear differences in water levels when salinity is included. In the salt-wedge regime, tides amplify along the salt-intrusion region (0-45 km) in the Base case, but dampen throughout in the Fresh case. No significant change in tidal range is observed in the well-mixed regime (Figure 1).

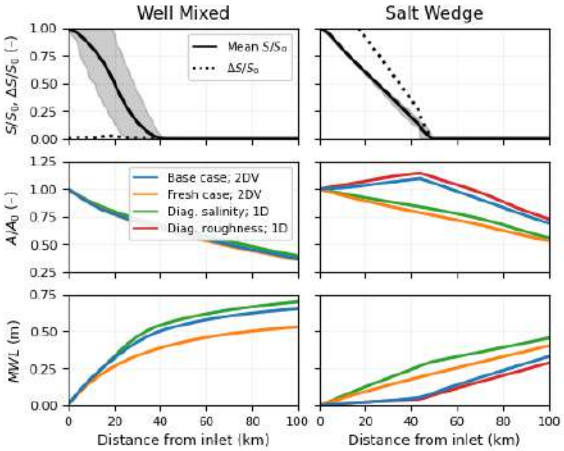

Figure 1. Hydrodynamic characteristics along the tidal river for well-mixed (left) and salt-wedge (right) regimes. Row 1: mean salinity, tidal salinity range, and stratification (Base case). Row 2: tidal range. Row 3: mean water level. Values are normalized by the value at the inlet where applicable

In the well-mixed estuary, mean water level (MWL) in the Fresh case is up to 0.20 m lower than in the Base case, reflecting a free-surface slopes induced by the depth-averaged salinity gradient. This process can be considered in a 1D model with a diagnostic salinity case (as shown in Savenije et al., 2007; Figure 1, green line).

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Contrarily, in salt-wedge estuaries, neglecting salinity increases MWL, and adding a 1D diagnostic salinity field worsens agreement with the Base case. This is because in salt wedge systems, the depth-averaged density gradient is balanced internally, and does not result in a free-surface slope.

Amplification in the salt wedge regime is shown to be induced by a combination of processes. Vertical salinity stratification suppresses turbulence and lowers peak near-bed flow velocities, reducing the effective roughness along the salt-intrusion length. This weakens dampening and enhances tidal penetration. Moreover, at the salt intrusion length, the tide is partially reflected due to the sudden transition from low to high effective roughness, resulting in local amplification. A diagnostically derived reduction in effective roughness in a 1D model (*Diag. Roughness case*, red lines) mimics this, reproducing the tidal range profile successfully.

Also alternative geometries are considered, wherein the river is prismatic, tides amplifies in the Fresh case or where the river is relatively shallow. Identified findings are found to be true across all geometries considered.

Conclusion

In stratified tidal rivers, vertical density gradients weaken tidal damping and enhancing tidal penetration. Moreover, at the salt intrusion limit, partial reflection of the tide locally promotes tidal amplification, resulting in local maxima in tidal range. Together, these processes increased modelled tidal ranges by up to 30% near the salt-intrusion limit.

This has important implications for flood-risk predictions, whereby generally depth-averaged models are applied which lack (accurate) inclusion of salinity-induced effects. A substantial reduction in effective bed roughness along the stratified region allows depth-averaged models to mimic the tidal dynamics obtained when considering depth-varying salinity dynamics.

Finally, our results highlight the strong coupling between salt dynamics and tidal water levels in rivers, linking seasonal variations in river discharge to the seasonality in tidal dynamics. Moreover, large-scale interventions, such as channel deepening and narrowing, are known to substantially strengthen stratification (Siemes et al., 2025) and will therefore also enhance tidal penetration and amplification.

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This work is part of the Perspectief Program Saltisolutions, which is funded by Netherlands Organization for Scientific Research (NWO) Domain Applied and Engineering Sciences in collaboration with private and public partners.

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A forgotten disaster: the 1926 Meuse flood

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Keywords — Flood, Meuse, Historical Reconstruction

Introduction

The 1926 Meuse flood, this year exactly 100 years ago, ranks among the most disruptive river disasters in the modern history of the Netherlands, showing widespread failures of flood defence infrastructure. Though part of a long tradition of Meuse floods, its extent and cascading effects made it a defining moment for both river management and society. This study reconstructs the event from historical hydrological records, government reports, maps, contemporary newspapers and historical websites. It aims to clarify the hydro-meteorological drivers, the failure of infrastructure and the social consequences, and to evaluate how the disaster influenced subsequent river reforms and recovery policy.

Meteorology and Hydrology

The year 1925 was characterised by a wet autumn and an early onset of winter with heavy snowfall. From 20 December, a series of depressions from the North Sea brought widespread rainfall, rising temperatures and snowmelt, pushing water levels to the highest values observed in centuries. On 1 January 1926, the Meuse at Maastricht reached an estimated 3,000 m^3/s (Departement van Waterstaat, 1926).

Failure of infrastructure

As water levels climbed, the system began to give way (Departement van Waterstaat, 1926). The Liège–Maastricht Canal was only just kept safe from failure. Major parts of Maastricht were inundated. Along the Common Meuse, long known weak spots once again failed and 35 dike breaches redirected floodwaters across ancient channels and low-lying floodplains. In Central Limburg the dikes proved systematically too low. Dike overtopping combined with dike breaches caused extensive regional flooding and damage to local infrastructure. North of this zone, the failures multiplied. In the Boxmeer-Oeffelt-Cuijk corridor, numerous breaches undermined the railway system, resulting in collapsed viaducts, bridges and embankments. These failures revealed the structural limitations of the sand-based dikes with shallow clay coverings.

The Beerse overlaat

For centuries, the Beerse Overlaat had served as a pressure valve for the Meuse system, allowing controlled spillover into Noord Brabant. After repeated calls from the Brabant population, the overlaat was raised in 1922 to reduce its frequency of operation. In 1926 it functioned to its full extent again and inundated large parts of Noord-Brabant, either directly or by blocking the discharge of tributaries into the Meuse (Fig. 1, Lely, 1926). The 1926 flood clearly demonstrated that the modification of the Beerse Overlaat had been insufficient.

Flooding of the Land van Maas en Waal

The most severe structural failure occurred on 31 December 1925 at Nederasselt (Departement van Waterstaat, 1926). The poorly maintained dike —further weakened by heavy rain, internal saturation and storm-driven wave overtopping— collapsed around 7 o'clock in the morning. The resulting breach rapidly flooded the Land van Maas en Waal. Despite improvised emergency works with canvas, gravel and rails, the breach widened to hundreds of meters. Only after military engineers cut openings in the downstream dikes of Alphen and Dreumel water could be released back to the Meuse. The region remained inundated for months.

Societal disruption

The human impact was severe (a.o. Van Hout, z.d.; Deurloo, z.d.). Dozens of villages across Limburg, Noord-Brabant and Gelderland were submerged, in places more than two metres deep. Families retreated to upper floors and drove small livestock into attics. More than 3,000 houses collapsed under the combined load of flood waters, westerly storms and frost. Flooded polders became vast sheets of ice, worsening suffering and obstructing relief. Roads and railways were heavily damaged, leaving transport and aid dependent on military boats. Livestock drowned and winter fodder spoiled. When the water finally receded,

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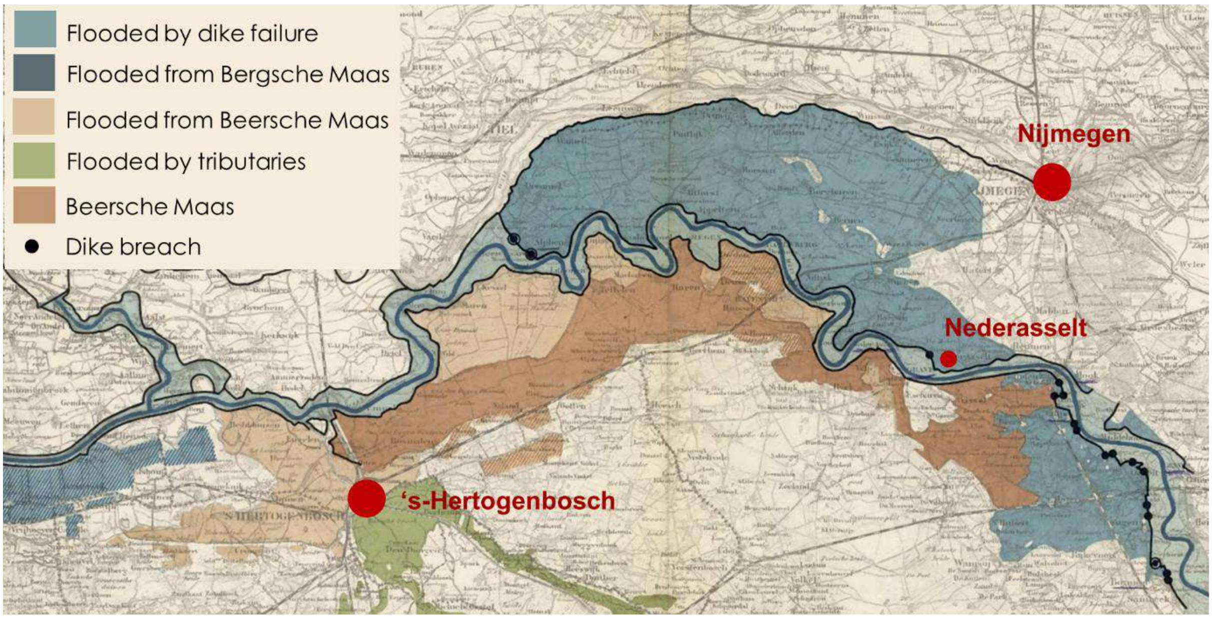

Figure 1. Inundations between Nijmegen and 's-Hertogenbosch in 1926 (map by I. Hemati after Lely, 1926).

residents faced the risk of disease. Homes and farmsteads had to be disinfected with creoline, lysol or lime, extending disruption long after the peak of the flood.

Social inequities

The government did not provide financial support to those affected, reasoning that river floods were simply part of the risk of living along the Meuse. National fundraising campaigns, however, collected substantial sums (Deurloo, z.d.). Yet the aid disproportionately supported wealthier homeowners, while poorer families received little to no assistance under the rationale that "those who own nothing have nothing to lose." This exclusion sparked growing public criticism. Local leaders and national advocates eventually mobilized additional support, which enabled the construction of 46 modest homes for the "forgotten families" (Deurloo, z.d.). The episode revealed how natural disasters can reinforce pre-existing social inequalities.

River reform

The flood event underscored the urgency of a fundamental redesign of the Meuse river system (Lely, 1926). Proposed measures included cutting major bends, deepening and widening the channel, excavating floodplains and canals, installing weirs, improving embankments, and permanently closing the Beerse Overlaat. These plans shaped the large-scale canalization and river-engineering works of the 1930s, marking a decisive shift toward a more regulated and hydraulically controlled Meuse. Continuous investments since the 1930s have further improved flood safety and navigability.

Comparison between 1926 and 2021

The 2021 flood exhibited a slightly higher discharge than the 1926 flood, with a steeper hydrograph. However, water levels remained markedly lower and the Meuse dike system resisted without breaches or major inundation. Because of the growth of the population and economy since 1926, an inundation on the order of 1926 would nowadays cause €10 billion in losses, lead to around 100 fatalities and affect approximately 145,000 residents (D. Riedstra, RWS, pers. comm.).

Conclusions

The 1926 Meuse flood was more than a hydrological extreme: it was a systemic crisis that exposed weaknesses in dike design, emergency preparedness, and social safety nets. It triggered far reaching engineering reforms and revealed the deep social inequalities that shaped disaster recovery. The event remains a key reference point for understanding modern flood risks in the Meuse basin and its lessons continue to resonate in contemporary flood management practice.

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POSTERS
DAY 1

Silting and permeability in the Common Meuse river bed

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Keywords — Morphodynamics, Fluvial, Ecology

1. Introduction

Gravel bed rivers are characterized by their coarse sediments, but can also contain sand (0.063-2 mm) and mud (<0.063 mm). These fine sediments (<2 mm) can cause the riverbed to clog up due to silting and with that lower the flow through the river bed due to decreased permeability. This affects among others sediment mobility, water quality and habitat availability (Brunke et al., 1999). The Common Meuse is a gravel bed river reach in the Netherlands which does not meet the standards for aquatic biodiversity set for the European 'Natura 2000' protected natural areas (Rijkswaterstaat, 2025). The clogged river bed with little pore water flow is one putative cause. Field observations however still lack. The aim of this study was to measure silting and permeability in the Common Meuse river bed. We expect the silting to be high at the downstream and land side of river bars, as slow flow enables deposition of fine sediment. The permeability is expected to be high at locations with little fine sediment and large height-induced pressure differences.

2. Methods

The Common Meuse is the gravelly river bed reach ($D_{50}\approx32$ mm) located in Limburg on the border with Belgium (Fig. 1). Fieldwork was conducted between April and November of 2025 on three river bars near Borgharen, Meers and Grevenbicht and around the sediment nourishment near Meers, which was undertaken from August till October by Rijkswaterstaat.

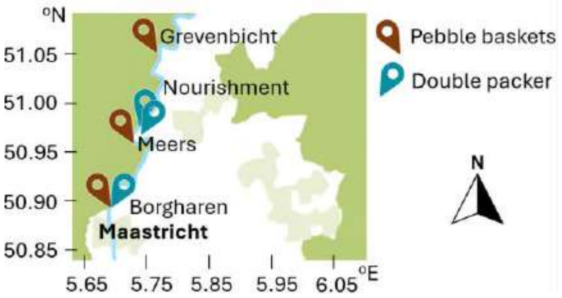

Figure 1: Common Meuse reach with pebble baskets and double packer measurement points at the four field sites.

2.1 Silting of pore space

Silting was measured using pebble baskets. Our perforated baskets (21cm diameter by 13 cm height) with an open top were filled with local sediment from which the fractions <2 mm were removed by in-situ sieving. The baskets were dug into the river bed and left for roughly 3 months. After this period, the baskets were retrieved, and dried, sieved and weighted in the lab. Differences between sites and side of morphological units were statistically tested. Linear regression was applied to check for a relation between silting and inundation time.

2.2 Permeability

The permeability of the river bed was tested using a double packer (Negreiros et al., 2023). It is a 1.2 m long pipe with depth-adjustable chambers, from which water can be slurped up using a pump. We determined the 1.5 minute average slurp rate from the weight of the slurped up water for three repetitions at 3, 9, 15, 27 and 39 cm depth into the river bed. Differences between sites were again statistically tested. Neighbouring ice cores were made using aluminium pipes of 50 mm that were hammered into the river bed and filled with dry ice. After an hour the samples were taken out and dried, sieved and weighed in the lab. We determined the fractions of mud, sand and gravel for the coupling to slurping rates, and grain size distributions for linear regression testing a relation between permeability and sediment fractions <2 mm.

3. Results

3.1 Silting of pore space

Silting ranged between 0.04 and 14.8 weight percentage of grain size fractions <2 mm of the total weight of the sample (Fig 2). There was a significant difference in silting between the bars as Kruskal–Wallis' H=10.9028 with p=0.0043. We found the full range of silting values in the bar near Borgharen, low values at Meers and high silting at Grevenbicht. We did not find the expected significant difference between upstream and downstream (Mann-Whitney's U = 25187.5 with p=0.5604) nor landside and channel side (Mann–Whitney's U = 18278.0 with p=0.4480) of the bar. The relation between silting and inundation time of the pebble baskets was weak, with an R^2 of 0.00, 0.33 and 0.39 for the bars Borgharen, Meers and Grevenbicht respectively.

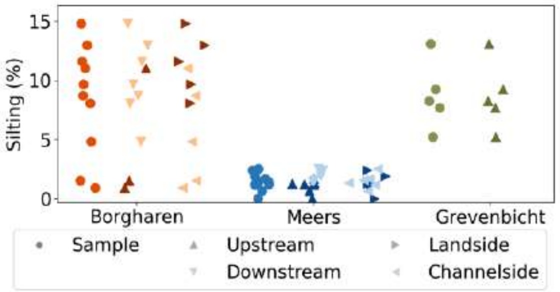

Figure 2: Silting at three sites (weight percentage of grain size fractions <2 mm of the total weight of the sample).

3.2 Permeability

The slurp rates were between 0 and 49.9 g/s (Fig. 3). Significantly different profiles were found at the three measurement sites, as Kruskal–Wallis' H=55.8573 with p=0.0000. The hypothesised higher rates were found for some of the locations with low fine sediment fractions and large pressure differences (M1, lower half of B1 and B1), but unexpected low values were measured in the nourishment material (N). The relation between slurp rate and fine sediment was weak (Fig. 4) with R^2 values below 0.35. The highest value was found for the mud grain size of <0.063 mm, indicating that this fraction was the main predictor for a decrease in permeability.

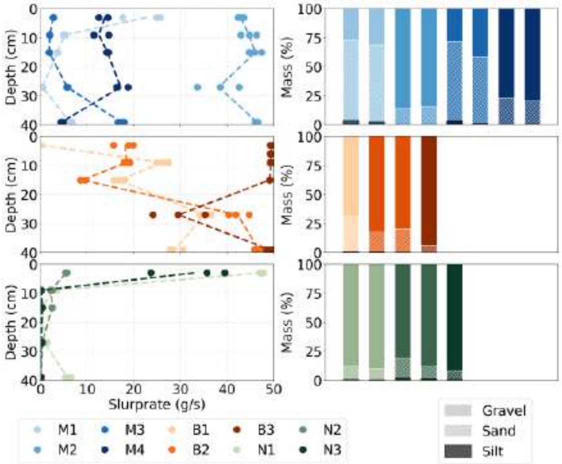

Figure 3: Slurp rate (left) and cumulative sediment fractions (right). M=Meers bank, B=Borgharen and N=nourishment.

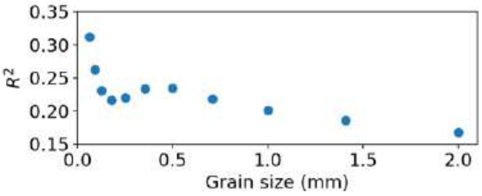

Figure 4: R^2 values of the linear regression of slurp rate with fine sediment fractions of sieve sizes <2 mm.

4. Discussion

The overall range of values for silting of the pore space is relatively large compared to other rivers in literature (for example Brunke et al., 1999). Permeability is variable, similar to (Negreiros et al., 2023). The hypothesised relations between silting and bar side, and between permeability and silting plus height induces pressure differences were weak. This indicates causes of spatial variability, such as sediment transport events. We are currently working on combining calculations of pore space depending on grain size distributions following the method of Yu Standish (Yu et al., 1991) with lab work on permeability, to understand the effect of different sediment mixtures. We will also analyse our pebble baskets at the nourishment location, creating insight into silting at this site. Using pebble baskets at different depths will allow us to determine depth-depending silting, improving the coupling of silting to permeability and reduce uncertainty.

5. Conclusion

Silting and permeability in the gravelly river bed of the Common Meuse show large spatial variation not clearly linked to the bar morphology and inundation time. There are significant differences between bars. The relation between permeability and the fraction of fine sediments is highest for the smallest grain sizes (<0.063 mm). Future work includes the coupling of field observations to pore space availability calculations and permeability tests in the lab, and analysis of silting of different river bed depths.

Acknowledgements

This study was funded by the Rivers2Morrow programme of Rijkswaterstaat. We thank the Stuttgart university for lending us their double packer, Bea for her explanation of the device, Seb, Rein, Joshua, Stefan and Sari for their field support, and Henk, Marcel and Mark for their technical support.

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Unique Data Available from Monitoring Longitudinal Training Walls in the Waal River

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Keywords —Monitoring, Longitudinal Training Walls, Rhine, Room for the River 2.0

Rijkswaterstaat (RWS) has initiated a new monitoring campaign in the Rhine River to evaluate alternative riverbed designs. The campaign focuses on the longitudinal wall system near Tiel at the Waal (Fig. 1). Longitudinal walls are flow regulation structures, replacing transverse groynes along the river. These walls divide the river into a main channel and a secondary (bank) channel. This measure offers an integrated solution: reducing flow velocity in the main channel to limit bed erosion, dampening wave action in bank habitats, and raising water levels during low discharge events. In the monitoring campaign, particular attention is given to the adaptability of longitudinal walls through adjustments to the inflow weir elevations. Hydraulic, morphological, and ecological parameters will be monitored from Q1 2025 to Q1 2028. The resulting dataset provides an excellent opportunity for collaborative research on alternative river design strategies.

Why Longitudinal Training Walls (LTD)?

Longitudinal walls, a variant within multi-channel river systems, are a key measure in the Room for the River 2.0 (RvR 2.0) program. They are considered promising because they address multiple challenges simultaneously. This integrated approach is essential as river systems face increasing pressure from climate change and autonomous riverbed developments. RvR 2.0 aims to ensure safe water conveyance, mitigate large-scale bed erosion, and maintain a balanced discharge distribution during low-flow conditions. Additionally, the European Water Framework Directive (WFD) requires the preservation and enhancement of riverine ecological values. A pilot project incorporating longitudinal walls was constructed in the Waal River between 2014 and 2016.

Current Knowledge

The 10-km pilot near Wamel, Dreumel, and Ophemert was monitored from 2015 until 2020. Results indicate that summer bed redevelopment reduces bed erosion but does not fully eliminate it (Mosselman et al., 2021). Navigability during low flows is expected to improve, although local dredging may increase. Ecological quality along the river margins has improved significantly. Preliminary findings suggest a modest positive effect on low-water levels, which could be enhanced by adjusting inflow weir heights. Social acceptance has grown among residents and anglers, while skepticism persists within the inland shipping sector. Overall, longitudinal walls show potential for addressing multiple river management objectives, but knowledge gaps remain. Further monitoring with refined methods could reduce uncertainties and inform cost-effective construction of LTDs at other locations along the river.

Rationale for a Second Monitoring Campaign

The length of the initial dataset is limited, constraining the ability to assess long-term effects on variables such as bed morphology and ecological development. Certain parameters (e.g., low-water levels and the influence of inflow weir adjustments) were insufficiently captured during the first campaign. The second monitoring phase aims to extend the time series and improve measurement accuracy, thereby enabling robust evaluation of longitudinal wall performance and informing adaptive river management strategies.

Project Objectives

The primary objective is to refine understanding of the fluvial functioning of longitudinal walls in the Waal River. Specifically, the study will assess:

- The long-term effect of installing LTDs. Hereby, the effects of LTD's and side channels are compared with the situation with transverse groynes (for hydraulic and morphologic variables) and with floodplain channels and groyne fields (for ecology).
- The regulatory potential of inflow weir adjustments on navigation, nature development, freshwater availability, and flood safety.

Findings will cover a broad understanding of the functioning of the LTDs and the effects on river functions and provide operational

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recommendations for optimizing inflow weir settings.

Data Availability

The campaign will generate high-resolution data on bed morphology, hydraulics, and ecological variables (Fig. 2). Measurements include:

- Flow velocities and discharge fractions in main and secondary channels at five discharge levels per year.
- Five bed elevation surveys per year to evaluate sedimentation and erosion patterns supplemented with Lidar data of the riverbank and sediment composition analysis.
- Water level surveys in the main- and side channel.
- Survey of fish and macro invertebrates (abundancy and species composition).
- Habitat use of migratory and other typical river fish species by acoustic detection systems.
- Habitat suitability analyses based on spatial data of water depth, flow velocity and substrate.

These datasets will enable integrated analyses of hydraulic performance, sediment dynamics, and nature value.

Interested in Collaboration?

We invite researchers and stakeholders to explore opportunities for data use, methodological improvements, and joint research initiatives. Please contact us to discuss potential collaborations.

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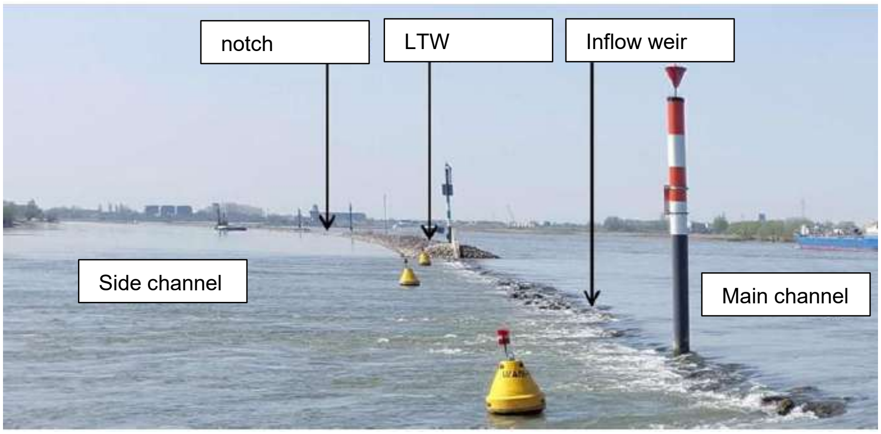

Figure 1. Longitudinal Training Wall (LTW) at Wamel, including main- and side channel, notch and inflow weir.

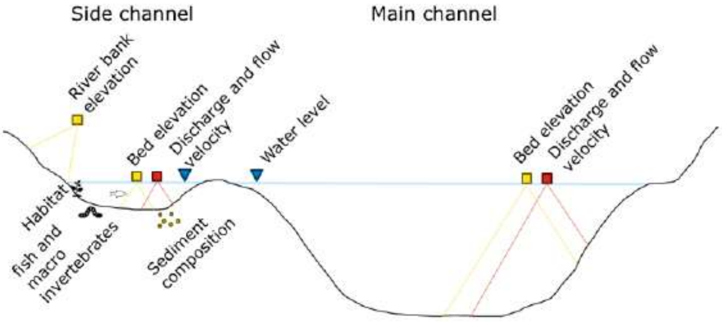

Figure 2. Schematical drawing of measurements ongoing at the Longitudinal Training Walls at the Waal (Tiel).

What are the modelled hydrological impacts of wetland restoration in lowland river systems?

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Keywords — Land use transition, Climate adaptation, Nature-Based Solutions

Introduction

Climate change is intensifying hydrological extremes, including floods and droughts (Tabari, 2020). While climate change increasingly affects regional and large-scale streamflow, localized hydrological responses remain significantly influenced by land-use and land-cover changes (Suttles et al., 2018). Consequently, land-use dynamics play a critical role in shaping catchment-scale hydrological responses, either worsening or reducing hydrological extremes. Given these compound pressures, traditional practices focusing on rapid floodwater conveyance are increasingly recognized as maladaptive (Ritzema & Van Loon-Steensma, 2018).

As an alternative, Nature-Based Solutions (NBS), such as wetland restoration, offer promising adaptation by enhancing water storage and reducing flood peaks (Faivre et al., 2018). However, the effectiveness of small-scale NBS interventions in headwater catchments remains underexamined.

To address this gap, we use the Soil and Water Assessment Tool Plus (SWAT+) to simulate the effects of NBS in the Linge catchment, an agricultural headwater basin in the Netherlands. We developed five NBS scenarios, combined with Royal Netherlands Meteorological Institute (KNMI) climate projections for 2050, to evaluate how NBS-driven land-use changes affect the water balance and to determine the thresholds needed to offset climate-driven hydrological extremes.

Methodology

The SWAT+ model uses geospatial and climate data inputs (Table 1) to evaluate five land-use scenarios ranging from Business-as-Usual (BAU) to transformative NBS interventions: small wetland, big wetland, multiple wetlands, and maximal wetland (max). These scenarios are combined with KNMI'23 climate projections for 2050 (2035-2064), which integrate greenhouse gas emissions levels and precipitation changes to generate four futures: mid-dry, mid-wet, high-dry, and high-wet (KNMI, 2025).

Table 1. Summary of data usage, source, and resolution.

Data variable	Source	Resolution /scale
Land use and land cover	LGN	10x10 m
Digital elevation model	AHN	5x5 m
Soil map	FAO	1:5,000,000
Climate data	KNMI	Daily

Result

Streamflow simulation for different scenarios under the current climate

Figure 1 shows that the scale of wetland restoration fundamentally dictates the efficacy of flood mitigation versus baseflow support. The “max” scenario achieves the strongest intervention, with a peak attenuation of 16.4% compared to BAU.
In contrast, the “small wetland” scenario achieves only marginal flood reduction (1.5%) but remains effective for baseflow augmentation, supporting 25% improvement over BAU during dry periods.

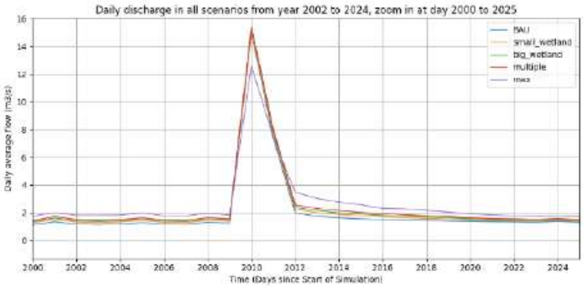

Figure 1. Zoom in on the daily discharge of all scenarios starting at day 2000 and ending at day 2025 of the full run (June 23rd to July 18th 2007, respectively).

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Change in high and low response under the current climate

Figure 2 reveals distinct wetland responses across flow regimes. At the Q0.1 threshold (0.1% exceedance possibility), only "small wetland" and "max" scenarios reduced peak flows (1.4% and 11.7%), while "big wetland" and "multiple" scenarios increased discharge (+0.8% and +2.5%). Moving to Q1, all scenarios increased discharge (+5.1% to +15.3%). Across the broader high-to-low-flow ranges, all scenarios increased discharge, with "max" increasing median flow (Q50) by 13.5%, and "multiple" proving most effective at Q10 (+6.5%) and Q90 (+8.5%).

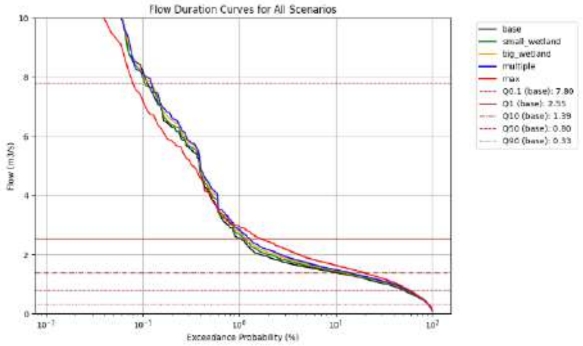

Figure 2. Exceedance probability of discharge on all scenarios with the percentile line

Change in high and low response under the future climate

Figure 3 compares Mid-Wet and Mid-Dry projections under BAU and "Max" wetland scenarios. Under Mid-Wet conditions, the current 7.8m3/s discharge (Q0.1) shifts to 0.3%, indicating more frequent extreme floods. BAU shows a 75.4% increase in extreme peak flow, which "Max" wetlands reduce to 39.5% (Table 5). Conversely, under Mid-Dry conditions, the same discharge shifts to 0.06% exceedance probability, indicating less frequent floods but greater water scarcity. BAU shows a 15.2% decline in low flows (Q90), worsening to 23.8% under "Max" as wetland evapotranspiration intensifies dry-period deficits. However, "Max" wetlands improve median flows (Q50) from -6.5% to +10.4%, providing critical buffering during moderate dry conditions.

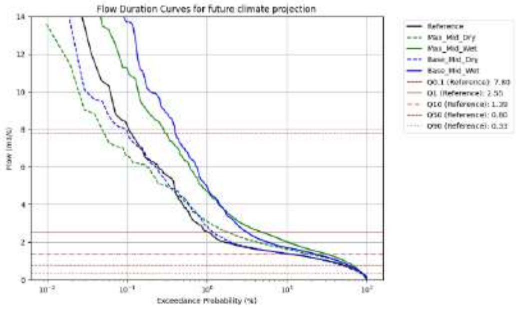

Figure 3. Flow duration curve of future climate projection with Q lines from BAU scenarios

Conclusion

This study reveals that the effectiveness of wetland restoration in the Linge catchment is highly scale-dependent. Peak flood attenuation requires extensive conversion (28% of the catchment area for an 11.7% reduction). Conversely, distributed wetlands prove more effective for baseflow support (8.5% vs 0.3% increase at Q90). However, NBS alone cannot offset extreme climate impacts. These findings indicate that NBS must be integrated with traditional infrastructure through a hybrid strategy, with upstream catchments serving as strategic regulatory zones and supplemented by active management measures to enhance storage capacity and support regional water security.

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Managing River Bank Protection by Groynes in Straight and Meandering River Reaches in Iraq

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Keywords — River banks, groynes, erosion

Introduction

Riverbank erosion is recognized as a major engineering problem worldwide. It results in the degradation of the surrounding riverlands, the impact of infrastructures, and human activity along the river valley (Fakhri et al., 2024). The problem is particularly severe in alluvial rivers where channel planform dynamics, high velocities, and river currents contribute to continuous bank instability. Addressing riverbank erosion requires the application of sustainable and cost-effective engineering solutions that can cover variable hydrological conditions while minimizing environmental impacts (Alwan and Fakhri, 2022). One of the techniques, which is used for riverbank stabilization, is the application of groynes. Groynes are weirs or hydraulic structures used to alter or sustain the direction of flow, constructed across the riverbank. Their purpose is to change the velocity distribution, decrease the shear stress near the bank, and promote local sediment deposition. As a result, the use of groynes leads to protecting the banks from erosive forces. Different shapes of groynes (such as angled, perpendicular, T-shaped, and L-shaped) are used depending on the hydraulic and geomorphological characteristics of the river reach.

Many studies have been done to understand the hydraulic behavior of groynes. Krishna et al., (2016) conducted experiments to investigate the effects of using cocologs groynes with different angles and configurations on controlling bank erosion. These tests were carried out in an experimental flume in cases with and without groynes. They found that using a single groyne leads to an increase in the water level and velocity in the center line upstream of the flume, and in all configurations, there was no erosion between the groynes. Abbas and Khassaf (2019), conducted an experimental study to investigate using S-shape groynes with different numbers and distances between the groynes. They showed that with increased flow depth and flow velocity, the scour depth increased. As the number and distance between groynes increased, the scour depth decreased. Al Sarefi and Azzubaidi (2021) investigated the use of elliptic groynes replaced in a flume with a submergence ratio equal to 75%. This study was conducted using a numerical simulation with CFD. Their study results indicate that velocity and shear stress measurements are not significantly affected by the number of groynes. The length of the riverbank that needs to be protected, which may be straight, curved, or meandering, determines how many groynes are needed.

This study aims to investigate the efficiency of placing groynes for the protection of the river banks in straight and meandering river reaches through hydraulic modeling with case study analysis. The study will focus on two areas in Iraq, the Tigris River at Al-Nuaamaniyah location as a fluvial flow, and the Shatt Al-Arab River at Al-Mekhraq location as a tidal flow. The research will provide a valuable view into the optimization of groyne design for conditions representative of Iraq's rivers.

The Research Statement

Some locations along the river in Iraq are experiencing bank instability problem, particularly along the Shatt Al-Arab and Tigris River. In the Al-Nuaamaniyah location, the meandering part of the Tigris River is affected by frequent bank erosion and slope collapse, especially during floods or high discharge events. This instability threatens the infrastructure along the right side of the bank. In contrast, in the Al-Mekhraq location along the Shatt Al-Arab, ebb and tide from the Arabian Gulf periodically reverse the river flow direction, creating additional hydraulic stresses that reduce the riverbank stability. Current management practices in these locations have not been effective. Placing stone measures is often ineffective, leading to repeated failures and economic losses. Groynes, as hydraulic structures, offer potential for sustainable riverbank protection; however, their performance in different hydraulic and geomorphological settings (such as straight versus meandering reaches, and fluvial versus tidal flow

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regimes) remains insufficiently studied in Iraq. Figure 1 shows the location of the Study areas on the Iraq map, whereas Figure 2 show how the measures, which is used in the Al-Nuaamaniyah location, is failed and collapsed after passing a high flow rate.

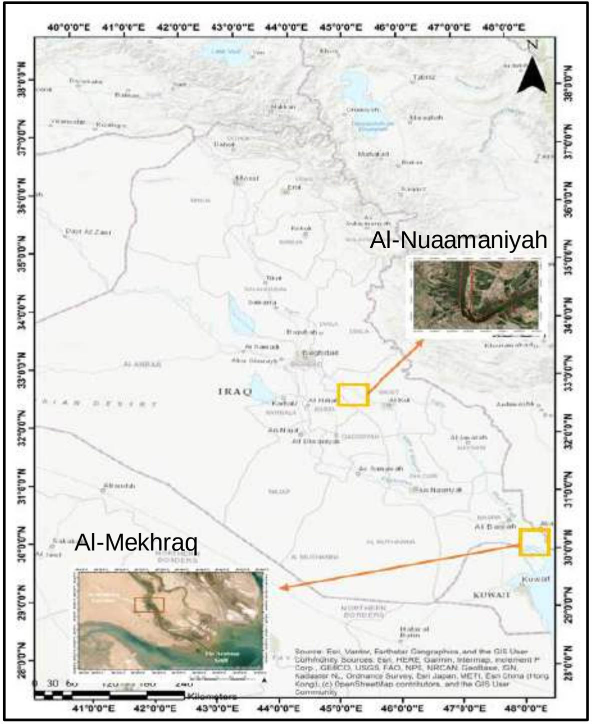

Figure 1. The locations of the two study areas on the Iraq map.

Figure 2. The collapse of the protection measure in Al-Nuaamaniyah location.

The Research Objectives

The study objective can be concluded as follows:

1. Assess the effectiveness of several types of groyne installations in reducing riverbank erosion at two critical case study locations in Iraq: the Tigris River near Al-Nuaamaniyah and the Shatt Al-Arab River at Al-Mekhraq Region
2. Investigate the hydraulic performance of various groyne types (e.g., perpendicular, angled, longitudinal, submerged).
3. Analyze the influence of groynes on key flow characteristics, including velocity distribution, flow direction, and shear stress patterns on riverbeds and banks.
4. Compare groyne performance under different hydraulic conditions, distinguishing between fluvial flow and tidal-influenced
5. Develop context-specific design guidelines and recommendations for the implementation of groynes and related riverbank protection.
6.

The Research Methodology

The Study will involve reviewing the previous research that has been implemented to understand the hydraulic behavior of groynes. The research includes collecting hydrological and hydraulic data, such as discharge, water levels, and tidal variations for the study reach, and geometric data such as cross-sections of terrain. The Hydraulic Model will be developed by HEC-RAS 2D software to analyze the study reaches.

Expected Scientific Contributions

This research will contribute to elaborating both theoretical and applied knowledge in the field of river engineering. Scientifically, it will provide an understanding of comparing groyne behavior in fluvial rivers and tidal river systems, which remains under research in the literature. The research will develop design guidelines for groynes, addressing a critical need for sustainable riverbank protection measures. The outcomes will support policymakers and engineers in planning erosion mitigation strategies, contributing to the preservation of agricultural lands, infrastructure, and communities along major rivers.

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Investigating the relationship between sedimentation hotspots and normal width variations

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Keywords — Normal width, River morphology, River maintenance, Dutch Rhine

Introduction

Over the past centuries, the Dutch Rhine has been heavily trained using guiding works such as fixed river banks and groynes. The main purpose of these guiding works is to efficiently guide water and ice, to keep the river in its horizontal position and to provide sufficient water depth throughout the year needed for navigation. The distance between opposing guiding works is the 'normal width' of the river.

Although the river is trained, numerous locations are known to Rijkswaterstaat that require regular maintenance in order to provide sufficient depth for navigation. There could be multiple causes for sediment deposits that create these bottlenecks. This research aims to find possible links between sedimentation hotspot locations and local variations in normal width. If no clear relation is found, other factors are explored. The full content of this research can be found in the study of Gradussen & Duró (2025).

Methodology

As a first step, historical graphs of the intended (i.e., designed) normal width are digitized and transformed into a GIS database to form a reference. Next, the current normal width of the Dutch Rhine branches is estimated. This is no straightforward exercise. In essence, the normal width is confined by two normal lines on opposite sides of the main channel. These lines connect the normal height along the left and right banks. The normal height is defined by the intersection between the elevation profile and a defined water level per cross-section. Since this information is not available, a more schematic definition is applied: the normal line is located at a distance of 5 m relative to beacons that are located on top of groynes and banks, as shown in Figure 1. This assumption simplifies the analysis significantly, and suffices for the study objective.

At locations where no beacons are present, often along stretched banks, the water-land boundary from the j24-Baseline database (Van Den Hoek, 2024) is used.

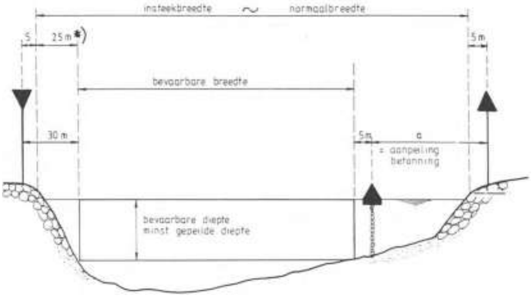

Figure 1. Definition of normal width, as assumed in this study to estimate the actual normal width (RWS, 2020)

At each hectometer, the distance between the two opposing normal lines, perpendicular to the river axis, is determined. Figure 2 shows the result along a stretch of the Waal river.

Figure 2. Resulting normal width along the Waal River

For each Rhine branch, the derived normal width is combined into longitudinal profiles. In reaches where structural differences between the current normal width and the designed normal width are observed, it is assumed that deviations stem from the simplified assumptions behind the derived normal lines. Therefore, the results are corrected here. Finally, locations are selected where the normal width deviates locally by at least 10% compared with the normal width of the surrounding kilometers. At these locations, we investigate whether normal width variations could provide an explanation for local sedimentation hotspots.

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Results

Overall, the current normal width is fairly constant along the Rhine branches. A limited number of locations can be found where the local normal width differs more than 10% from the surrounding river kilometers. These locations are sometimes found near quay walls (e.g., Arnhem, Zwolle, Deventer) where a local widening is intended to facilitate the mooring of vessels. Here, sedimentation hotspots are common (Mustafa, 2022; Van Putten & Tönis, 2022). Other significant differences in normal width are found near ferry crossings and bends.

Figure 3 shows the longitudinal profile of the normal width along the Waal River. The figure marks an example of a river bend where a local deviation from the surrounding normal width is found at km 871. A detailed view of this location is given in Figure 4. The deviation occurs over a distance of 600 m, mainly due to the absence of two or three groynes. This location is, in fact, known to Rijkswaterstaat for its intensive maintenance (Van Putten & Tönis, 2021). Yet, due to strong cross-sectional processes in river bends, it is uncertain whether, and to what extent, this sedimentation is caused by a local increase in normal width. Likely, point bar formation plays an important role here as well.

Rijkswaterstaat also observes ongoing sedimentation upstream of this location, within the river bend between km 869 and 871, despite a rather uniform normal width. In the inner bend, the existing groyne fields are completely filled with sand, illustrating the likely significant role of the point bar formation in the experienced maintenance at these hotspot locations.

Conclusions

Normal width variations do not seem to explain the observed sedimentation hotspots alone. Hotspot locations cannot always be directly linked to local normal width variations. Two- and three-dimensional processes and geometric floodplain variations may also play a major role. Every location requires a dedicated analysis without generalization. Especially at river bends, processes such as point bar formation should be closely evaluated.

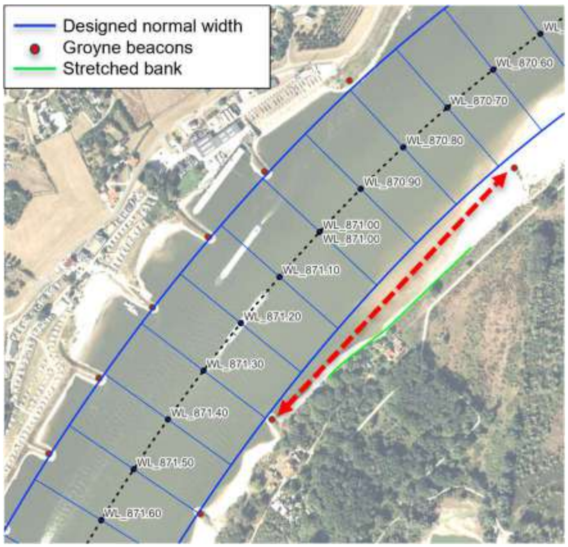

Figure 4. Zoom of the normal width at Waal km 871

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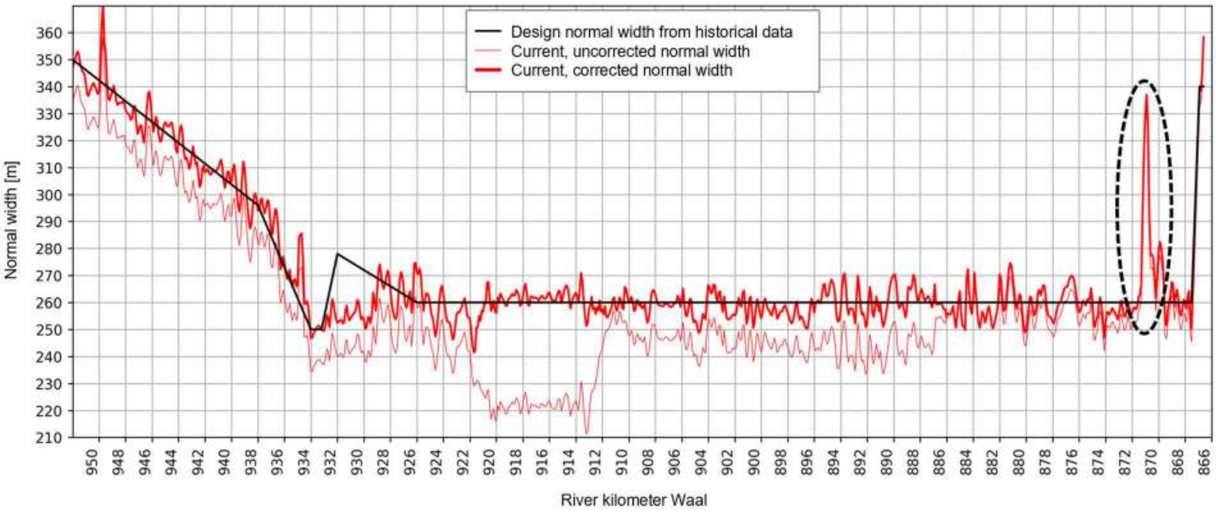

Figure 3. Longitudinal profile of the normal width along the Waal

Evaluation of a flexible groyne in comparison with a traditional groyne

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Keywords — Groynes, climate adaptation

Introduction

To improve the navigability and the discharge of river ice in the Dutch rivers, thousands of groynes have been built in the past. However, these traditional groynes are expensive and time-consuming to maintain, as they are built layer by layer with sand, geotextile and stones. There is also a growing need for (climate-)adaptive and robust interventions to alter the discharge distribution. Therefore, an innovative alternative - the 'flexible' groyne - has been developed in a long-term alliance between Deltares, Rijkswaterstaat and multiple contractors. The flexible groyne consists of individual concrete ('Xstream') blocks with protrusions that can interlock. The blocks can be placed directly on the river bed and they form a semipermeable structure with a steep slope of 1:1. This type of groyne is called flexible because it is easy to adjust: blocks can simply be added when maintenance is needed, and the groyne can be quickly extended during low waters or lowered during high waters.

To test the performance of a flexible groyne, a field pilot project has been running in the IJssel river near Kampen since 2019 (Buschman & Kosters, 2021; Buschman et al., 2024; Groenewege et al., 2026). First, three short flexible groynes were built to assess their stability under real flow conditions. In 2022, two groynes were removed and their blocks were used to extend the third groyne (Figure 1) to match the length of traditional groynes in the same area. Since then, ongoing research has evaluated the functionality of the groyne compared to traditional groynes, with respect to flow channeling, morphological impact, and ecological value (among other aspects).

Methods

The functionality of the flexible groyne has been primarily evaluated through several years of field monitoring. The flow fields were mapped around the flexible groyne and adjacent traditional groynes using ADCP measurements. Furthermore, the riverbed evolution was tracked with repeated multibeam surveys (before and after extension of the flexible groyne). Finally, the ecological value was assessed via field observations and fish surveys in adjacent groyne fields, comparing fish abundance and species composition between groyne types.

Figure 1: Photograph of the extended flexible groyne in the IJssel river (source: Robert Groenewege)

Results

The depth-averaged flow field around the flexible groyne was found to be comparable to that of adjacent traditional groynes, successfully directing discharge into the navigation channel (Figure 2). However, recirculation within the downstream groyne field is notably weaker and more diffuse. This is attributed to the groyne's partial permeability and/or steeper slope (Veraart, 2025).

The scour hole at the flexible groyne head is consistently shallower and smaller than at adjacent traditional groynes (Figure 3)

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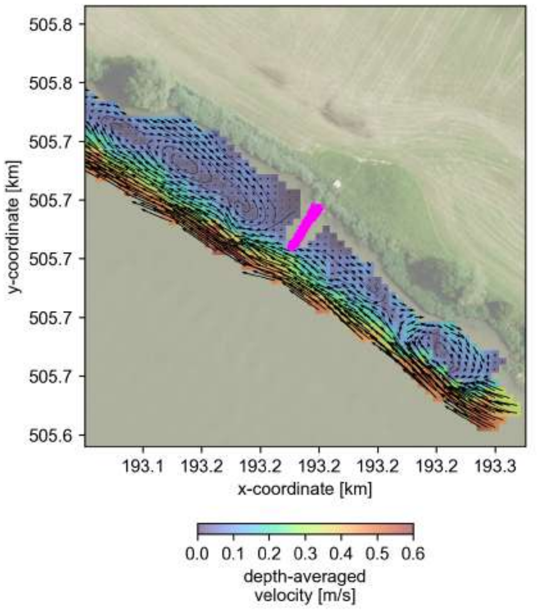

Figure 2: Depth-averaged flow field from ADCP measurements, showing comparable conduction of the flow towards the navigation channel but a different recirculation pattern behind the flexible groyne (in pink) (Groenewege et al., 2026, Fig. 3.3)

(Buschman et al., 2024; Groenewege et al., 2026). Notably, a sharp, elongated deposition ridge formed along the full length of the downstream groyne field — a feature absent behind traditional groynes. After several years, the riverbed around the flexible groyne seems to approach a dynamic equilibrium, and it is evident that the groyne can maintain the navigation channel depth as well as traditional groynes (Figure 3) (Groenewege et al., 2026).

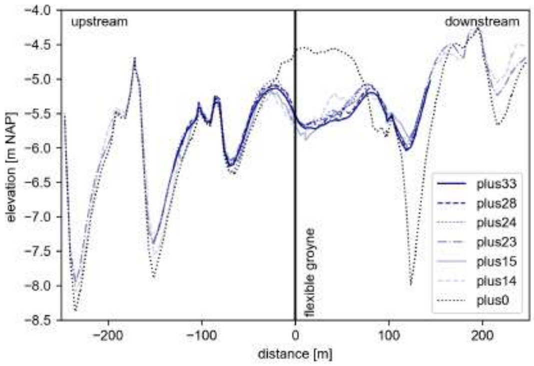

Figure 3: Longitudinal profiles of the riverbed elevation near the flexible groyne at various times during the monitoring period. 'PlusX' signifies the number of months after groyne extension. (Groenewege et al., 2026, Fig. 3.11b)

The fish surveys did not reveal a clear picture of the added ecological value of a flexible groyne (Groenewege et al., 2026). No significant differences were found in total abundance between flexible and traditional groyne fields. Rheophilic species occurred relatively more downstream of the flexible groyne, but absolute numbers were lower, exotic species were more abundant, and the ecological quality remained low for both groyne types. However, field observations have shown that blocks inside the groyne became colonized by various organisms, such as mussels and sponges (Buschman et al., 2024).

Conclusion

The flexible groyne in the IJssel river performs comparably to traditional groynes for flow conduction and channel maintenance, although its performance under extreme discharges remains untested in the field. The shallower scour hole and a persistent downstream deposition ridge reflect the unique geometry and permeability of the structure. However, the ecological benefits still remain inconclusive. To draw more robust conclusions, statistical analysis is recommended of multi-year surveys across multiple flexible groynes.

Acknowledgements

This research has been led by the 'Innovation Team Climate-Resilient Hydraulic Engineering', which besides the author includes Bas Reedijk (Delta Marine Consultants), Yuri Wolf (Rijkswaterstaat), Guillaume Doudart de la Grée (De Meteoor/BTE Groep), Tim van der Lugt (Van den Herik) and Dennis Wissink (Beeliners).

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Constructing water depth maps: comparison of bedform statistics and shoals

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Keywords — Bed level, River dunes, Shoals

Introduction

Rijkswaterstaat Oost-Nederland uses water depth maps to identify local shoals in the fairway and to assess the effects of river interventions on navigability of the Dutch Rhine branches. These maps are a key operational tool for fairway management and for the permitting of river interventions. In the maps, a theoretical maximum bed elevation is compared with the water level at the agreed low discharge (OLR, *overeengekomen lage rivierafvoer*). This results in a predicted water depth during low-flow conditions, which must exceed 2.8 m within the fairway to ensure safe navigation.

The water depth maps were recently due for an update, incorporating revised low-water reference conditions and the most recent multibeam bed elevation surveys. This update provided the opportunity to rebuild the methodology and integrate insights from recent research programmes, including Rivers2Morrow and related morphological studies of the Dutch Rhine branches.Compared to the previous edition, the main methodological differences are related to the incorporation of bedforms, as the quantification of dune heights is a critical aspect of shoal identification. How do dune amplitudes derived using the updated method compare with recent findings, particularly those reported by Lokin et al. (2021) and Zomer et al. (2023)? Methodological choices in trend estimation, spatial averaging, and the treatment of temporal variability directly influence the derived dynamic bedform amplitudes and, consequently, predicted fairway depth. The updated workflow therefore allows assessment of whether methodological improvements lead to systematic differences in estimated dune heights and associated shoal risk. In addition to evaluating bedform statistics, the updated maps were validated against reported shoals.

Methods and data

The updated methodology builds on the approach of Sieben and Van Loo (2014), in which bed elevation time series are decomposed into a local morphological signal and superimposed spatially static and dynamic bedforms. The analysis was performed for all Rhine distributaries in the Netherlands, using multibeam bed elevation measurements collected between 2015 and 2024. In this abstract we focus on the Waal River branch.

First, the bed elevation rasters from repeated multibeam surveys were spatially aligned and analysed on a 1×1 m grid. For each location and each survey, the bed elevation was smoothed in the streamwise direction using a rectangular moving average window of 500 m length and 25 m width. The smoothed bed represents the underlying morphological signal. A linear temporal trend was derived from the smoothed bed elevations, representing bed level development.

Local deviations from the smoothed bed were subsequently analysed to characterise bedforms. The temporal mean of these deviations represents static bedforms (e.g. groyne-related features and other persistent structures), while the square root of the local temporal variance quantifies the amplitude of dynamic bedforms such as dunes. This decomposition enables separation of structural river training effects from migrating bedforms.

Shoals were identified by determining the probable highest bed elevation for each 1x1 m grid cell. This was done by superimposing: (1) the trend-based bed elevation for the reference year of the low-water reference, (2) the static bedforms, (3) the amplitude of the dynamic bedforms and (4) a correction representing the seasonal variance of the mean bed. Locations where the reconstructed highest bed elevation approaches or exceeds the fairway depth criterion (low-water reference minus the guaranteed depth) were classified as potential shoals. The spatial distribution of these predicted shoals will becompared with reported least measured depths to evaluate the performance of the method.

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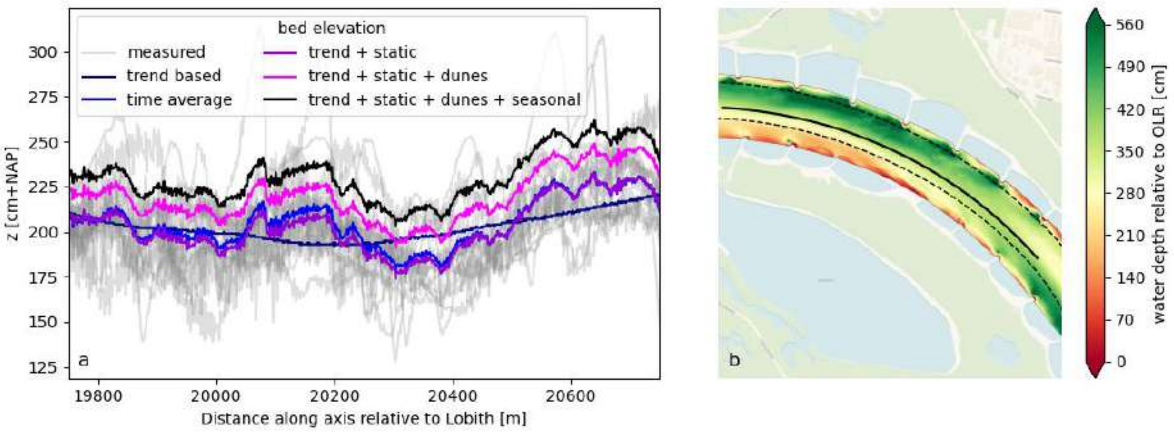

Figure 1: First results of the analysis in a snapshot of the Waal River bend between Ooij and Bemmel (river kilometre 877-879). A) the bed elevation results along the centre line transect. In grey all input measurements, in dark blue the bed elevation based for the reference year 2021 derived from the trend in the smoothed signal, in blue the local average, in black the bed elevation that will be used in the water depth maps, which is the bed elevation from the trendline, combined with the static bedforms, the standard deviation from the dunes and the seasonal variance. B) Reference bed elevation with respect to the OLR, water depth, for the reference year 2021. The dashed lines indicate the fairway and the black line indicates the location of the transect.

Results

Bed elevation and water depth

Figure 1a shows the bed elevation of a 1.5 km long stretch of the Waal River between Ooijen and Bemmel (rkm 877-879).

The grey lines represent the bed elevation measurements included in the analysis. Most of the measurement lie below the black line, which represents the reconstructed theoretical maximum bed level (trend + static bedforms + dunes + seasonal correction). The few exceedances correspond to large dunes measured during high-water conditions.

Figure 1b shows the water depths with respect to the reference water level, OLR. When this water depth exceeds 2.8 m in the fairway, the water depth is considered sufficient. Smaller depths can cause hinder for navigation.

Dunes

The spatial distribution and magnitude of derived dune heights were compared with results reported by Lokin et al. (2021) and Zomer et al. (2023). For the Middle Waal, between Nijmegen and St. Andries (rkm 890–924), previous studies reported dune heights between 0.5 m during low-flow conditions and 1.5 m during peak flows, defined as the vertical distance between dune crests and troughs.

Our preliminary results show standard deviations of the dune signal of approximately 0.3 m in this river reach. Because the standard deviation represents a statistical measure of amplitude rather than full crest-to-trough height, the results are consistent in order of magnitude but reflect a different definition of dune height.

For the Boven Rijn, the derived standard deviations are substantially smaller, between 0.05 to 0.1 m, reflecting the tendency of dunes in this reach to flatten during median to low-flow conditions.

Outlook

As a next step, the predicted water depths will be systematically compared with reported least measured depths (MGD, *minst gepeilde diepte*) to validate the water depth maps. This validation aims to confirm that shoals identified in the maps correspond to field observations, while ensuring that no significant shoals are missed. Additional validation steps include:

- Comparison of bed elevations, trends, and key bedform parameters with the current operational water depth maps.
- Comparison of derived erosion and sedimentation trends with reported results by Ylla Arbós et al. (2024) and Huthoff et al. (2021).

Acknowledgments

This project was executed on behalf of and in cooperation with Rijkswaterstaat Oost-Nederland.

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

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

Introduction

The research program Rivers2Morrow started in 2018. It consists of 11 PhD studies, focusing on the long-term development (until 2100) of the lowland river area. By increasing system knowledge in the field of morphology, hydrology, ecology and governance, it can help the Netherlands to make the river area sustainable and climate-proof. The results of this research can add to substantiate policy decisions and make the management and maintenance of rivers more effective and efficient.

Knowledge tracks and policy themes

Rivers2Morrow is structured along three interrelated knowledge tracks addressing the long-term resilience of the Dutch river system under climate change.

1. How does the river function – now and in the future? This track investigates hydrodynamic and morphodynamic processes under changing discharge regimes, including discharge distribution within the Netherlands, sediment budgets and riverbed/bank stability across spatial scales, groundwater interactions, and river–floodplain–ecosystem feedbacks.

2. What are the major issues for the functions of the river? This track develops knowledge for adaptive river management, focusing on innovative and conventional interventions, advances in monitoring and modelling, no-regret and integrated strategies, and cross-sectoral and transboundary collaboration.

3. What is needed for sustainable design and management of the river? Building on system understanding, this track examines key societal functions and emerging pressures: flood safety under increasing peak discharges and sea level rise, freshwater availability under growing demand and prolonged low flows, navigability in relation to morphological development, and ecological integrity under climate change.

While Rivers2Morrow was initially centred on hydro-morphodynamic processes, the program is increasingly expanding towards the integration of ecological functioning and water quality dynamics.

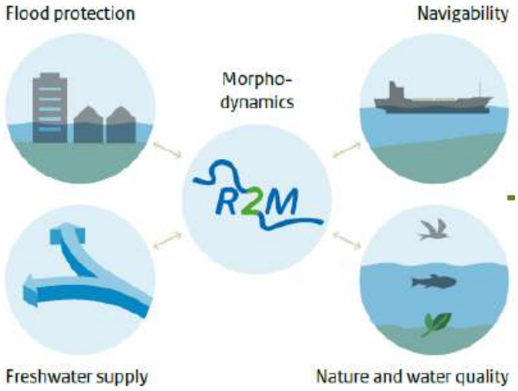

Figure 1. Policy themes of Rivers2Morrow.

The interaction between discharge, sediment transport, channel–floodplain morphology, and ecohydrological and biogeochemical processes determines how the river system can fulfil four core functions: flood protection, navigability, freshwater supply, and nature and water quality. These coupled processes shape not only channel stability and discharge capacity, but also habitat development, ecological resilience, and water quality under climate change.

By broadening its focus from morphodynamics to an integrated physical–ecological system perspective, Rivers2Morrow aims to better understand trade-offs and synergies between river functions and to support adaptive, future-proof river management.

Organisation

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

Results

Recent Rivers2Morrow research provides new insights into the morphodynamic evolution of the Rhine–Meuse system and its implications for river management. Field measurements and modelling show that bed forms remain highly dynamic across discharge conditions: dunes migrate not only during high flows but also at low discharge, influencing navigability and dredging needs. The interaction between large and small dunes proves essential for accurately estimating sediment transport, highlighting the importance of high-frequency bed monitoring tailored to dune scale. These insights enable more effective and longer-term dredging strategies.

At larger spatial and temporal scales, the Rhine continues to adjust to past river interventions, with ongoing bed erosion, sediment coarsening, and gradual adaptation of the longitudinal bed profile. Morphological responses to human interventions remain stronger than those to climate change, although altered discharge regimes increasingly influence bed levels and discharge distribution at bifurcations. Rapid sequences of peak flows can temporarily alter sediment supply balances at bifurcations, potentially affecting discharge partitioning between branches.

In the Rhine–Meuse delta, sediment budgets indicate a structural imbalance: more sediment is dredged than supplied by rivers and sea, implying continued net sediment extraction in the coming decades. At the same time, upstream large-scale interventions have reduced the supply of fine sediment, a trend expected to outweigh climate-driven increases in sediment delivery. Together, these findings underline that long-term river evolution in the Dutch system is primarily governed by the interplay between sediment management, legacy effects of past interventions, and changing hydrological conditions. (Ten Brinke et al. 2025)

Taken together, the programme demonstrates the value of combining detailed field observations, modelling, and system-scale synthesis to bridge fundamental morphodynamic research and applied river management. Rivers2Morrow provides a framework for connecting process understanding to long-term, cross-functional river governance in a changing climate.

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Expected ice loads on hydraulic structures in the Maas in a scenario of decreased AMOC strength

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Keywords — River ice, AMOC, Maas

Context

Due to the gradual decrease in flow of the Atlantic Meridional Overturning Circulation (AMOC) and given the geographical position, a change in climate in the Netherlands is expected (Van den Dool, 2025) & (Carrington, Damian, 2025). The AMOC transports warm ocean water to Northern Europe leading to a temperate maritime climate in the Netherlands. A gradually decreasing or complete collapse of the AMOC certainly results in a colder Northern Europe. Resulting lower air and surface temperatures, will impact ice formation on rivers, such as the Maas. Other claims of consequences in case of an AMOC collapse are: less precipitation in Europe, and faster sea level rise in the Atlantic Ocean (Van den Dool, 2025).

Motivation of research

The probable occurrence of river ice in the future signifies the need to determine whether the design ice loads on structures are covered by today's Dutch infrastructure and guidelines. River ice occurs more often in Canada, such as in Newfoundland and Labrador, situated on the same latitude as the Netherlands, implying the large influence of the Atlantic Ocean on the countries' climate.

Since it is a relatively recent development that the AMOC appears to reduce in strength, not too many researchers have investigated its potential consequences. The effects on hydraulic structures that are situated in Dutch rivers have not been investigated yet.

River ice

Historically, river ice formation in the Netherlands was not uncommon and occurred once every 5 years (Gerritsen, 1971). Consequences were ice jams increasing the water levels in the Dutch rivers and undermining the dike stability and introducing flooding risks. The rise of water levels is caused by a decrease in the hydraulic radius of the river's cross-section, in the discharge coefficient (Chezy coefficient) of the river, and the formation of ice jams or hanging dams, see Fig. 1. River ice has not recently developed in one of the Dutch rivers. However, if a colder climate were to rule the Dutch rivers, it is likely that frazil ice may form possibly turning to ice floes or even hanging dams and ice jams. Ice formation in rivers occurs only if velocities are smaller than 0.6 m/s (Ashton, 2010). Then, an ice cover is formed at freezing temperature. At higher velocities the turbulence is sufficiently strong to submerge ice crystals and supercooled water parcels. With strong mixing, ice particles are dispersed over full depth of river flow. Agglomerated particles float to surface to form ice cover.

If stream velocity is larger than 0.6 m/s, slush with a high porosity is produced from frazil ice, which agglomerates into pans and floes.

Maas

The Maas has a history of river ice formation in previous centuries, associated with flooding risks. Because of the navigation through the Maas, with sufficient water levels maintained by seven sluice and weir complexes, it is interesting to determine the consequences for (these structures in) this precipitation-fed river in case of an AMOC collapse.

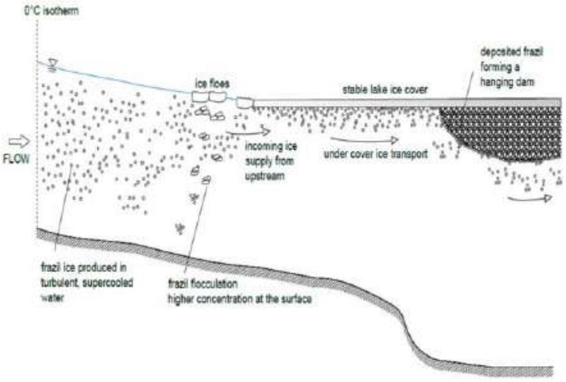

Figure 1. Hanging dam formation in a lake; the principle is the same for rivers (Senarathbandara, Clark, & Dow, 2023).

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Modelling Salt Intrusion Response to the Tidal Park Feijenoord in the Nieuwe Maas Using a Refined 3D Hydrodynamic Model

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Keywords — Salt intrusion; Estuarine mixing; Numerical modelling; D-HYDRO RMM3D; Tidal dynamics; Longitudinal dispersion

Introduction

Accurate assessment of the effects of the proposed Tidal Park Feijenoord on salt intrusion in the Nieuwe Maas is needed for permitting, particularly given the sensitivity of upstream freshwater intake locations and strategic freshwater buffers along the Hollandse IJssel and Lek. Earlier assessments using the standard RMM3D implementation (by Deltares in 2025) suggested salt increases of several percent and were explicitly based on a conservative upper-bound approach. A subsequent quick scan with a refined TRIWAQ model indicated smaller increases. The present study employs a refined RMM3D implementation to provide a more robust, physics-based estimate of expected effects, and places results in the context of recent understanding of estuarine mixing and dispersion processes (e.g., Bo & Ralston, 2022; Hendrickx & Pearson, 2024; Hendrickx et al., 2023).

Methods

The D-HYDRO RMM3D model grid was refined by a factor of four in both horizontal directions in the project area, enabling detailed representation of the Tidal Park layout and adjacent Zuiddiepje channel bathymetry. Simulations compared a reference scenario with a scenario including the Tidal Park during a low-flow and high-salinity period (October 2018), using boundary forcing of tides and river discharge. The refined grid especially improved the functioning of the Zuiddiepje, the channel south of island of Brienenoord.

Results

Simulated changes in chloride concentration at upstream locations remain small. At Krimpen aan den IJssel, average chloride increases are approximately 1.2% relative to the reference. At Kinderdijk and Brienenoordbrug, the corresponding increases are ≤0.3% and ≤0.1%, respectively. Across all stakeholder-relevant intake locations, percentage changes remain within 0–1.3%, and exceedance durations of critical chloride thresholds (e.g., 200 mg/L) change by ≤2%, even under conservative assumptions.

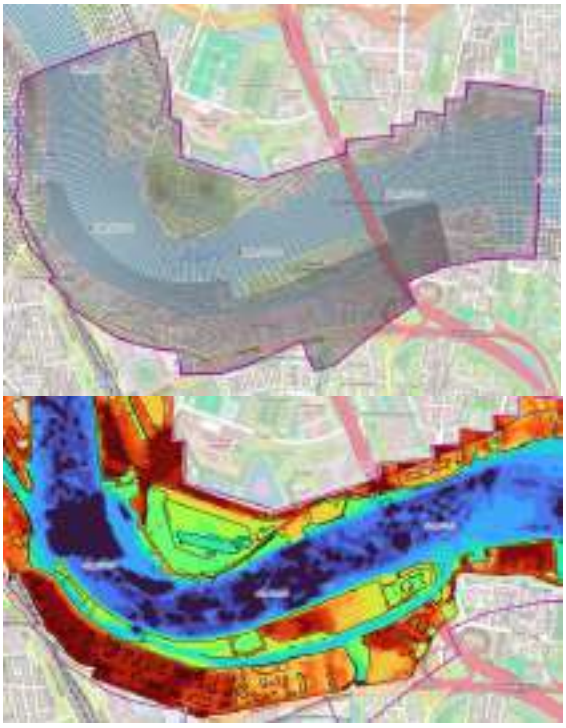

Figure 1: Upper: RMM3D local grid refinement. Lower: Implementation of Tidal Park Feijenoord.

The refined model results show significantly lower effects than the earlier standard RMM3D assessment (Deltares) *and* the quick scan with a refined TRIWAQ model. The differences arise primarily from improved representation of side channel geometry (flow through the Zuiddiepje) and local narrowing due to the intervention, which affect both mean advection and mixing processes, and highlight the importance of sufficient resolution and accurate representation of these processes.

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Process Interpretation

The net response of salt intrusion emerges from the balance between multiple interacting physical mechanisms, consistent with contemporary research on estuarine mixing and longitudinal dispersion:

1. Velocity redistribution and longitudinal dispersion. Channel narrowing increases velocities in the main channel, particularly during ebb, enhancing downstream salt export. However, enhanced shear and turbulence increase longitudinal dispersion, which, in a well-mixed tidal system, can promote upstream spreading of the salt front, as described in classical theories (e.g., Taylor, 1954) and their application to estuarine curvature effects (Geyer et al., 2008; Bo & Ralston, 2022).
2. Stratification effects and erosion pit dynamics. Near the western boundary of the project area, an 18 m-deep erosion pit retains saline water near the bed through slack tides. In the reference situation, weak ebb currents leave such saline pools available for subsequent flood-driven upstream transport. In the Tidal Park scenarios, heightened ebb velocities partially destratify and flush the pit, reducing the upward salt flux and illustrating the importance of vertical mixing and stratification dynamics articulated in recent estuarine research (e.g., Geyer et al., 2008; Hendrickx & Pearson, 2024; Hendrickx et al., 2023).
3. Phase interactions with secondary channels. In the reference scenario, a phase lag between the Zuiddiepje and the main channel introduces freshwater “after-supply” into the main channel during flood, locally reducing salinity. Restricting flow through the Zuiddiepje in the Tidal Park scenarios diminishes this process, slightly increasing local salinity — analogous to mechanisms described in studies of shallow channel interactions and dispersion.
4. Net outcome as an emergent balance. The combination of enhanced ebb export, increased shear dispersion, altered stratification, and modified freshwater after-supply from secondary channels yields a complex yet modest net influence on upstream salt intrusion.

Conclusions

Using a refined and validated implementation of the D-HYDRO RMM3D model, this study concludes that the effects of Tidal Park Feijenoord on upstream chloride concentrations are limited (<1.3% on average) and the resulting impact on freshwater intake operations has been estimated.

The findings highlight the importance of using appropriately high-resolution models accurately capturing the interplay between advection, dispersion, and stratification mechanisms and provide a quantitative basis for evaluating what magnitude of change should be considered relevant within regulatory assessment frameworks.

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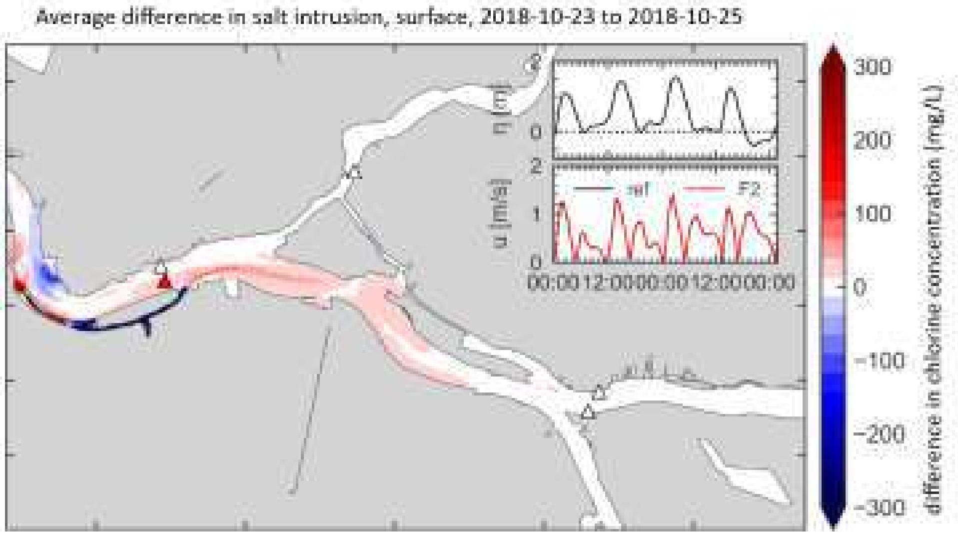

Figure 2. Difference in average chlorine concentrations due to construction of the Tidal Park Feijenoord

Finding opportunities for flexible vegetation management in the Biesbosch

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Keywords — Vegetation management, Water safety

Introduction

Vegetation plays an important role during periods of high discharge. Since rough vegetation acts as a barrier that causes water to slow down, the presence of such vegetation can lead to local water level increases (Rijkswaterstaat, 2025a). For this reason, Rijkswaterstaat – the Dutch governmental body responsible for water and infrastructure – has developed the vegetatielegger: a map that determines the desired vegetation types along river floodplains (Fig. 1).

The vegetatielegger helps to manage water levels, but it can limit the potential for nature development. Such is the case for the Biesbosch, Europe's largest freshwater tidal wetland (Staatsbosbeheer, 2026). Future succession of novel vegetation was not incorporated when the vegetation layer for this area was determined. This means that large areas of rough vegetation should technically be removed to prevent water level increases, even though developments in the Biesbosch such as the depoldering of the Noordwaard have contributed greatly to water safety (Rijkswaterstaat, 2025b). The Dutch forestry service would rather see this vegetation remain because of its unique values. Thus, both parties now find themselves in a long-lasting discussion about the reference situation that should be used for the vegetatielegger in the Biesbosch.

In this case study I assessed the potential for rough vegetation development and maintenance in the Biesbosch. By doing so I hope to present new opportunities for combining water safety and nature conservation in the Biesbosch, and possibly other areas as well.

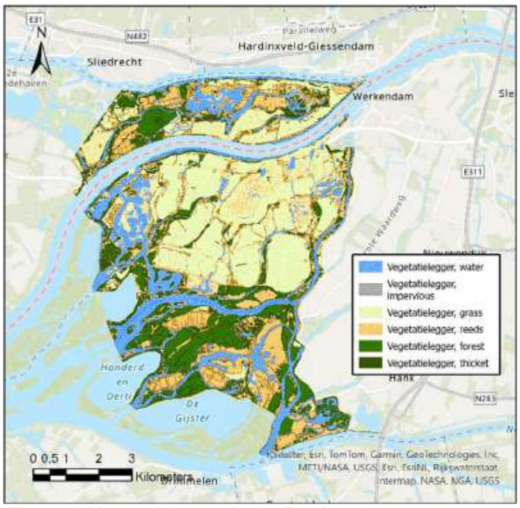

Figure 1. Vegetatielegger in the Biesbosch.

Modelling in D-Hydro

To assess the influence of rough vegetation I used D-Hydro modelling software to run simulations.

Suitability map

First, I tried to create a suitability map for rough vegetation. I did so by making a scenario in which all vegetation in the Biesbosch was smoothed to exclude its influence on hydrology. Then, I used the results from the D-Hydro simulation as input for the suitability map. I did so by reclassifying the Q (discharge, m^3/s) to different categories ranging from least to most suitable. In general, higher discharge through an area means that this location is less suitable for rough vegetation as it will have a more significant slowing effect. This leads to higher water level increases.

Mixed vegetation classes

Additionally, I investigated the potential for applying a different type of classification to the vegetation in the Biesbosch. Currently, the vegetatielegger classifies vegetation in high detail using four classes: grass, reeds, thicket, and forest. However, the spatial precision with which these classes are registered limits the potential for smaller patches of rough vegetation

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to emerge among more smoothly vegetated areas. There are three other classes in the vegetatielegger which are based on percentage ranges that the total area of grass and the combination of thicket and forest within the area should fall in. Such mixed vegetation classes allow for more flexibility in vegetation management as long as the ratios stay within range. I assessed the potential for applying this classification in the Biesbosch by partitioning the park into several areas for which I calculated the vegetation percentages and assigned the corresponding mixed classes. I then compared this new classification to the current one to observe how much water levels deviated. If the deviation was too substantial, I made smaller partitions. Areas which turned out to be too sensitive to adjustments were excluded.

Results

The suitability map shows that several areas in the Biesbosch are highly suitable for rough vegetation, whereas others best remain smooth (Fig. 1). This map can inform the forestry service in which areas they can pursue more rough vegetation development and in which sensitive areas vegetation might need to be removed.

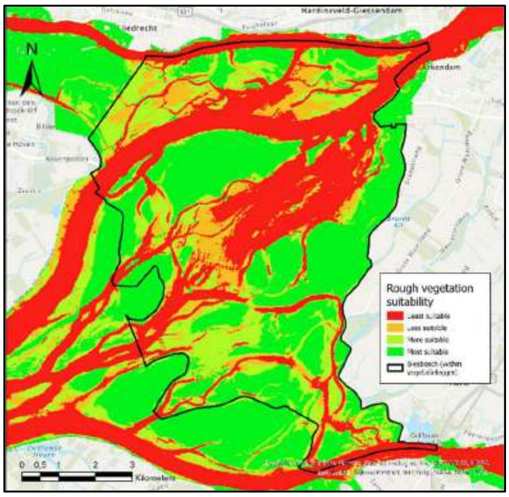

Figure 2. Rough vegetation suitability map based on discharge without the influence of vegetation.

I found three areas which could be suitable for mixed vegetation classes (Fig. 3). These can all be found in the Sliedrechtse Biesbosch, where tidal dynamics are most strongly present and vegetation is generally less mature than in the southern Biesbosch. The resulting differences in water level on the river axes between the two types of classification are limited (Fig. 4). The altered classification in the three areas can allow for a more diverse vegetation mosaic as long as more sensitive locations do not become too roughly vegetated.

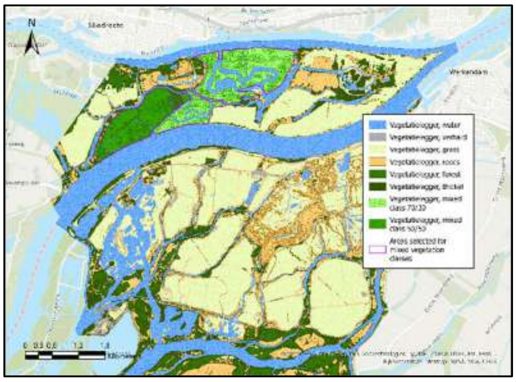

Figure 3. Updated vegetatielegger with mixed vegetation classes applied to three areas.

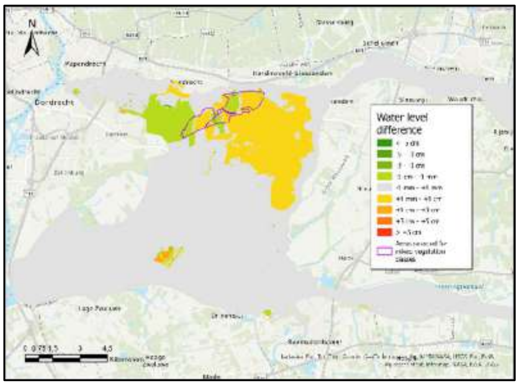

Figure 4. Water level difference resulting from the updated vegetatielegger.

Conclusion

This research has shown that there are opportunities for more dynamic vegetation within the Biesbosch without compromising water safety. These could come from development in places with low sensitivity, as well as a more flexible classification system. Results from both maps can also be combined to apply mixed classes specifically in areas with low discharge, thereby simplifying vegetation management with low risk. Stakeholders should keep in mind that vegetation is not static, and an integrative approach can prevent future clashes between nature and water safety.

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Using environmental DNA to inform rehabilitation practices for rheophilic fish in the river Meuse, the Netherlands

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Keywords — Freshwater fish diversity, river restoration, eDNA

Introduction

The rapid decline of fish diversity in rivers has sparked global efforts towards river rehabilitation (Wohl et al., 2015), but the crucial task of evaluating the benefits of rehabilitation measures is often performed insufficiently (Rogosch et al., 2024). This is the case for many rivers in North-Western Europe, which belong to the world's most heavily impacted. Among them is the river Meuse, the second largest river in the Netherlands. One of its most severely adapted sections, the 'weir-regulated Meuse' (WRM), is a 70km impounded and navigated river stretch that lacks a natural water flow due to four weirs. These adaptations drastically impacted fish populations, especially native, rheophilic (flow-preferring) fishes. To combat these radical declines, ecological rehabilitation measures have been implemented since the early 1990s as part of the Water Framework Directive (WFD), specifically targeting the rheophilic fish species. As the main channel of the WRM is connected to various free-flowing tributaries, potentially offering benefits for rheophilic fish, rehabilitation measures have largely focused on these tributaries, removing excessive gravel and rewetting floodplains. However, little is known about how different life stages of rheophilic fish use the WRM across space and time, which hinders the optimization of rehabilitation. Hence, the objectives of this study are to evaluate the benefits of various rehabilitation measures and assess the distribution of successive life stages of rheophilic fishes in relation to habitat characteristics and connectivity.

Combining techniques to evaluate river rehabilitation

Our approach was to extensively monitor the distribution and movement of juvenile and adult fish at multiple spatial-temporal scales. We specifically focused on five rheophilic target species: barbel *(Barbus barbus)*, chub *(Squalius cephalus)*, dace *(Leuciscus leuciscus)*, ide *(Leuciscus idus)* and nase *(Chondrostoma nasus)* - selected as riverine fish that require both flowing water during at least one life stage and a good connectivity between habitats (Stoffers et al., 2022). Their relatively strict habitat requirements make them particularly vulnerable to human modifications, and they are indicators of healthy riverine systems (Stoffers et al., 2022). We aimed to gain a comprehensive understanding of these species' ecology in the WRM, for which we targeted multiple life stages. This required a combination of different techniques: we used conventional net monitoring to evaluate the nursery function of rehabilitated habitats for Young-Of-Year (YOY) fish and acoustic telemetry to understand spatial-temporal movements of adults.
As a first step of our evaluation, we used environmental DNA (eDNA) to 1) visualize the spatial distribution of rheophilic fish in the WRM system, including its tributaries, and 2) to assess the potential importance of free-flowing tributaries for rheophilic fish in the WRM. We strived to generate spatial distributions of fish using eDNA to inform rehabilitation measures in the WRM.

eDNA metabarcoding

eDNA metabarcoding is a technique in which can be used to detect and identify species from water, soil or air (Rees et al., 2014). We used it to assess the diversity of freshwater fish at 29 different sites along a 90km river stretch, including eight tributaries. This covered both the WRM and the Common Meuse (CM), which is a semi-free flowing river stretch upstream of the WRM. We collected water samples in June and September 2025 for DNA extraction. The distribution of fish species in the main channel

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and tributaries was revealed (Fig. 1A) and we identified important river stretches for our five rheophilic target species (Fig. 1B). Our results provided a complete overview of rheophilic fish distribution in the main channel and tributaries of the WRM, revealing the potential importance of tributaries. By identifying critical river stretches for rheophilic fish conservation, our data can inform future rehabilitation efforts in the WRM and across other river systems.

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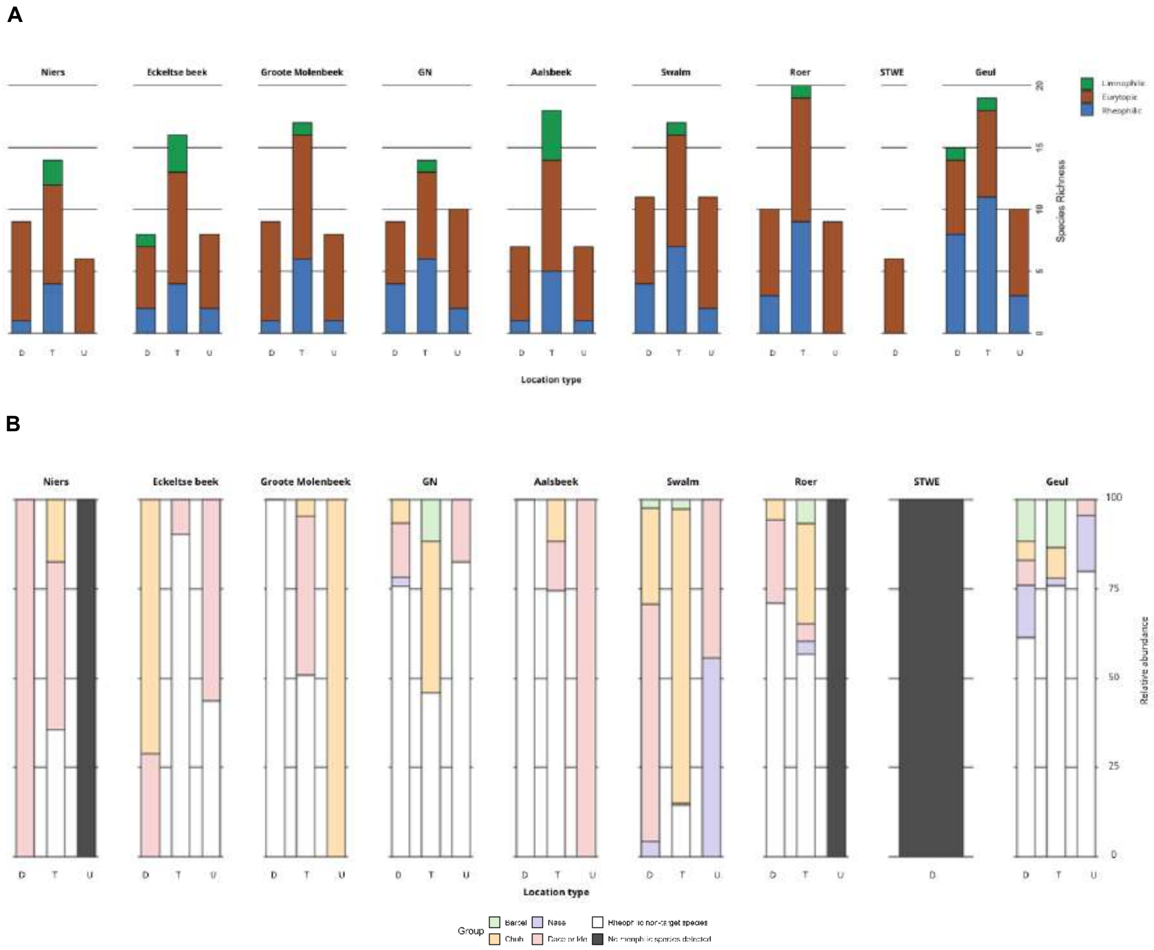

Figure 1. A visualisation of the detected species richness and rheophilic fish composition, from water samples collected in June and analysed with eDNA metabarcoding. A) shows the number of species that were detected per sampling site, indicated by the height of the bars. The colours indicate the relative number of fish species belonging to the guild of limnophilic (green), eurytopic (orange) or rheophilic (blue) fish. B) shows the composition of rheophilic fish that were detected,, showing the relative abundances of the rheophilic target species of this study. In both figures, the location types are indicated by D = in the main channel, downstream of a tributary, T = in the tributary and U = in the main channel, upstream of a tributary. The specific tributary names are indicated on top of the bars, in which GN represents 'Geldernsnierskanaal' and STWE a location in the main channel, at the town of Stevensweert.

Analytical and numerical assessment of lateral exchange effects induced by porous longitudinal training walls

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Keywords — longitudinal training wall, lateral exchange

Introduction

River management has been practiced in the Netherlands for centuries, with groynes traditionally playing a key role. However, groynes do not provide a comprehensive solution to all challenges associated with rivers (Mosselman et al., 2021). Therefore, longitudinal training walls were introduced. These are long, narrow walls constructed parallel to the riverbank that divide the river into a main channel and a side channel.

At high discharges, longitudinal training walls improve flood safety, while at low discharges they enhance navigability (Osorio et al., 2020). Because separate longitudinal water level profiles develop in the two channels, water levels within a cross-section can be different. Due to the porous nature of the training wall, these differences generate lateral flow between the main and side channel.

This research investigates the following research question: *How does lateral exchange between a main and side channel through a porous longitudinal training wall affect river water depth?* This is particularly relevant during low discharge conditions, when minimum navigational depth is critical and lateral discharge towards the side channel may further reduce water depth in the main channel.

Methodology

In this research, both an analytical and a numerical approach are applied. The analytical approach is primarily aimed at gaining conceptual insight and identifying relationships between parameters, whereas the numerical approach focuses on generating quantitative results to further investigate these relationships. For both approaches, the starting point for describing the problem consists of the conservation of mass and the conservation of momentum. The mass balance equations for the side channel and the main channel are coupled with Darcy's law to describe the flow through the porous training wall.

Analytical approach

For the analytical approach, the momentum balance equations and the Darcy-coupled mass balance equations are formulated as follows:

$$u_1 \cdot \frac{\partial u_1}{\partial s} + g \cdot \frac{\partial h_1}{\partial s} + \frac{c_f u_1^2}{h_1} = 0 \tag{1}$$

$$u_2 \cdot \frac{\partial u_2}{\partial s} + g \cdot \frac{\partial h_2}{\partial s} + \frac{c_f u_2^2}{h_2} = 0 \tag{2}$$

$$h_1 \cdot \frac{\partial u_1}{\partial s} + u_1 \frac{\partial h_1}{\partial s} = -\frac{H}{B_1} \cdot k \cdot \frac{h_1 - h_2}{B_{dam}} \tag{3}$$

$$h_2 \cdot \frac{\partial u_2}{\partial s} + u_2 \frac{\partial h_2}{\partial s} = +\frac{H}{B_2} \cdot k \cdot \frac{h_1 - h_2}{B_{dam}} \tag{4}$$

In Eqs. (1) and (2), it is assumed that no momentum is lost during the lateral discharge exchange. In the mass balance equations, Eqs. (3) and (4), the right-hand term represents the Darcy term to describe the lateral exchange flow The conveyance ratio, expressed as H/B, is assumed to be independent of the water depths h_1 and h_2. This assumption was made to avoid additional nonlinearities, which are generally difficult to treat analytically.

The next step in the analytical approach is to attempt solving the system of equations using methods such as variable elimination, linearisation, and further simplifications.

Numerical approach

A Python model was developed to obtain quantitative results for answering the research question. The model is based on the forward Euler method and is used to generate backwater curves for both the main channel and the side channel. These curves are computed using a prescribed, constant downstream water depth as boundary condition. Then, the backwater curves of the channels with lateral exchange can be compared to the backwater curves of the reference situation without lateral exchange in order to identify its influence on the water depth in both channels.

The most important parameters of a longitudinal training wall in this study are its width (B_{dam}) and its hydraulic conductivity (k). These parameters were varied during the model simulations in order to assess their individual

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influence on the water depth in both channels. All other model parameters were kept constant, as their individual influence on the water depth is outside the scope of this research. The selected parameter values (e.g. discharge, channel width, roughness) were chosen to be representative of the River Waal.

Results

Analytical results

The research has demonstrated that the problem formulation considered in this study is analytically intractable in its current form. Several attempts were made to derive a closed-form solution; however, these consistently resulted in highly complex equations that could not be solved explicitly.

Although additional simplifications or linearisation steps could potentially render the problem analytically solvable, such modifications would significantly reduce the physical representativeness of the model. As a result, the analytical solution would no longer provide meaningful insight into the actual hydraulic behaviour of the system.

Numerical results

The numerical model indicates that the influence of lateral exchange on the water depth in the main channel is marginal. For model simulations using realistic values for the wall width and hydraulic conductivity, the reduction in water depth remained below one millimetre. Although variations in wall width and hydraulic conductivity resulted in observable differences, the magnitude of these effects remained limited. The model further shows that the absolute exchanged discharge is considerable in magnitude; however, relative to the prescribed reference discharge, it represents only a small fraction. The results are summarised in Table 1, which presents the minimum water depths along the river reach for which the backwater curves were computed. A downstream water depth of 2.5 m was imposed to analyse the system's behaviour under low-flow conditions.

Table 1. Minimal water depths in main channel (h1) and side channel (h2) for different wall widths (B) and hydraulic conductivities (k).

k	B (m)	min h1 (m)	min h2 (m)
0 (ref.)	1.5	2.4737	2.3969
0.01	1.5	2.4734	2.3983
1	1.5	2.4616	2.4505
1	0.5	2.4729	2.4009
1	5	2.4736	2.3973

Conclusion

Based on the results of the numerical approach, it can be concluded that lateral exchange through a porous longitudinal training wall does influence the water level in a river; however, the magnitude of this effect is minimal and can be considered negligible in practical applications. This finding supports the applicability of longitudinal training walls, as lateral exchange does not compromise the minimum navigational depth during periods of low discharge.

Further research is recommended. First, the analytical approach could be elaborated, as no conclusive results were obtained within the scope of this study. In addition, it would be valuable to investigate under which hydraulic conditions lateral exchange becomes significant. The present study focuses on large rivers with relatively high discharges; in smaller rivers with lower discharges, lateral exchange may have a more pronounced impact.

Acknowledgements

I would like to thank Robert Jan Labeur for supervising this research and for providing me with valuable knowledge and insights on the topic.

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Turbulence-Particle Interactions as possible mechanism behind Dune Height Bimodality at Large Transport Stages

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Keywords — River Dunes, Turbulence-Particle-Interactions, ACVP

Introduction

Bedforms are ubiquitous in sand bedded rivers (Venditti and Bradley, 2022) and impact flood risk, biodiversity and navigability. They result from the interaction between mobile bed material and the forces of flowing water. When moving from low to high flows, bedform heights usually increase towards a maximum before being washed out to a flat Upper Stage Plane Bed (USPB) again at high flow. This can be seen in the black line in figure 1, in which Δ/h represents normalised dune height.

However, variability in bedform dimensions increases with transport stage T ($T = \theta/\theta_c$) (Venditti et al., 2016; De Lange et al., 2025) and De Lange et al. (2025) have revealed that this increase in variability can partly be explained by a bimodality in dune height when $T > 18$. They describe an additional stable state with taller bedforms that diverges from the dune height predictor curve of Venditti and Bradley (2022), which predicts declining dune heights above $T = 18$. Both curves are visible in figure 1.

It is hypothesized that the transition between the state of high dunes and USPB occurs due to an increase in the local suspended sediment concentration (SSC), which in turn can suppress turbulence intensity (Allen and Leeder, 1980; Guta et al., 2022), allowing for higher flow velocities near the stoss side of the dune, resulting in dune erosion and flattening. However, this hypothesis was not tested yet as no measurements of flow, turbulence and SSC were performed. Therefore, the physical mechanism that causes this bimodality remains uncertain. Also, the range of T over which the bimodality persists is still unknown. The performed experiments were limited to transport stages between 5 and 30. Above this range it is unknown whether the second mode either keeps diverging from the predictor curve, or converges back towards USPB. Furthermore, longer time-series are needed to accurately quantify the stability of each state and characterize the transitions between them.

In this research we have used hydroacoustic methods to observe and better understand turbulence-particle interactions, this will be used in bedform flume experiments to test the aforementioned hypothesis on the origin of dune height bimodality.

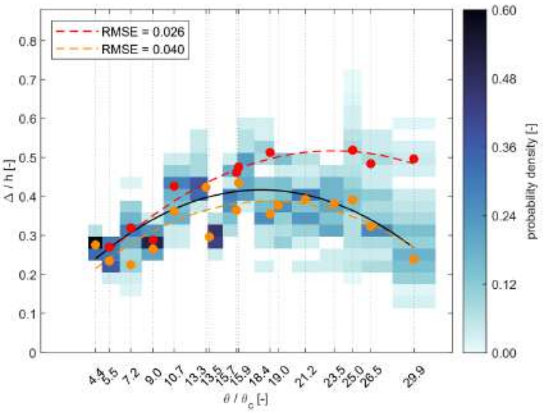

Figure 1: Probability density plot from De Lange et al. (2025) showing the distribution of normalized dune heights over transport stage using data from their own experiment and experiments by Venditti et al. (2016). The orange points indicate the lower mode of the distribution at that T, the red points show the higher mode. The black curve is the empirical bed form predictor by Venditti and Bradley (2022)

Phase 1: Observing Turbulence Modulation by Suspended Particles

A single frequency commercial Acoustic Concentration & Velocity Profiler (ACVP) (Hurther et al., 2011) was used to observe turbulence modulation in oscillating grid turbulence. By comparing turbulence intensities from runs with and without solid particles present, turbulence modulation by 600 μm polystyrene particles was identified, see figure 2. Micro-bubbles were used as fluid tracers and their motion was resolved to characterize the undisturbed turbulence. Then, without the presence of micro-bubbles, the turbulent motion of the inertial particles was resolved. Lastly, the apparent turbulence intensity of the mixed signal -when both

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phases were present- was recorded.

Comparing the three resulting turbulence intensities allowed for qualitative identification of turbulence strength modulation. In this case the presence of particles resulted in an increase of the horizontal turbulence intensity, especially far above the grid. This observation is in line with results obtained by Poelma et al. (2007).

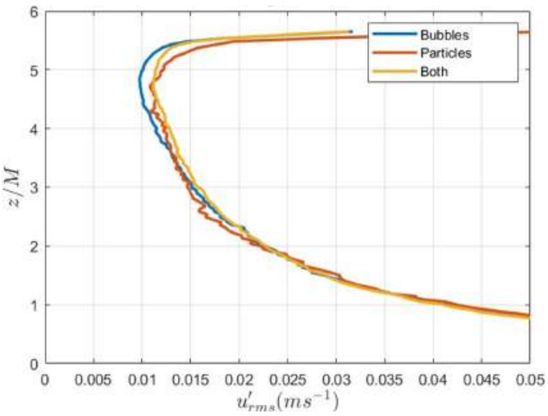

Figure 2: Horizontal turbulence intensities, lines show acquisitions with different dispersed phases present. z is height above the grid, M is the grid mesh size

Phase 2: Testing the effect of turbulence-particle interactions on dune dynamics

To test whether the interactions between SSC and turbulence intensity are responsible for the observed bimodality in dune heights, an ACVP device is to be used. The device, an Ubertone Lab-2C was developed for velocity profiling, but by inversion of the acoustic backscatter intensity as described by Hurther et al. (2011), concentration can be determined. This device will obtain vertical profiles of flow velocity and SSC at high spatial and temporal resolution on the order of millimetres and milliseconds. Using this data, turbulence intensities can be related to SSC and if present a relation can be found.

For this purpose, physical experiments have been set up using a flume at the Kraijenhof van de Leur laboratory for water and sediment dynamics at Wageningen University and Research. The flume is 15m long, 1.2m wide, 0.5m deep and has a maximum discharge of around 100ls^{-1}. Light weight polystyrene particles will be used as sediment in order to reach higher transport stages than can be achieved using regular sediment. Relative dune heights of the dunes formed by these particles show good agreement with dunes in deep flow rivers (Naqshband and Hoitink, 2020). The experiments will consist of nine 24h runs where dune height and length over the 8m long measured section will be tracked by an array of 32 SeaTek acoustic ranging transducers. The ACVP will be placed half way along the set of transducers.

As the experiments will still be ongoing during the the NCR days, preliminary results will be presented. These include: dune size frequency distributions as a function of transport stage, velocity and concentration profiles and first observations on the mechanisms at play.

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Using scenario discovery to identify system deficiencies in a river delta affected by deeply uncertain climate change

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Keywords — Scenario discovery, System deficiencies, Climate change, River functions, Deep Uncertainty

Introduction

Due to the changing climate, river functions (e.g. navigation and freshwater supply) are put under such stress that river systems might not be able to fulfil human demands in the future. In such cases, system deficiencies occur.

Much research into these deficiencies is carried out through hydrodynamic modelling. These studies are often limited in space (e.g. case studies or small regions) and scope (e.g. a stress-test on navigation or freshwater availability only) due to various reasons. Previous research shows however, that in complex interconnected river systems, the influence of feedback mechanisms should be addressed carefully (Welsch et al., 2026). Additionally, by restricting climate change studies in space and scope, the trade-off between river functions becomes cluttered and possibly limited in solution space.

In this research, we provide and apply a methodologic approach to expose the origin and spatial distribution of system deficiencies during droughts illustrated as an example for a single river function: navigation. We focus on the Dutch main water system (Figure 1).

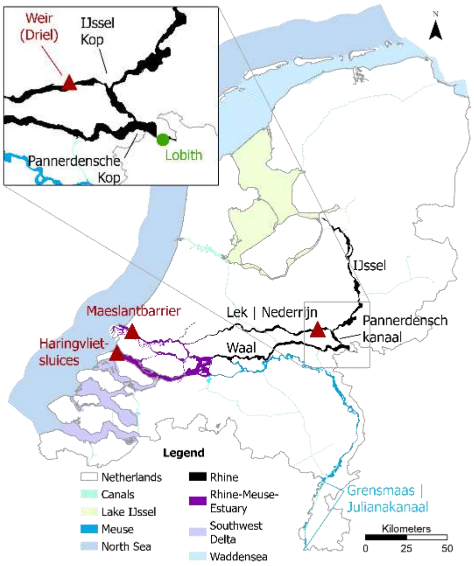

Figure 1. Overview of the Dutch main water system reprinted from Welsch et al. (2026).

Table 1. Ranges for the considered boundary conditions.

Boundary	Range
Q Rhine	500 – 3000 m^3/s
Q Meuse	30 – 300 m^3/s
Sea level rise	0 – 5 m
Lake IJssel	-1 – +1 m

Method

To expose system deficiencies, we take on a scenario approach in line with the scenario discovery method as described by Bryant and Lempert (2010), which consists of four steps.

First, we generate a set of scenarios which represent future conditions in periods of droughts in the Netherlands. For this, we vary the discharges in the Rhine and Meuse, the sea level rise and the water level in Lake IJssel (Table 1). The scenarios are drafted by sampling 2048 combinations of these conditions using a Sobol scheme assuming uniform distributions and no correlations between boundaries. Second, the scenarios are evaluated using a 1D hydrodynamic model (SOBEK) as developed by Welsch et al. (2026) using semi-stationary conditions (idealised tide, constant river discharges and a Q-h relation at Lake IJssel).

Third, we evaluate for which scenarios the river system exceeds acceptable limits with respect to the considered river function. This basically filters the scenarios in two categories: acceptable vs. system deficiency. For navigational use, we set the acceptable limit at a minimum water depth of 2.80 m.

Fourth, we apply a multi-dimensional bump hunting algorithm (PRIM) to define a rectangular hypercube which captures the scenarios flagged in the third step. The limits of these hyperrectangular boxes provide insights in the relative importance of the boundary conditions which describe the scenarios.

PRIM trade-offs

The rectangular hypercubes described by the algorithm are never perfect: they might either contain scenarios flagged as acceptable or they describe not all scenarios flagged which are

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considered a system deficiency. This trade-off is described in terms of *density* (what percentage scenarios in the box are considered as a deficiency) and *coverage* (what percentage of deficiency scenarios are in the box) and is up to the researcher.

We base the selection of the box on two criteria: (i) the minimum density should be 80% to consider the results relevant, and (ii) we choose the box with the highest density, given that the marginal increase in density should be greater than the marginal decrease in coverage.

Results

Spatial analysis of the occurrence of system deficiencies (Figure 2, top) shows that the deficiencies are mainly occurring upstream, with the largest number of scenarios leading to a deficiency in the rivers Meuse, IJssel and the upstream part of the Rhine (near the Dutch-German border). In the downstream sections of the rivers, less to no deficiencies are found, as the backwater effects from the sea provide sufficient water depth for navigation. As sea levels increase (due to climate change) the navigational depth increases, leading to less deficiencies. The high occurrence of deficiencies in the upstream part of the Meuse is most likely because the modelling of the locks in this river section is performing insufficiently.

Applying the PRIM algorithm to each individual location, the main contributing boundary conditions emerge (Figure 2, bottom). Note that not all locations provide a successful analysis, as we expect a minimum density of 80% for a box to be defined. Thus, if there are too few scenarios leading to a deficiency, or the deficiencies occur under the full range of boundary conditions, we consider no significant outcome of dominant boundary, respectively.

The water levels in the most upstream regions of the rivers are dominantly affected by the upstream river discharges, while in the downstream regions the sea level plays an increasing role. Although this is in line with expectations based on general river dynamics, this analysis shows the transition areas where the interplay of boundary conditions plays a role.

Conclusion

In this study, we generated a wide variety of possible future conditions and applied scenario discovery on a single river function. Thereby, we showed the potential to identify (i) the spatial distribution of system deficiencies and (ii) relevant boundary conditions.

In the case of our study area, we showed that navigation deficiencies occur mostly upstream, due to the river discharges, while downstream the backwater effects reduce deficiencies.

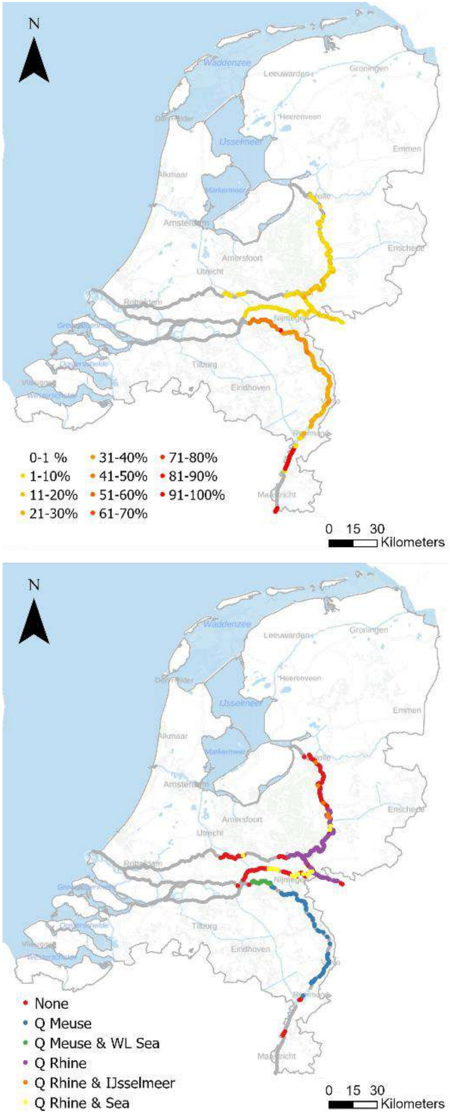

Figure 2. Top: fractions of scenarios leading to a system deficiency. Bottom: main contributors to the system deficiencies based on the PRIM algorithm.

Future Research

We strive to extend this research by expanding the analysis with additional river functions, such as freshwater supply and ecological services. In doing so, insights can be gained on how the effects of climate change and different river functions relate to each other.

Aknowledgement

This work is co-funded by Rijkswaterstaat within the “Kennisimpuls Klimaatadaptatie”.

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Advancing recognitional justice in integrated river basin management through stakeholder analysis

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Keywords — Integrated River Basin Management, Recognitional justice, Stakeholder analysis

Background

Integrated river basin management (IRBM) has been touted as a means to more inclusive and sustainable water management. However, over the last three decades, such approaches have struggled to meet sustainability and equity expectations (den Haan et al., 2019; Hallett and Hobbs, 2020; Molle, 2008). One of the key challenges to IRBM is overcoming the so-called "implementation gap," that is, moving from theory to practice to enact systemic and holistic basin strategies (Crase and Cooper, 2015; Watson, 2004). We suggest that a critical factor in overcoming the implementation gap is broadening the understanding of river basins and the stakeholders within them. Expanding the recognition of who and what "counts" as a relevant river basin stakeholder creates opportunities to incorporate historically excluded actors and their knowledge into the design of river basin strategies. Doing so may help address previously overlooked challenges and possible solutions. Recognitional justice, which refers to the acknowledgement and respect for diverse identities and practices, provides a lens through which river basin managers may identify historically excluded actors and perspectives. In this way, recognitional justice and stakeholder analysis go hand-in-hand. However, the extent to which recognitional justice is integrated into stakeholder analysis in IRBM remains underexplored. Therefore, understanding the role of recognitional justice in stakeholder analysis is a critical first step in advancing both the inclusivity and sustainability goals of IRBM.

Methods

A scoping review was conducted to identify and analyse stakeholder analysis methods applied in river basin management. The selection criteria for articles required empirical evidence, a detailed account of stakeholder analysis and engagement, and an objective to deliver outcomes across the social and ecological dimensions of river basins. We analysed these examples from practice to examine the top-down (led by formal decision-makers) or bottom-up (grassroots led) approaches used in three stages of stakeholder analysis: defining the system, stakeholder identification, and stakeholder categorization.

Results

The results of the scoping review provide a range of examples of stakeholder analysis methods; however, it is often in the way these methods are applied that ultimately influence recognitional justice. Both top-down and bottom-up approaches are used across all three phases of stakeholder analysis, though the use of top-down methods prevails. In both top-down and bottom-up approaches, justice and inclusion remain nearly absent in the determination of methods used. In some cases, stakeholder analysis continues to be done in a more ad hoc manner, relying on the "usual suspects" as participants.

Conclusion

Both top-down and bottom-up approaches come with justice-related considerations and trade-offs. More top-down methods can ensure continuity and cohesion with existing studies and previous stakeholder inputs, while more bottom-up methods invite unforeseen and locally relevant perspectives. Additionally, the results of the scoping review show that stakeholder identification and categorization is often conflated with participant engagement. Such conflation may foreclose the opportunity to integrate recognitional justice by failing to first explore who and what are considered within the river basin system before then determining who and what should be invited to participate in river basin planning. Ultimately, integrating

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considerations of recognitional justice can help to determine between and balance top-down and bottom-up approaches, while maintaining and holistic and intentional stakeholder analysis process. This integration of recognitional justice in the river basin context may be useful for expanding the stakeholders and perspectives in IRBM to identify overlooked challenges and opportunities.

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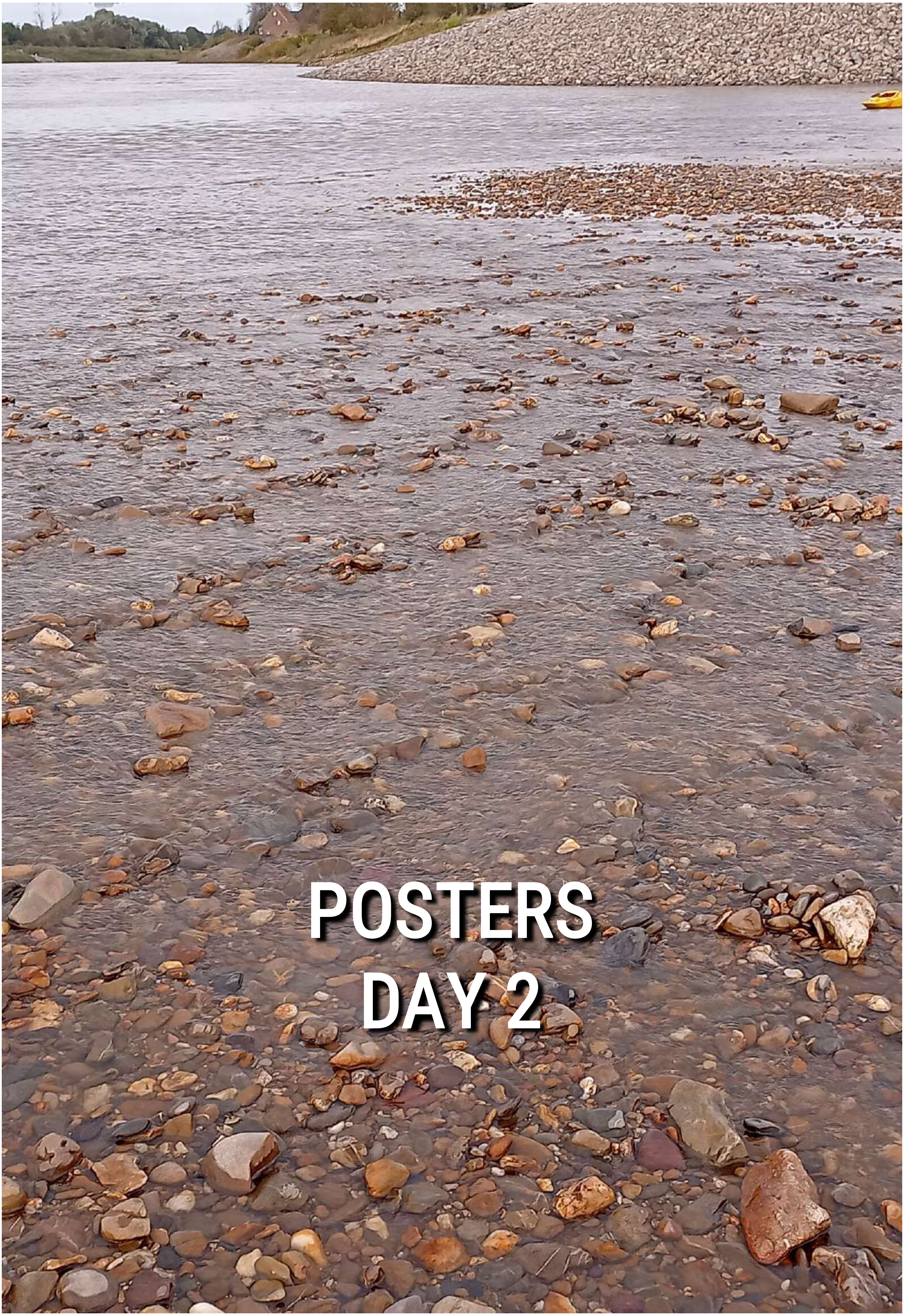
Acknowledgements

Funding for this research project is under the SpongeWorks project, which has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101156116 and from the UK Research and Innovation/HM Government. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or of the UK Research and Innovation / HM Government. Neither the European Union, the granting authority nor the UK Research and Innovation / HM Government can be held responsible for them.



POSTERS
DAY 2

Rivers and Rhinos: Linking river flow alteration to habitat quality for endangered floodplain herbivores

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Keywords — River flow regimes, Vegetation guilds, Herbivores

Introduction

River flow regimes strongly shape floodplain ecosystems. However, human activities are increasingly altering these freshwater systems with uncertain consequences for floodplain-dependent wildlife. The subtropical Karnali River floodplains at the foot of the Himalayas are a prime example of this. We previously showed that since the shift of the main discharge channel (Geruwa River) away from the western boundary of Bardia National Park in 2009, this reduction in the river flow regime was followed by lower dry-season water availability, reduced hydromorphological dynamics, and the expansion and changes in floodplain vegetation. These changes in the river system can strongly influence the pioneer grasslands and wetlands that serve as the primary forage for the vulnerable greater one-horned rhino (*Rhinoceros unicornis*), a floodplain habitat specialist, and support prey base of the endangered Bengal tiger (*Panthera tigris tigris*). However, quantitative relationships between altered flow regimes and the habitat quantity and quality of terrestrial wildlife remain understudied.

Method

To make these relationships explicit we will use the response-and-effect framework. We collected vegetation and soil properties across elevation zones above the active river channel to capture the flood gradient. We relate these field observations quantitatively to flood and groundwater regime characteristics derived from hydrodynamic and groundwater flow simulations. We identify (i) *flow response guilds,* describing how vegetation responds to hydrologic change, and (ii) *habitat effect guilds,* characterizing the influence of these changes on the availability of shelter and forage that vegetation provides. Preliminary results suggest that sites experiencing regular flooding provide high forage quality (nutrient-rich) and forage quantity (more green leaves) in the dry winter season, contributing to availability of higher habitat quality for herbivores.

Future outlook

The plot-level data will then be upscaled using multispectral and light detection and ranging (LiDAR) datasets to capture fine scale spatio-temporal patterns of habitat quantity and quality and directly link our results to wildlife habitat use. By explicitly modelling the relationship between the river flow regime and terrestrial wildlife habitats, we generate empirical evidence to inform adaptive hydrological management and extend the environmental flow framework to sustain floodplain-dependent megafauna.

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SNAPFLOOD: Stochastic Neural network APproach to forecast river FLOOD probabilities in real-time

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Keywords — Real-time flood forecasting, Flood probabilities, Machine learning

Introduction

River floods are amongst the world's most damaging and frequently occurring natural hazards. Forecasts of the spatiotemporal flood evolution are required to communicate safe evacuation routes to those potentially affected. Two-dimensional depth-averaged (2DH) hydrodynamic models are typically used to simulate flood propagation. Although accurate, these models cannot be used for short-term forecasting due to long simulation times (*Khosk Bin Ghomash et al.*, 2024). Therefore, artificial neural networks (ANNs) are more often applied because of their ability to mimic complex non-linear input–output behaviour. ANNs are extremely fast, making them suitable for forecasting overland flow quickly (*Besseling et al.*, 2024). However, three scientific challenges exist to operationalise ANNs in flood management successfully (*Bomers and Hulscher*, 2023):

1. ANNs are 'data-hungry': they need a large training dataset to learn input–output relations of the physical system.
2. ANNs have limited generalisation abilities: once an ANN is trained on a specific river catchment and flood trigger, it has difficulties in accurately predicting inundation for unseen topographies and flooding scenarios.
3. Weather forecasts are uncertain requiring stochastic flood forecasting approaches, while only deterministic ANNs are being developed so far.

Research aim

This project aims to develop a neural network approach that predicts river flood probabilities in real-time. This approach will allow water managers to make informed decisions on evacuation strategies and mitigation measures. The combined stochastic nature of extreme rainfall, dike overflow and breaches are integrated into an ANN architecture (Fig. 1) by including physical constraints to improve generalisation. By training the ANN on a wide range of landscape properties, the ANN can be applied to various river basins worldwide without retraining.

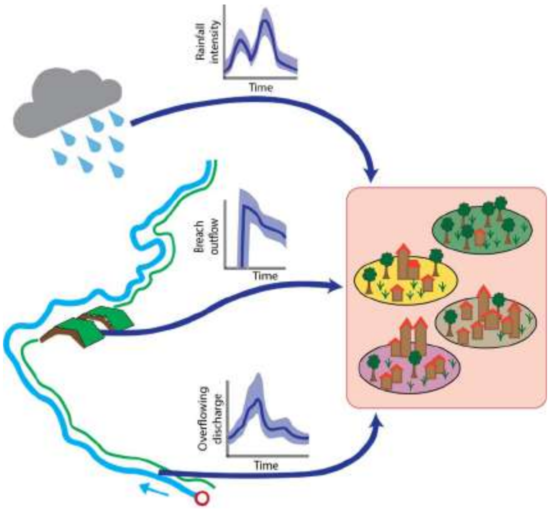

Figure 1: The spatiotemporal flood evolution in a river basin is influenced by (1) rainfall, dike breaches and overflow, and (2) landscape properties (slope, surface roughness, infiltration capacity)

Method

To train the neural network, a sufficiently large dataset needs to be created. A wide range of synthetic, yet realistic, flooding scenarios based on open-source data of rainfall and discharge observations will be simulated using the FASTFLOOD software (*Van den Bout et al.*, 2023). Furthermore, landscape properties influence the spatiotemporal flood evolution. Therefore, schematized study areas are created in which slope, surface roughness, and infiltration capacity are systematically varied. This training dataset is used to train, validate (to prevent overfitting) and test the ANN.

A neural network will be developed that allows for adaptive mesh refinements and per-pixel independent dynamic time-stepping. This method aligns with the fast numerical approach implemented in FASTFLOOD, and will ensure that the calculation time of the ANN remains limited even though probabilistic output

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is produced.

The uncertainty in forecasts regarding rainfall intensities, dike overflow and breaches will be included as stochastic input variables using a stochastic differential equation approach. The probability density functions of the boundary conditions are implemented as propagation rules in the ANN architecture. These rules learn how fluxes are exchanged between cells, based on topographical slopes and water level gradients. As such, the fluxes exchanged between cells are stochastic, and spatiotemporal flood probability maps are predicted as output (Fig. 2). By including physical constraints during the training, the ANN has the potential to generalise to scenarios beyond the training dataset.

The predictive accuracy of the ANN will be compared to FASTFLOOD output and open-source data of recent floodings worldwide. Furthermore, by comparing the results of the ANN with those of conventional ensemble simulations, the accuracy and reduction in total computation time of the ANN approach will be confirmed.

Knowledge utilisation and expected outcomes

The developed neural network enables a crisis team to create real-time probability maps of flood arrival times and inundation depths based on expected weather conditions. This allows for permanent monitoring of flood probabilities and improved decision-making regarding mitigation measures. Mitigation measures for river floods include evacuations and, e.g., flood retention areas to reduce the number of casualties and economic damage. Decision-making will thus have large safety and economic benefits. A workshop is organised at the beginning of the project with various water authorities to co-create and provide input on the practical requirements of the developed flood forecasting system. At the end of the project, a training with the Dutch water management crisis team is organised to mimic decision-making during a forecasted flooding event.

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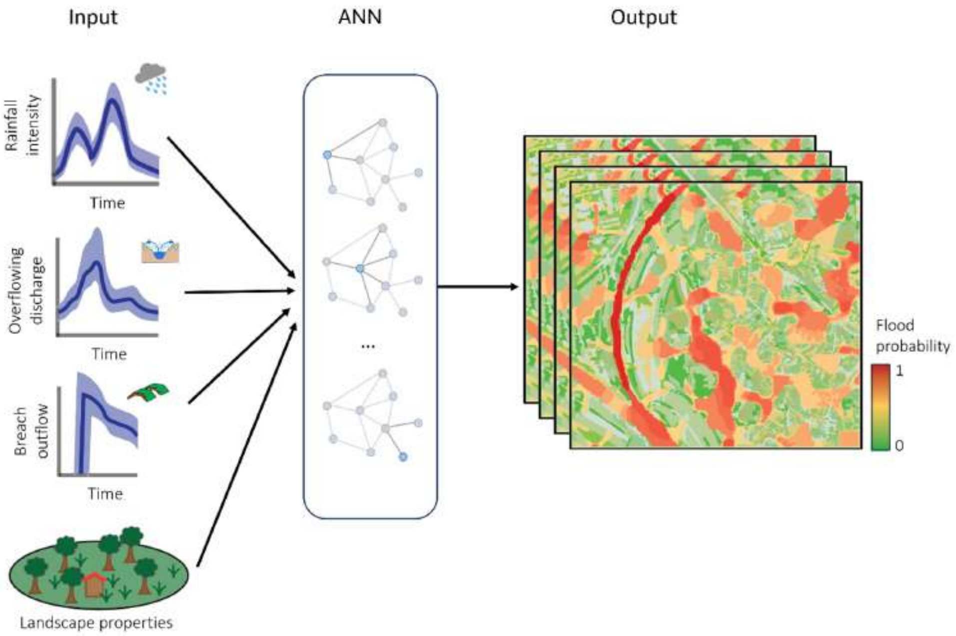

Figure 2: The developed neural network predicts flood probabilities over time based on landscape properties and the combined effect of rainfall, overflow, and dike breaches.

Delta-ENIGMA: advancing biogeomorphology research in deltas through observation and experimentation.

Smriti Dutta[a], Hans Middelkoop[a] and Gerben Ruessink[a] on behalf of the entire Delta-ENIGMA
consortium (UU, TUD , UT, WUR, NIOZ, Deltares, TNO-GDN)
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Keywords — delta, biogeomorphology, rivers, estuaries, dunes, observatory, climate adaptation

Introduction

Deltas and coastal plains are among the most dynamic and productive landscapes on Earth, shaped by the continuous interaction between physical and biological processes. This interplay has built and continuously reshaped the Dutch delta across spatial and temporal scales. However, delta's worldwide are facing growing risks from climate change, sea-level rise, land subsidence, and intense human intervention. Understanding how biological and physical processes interact is therefore crucial to predicting delta resilience, identifying potential tipping points, and developing effective adaptation strategies.

Delta systems evolve through bio-physical interactions operating under both everyday conditions and extreme events, such as floods and storms. However, these interactions remain insufficiently quantified at the scale of entire deltas, particularly during extreme events, due to limited long-term and integrated observations. And that is where Delta-ENIGMA comes in. Delta-ENIGMA is a 10-year NWO-funded Large Scale Research Infrastructure (LSRI), in which a consortium of seven Dutch institutions of NCK and NCR closely collaborate.

Methods

Delta-ENIGMA aims to advance our understanding of delta-scale biomorphology and how this shapes deltas by establishing an observation network across rivers, estuaries, and beach-dune systems. Central to this effort is the deployment of state-of-the-art field instrumentation, including high-resolution 3D laser scanners, multibeam echosounders, submerged flow and sediment sensors, wave recorders, and multispectral drones. These measurements are complemented by targeted monitoring during extreme events, capturing high-impact processes that strongly influence long-term delta evolution. Delta-ENIGMA also upgrades and develops laboratory facilities such as a wind tunnel, mesocosm systems, and advanced bio-morphodynamic flumes to experimentally investigate processes that are difficult to observe directly in the field but critical for future climate scenarios.

To maximize scientific and societal impact, Delta-ENIGMA integrates its observational and experimental facilities within an open, federated data infrastructure and a knowledge interaction platform. Data-infrastructure incudes data quality control, documentation with standardized metadata, structuring in consistent formats, and centralized storage.

Delta-ENIGMA provides researchers and policymakers with unprecedented access to high-quality data, experimental facilities, and collaborative environments, that will boost bio-geomorphology research, and enables linking fundamental biogeomorphological understanding to applied research and innovation. Delta-ENIGMA facilities position the Dutch delta as a unique Super Site for advancing climate adaptation and sustainable delta management.

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Figure-1 Locations across the map of Netherlands including sites for field measurements, laboratory facilities, productive knowledge interaction facility (PROD) and open database

Results

In the last 2 years, Delta-ENIGMA successfully achieved several keys tasks and objectives. Effective collaboration among partners and open communication facilitated the integration of expert knowledge. Locations for observation and measurements have been selected (Fig.1), and installation of equipment has initiated. Key sites are:

- River: Rotterdam, Hoek van Holland and Afferdense en Deestse Waarden
- Estuary: Zuidgors and Waarden, both in the Western Scheldt
- Beaches and dunes: Sand Motor (nourishment), Egmond aan Zee (recreational beach) and Castricum (dynamic dune management)

Besides that, the appropriate equipment for storm events and extreme conditions (e.g. AQUADOPP, turbidity logger, ADCP's, wave recorders, multispectral drone) has been acquired. Various 'Quick reaction Force' teams have been set-up to go out into the field when an extreme event is imminent., and first extreme events have been sampled, including the Afferdense and Deestse Waarden during the February 2026 high Rhine discharge event.

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

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

Prospects

Delta-ENIGMA provides instruments and facilities, but does not involve the further data analysis and research. We therefore encourage researchers from the Netherlands and abroad to utilize our facilities in ongoing and new research ideas in the broader field of bi-morphology of rivers, deltas or coastal areas. Submit proposals that make use of Delta-ENIGMA's facilities and data. PhD proposals are highly encouraged in 2026 and for the subsequent years.

Numerical Study of Suspended Sediment Dynamics in a Free Surface Flow Constructed Wetland in Norway

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Keywords — suspended sediment, constructed wetland, vegetated filtering process

Introduction

Constructed wetlands have been widely applied as filtering tools to treat polluted water in various water treatment systems worldwide (Gaballah et al., 2024). Based on the flow passing routine, the constructed wetland (CW) can be classified as free-surface flow constructed wetland (FSFCW) or subsurface flow constructed wetland (SFCW). The FSFCW has significant benefits, being low-energy-consuming, and being cost-effective in construction and management (Vymazal, 2010). In this way, it has been widely applied across different local environmental conditions, from tropical to cold climates, to treat polluted water from both urban and agricultural sources (Terzakis et al., 2008; Kynkäänniemi, 2014).

Usually formed by a relatively deeper, non-vegetated sedimentation pond followed by a sequence of several shallow vegetated sections, the FSFCW has been applied in agricultural catchments in southern Norway (Braskerud, 2001). One application is the Skuterud wetland, located downstream of an agricultural catchment (Figure 1). Constructed in 2000, this wetland has been filtering nutrients and suspended sediment from the catchment runoff for more than 20 years (Blankenberg et al., 2016).

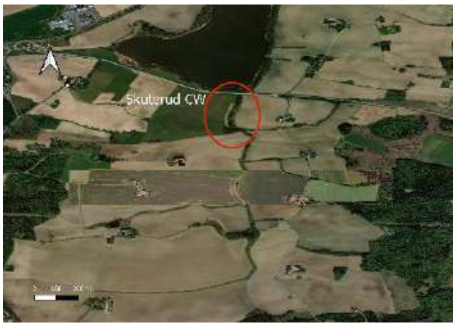

Figure 1. location of the Skuterud catchment and the Skuterud constructed wetland, the flow is from South to North

There are three filtering components contained in the Skuterud wetland (Figure 2). At first, the upstream water flows into a 1.5m in-depth sedimentation pond as a primary sedimentation treatment. Successively, the flow passes through the stone barrier and enter two shallower (about 0.5m in depth) vegetated sections. In this part, the local vegetation species is established and serves as a filtering tool to further purify the water. After that, the treated flow leaves the wetland by passing through the downstream channel.

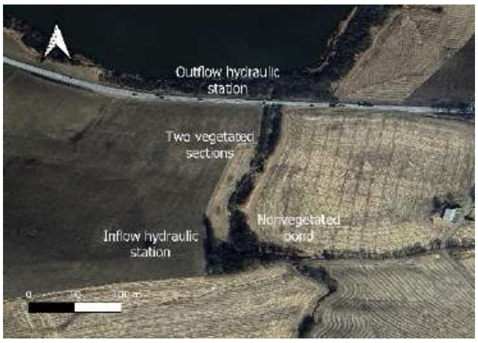

Figure 2. Structure and measurement system of the Skuterud CW

The management and study of this wetland is under the charge of the Norwegian Institute of Bioeconomy Research (NIBIO). Two monitoring stations are placed upstream and downstream of the wetland (Figure 2). The downstream station measures stages and discharges and gets automatic grab samples of water to measure water quality parameters including sediment concentration. Likewise, in the upstream monitoring station similar grab samples are automatically taken. Water samples are collected regularly from both monitoring stations and are sent to the laboratory, where sediment, nitrogen and phosphorus concentrations are analysed (Blankenberg et al., 2013). The collected measurement data is regularly uploaded to and managed by the Agricultural Environmental Monitoring Programme (JOVA) in Norway (https://jovadata.nibio.no/download/catchment/sku/hydrology). Three excavation works have been conducted to empty the wetland in 2005, 2010, and 2015, respectively (Krzeminska, 2021; Krzeminska et al., 2023).

Numerical tools have also been developed to study the detailed transport processes within the constructed wetland. (Langergraber, 2011)Specifically, for the FSFCW, the processes-based model has advantages and has been investigated to reproduce both physical and biochemical processes inside the complex locally CW system.(Gaballah et al., 2024) So far, the simulation of constructed wetlands is still rare, and this study aims to numerically reproduce Skuterud CW to examine how physical processes among suspended solids, emergent vegetation, and flow, including suspended sediment transport, operate in it. Moreover, as a further step, this study aims to explore how vegetation and sediment inflow characteristics affect the filtering efficiency of an FSFCW.

Methodology

The Skuterud CW is reproduced in Delft 3D 4.04.01, and the 2DH model is established. The domain of the model comprises the whole constructed wetland between the two monitoring stations. As shown in Figure 3, the wetland is schematized as a 305 m-long rectangular shape with varying widths. The bed topography of the wetland is based on existing document records (Krzeminska et al., 2021) and on-site measurements taken in the context of this research.

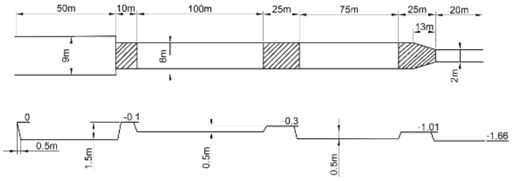

Figure 3 Schematized layout of the Skuterud CW, upper: the top view; lower: the longitudinal view, the flow direction is from left to right

For the vegetated sections, emergent vegetation is modelled using the drag force approach in Delft 3D and treated as rigid cylinders. Suspended sediment transport is calculated using the 2DH advection-diffusion equations. The grid size is 0.5m in both directions. A 40-day short-term period is selected from the monitoring dataset, and the daily discharge and water level are used as the upstream and downstream boundary conditions, respectively. The time step is 0.001 minutes.

Expected results

This study starts by establishing a warm-up model to account for differences in water level across sections of the wetland; hence, a reasonable initial water level distribution is obtained. Then the selected 40-day short-term is reproduced. The parameters for vegetation, sediment, and flow will be calibrated and validated by comparing simulated results with monitoring data, especially the difference in suspended sediment concentration between the inflow and outflow cross-sections. Based on this validated basic case, additional scenarios with varying vegetation parameters and cover schemes, as well as sediment characteristics, will be investigated. By comparing simulated results across different scenarios, the relationship between vegetation characteristics, sediment inflow conditions, and the filtering efficiency, will be discussed. Therefore, the results of this research will be useful in supporting constructed wetland designs.

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Spatial variation in the composition of recent deposits of fine sediments along the Rhine River

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Keywords — Rhine River, fine sediment, geochemistry, event deposits, PCA, provenance

Introduction

Recently deposited fine sediment can provide a practical snapshot of sediment sources and along-river mixing, but this signal can be blurred by temporary storage and reworking in the river corridor (Ciszewski & Grygar, 2016). This is particularly relevant in the engineered Rhine, where reach-scale differences in tributary inputs, confinement and channel works affect transport and storage of fine material (Frings et al., 2019). This study quantifies the spatial variation in element concentrations of recently deposited fine sediments along the Rhine mainstem sampled during a multi-day campaign in September 2025, and evaluates dominant downstream patterns using correlation analysis and principal component analysis (PCA) (Van Der Perk & Vilches, 2020). This work builds on an event-based approach in which recently deposited fine sediment was sampled along the Rhine mainstem after a minor high-water event in the summer of 2023 and interpreted using multivariate analysis and spatial modelling to infer provenance and downstream mixing (Van der Perk et al., 2026)

Method

Fieldwork was carried out from 22–26 September 2025 along the Rhine mainstem from the High Rhine (near Küssaberg) downstream into the Rhine–Meuse delta (Rotterdam/Botlek area). In total, 45 sediment samples were collected (mainstem and tributary mouths), targeting fresh fine deposits on stable bank surfaces close to the waterline (Figure 1). Samples were oven-dried, homogenised, digested using HF-based total destruction and analysed by ICP-MS and ICP-OES. Analytical precision was evaluated using two analytical duplicate pairs (mean RPD typically <10%). For downstream pattern analysis and PCA, three non-representative samples were excluded, resulting in a cleaned Rhine mainstem dataset of n = 37. Element selection for the multivariate analysis was restricted to the subset (n = 41) that can be compared to available geochemical reference/baseline information for the Rhine basin and Europe (FOREGS Geochemical Atlas)(Salminen et al., 2005). PCA was performed on 40 elements (standardised concentrations), because W was excluded due to potential tungsten–carbide contamination during milling.

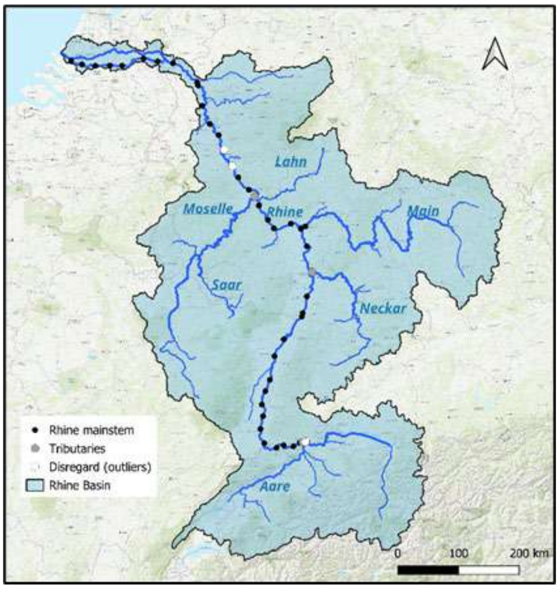

Figure 1: The Rhine basin with sampling locations of freshly deposited sediments in 2025.

Results

Concentration–distance plots show clear downstream organisation over the short campaign window. Most elements generally increase downstream, most clearly for a trace-metal-associated group (e.g., Mn, Pb, Zn, Cd), which rises downstream and shows a modest reduction towards the delta (Figure 2).

Figure 2: Downstream trends for trace-metal associated elements. Concentrations of lead (Pb) and zinc (Zn) of recent fine sediment deposits are plotted against Rhine-km.

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Rare earth elements and associated actinides (e.g., La, Th) show coherent spatial structure with relatively elevated values in the Middle Rhine and lower values toward the downstream end. In contrast, Sr shows an overall downstream decrease and negative correlations with most other elements (Figure 3).

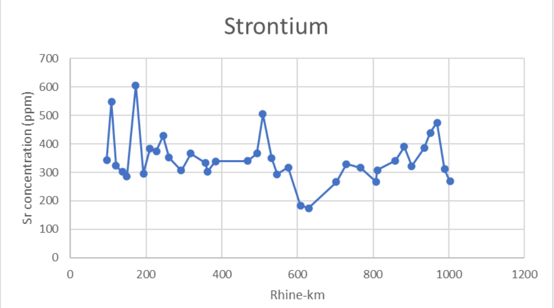

Figure 3: Concentration of strontium (Sr) of recent fine sediment deposits is plotted against Rhine-km.

A small but consistent uptick in several element concentrations occurs in the final samples near Rotterdam (~Rhine-km 970–1000), suggesting a local downstream-end effect in the delta/port region. PCA indicates that most variance is captured by two axes (PC1 = 71.7%, PC2 = 16.4%; total 88.1%). PC1 (Figure 4) represents a broad coherent gradient shared by most elements (Sr loading oppositely), while PC2 reflects a secondary contrast between a lanthanide-associated group and a trace-metal-associated group.

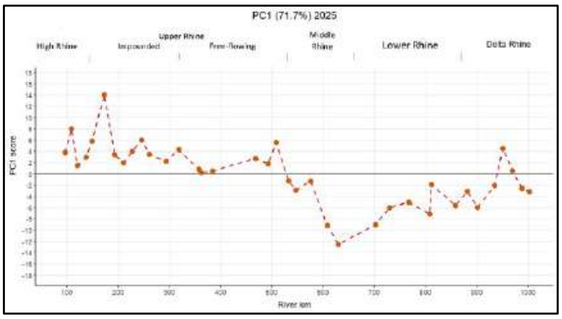

Figure 4: Downstream variation in PC1 scores (71.7% explained variance) along the 2025 Rhine mainstem transect. PC1 scores are plotted against Rhine-km.

Conclusion

The 2025 event-deposit dataset demonstrates strong reach-scale geochemical organisation along the Rhine, even within a short sampling window. The dominant pattern (PC1) suggests systematic downstream changes in sediment composition modified by reach-scale mixing and corridor exchange, while PC2 captures a secondary compositional contrast. Interpretation of individual event-deposit signals remains uncertain because parts of the Middle and Lower Rhine were sampled during rising stages. Overall, the study highlights both the value of event-deposit sampling for detecting coherent downstream patterns and the importance of hydrological context for interpreting them, including a downstream-end uptick near Rotterdam.

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Exploring spatio-temporal river water temperature patterns in Dutch small and large rivers

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Keywords — climate change, river water temperature, data analysis

Introduction

Increasing water temperatures can considerably alter the physical, chemical and biological processes in aquatic ecosystems and are an essential component of the Water Framework Directive. Due to climate change, river water temperatures are expected to rise significantly in Europe (Van Vliet et al., 2013). Various studies indeed show such increasing river temperature trends, for example in Germany (Arora et al., 2016), Poland (Zhu et al., 2022) and Switzerland (Michel et al., 2020). Apart from increases in atmospheric temperature (e.g. Arora et al., 2016), also other factors influencing river water temperature increase are mentioned in scientific literature, for instance urbanisation (Grey et al., 2023) and changes in land use and spatial characteristics of the catchment (e.g. catchment size) (Arora et al., 2016; Zelenakova et al., 2018). This study aims to gain insight into the impact of climate change on river water temperature and in potential differences of water temperature between rivers because of differences in river and catchment characteristics and management practices.

Method

We analysed an extensive dataset of river water temperatures retrieved from the Waterkwaliteitsportaal (https://wkp.rws.nl/) and from multiple water authorities. The dataset contained more than 30,000 numerical temperature measurements. After applying selection criteria requiring time series of at least 15 years and a minimum of 10 measurements per year, the analysis was conducted in 23 rivers at 56 locations (Figure 1). We compared trends between rivers differing in size (small versus large) and flow velocity (fast versus slow), based on the WFD characterisation of rivers.

Results and Discussion

A seasonal Mann-Kendall test showed that all Dutch rivers with a significant temperature trend ($p < 0.05$) are warming, with rates ranging from 0.02 °C to 0.17 °C per year (measured at individual locations). Although small rivers show faster increases than large rivers (Figure 2), this was not statistically significant. An overview of the monthly average river water temperature shows that the temperature follows an annual cycle and that large rivers typically have a higher average temperature from April to December (Figure 3). Furthermore, comparison of two different periods showed that the temperature increase in recent years (1999-2024) is significantly higher than the period of 1973-1998. In both periods, no significant difference was found between small and large rivers, or between fast and slow-flowing rivers, possibly due to the small sample sizes of the groups (large rivers and fast-flowing rivers).

Figure 1: Measurement locations of the data-analysis with corresponding rivers

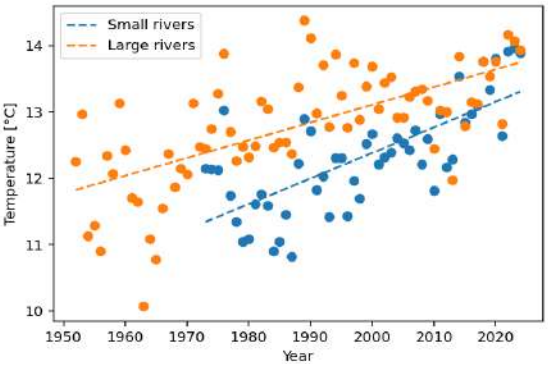

Figure 2: Average yearly temperatures for small and large rivers with a linear interpolation

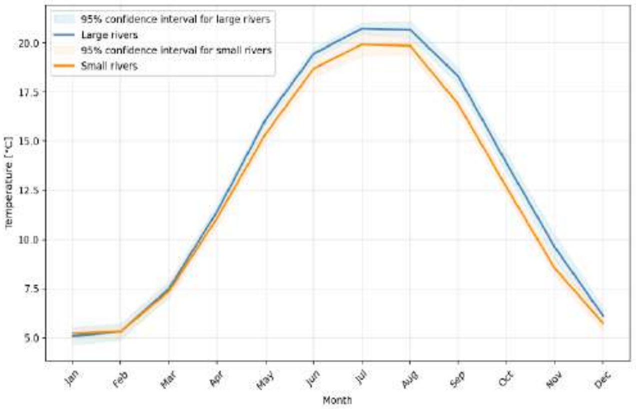

Figure 3: Average monthly temperatures for small and large rivers

River temperature trends can vary per season, for example, Arora et al. (2016) and Zhu et al. (2022) found temperature increased most in summer and Soana et al. (2024) found that temperature increase was highest in autumn. In Dutch rivers, temperature increases year-round, similar to a study of Michel et al. (2020). Temperature trends are most variable in autumn and winter and more consistent in spring and summer (Figure 4).

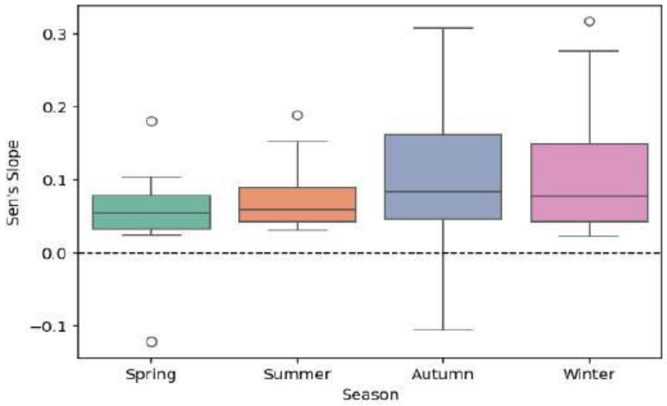

Figure 4: Significant temperature trends in Dutch river per season. Trends are calculated with Sen's slope.

Beyond temporal and seasonal trends, spatial variability in temperature increases was also observed. A visual assessment of the spatial distribution of temperature trends showed that increases in temperature are highest in the western part of Noord-Brabant, Dordrecht and at the border with Germany near Nijmegen. The lowest increases are found in the north of the Netherlands. Trends in nearby locations in the same river vary noticeably, suggesting that factors other than river typology and general location might play an important role.

Conclusion and recommendations

Our data analysis of 23 rivers at 56 locations showed that river water temperatures are rising in Dutch rivers, with trends ranging from 0.02 to 0.17 °C per year. River warming has accelerated in recent years. Although the temperatures in small rivers increase faster than in large rivers, this difference is not statistically significant. Identifying spatio-temporal trends in river water temperature can be used for targeted climate adaptation measures and the design of Nature-based Solutions to mitigate further warming in lowland river systems.

Acknowledgements

Additional data is provided by Hoogheemraadschap de Stichtse Rijnlanden, Rijkswaterstaat, Waterschap Aa en Maas, Waterschap Brabantse Delta, Waterschap de Dommel, Waterschap Drents Overijsselse Delta, Waterschap Hunze en Aa's, Waterschap Limburg, Waterschap Noorderzijlvest, Waterschap Rijn en IJssel, Waterschap Rivierenland and Waterschap Vechtstromen.

This research is part of the project 'Kleine Rivieren voor Klimaat' (Small rivers for Climate), funded by SIA Raak Publiek (grant no. SIA RAAK.PUB14.042).

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Tributary mouth widening effects on hydro- and morphodynamics in small, sand bed rivers

In-progress research, methods, and expectations

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Keywords — Nature-based Solutions, Small Rivers, Confluences, River Morphodynamics

Introduction

Rivers have been a focus for human interventions in the environment for centuries, and extensive engineering work has improved water availability, flood safety, and shipping. This has, in general, led to narrower, deeper, and faster flowing rivers that are now being identified as problematic for freshwater aquatic ecosystems and their corresponding ecosystem services (Admiraal et al., 1993; van Rees et al., 2023). Nature-based solutions (NbS) are being used more frequently to simultaneously achieve river management goals and improve aquatic ecosystems. These solutions employ natural processes to achieve human management aims.

Small rivers in developed areas are under pressure between intense human use and limited aquatic habitat area. Programs like the European Water Framework Directive have identified the importance of ecosystem health and habitat availability even in small waterways (European Water Framework Directive, 2000). Many organizations are pursuing projects to protect or improve freshwater habitat in such areas. However, a lack of understanding of river processes makes implementing such projects while guaranteeing flood safety and river-adjacent land stability difficult.

A specific NbS proposed to restore habitat in channelized rivers is tributary mouth widening. This involves artificially widening and deepening the area around the mouth of a tributary. This increases the low-velocity habitat in channelized rivers, especially during high flow conditions. While generally accepted as beneficial for ecology and habitat diversity (Leite Ribeiro et al., 2016), the effects of such an intervention on confluence hydrodynamics and morphodynamics are relatively unknown, especially in lowland, sand bed rivers. This abstract covers the research approach of this ongoing research.

Research Approach

Previous research into tributary mouth widening has focused on mountainous rivers and consisted exclusively of flume experiments (Guillén-Ludeña et al., 2017; Leite Ribeiro et al., 2016). This current research project will use a multi-method approach, incorporating field data collection, flume experiments, and numerical modelling for a comprehensive view of the processes. For all methods in this study, a general tributary mouth widening design as shown in Figure 1 will be used.

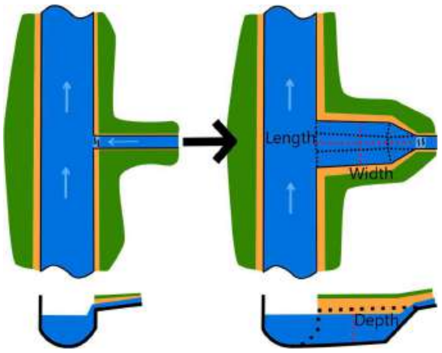

Figure 1. Generic tributary mouth widening design explored in this project. This intervention includes both a widening of the tributary and a deepening of the tributary mouth.

Field data collection

Two tributary mouth widening implementations in the River Dinkel (Eastern Netherlands, Overijssel province) are being measured to track the effects of this intervention. 3D velocity transects, high frequency point 3D velocity measurements, and bathymetry in the confluence zone are being measured during high water periods to capture the velocity field, turbulence, and morphological development. The interventions into these sites occurred recently (Figure 2); monitoring began before construction and will continue for 3 years following construction. This will allow for tracking the development of such confluences during the time of greatest anticipated morphological change.

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Figure 2: Images of tributary mouth before and after tributary mouth widening intervention in field site 1. The site is located on the River Dinkel in the eastern Netherlands. Construction occurred in October 2025. Both photos taken from approximately the same position.

Flume Experiments

Flume experiments will be conducted in the Metronome flume at Utrecht University to investigate the morphological development of tributary mouth widening. These experiments will aim to replicate the processes seen in the field sites and to expand the parameter space of potential tributary mouth widening interventions and explore longer time scales than the field data collection. Configuration variables that will be varied can be seen in Table 1.

Table 1. Selected confluence parameters to vary in the flume experiments and numerical models.

Parameter	Variations
Discharge Ratio between tributary and main channel	0, 1/8, 1/4
Confluence Angle	30°, 60°, 90°
Widened Width	1x main channel, 1.5x main channel
Tributary Bed Slope	Level concordant bed, level discordant bed, sloped bed
Armouring	Unarmoured, armoured downstream bank

Numerical Modelling

The flow dynamics and turbulence intensity are important aspects of confluence aquatic habitat. Numerical modeling of the flow in the confluence following tributary mouth widening will allow for an analysis of these processes in greater detail than the field measurements and flume experiments. 3D eddy-resolving numerical models will be run in OpenFOAM, an open source computational fluid dynamics software. A model with idealized confluence bathymetry will be run for the same variety of confluence configurations as the flume experiments (Table 1), and these model runs will be repeated with a natural confluence bathymetry, obtained from the field data and/or the flume experiments.

Anticipated Results

This research is ongoing, but by the NCR Days Conference initial numerical modelling of idealized river confluences with various widening configurations are expected to be completed, and these results will be shared.

Acknowledgement

This research project is funded by the National Growth Fund, submitted by the Ministry of Infrastructure and Water Management and the Ministry of Agriculture, Fisheries, Food Security and Nature, as part of the NL2120 program.

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Reoccurring quasi-steady states in experimental estuaries

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Keywords — Estuary, morphology, steady state

Introduction

Estuaries around the world are important areas for both ecosystems and societies, hosting protected nature as well as the gateways to the large ports and global trade. Complex interactions between river flows and tidal flows result in complex patterns of sediment transport, leading to the formation and development of dynamic braided channel networks. These morphodynamics have profound effects on both ecosystems and human activities, such as construction of dikes or dredging, which in turn influence the estuarine morphodynamics themselves. Human activities could result in profound changes of the “equilibrium” steady states in such estuaries (Elias et al., 2023; Van Maren et al., 2023). It is therefore important to have a better understanding of the sediment transport processes in estuaries, to improve the decision making for making both ecosystems and societies more resilient in a world that is moreover affected by climate change and sea level rise. Because of the size of estuaries and the continuously changing tidal flows, it is difficult to study real estuaries in both the spatial and temporal domains. Therefore, we conduct scale experiments of rapidly developing estuaries in a laboratory flume, allowing for collecting dense datasets of large timeseries.

Methods

We conducted our experiments in the Metronome facility, which is a 20 by 3 m periodically tilting flume used for emulating tidal systems (Kleinhans et al., 2017; www.uu.nl/metronome). With a tilt period of 40 s over a mobile sand bed, we induce a reversing shallow flow which results in self-formed channel-bar patterns that scale the same as in natural estuaries.

We have conducted a total of 20 experiments of estuaries with different configurations of fixed banks of rough sandpaper, including repeat experiments. Experiments run up to 25,000 emulated tidal cycles, from each of these cycles we collect imagery of seven different overhead cameras. Important here are two recent advancements in our laboratory, which are: (i) processing of all the raw data within a single “base model” geometry (Nota et al., 2026a); and (ii) applying Machine Learning to quantify water depths from overhead imagery into water depth maps (Fig. 2; Nota et al., 2026b). Thanks to both advancements, we can now quantitatively study changes in water depths over a wide range of timescales at optimized accuracies. Here we present our first such quantitative analyses on identifying the formation and possible change of quasi-steady state morphology of our experimental estuaries.

We identify quasi-steady states in an experiment through quantifying correlations between all available timesteps of water depth maps within the experiment. For this purpose, we use the metrics of Median Absolute Deviation (MAD) and Dynamic Time Warping (DTW), both showing perfect agreements at 0. MAD is derived from 1-to-1 cell deviations, whereas DTW allows for positional movement of cell y-coordinates to optimize Euclidean distances between timesteps. If there is a longer period within an experiment of low values of these metrics, we can consider the morphology to be in quasi-steady state.

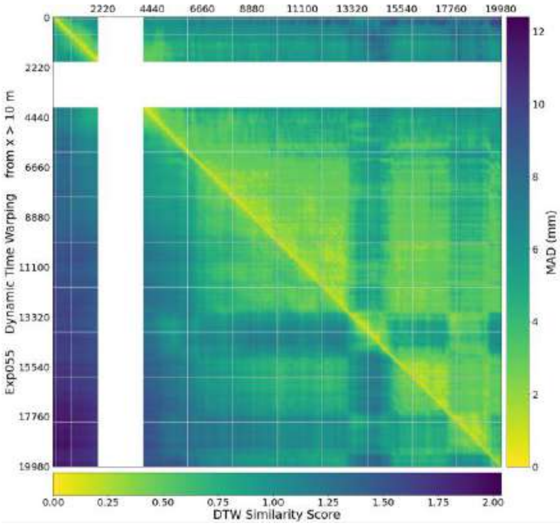

Figure 1. Correlations between 20,000 emulated tidal cycles within a single experimental estuary (in steps of 20 cycles). The experiments shows reoccurring quasi-steady states as alternating periods of more correlated morphologies (with lower values for MAD and DTW). There is no data between 2000 and 4000 tidal cycles.

Results and discussion

Fig. 1 provides the result of one experiment, which resembles an irregular checkerboard pattern of alternating regions of higher correlation (e.g. between 6,000-13,000 and

15,000-17,000 cycles). This implies that this experiment consists of alternating quasi-steady states with a quasi-cyclic behaviour. In other experiments, we observe either similar patterns as in Fig. 1, or a single persistent steady state. The occurrence of persistent steady states or reoccurring quasi-steady states may depend on different boundary conditions, such as planform configuration, degree of confinement, tidal settings, and perturbations. Moreover, these results can imply that heavy human engineering and changing environmental conditions can force estuarine morphology into a different steady state.

Conclusions

We conducted 20 laboratory scale experiments of estuaries, under various configurations and settings, aimed at identifying steady state morphology. We identified either the formation of single steady states, or alternating quasi-steady states with a quasi-cyclic behaviour. Our results demonstrate that our small-scale estuarine experiments are capable of showing complex behaviour of alternating quasi-steady states. This has implications on real life efforts to conduct field surveys in estuaries, as well as to numerically model estuarine morphodynamics.

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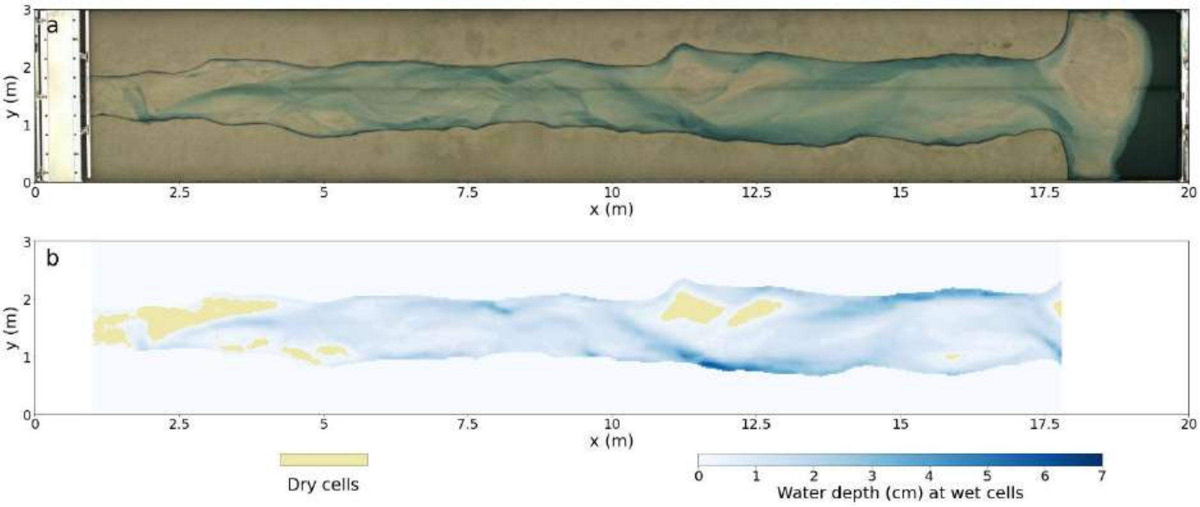

Figure 2. Illustration of: (a) the overhead imagery of a single timestep in an estuarine experiment in the Metronome after 12,675 tidal cycles; and (b) the quantitative determination of water depths from this imagery through Machine Learning. From Nota et al. (2026b).

Linking microplastic deposition to sediment deposition: a field study

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Keywords — Microplastic fate, Microplastic-sediment aggregation, Cohesive sediment

Background and Hypothesis

Microplastics are increasingly recognized as contaminants of concern in rivers and estuaries. Identifying where these microplastics accumulate is essential for understanding their environmental impact and informing monitoring strategies. A key process influencing microplastic fate is microplastic–sediment aggregation, in which microplastics become incorporated into aggregated sediments (sediment flocs). Laboratory studies show that incorporated microplastics settle at velocities similar to sediment flocs. We therefore hypothesize that once incorporated, microplastics are transported and deposited alongside fine sediment. This study tests this hypothesis through field measurements in the Port of Rotterdam.

Field Measurements and Experimental Design

To evaluate this hypothesis in situ, measurements will be conducted in a harbor basin along a transect with decreasing hydrodynamic energy. This spatial gradient is essential, as flow conditions control sediment deposition. At four locations along the transect, sediment traps will be deployed to collect settling material, and water samples will be taken at the same sites to characterize suspended material. The deposition patterns of microplastics will be analyzed together with those of settling sediment. By comparing the concentration and composition of microplastics in the sediment traps with those remaining in the water column, we can assess which types and sizes of microplastics are more likely to settle. All sediment and water samples will be analyzed in the laboratory to determine microplastic concentrations and characteristics (type, size, and shape). In addition, deposited sediment will be characterized for grain size and organic matter content.

Expected Insights and Environmental Implications

With these measurements, we aim to identify similarities and differences in the deposition patterns of sediment and microplastics under real field conditions. We will examine how microplastic characteristics and size influence their likelihood of settling, and we will investigate the mechanisms driving these patterns, particularly the role of microplastic–sediment aggregation. Understanding aggregation and settling processes in a natural environment, beyond laboratory experiments, is crucial for identifying where microplastics accumulate and for predicting their sinks in rivers and estuaries.

Shifts toward drier-associated terrestrial plant species along the Waal River between 1993 to 2023

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Keywords — Floodplain ecology, Ellenberg indicator values, Species shift

Introduction

Large-scale river interventions and training measures alter the hydrological connectivity of floodplains. This may shift vegetation species compositions towards those with drier or wetter habitat preferences, but rates and directions of change remain unknown. Observations are needed to better constrain predictions of floodplain vegetation change as a function of hydrological constraints such as average groundwater levels. A great example of a large lowland river which has undergone substantial human modifications in the past is the Waal River, the largest distributary of the Rhine in the Netherlands. Due to historic river training measures, such as fixation of river channel through groynes, progressive river bed incision has occurred over past decades (Ylla Arbós et al., 2021). Riverbed incision has been reported to cause declining groundwater levels in surrounding floodplains during low discharge conditions (Grabowski et al., 2022). At the same time, the implementation of Room for the River measures, such as lowering of minor embankments and floodplain sections and the construction of side channels, have restored hydrologic connectivity of floodplains likely supporting species with wetter habitat preferences (McCabe et al., 2025).

Here we investigate whether terrestrial plant species in the Waal floodplains have shifted toward species associated with drier or wetter conditions between 1993 and 2023 using the Ellenberg moisture indicator (Tichý et al., 2023) and 50,000 structured species observations.

Methods

We obtain terrestrial plant species observations from the Dutch National Database Flora and Fauna covering 30 years from 1993 to 2023 (NDFF, 2026). The observations were limited to the floodplain area along the Waal River. For this study observations from 7 structured protocols were used. Average European Ellenberg-type moisture indicator values were used to identify preferred moisture levels for all species (Tichý et al., 2023), ranging from 1 (very dry) to 12 (aquatic). The values are expert-assigned rankings of plant species reflecting their ecological optima along key environmental gradients such as light, temperature, nutrients and moisture (Tichý et al., 2023).

An example of a common species in floodplains associated with dry conditions is, *Eryngium Campestre* with an average Ellenberg moisture value of 2.97 and for wet conditions, *Persicaria amphibia*, with an average Ellenberg moisture value of 10.63 (Tichý et al., 2023). After filtering species without Ellenberg moisture values or unresolved taxa, 50,081 observations remained from the original 98,958 records. An example of a characteristic species for Dutch floodplains and with missing Ellenberg moisture value is *Cirsium Arvense*.

For each year, the median Ellenberg value was calculated using all species observation of all floodplains. A linear regression was fitted to the yearly medians to assess temporal trends.

In addition, to capture potential trends at a finer scale, the same method was applied on the level of individual floodplain sections. A floodplain was included in the trend analysis only if it had been sampled more than five times during the study period, with at least 30 observations in each sampled year. This resulted in selection of 25 Waal floodplain sections covering in total 47477 reported observations.

Results

Over the past 30 years, we observe an increase in vegetation species that prefer drier floodplains, which is expressed by a negative slope of -0.047 (Figure 1). Although the trend is statistically significant (p-value = 0.0014) the magnitude of the change is small. The distribution of Ellenberg numbers covers the range from 12 (aquatic) to 2 (dry) for most of the years. However exceptions

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were the years 1994, 1996, 1998, 2015 and 2016 corresponding to years with smaller annual observations numbers (see Fig.1).

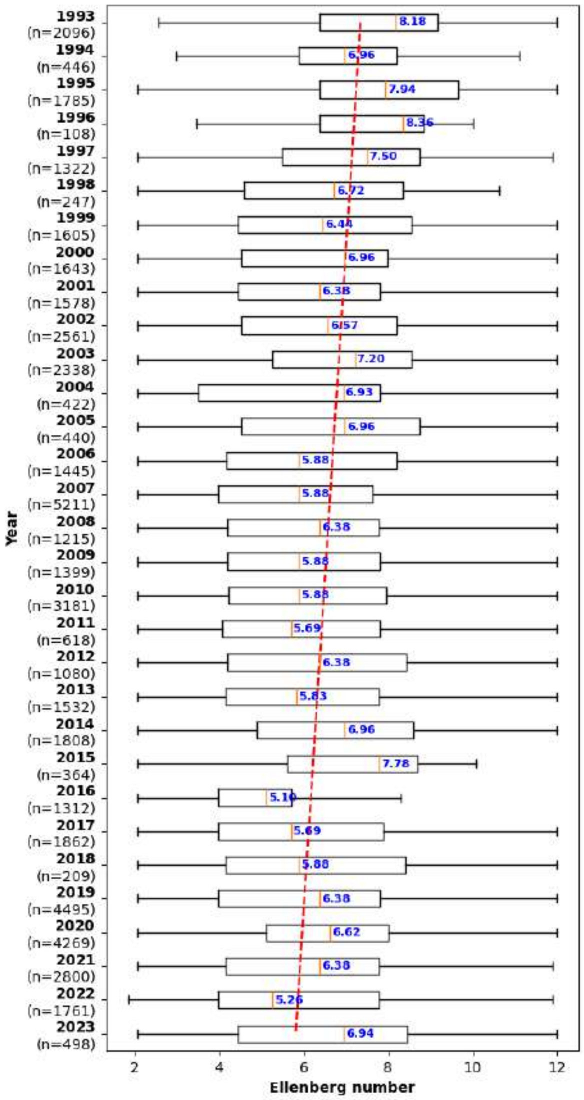

Figure 1: Distribution of annual Ellenberg moisture indicator values for Waal River floodplains. Annual medians in blue. (Linear regression of medians red dashed line:: slope -0.047, p-value 0.0014, R^2 =0.29).

Zooming in from the full river reach to individual floodplain sections (FPS) it was present that not all floodplain section exhibited a statistically significant trend towards species preferring wetter or drier conditions. Exemplarily 5 floodplain sections are presented in figure 2, with significant trends towards species preferring drier conditions ($p < 0.05$) observed for Millingerwaard (FPS1), Oosterhoutssche Waarden & Ossenwaard (FPS 3) and Willemspolder (FLPL 5). No trends were detected for Ewijkse Plaat (FPS 4) and Gendtse Waard (FPS 2).

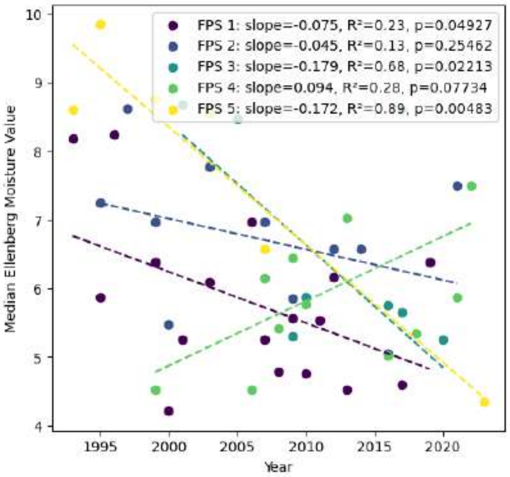

Figure 2: Median Ellenberg moisture values for selected floodplain sections (FPS), sorted from upstream (low number) to downstream (high number). 1: Millingerwaard, 2:Gendste Waard, 3: Oosterhoutssche Waarden & Ossenwaard, 4:Ewijkse Plaat, 5: Willemspolder

Conclusion

Our preliminary results indicate that a small but significant shift towards species preferring drier conditions was present in the Waal river floodplains over the period between 1993 to 2023. This shift could have been caused by channel bed incision, but alternative hypotheses will be tested in future work (groundwater levels, terrain height changes or meteorological differences). Ultimately, these findings can help to better predict how river interventions and associated hydrological changes affect vascular plant composition in floodplains.

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Hydro- and morphodynamic LES modelling of scour holes in rivers

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Keywords — Scour holes, LES modelling, heterogeneous subsoils

Introduction

Scour holes are local depressions in the river bed induced by hydrodynamic or geotechnical conditons. They have been observed in rivers around the world. These scour holes can pose a potential risk for the stability of dikes and infrastructure (e.g. Huismans et al., 2021; Barneveld et al. 2025).

Ensuring flood safety and functioning of essential infrastructure like pipelines and ferry landings requires effective prevention and management of scour holes. However, this is not straightforward, as their formation and evolution may be dependent on upstream conditions or subsurface architecture (Barneveld et al. 2025; Oldenhof et al. 2026a).

Local scour around a structure has been extensively studied for decades (e.g. Hoffmans & Verheij, 1997). However, multiple scour holes in the Rhine-Meuse system have formed over longer river sections in the absence of flow-obstructing infrastructure. Fig 1. shows an example of these scour holes along a section of the Meuse River after an extreme discharge event in July 2021 (Barneveld et al. 2025).

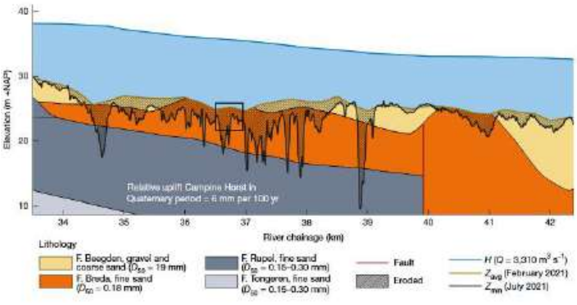

Figure 1. Scour holes in the Meuse River (dashed areas) after the 2021 flood event (Barneveld et al., 2025).

Subsurface geology was a primary trigger of the formation of these scour holes, as an easily erodible sediment layer was exposed in a hardly erodible cover layer. This type of scour hole formation has also been observed in other parts of the Rhine-Meuse river system (Sloff et al., 2013,). Fig 2. shows a schematized description of scour in a hardly erodible layer.

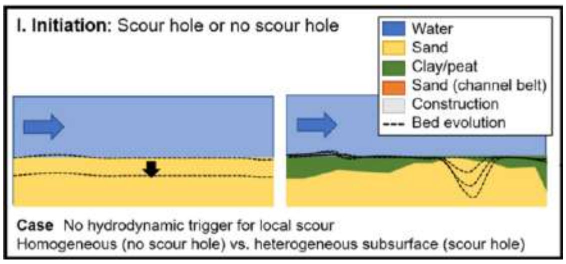

Figure 2. Example of the initiation of a scour hole in a heterogeneous subsoil (adapted from Huismans et al. (2021)).

In this research, scour holes in these heterogeneous riverbeds are studied. Better understanding of morphological development of scour holes could contribute to forming effective river management strategies.

Previous modelling studies on scour holes either only concerned the hydrodynamics in scour holes in heterogeneous subsoils or considered local scour around a structure. In this study, scour hole development in a heterogeneous riverbed is modelled both including both hydro- and morphodynamics. The aim of this study is to investigate the effects of flow conditions and subsoil composition on scour hole formation and development in rivers with heterogeneous subsoils.

Methods

As flows in scour holes are highly turbulent and have three-dimensional characteristics, a Large Eddy Simulation (LES) approach is likely to provide the most accurate estimations of flow and sediment transport. The relatively efficient open-source software TUDflow3D for process-based Computational Fluid Dynamics (CFD) modelling has been used effectively for scour simulations (De Wit et al., 2023) and is therefore also used in this study. The model is set up at an experimental scale, so results can be

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compared quantitatively with flume measurements by Oldenhof et al. (2026b).

First, the hydrodynamics in a predefined scour hole with a fixed bed are simulated. This step aims at validating the presence of flow characteristics like flow separation, a horseshoe vortex and the downstream wake in the model.

Secondly, sediment transport and bed evolution are added to study the formation of a scour hole in an exposed sandy patch in a gravel bed river starting from a flat bed situation. The shape of the developed scour hole is compared to the flume experiments and scour holes in the field. In the field, these scour holes have mild slopes around the edges and are relatively shallow (Oldenhof 2026a).

If the model provides accurate estimates of hydrodynamics and scour hole shape, the model can be extended to investigate the effect of an extreme discharge event on the development of an existing scour hole. Moreover, model simulations with a coarse top layer at the bed and a fine layer below could provide insight into the model’s capabilities to simulate the effects of bed form development on scouring potential.

Outlook

LES modelling could improve the understanding of flow processes and morphological development of scour holes in heterogeneous subsoils. This study will provide insights into the effects of (high) discharge and shear stresses and subsoil composition on scour development and the effect of bed forms on the potential for scour hole formation. Results could be used to identify locations with increased scouring potential. Moreover, it might support policy decisions on management of existing scour holes or prevention of scour holes at vulnerable locations in the river system.

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The Science Behind Room for the River 2.0's Bed Erosion Control Measures

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Keywords — Erosion, Room for the River 2.0

Introduction

The Room for the River 2.0 (RftR 2.0) program aims to stop large-scale bed erosion of the Rhine branches in the Netherlands. The authors have contributed to selecting and developing feasible solutions now under consideration for RftR 2.0. These solutions are grounded in a solid understanding of the flow and sediment transport processes driving the erosion. In this paper we show that not the total sediment transport, but the longitudinal gradient in transport is key to the large-scale erosion of the Waal River. We also discuss how this affects potential solutions and how uncertainties play a role.

Gradients

The RftR 2.0 prognosis is based on extrapolations of bed-level trends over the past 20 years. In the Waal, down to about km 930 (Zaltbommel), a clear erosion trend is present. Following Exner's law of mass conservation, this erosion translates to a positive gradient in sediment transport: more sediment leaves a river section than enters it. The cause of this gradient can be traced through the process of bed-material transport. We apply the Meyer-Peter and Müller (1948, MPM) shear-stress based transport formula for gravel and sand:

$$s_i \sim p_i D^{\frac{3}{2}} (\mu\theta - \xi\theta_{cr})^{\frac{3}{2}} =$$

$$= p_i D^{3/2} \left(\boldsymbol{u}^2 / \left(\sqrt{\boldsymbol{C}} \cdot C_{90}^{3/2} \Delta \boldsymbol{D} \right) - \xi\theta_{cr} \right)^{3/2}$$

Where D=grain size, C=Chézy roughness based on bed forms and grains, C_{90}=Chézy roughness based on grains, p_i=fraction, u=flow velocity, ξ=hiding and exposure function, θ=Shields value, θ_{cr}=critical Shields value.

Figure 1 shows a downstream fining gradient in measured grain size, while Figure 2 shows that flow velocity remains practically constant along the eroding reach for all discharges. Roughness does not contribute to the gradients either.

Using MPM in the 2D morphological model for the Rhine branches, we find that discharges between 1400 and 4500 m³/s at Lobith contribute most to annual transport rates and transport gradients (Figure 3).

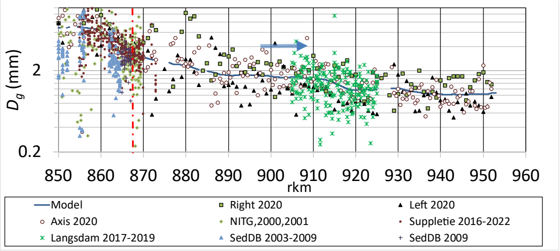

Figure 1. Geometric mean grain size along Boven Rijn and Waal measured and average model input. Dashed Red line is location of Pannerdense Kop

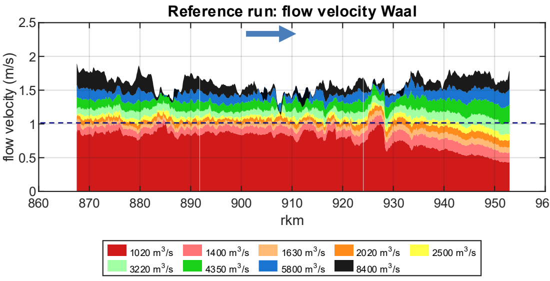

Figure 2. Flow velocities along the Waal for different discharges

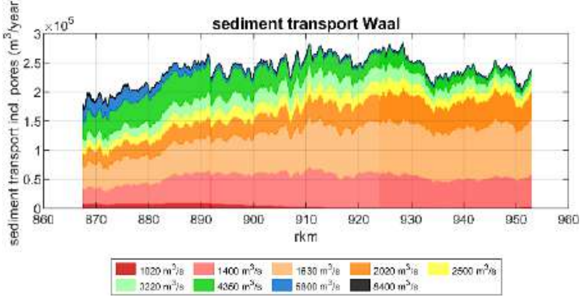

Figure 3. Computed annual sediment transport (DVR model) subdivided per discharge step

Similarly, Figure 4 shows that grain-size fractions 0.25–0.5 mm and 0.5–1.0 mm (sand) drive most of the transport gradient, due to the relative downstream increase in sand content.

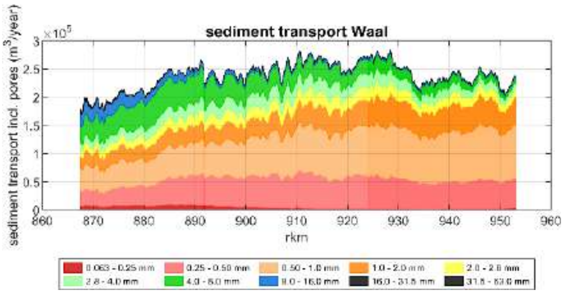

Figure 4. Computed annual sediment transport (DVR model) subdivided per size fraction

Due to ongoing erosion in both the Waal and the Pannerdensch Kanaal and Nederrijn, the discharge distribution gradually shifts toward the Waal. Because the Waal is much wider, equal erosion in both branches leads to a relatively larger increase in flow area in the Waal, making this a robust trend. Model simulations show that strong deepening of the Pannerdensch Kanaal cannot stop or reverse this shift. This confirms that mitigating erosion in the Waal is more effective and urgent than stopping erosion in the Pannerdensch Kanaal and Nederrijn.

Uncertainties

At shorter time scales (5–10 years), measured bed-level trends show much larger variation in both time and space. This is caused by, for example, the gradual implementation of RftR 1.0 measures such as groyne lowering and floodplain works, and by discharge fluctuations. Also, not all remaining sediment extractions in recent years have been fully accounted for in the translation of bed-level trends to transport gradients, meaning the defined gradient may be somewhat smaller than estimated.

The choice of transport formula also introduces uncertainty. When testing alternatives such as Ashida and Michiue (1972), Wilcock and Crowe (2003), and Engelund and Hansen (1967) in the 2D model, the overall contributions of discharge steps and sediment fractions remain comparable. However, most alternative formulas — except Engelund and Hansen — give a larger overall transport gradient than MPM. Increasing the effect of hiding and exposure also amplifies the computed erosion rates in the Waal.

Bed-erosion control measures

Which are the possible solutions for RftR 2.0 that are following from these analyses, and how can they be made effective or not?:

- Nourishments are the most flexible approach, as they can be adjusted if the effect differs from expectations or conditions change. However, they do not eliminate the gradient causing erosion and must therefore be continued indefinitely. A volume of approximately 150,000 m³/year is needed, largely from external sources, and must be distributed evenly over the eroding reach.
- Elimination of the downstream fining trend is considered too uncertain and too intrusive. This option has not been studied further.
- The multi-channel approach is most effective for creating a counteracting gradient in flow velocity by gradually widening the river downstream. For this to work, the multi-channels must reduce flow velocity in the main channel for middle-range discharges between 1400–5000 m³/s — the range shown to dominate the transport gradient. The channels must also increase in size downstream to allow a gradual decrease in flow velocity. As a result, the multi-channel solution must cover the full length of the Waal down to around Zaltbommel, where the transport capacity naturally drops to the level at the upstream start of the Waal. Sections that are not widened will continue to erode and will reduce the effectiveness of adjacent widened reaches. Disadvantages include limited adaptiveness and potential maintenance issues.

Further research and pilots with intensive monitoring are needed before a final decision can be made. For example, pre-nourishment with coarse material before regular finer sediment nourishments has proven effective in the Niederrhein, but it is not yet known whether this approach would work for the sand bed of the Waal.

Conclusions

The gradient in sediment transport — not total volume — drives Waal erosion, caused mainly by downstream fining at constant flow velocity. Medium discharges and sand fractions dominate the gradient and must be the target of any solution. The discharge shift toward the Waal is irreversible — fixing the Pannerdensch Kanaal won't help. Nourishments are flexible but must continue forever. The multi-channel approach can structurally fix the gradient, but must cover the full Waal length to Zaltbommel — gaps will undermine the entire solution. Both the prognoses for future erosion, and the effects of proposed solutions still contain various uncertainties. More research is needed to guarantee no-regret solutions for the future.

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Exploring measure possibilities within Room for the River 2.0 for the IJssel River near Steenderen, The Netherlands

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Keywords — Room for the River 2.0, IJssel

Introduction

The vulnerability of the Dutch river systems became evident when two major high-water events occurred in the 1990s. These events laid the foundation for integrated river-management strategies, such as Room for the River 1.0 (Ruimte voor de Rivier) program. Between 2007 and 2019, 34 measures like widening floodplains and bypass-channel constructions were implemented to reduce flood risk and improve spatial quality along the major rivers. As the rivers in the Netherlands continue to face increasing spatial pressure as well as more extreme high- and low flow conditions due to climate change, risk policy is more essential than ever. Within the recently launched Room for the River 2.0 program, future spatial demands for the rivers are being reassessed, including the changing discharge distribution of the Rhine branches (N. Asselman et al. [1], 2025). RftR 2.0 addresses a broad set of river functions: flood safety, riverbed restoration, ecological values and recreation, navigation, freshwater supply, regional economic development and spatial quality. Within this context, the IJssel River contains several hydraulic and ecological bottlenecks, and projected changes in Rhine branch discharge distribution highlight opportunities for further exploration of system-improving measures.

Study area

This internship investigates the area around Steenderen, located along the IJssel. This area has been identified as a 'searching area' for potential spatial reservations (BKL-area) beyond the floodplains (N. Asselman et al. [2], 2025). This area provides room for various types of river-widening measures. It currently contains hydraulic bottlenecks due to river narrowing and limited floodplain connectivity, also from an ecological perspective. The geomorphological structure of the IJssel valley in this region seems favourable for increasing the river area. Advisory documents (Consortium Ruimte en Afvoercapaciteit voor de Rivier 2025) indicate that potential dike relocations could reduce the water levels by approximately 35 cm. However, these estimates can be more specific. The aim of this study is therefore to explore what measures could contribute to make room for the river and reduce bottlenecks in the IJssel.

Methodology

This study compromises three components:

(1) System analysis: previous ideas of measures in the area are being reassessed and the hydraulic, ecological and geomorphological situation is analyzed. Background documents from RftR 2.0 and KRW (*Kaderrichtlijn Water*) are reviewed to identify the bottlenecks and opportunities in the research area.

(2) Variant development: conceptual design variants, such as dike relocations or floodplain- widening interventions are developed. The integral designs are based on the spatial characteristics of the area as well as hydrodynamics, land use, geomorphology, and existing KRW ambitions. These variants are qualitatively evaluated for spatial feasibility and expected hydraulic influence (high and low), after which a selection is refined further.

(3) Hydrodynamic modelling: the selected variant(s) are schematized using Baseline tools in ArcGIS Pro. A local model grid is generated with RGFGRID and integrated into the D-Flow FM model for hydraulic calculations. Simulations for scenarios are conducted under representative discharges. Post-processing tools are used to assess changes in hydraulics, and ecological implications are interpreted qualitatively.

Expected outcomes

Given the ongoing nature of the study, the content of this abstract/poster is initial and

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subject to refinement. This study is expected to identify one or more possible variants that contribute meaningfully to future discharge and storage capacity in the Steenderen area, also considering the RftR 2.0 considerations on for example spatial quality. The results of the hydrodynamic modelling will quantify the potential water level reduction and evaluate effects on flow velocity and floodplain functioning. Ultimately, the findings of this research would strengthen the case for the BKL-reservation Steenderen within the Room for the River 2.0 programme.

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To Aggrade or to Erode: Side Channels alongside Longitudinal Training Walls

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Keywords — LTW, Side channel morphology

Introduction

Ongoing riverbed degradation in the Waal River threatens navigability and alters discharge distribution within the Rhine delta (Arbós et al., 2024). Within the Dutch Room for the River 2.0 programme, creating multi-channel system is considered to mitigate this degradation. Longitudinal Training Walls (LTW) are a variant on such a system in which during intermediate and high flows part of the discharge is conveyed by a side channel. This reduces the flow velocity and thereby sediment transport in the main channel during these morphologically-important discharges. By reducing the sediment transport, LTWs can mitigate further bed incision.

Recent numerical modelling demonstrated that replacing groynes by LTWs along a 50 km reach of the Waal River can stop riverbed degradation (Barneveld et al., 2025). However, the computations predicted substantial sedimentation in the side channels resulting in an estimated maintenance need of approximately 200,000 m³ per year. The bed of the side channels was schematized with a nonerodable layer which effectively suppressed sediment outflow from the start of the computations resulting in sediment accumulation. The large maintenance need strongly influences the predicted long-term feasibility of LTWs.

The objective of this research is to determine the effect of side channel bed erodibility on its morphological development and maintenance need. We focus on the sensitivity to sediment layer thickness and initial grain size.

Method

A two-dimensional Delft3D model of the Waal River (Sloff et al., 2024; Barneveld et al., 2025) is applied to simulate side channel development. Fourteen side channels (80–100 m wide) are schematized along the inner-bends of the river with overlapping inlets and outlets. We computed five scenarios with two erodible layer thicknesses (0.4 m and 1.0 m) combined with fine and coarse grain sizes and a non-erodible reference case (0.0 m).

Results

An erodible side-channel bed fully changes the morphological response (Fig 1). Instead of net sedimentation, net erosion occurs. The amount of erosion increases with layer thickness: a 1.0 m erodible layer yields substantially more erosion than a 0.4 m layer, demonstrating that sediment export is constrained by sediment erodibility. A coarser initial grain size further reduces sediment transport, erosion and thereby maintenance need.

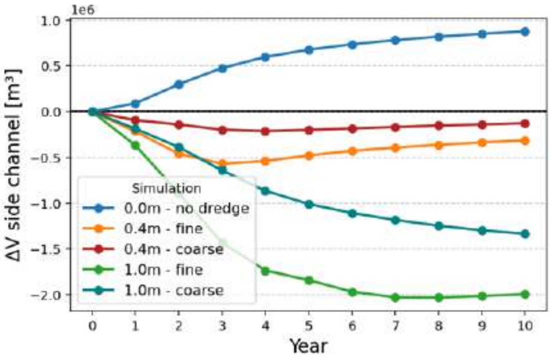

Figure 1. Total yearly sediment volume change over all side channels with respect to the initial bed.

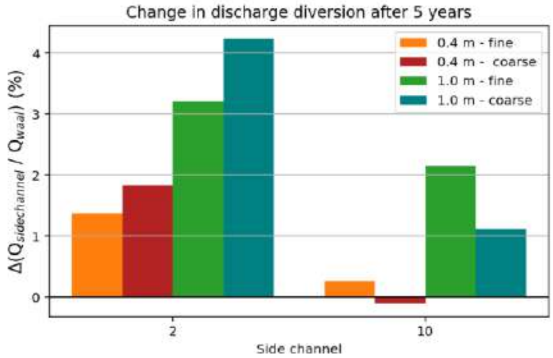

Figure 2. Change in discharge conveyance of the side channel after 5 years of computation for an upstream (2) and downstream side channel (10).

The observed erosion enhances discharge through the side channels, leading to an increased discharge conveyance in the side channel reducing discharge in the main channel (Fig. 2). This discharge increase can result in large aggradation of the main channel.

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Discussion

The results show that instead of 200.000 m^3/yr of aggradation in the side channel, with a slightly different assumption on erodibility a similar amount of yearly erosion can be expected. It shows the sensitivity of the model to such assumptions and the need for further research. We identify the following two main uncertainties:

Grid resolution

The grid is relatively coarse for the small channels that are considered. Additonalg rid cells over the width are needed to calculate the morphodynamics in a channel. In the model, the side channel is represented by only 3-4 grid cells. A model with a finer resolution might lead to a different discharge and sediment transport in the side channel and a change in sediment supply.

Sediment inflow over the sill

The entrance weir of the side channel is fully implemented in the bed schematisation, and this reduces the sediment supply to the side channel by bed slope effects. The bed slope relation used is calibrated on the 2D morphodynamics but overestimates the bed slope effect compared to experimental values (Baar et al., 2018). In addition, the model does not take suspended bed-material load nor the complex flow near weirs into account (De Ruijsscher et al. 2020). This results in large uncertainty in the sediment supply and thereby the bed-level development.

Conclusion

The computations show that the side channel is as likely to erode as to sedimentate. In Barneveld et al. (2025), the sediment transport in the side channel was underestimated resulting in sedimentation. The largest uncertainty now is the sediment supply to the side channel. This requires a more detailed model with additional calibration and validation.

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Tracing the source and fate of suspended matter in the Dutch Rhine branches

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Keywords — Sediment transport, fingerprinting, sampling, continuous flow centrifuge

Context and objective

In the framework of Delta-Enigma infrastructure, a sampling programme of suspended sediments has been set up to determine their transfer trough the Dutch Rhine Delta. For this purpose, the downstream variation in geochemical composition of suspended sediments is monitored along the main Rhine branch in the Netherlands (Bovenrijn – Waal – Merwede – Oude Maas).

Suspended sediment sampling and analysis

In close collaboration with Rijkswaterstaat, suspended sediment is sampled at eight locations twice a year since mid-2024 (Table 1; Fig. 1). During each sampling campaign, suspended sediment is sampled from the river water at six locations using a mobile centrifuge trailer owned by Rijkswaterstaat (Marine Systems, 2021). At the two other locations (Lobith and Vuren) suspended sediments are sampled in the frame of the regular MWTL (*Monitoring Waterstaatkundige Toestand des Lands*) monitoring programme of Rijkswaterstaat.

During sampling, river water is sucked in through a pump and transported to the continuous flow centrifuge, in which the suspended sediment is deposited on PTFE liners by centrifugation (Rijkswaterstaat 1996). After freeze drying, the samples are analysed for total element concentrations after total digestion with HF using ICP-MS and ICP-OES, and organic carbon using direct combustion/infrared detection at the GeoLab facility of Utrecht University.

Data processing outlook

From the downstream changes in sediment geochemical composition, the suspended sediment delivered from the upstream Rhine river basin will be traced through the Dutch delta and the downstream mixing with additional sediment sources including tributary inflows, riverbanks, and channel bed substrate will be quantified.

So far, three sampling campaigns have been carried out (September 2024, April and December 2025) (Table 1), all during relatively low water discharges. At the poster, I will present some first preliminary results from these first three sampling campaigns.

Table 1. Sampling locations

Location	**River branch**	**River km**	**Sampling campaign**		
			Sep. 2024	**Apr. 2025**	**Dec. 2025**
Lobith	Bovenrijn	862.5	x	x	x
Nijmegen	Waal	884.5			x
Druten	Waal	903	x	x	
Wamel	Waal	915	x	x	x
Zaltbommel	Waal	934.5		x	x
Vuren	Waal	951.5	x	x	x
Dordrecht	Nieuwe Merwede	971	x	x	x
Zwijndrecht	Oude Maas	984	x	x	x
Hoogvliet	Oude Maas	1004	x	x	x

Acknowledgements

The sampling campaigns were conducted with the support of Arjen Ponger and Rena Hoogland (Rijkswaterstaat-CIV). Afshin Neshad Ashkzari, Helen de Waard, Karin Oostdijk, Jan van Tongeren GeoLab are thanked for carrying out the sample preparation and analysis.

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Figure 1. Sampling locations along the main branch of the Dutch Rhine

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Visual analysis explains extrapolation uncertainty of calibration methods in rivers

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Keywords — Hydrodynamic modelling, calibration, uncertainty, lowland rivers, hydraulic roughness.

Introduction

Two-dimensional hydrodynamic models are widely used to predict water levels in rivers. Especially for flood risk management, hydrodynamic models provide valuable insights in extreme events with discharges beyond the range of available measurements (Kuhanestani et al., 2024). These predictions are strongly dependent on the model calibration. It is therefore very important to consider the uncertainties in input data and model parameters during the calibration procedure, as these uncertainties will propagate through the model and eventually affect the simulated water levels (Warmink et al., 2007).

Fundamental to the propagation of uncertainties is the calibration strategy that is applied. Different calibration strategies, such as channel-only calibration (applying a calibration factor to only the main channel Manning roughness) or joint-calibration (applying a calibration factor to both the main channel and the floodplain Manning roughness), may lead to significant differences in simulation outcomes.

Focusing on the uncertainty in roughness parameters and the uncertainty in upstream boundary discharge during the calibration procedure, this study investigates how the propagation of these uncertainties depends on the calibration strategy that is used.

Method

In the 2D hydrodynamic D-Flow FM model of the river Waal (Kosters et al., 2022), calibrations are performed for two sources of uncertainty. Based on a Monte Carlo analysis that was performed by Berends et al. (2019), two sets of roughness values – representing the upper and lower limit of a confidence interval – have been defined to consider roughness uncertainty in the model. Regarding the uncertainty in upstream boundary discharge, an upper and lower limit of +3.8% and -1.5% deviation with respect to the current discharge data have been assumed respectively. This is based on an analysis of the water balance at Pannerdensche Kop and measurement deviation at other branches.

To gain more theoretical insights, a second model with a more simplified nature will be introduced. This model is based on the Divided Channel Method (DCM), where a distinction is made between a floodplain and a main channel section. For a pre-defined static discharge and a single cross section definition, the model calculates the water levels that correspond to a particular combination of the main channel and floodplain roughness (n_{mc} & n_{fp}). By considering these parameters as independent variables and using various combinations of roughness values as model input, the relation between water levels and roughness values is obtained.

Results

Regarding the roughness uncertainty, clear differences are found between the two calibration strategies in the 2D D-Flow FM model (Fig. 1). The absolute difference in simulated water levels for the extrapolated discharge is 0.12m at most for the joint-calibration, while the channel-only calibration shows a maximum difference of only 0.05m.

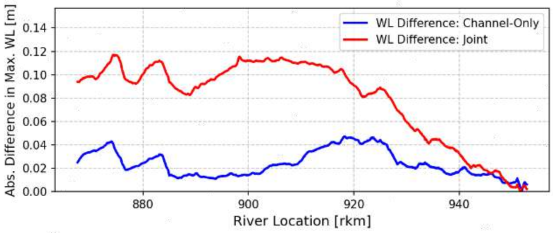

Figure 1. Absolute difference in maximum simulated water levels for both calibration methods, based on the upper and lower limits of the roughness uncertainty. The conventional Rhine kilometre (rkm) indicates the location along the river.

The differences between the two calibration methods can be explained using the simplified DCM model. The two white dots in Fig. 2 represent the starting points of the calibration based on the Monte Carlo data (the small grey dots). The black line presents all possible locations where the calculated water depths correspond to the observations. The calibration can then be visualized by moving from the

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original position to a point on this line. The path towards this line depends on the calibration strategy that is used: horizontal for channel-only and diagonal for joint-calibration. The points on this line will not have the same water level anymore when extrapolated to a high discharge event. Hence, the difference between the two methods can be explained by the distance between the red points (joint-calibration) compared to the blue points (channel-only).

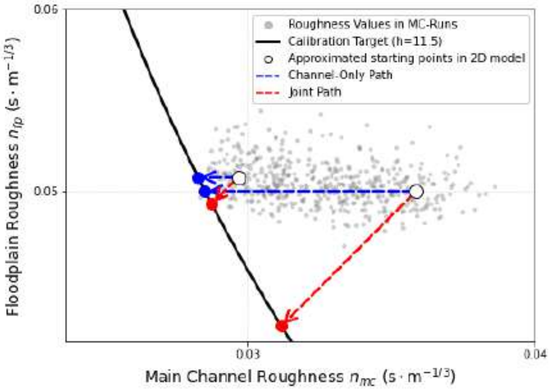

Figure 2. Visualization of the calibration procedure for the roughness uncertainty cases. Due to the simplified nature of the DCM model, it can be questioned whether the water depth of 11.5m is representative in an absolute sense. However, based on the values of the calibration factors that are obtained in the 2D model, it is assumed that this accurately visualizes the calibration.

For the discharge uncertainty, the absolute difference in simulated water levels is relatively high for both calibration methods (Fig. 3). The channel-only approach shows slightly more consistent results than the joint-calibration, with a smaller water level difference across the model domain. Furthermore, in contrast to the roughness uncertainty, their paths seem almost identical with similar peaks and curves.

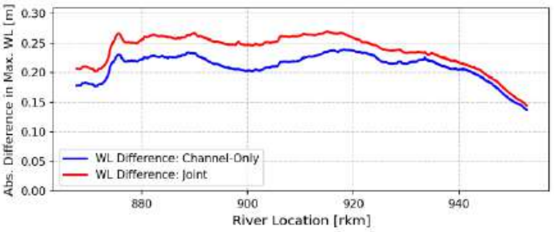

Figure 3. Absolute difference in maximum simulated water levels for both calibration methods, based on the upper and lower limits of the discharge uncertainty.

A visualization of the calibration including discharge uncertainty is presented in Fig. 4. Clearly visible is that for both calibration methods, the angle between the line connecting the roughness points (indicated by ΔWL) and the calibration line (black) is similar for both methods. As a result, the differences between the two methods are relatively small and their paths in Fig. 3 are very similar. Water levels at extrapolated discharge were also calculated in the simplified model for the calibration points. The absolute difference in water levels in the DCM model are comparable to the results of the 2D model (0.25m for channel-only, 0.27m for joint).

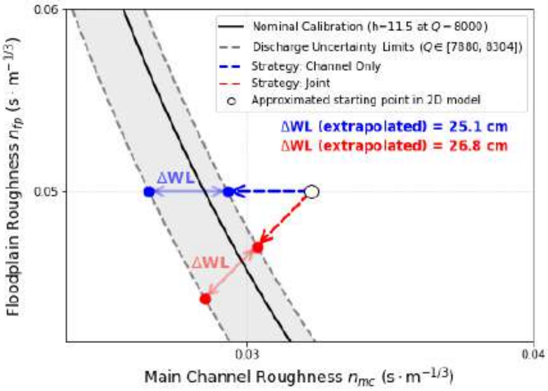

Figure 4. Visualization of the calibration procedure for the discharge uncertainty cases. ΔWL is included to indicate where the difference in simulated water level comes from and the values for ΔWL in the top right corner are calculated by the DCM model.

Conclusion

We conclude that, for the river Waal, the channel-only method is less sensitive to both types of uncertainties. Especially for the roughness uncertainty, significant differences in maximum water levels are visible. This can be explained by the fact that the variation in floodplain roughness is very small in the Waal case. As a result, when significant correction is needed, joint-calibration leads to unrealistic roughness values. Important to note is that the variation in floodplain roughness in this study is based on several assumptions. For example, classification error is not considered.

Furthermore, results show that the DCM-model is able to provide valuable insights and logical explanations for the behaviour of water level uncertainty after calibration in a 2D model.

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Balancing accuracy and efficiency in centennial-scale 2D morphodynamic river modelling

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Keywords — Flexible Mesh, Morphology

Introduction & Broader Context

Engineered river systems, such as the Lower Rhine, are currently facing pressures from historical channelisation and projected climate change, which, together, exacerbate issues such as channel bed incision and skewed discharge partitioning at bifurcations (Ylla Arbós, 2021; Blom, 2024). In response to these challenges, Rijkswaterstaat is currently exploring various large-scale intervention strategies under the new Room for the River 2.0 programme. To determine how robust these interventions remain under future climate scenarios characterised by increased hydrograph variability and sea level rise, river management requires simulating large-scale measures, such as Longitudinal Training Walls (LTWs) with or without side channels, and floodplain lowering, over a centennial timescale.

While one-dimensional (1D) models have been successfully employed for long-term simulations of the Lower-Rhine (Ylla Arbós, 2023; Chowdhury, 2025), they rely on nodal-point relations, of which the formulation contains challenges to adequately capture critical 2D/3D flow structures, lateral morphological changes, and complex bifurcation feedback mechanisms that influence the discharge partitioning in the system. As an alternative, we consider two-dimensional (2D) depth-averaged morphodynamic modelling. However, applying high-resolution 2D models over large spatial domains (~400 km) for century-long periods presents a computational bottleneck.

Methodological outline

To overcome this prohibitive computational cost, this study investigates the optimal flexible mesh resolution required for large temporal and spatial scale 2D simulations. Using the D-Flow Flexible Mesh (FM) solver on a High-Performance Computing (HPC) cluster, we test an automated workflow where the grid resolution is strategically varied. The mesh is refined to a maximum resolution of approximately 5 x 10 m around complex, critical areas, specifically sections containing LTWs, while other, uniform river reaches without expected complex flow patterns are deliberately

coarsened to cell sizes in the order of hundreds of meters. We systematically quantify the trade-off between computational gain and physical accuracy over a 10 km straight, uniform river section on a large time scale. Bomers et al. (2019) demonstrate that coarse grid resolutions introduce significant numerical friction and grid shape influences numerical viscosity in hydrodynamic modelling. Building upon this, our study investigates how these induced hydrodynamic distortions cascade into morphodynamic results. Specifically, we examine the isolated effects of overall grid coarsening and the spatial transitions between fine and coarse resolutions on morphological outcomes. To quantify these effects, the performance of the strategically coarsened models is evaluated against a fully high-resolution baseline prediction on a uniform river section.

Expected Outcomes and Significance

This study explores the minimal required level of detail necessary to adequately (accurately and within reasonable time) represent various river interventions and complex bifurcation hydrodynamics in a 2D flexible mesh. The research gives information about the extent to which the grid can be strategically coarsened to accelerate centennial-scale morphodynamic simulations. The main outcome is a practical grid-generation strategy that balances computational efficiency and morphodynamic accuracy. This approach can be used for subsequent large-scale, long-term 2D morphodynamic simulations to achieve computational feasibility. The subsequent full-scale models will be used to explore further the non-linear interactions of combined river interventions under climate change scenarios, directly contributing to the design of a future-proof, climate-resilient river network.

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Navigating Rivers: NCR-days themed River Walk

Campus 17:15 – Kromme Rijn – Tolsteegsingel – 18:15
Nieuwe Gracht – Oude Gracht – Catharijnesingel – Restaurant 19:00

Kim Cohen* -- *Department of Physical Geography, Utrecht University*

Keywords — Discharge Loss, Bifurcation, Fishing Permits, Legacy Geomorphology, Room for the Singel, Old NCR

Itinerary

Utrecht is a city on the meandering Rhine and we will discover how the river was and is running in a 6.5-km walk, lasting 1h45. We start at the campus and end downtown, in time for diner.

17.15-18.00: we walk along the **Kromme Rijn**. Biggest looser amongst the Dutch rivers, as briefly to explain at one stop. Otherwise we just pull along a towpath **(jaagpad)**, enjoying fresh air.
18:00-18:15 **Ledig Erf mega-bifurcation**. Here the river today splits into Vaartsche Rijn, Singel and Oude Gracht. Here the river originally split into Oude Rijn and Utrechtse Vecht. An explanation will follow.
18:10 **Tolsteeg singel**: natural feature (!).
18:20 **Nieuwe Gracht**: response to 1374 flood?
18:40 **Oude Gracht**: bankful wharves.
18:50-19:00 Room for the **Catharijne singel**.

Background

Utrecht (Fig. 1) as a settlement goes back to Roman times. It takes its name from a fort (*castellum*) dubbed ***Traiectum***, founded on the point bar of the Rhine of the time, opposite the fork of the river Vecht (50 AD), nowadays **Domplein**. Romans went, returned and went (270-400 AD). Discharge division between Rhine and Vecht varied. Bishops came (690 AD), went (866 AD) and returned (918 AD), Danish viking warlords interrupting. Meanwhile, Rhine and Vecht gradually lost discharge, except during passage of peak discharge. Frankish, German and Habsburgian Emperors ruled. Utrecht Church and Commerce made mutual deals. One such a double deal regarded city rights, embankment of the Lek, damming the Kromme Rhine upstream and digging of the Oude Gracht and Vaartsche Rijn (1122 AD).

Kromme Rijn discharge division

Combining geomorphology (meander size), geology (dating), sedimentology (bar accretion, abandonment-stage deposition, flooding) with network analysis (acknowledging bifurcations and avulsion) the discharge loss of the Utrecht rivers (Kromme Rijn, Oude Rijn, U. Vecht) in the delta to successors as Lek, Waal, Hollandse and Gelderse IJssel was postulated (Fig. 2), at least for normal stages of Rhine discharge (below bankful, pre- and post-embankment).

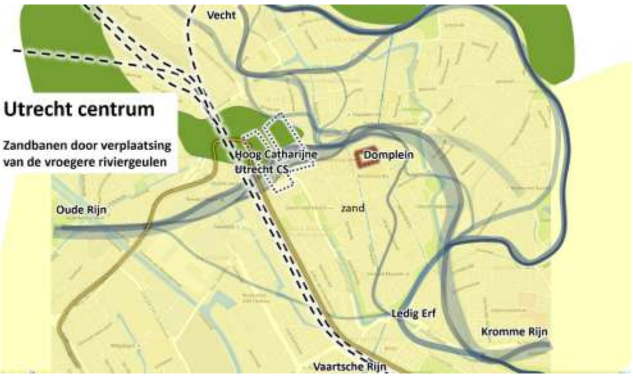

Figure 1. Roman and Medieval Utrecht Rhine and Vecht meanders (blue) and the sandy deposits (yellow) their migration left below most of the city.

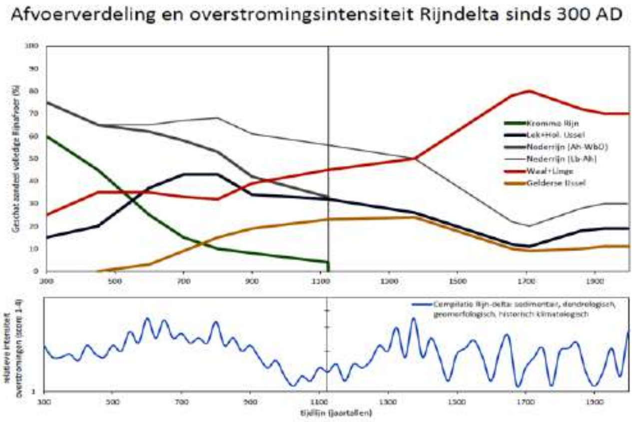

*Figure 2. **Kromme Rijn** discharge loss 300-1122 AD [~60% dropping to ~5%; at flows ~3000 m^3/s at Lobith] compared to discharge further Rhine delta network [**Nederrijn**; **Lek**; **Waal**; **Gelderse IJssel**] up to present. Aligned with a flooding intensity compilation based on archaeology, oxbow sedimentary fills and tree-rings (first millennium) and historic accounts and instrumented record (second millennium). Intensity peaked 550-800 and 1342, 1374. It was low 1000-1200 AD. Cohen (2022).*

It shows the Late Roman Kromme Rijn to lose discharge to the upcoming Lek and Hollandse IJssel (Van Dinter et al. 2017). From about 550 AD and throughout the flooding intense Dark Ages, the Lek was the largest branch, with the Waal slowly catching up, surpassing it from 900 AD, also helped by the new formed Gelderse IJssel (owing to floods between 650 and 800). It left the Kromme Rijn a lazy river, well navigable throughout the year (Dorestad as a southerly Frisian trade centre), and used by the Rhine to divert flood waters at times of flood, testified for by clays separating Roman time archaeological surfaces from Medieval ones in the inner city. **The meanders of the Kromme Rijn we walk along, last migrated naturally during the passing of Dark Ages floods.**

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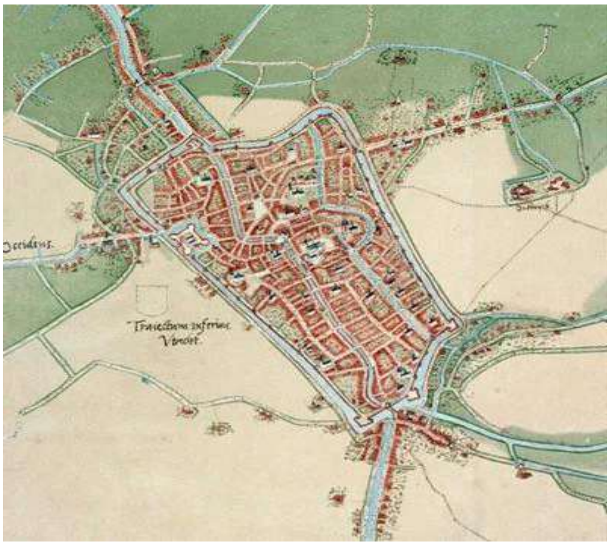

Figure 3. Utrecht ca. 1550 (Jakob van Deventer historic map). Note SE corner of city where Kromme Rijn – Ledig Erf – Tolsteeg-singel reveal meander morphology, with Abstede on the inner bank.

Ledig Erf – Tolsteeg-singel

At Ledig Erf around the year 1000, you would have seen the bifurcation of Rhine into Vecht and Oude Rijn. The former is still the Tolsteeg singel waters. The latter is the bendy southern tip of the Oude Gracht (Twijnstraat wharf). Figure 3 shows the situation 500 years later, with additional waters added. It is now a quadri-furcation. The **natural origin of the Tolsteeg section of the Utrecht singel** (city moat) echoes in historic documents via **fishing rights for the Bishop**. In the newly 'man-dug' further sectors of the Singel, not Bishop but citizens held those rights (Van Dinter et al., 2017**)**

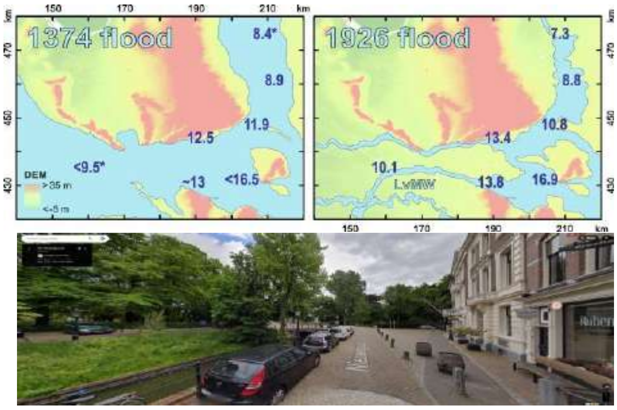

Figure 4. Maps comparing 1374 and 1926 winter flood peaks: extent and water table heights (Van der Meulen et al. 2022). Foto: Utrecht: Nieuwe Gracht facing Tolsteeg and Abstederbrug, with bending street line facade. Wharf +1 m. street +3 m NAP.

Abstederbrug – Nieuwe Gracht

The **Nieuwe Gracht** (Fig. 4) was dug in 1390-1393, a decade or so following the 1374 flood, historically known to have majorly affected the city (as did the plague in the 1350s). Where we enter the street along the canal, a knick in the house facades echoes the course of a medieval channel (Kipp-Brinkman, 1994). Some regard this a natural crevasse, others a trace of 1374 flood waters piercing the then city wall. The latter idea puts an extra tentative central delta flood marker for the **'1374 millennial flood',** estimated to have peaked between 14,400 and 18,500 m^3/s (at 'Lobith'; Ngo et al. 2023).

Figure 5: bouwgeschiedenisutrecht.nl/project/Werven

Oude Gracht – Bankful Wharves

The Oude Gracht (Figs 1,3,5) has several sections. The north (dug 1050 AD) connects the centre proper to the river Vecht. The south connects the centre proper to Rhine (dug ~1125 AD) and Vaartsche Rijn (dug ~1150 AD) that connected through to Hollandse IJssel and Lek. Near city hall and Domplein, the two sections connect. Figure 1 reveals that section to trace the Late Roman main Rhine channel. Water table and width of Oude Gracht + wharves still echo accommodation of routing fluctuation discharge through the city, changed with the 1122 decisions. Loss of annual flooding regime allowed for commercial adaption. Sloping banks became wharf + cellars. **Imagine this bankful.**

Room for the Catharijne-singel

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About NCR

Objective of NCR

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

The objective of NCR is:

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

This translates to:

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

Domains

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

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

NCR Organisation

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

- **Programme Secretary (Dutch: Programmasecretaris)**
  Safeguards the continuity of NCR activities, secretary to SB and PC; monitors of agreed actions by the SB and PC; reports of NCR finances; management of all NCR communications.
- **Supervisory Board (Dutch: Commissie van Toezicht)**
  Supervises the implementation of the cooperation agreement, settles disputes and approves the scientific programme.
- **Program Committee (Dutch: Programmacommissie)**
  Determines the scientific programme, stimulates and initiates proposals for activities and integration of knowledge, ideas, experiences and results.
- **Young NCR (Dutch: Jong NCR)**
  Established in December 2020, YNCR strives to strengthen the network of young/early-career scientists within NCR.

Institutional partners

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

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

Accountability

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

Table 1: The composition of NCR Boards in 2026. Persons marked with * are chairpersons.

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