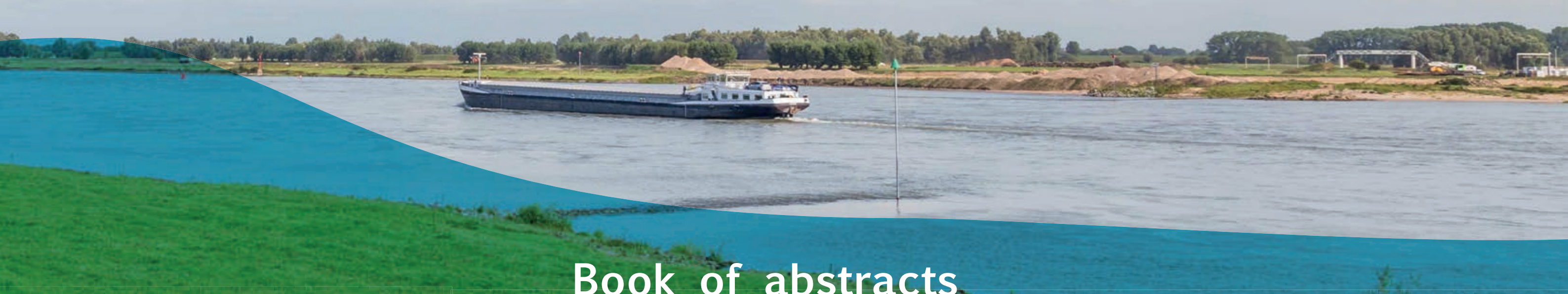

Book of abstracts

Land of Rivers

NCR DAYS 2019 | Utrecht,
January 31, February 1

Esther Stouthamer, Hans Middelkoop, Maarten Kleinhans,
Marcel van der Perk, Menno Straatsma (eds.)

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River studies

NCR DAYS 2019

Land of Rivers

Esther Stouthamer, Hans Middelkoop, Maarten Kleinhans
Marcel van der Perk & Menno Straatsma

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Preface

It is a great pleasure to welcome you at the 21st annual meeting of the Netherlands Centre for River studies (NCR-Days) at Utrecht University. The theme of the NCR-Days 2019 is 'Land of Rivers' closely linking up with river, estuary and delta research carried out at Utrecht University. The theme highlights the linkages between the river and the land, formed and shaped by nature and humans. We have put together an exciting programme with inspiring plenary keynote lectures, oral and poster presentations and interactive workshops.

We have defined four plenary sessions, focusing on different subjects: discharge extremes, ecology and morphology, river management, and long-term river behavior. Every session starts with a keynote lecture fitting the subject, and is followed by four oral presentations and pitches for the poster presentations. On Friday there will be three interactive workshops: Virtual River demonstration, River Lab and Sediment management strategies.

The keynote lectures will be given by dr. Menno Straatsma (Utrecht University), prof. Helmut Habersack (University of Natural Resources and Life Sciences Vienna), prof. Lotte Jensen (Radboud University Nijmegen), dr. Astrid Blom (Delft University of Technology). They will cover intervention planning in lowland rivers, sediment transport and river morphology, the Dutch identity and water management from a cultural-historical perspective, and channel incision and rapid bed surface coarsening in the branches of the upper Rhine delta. These lectures will set the scene for sixteen oral presentations and thirty poster presentations.

The scientific program subsequently sets the scene for lively social interaction during the breaks and joint dinner on Thursday. Be prepared to enjoy good food and to answer fluvial trivia during the evening pub quiz.

The organization of the NCR-Days greatly benefited from the support of Ruth de Klerk, Pepijn van Elderen, Margot Stoete, Harold van de Kamp, Tim Winkels, Willem-Jan Dirkx, Bas Knaake, Teun van Woerkom, Donald Schuurman, Monique te Vaarwerk and Koen Berends.

We wish you all inspiring and joyful NCR-Days!

Esther Stouthamer
Hans Middelkoop
Maarten Kleinhans
Marcel van der Perk
Menno Straatsma

Program

NCR Days 2019 Conference Programme

Thursday, January 31	
Marinus Ruppert Building – hallway	
09:00	Registration
	Coffee and tea
Marinus Ruppert Building – Paars	
09:30 – 9:45	**Opening & announcements**
09:45 – 12:00	**Session 1 – Discharge Extremes** *Chairs: Esther Stouthamer/Iris Niesten*
9:45 – 10:30	**Keynote:**
	A level playing field for intervention planning in lowland rivers
	Menno Straatsma (Utrecht University)
10:30 – 10:45	**Effect of upstream flooding on extreme discharge frequency estimations**
	Rita Lammersen (Rijkswaterstaat)
10:45 – 11:00	**The effect of dike breaches on downstream discharge partitioning**
	Anouk Bomers (University of Twente)
Marinus Ruppert Building – hallway	
11:00 – 11:30	Break
Marinus Ruppert building – Paars	
	Session 1 – Discharge Extremes (continued)
11:30 – 11:45	**Should we build more side-channels?**
	Koen Berends (University of Twente/Deltares)
11:45 – 12:00	**Experiments on the relation between grain size distribution and the initiation of pipe erosion**
	Willem-Jan Dirkx (Utrecht University)
Marinus Ruppert Building – hallway	
12:00 – 14:00	Lunch & Poster sessions 1 & 2
	see poster programme
Marinus Ruppert Building – Paars	
14:00 – 16:45	**Session 2 – Ecology and Morphology** *Chairs: Marcel van der Perk/Frances Dunn*
14:00 – 14:45	**Keynote:**
	Sediment transport and river morphology – an important link
	Helmut Habersack (University of Natural Resources and Life Sciences Vienna)
Marinus Ruppert Building – Paars	
14:45 – 15:00	**Modelling degradational rivers**
	Víctor Chavarrías (Delft University of Technology)
15:00 – 15:15	**Monitoring flow and sediment transport at strongly asymmetric bifurcations of a large sand-bedded river**
	Karl Kästner (Wageningen University)
15:15 – 15:30	**Measuring and modeling the development of side channels**
	Pepijn van Denderen (University of Twente)
Marinus Ruppert Building – hallway	
15:30 – 16:00	Break

NCR Days 2019 Conference Programme

Marinus Ruppert Building – Paars		
	Session 2 – Ecology and Morphology (continued)	
16:00 – 16:15	**Upstream perturbation and floodplain formation effects on meandering river pattern and dynamics**	
	Steven Weisscher (Utrecht University)	
16:15 – 16:30	**Levee morphology and evolution in the fluvial-tidal realm**	
	Lonneke Roelofs (Utrecht University)	
16:30 – 16:45	**Removal of bank protection to ecologically improve the River Meuse**	
	Clara Chrzanowski (Deltares)	
Marinus Ruppert Building – hallway		
16:45 – 18:15	Drinks & Bites	NCR boards meeting
19:00 – 22:30	Conference dinner & Pubquiz	
	Restaurant De Rechtbank (welcome from 18:30)	

Friday, February 1			
Marinus Ruppert Building – hallway			
08:30	Registration		
	Coffee and tea		
Marinus Ruppert Building – Paars			
09:00 – 9:15	**Opening & announcements**		
09:15 – 11:45	**Session 3 – River Management** *Chairs: Menno Straatsma/Koen Berends*		
9:15 – 10:00	**Keynote:**		
	Dutch identity and water management: a cultural-historical perspective		
	Lotte Jensen (Radboud University Nijmegen)		
10:00 – 10:15	**The added value of Nature-Based Solutions**		
	Ralph Schielen (University of Twente/Rijkswaterstaat)		
10:15 – 10:30	**Controls of renewed sediment trapping in low-lying polders of the Bangladesh Delta**		
	Md Feroz Islam (Utrecht University)		
Marinus Ruppert Building – hallway			
10:30 – 11:00	Break		
Marinus Ruppert building – Paars			
	Session 3 – River Management (continued)		
11:00 – 11:15	**Improving accuracy of weir/groyne discharge formulations for highly sub-critical (submerged) conditions**		
	Harmen Talstra (Svašek Hydraulics)		
11:15 – 11:30	**Community of Practice Lowland River Systems**		
	Rien van Zetten (Rijkswaterstaat)		
11:30 – 11:45	**Poster pitches (sessions 3, 4)**		
11:45 – 12:30	**Workshop**	**Workshop**	**Workshop**
	Virtual River demonstrator *Robert-Jan den Haan*	RiverLab *Aukje Spruyt*	Sediment management strategies *Matthijs Boersema*
Marinus Ruppert Building – hallway			
12:30 – 14:00	Lunch & Poster sessions 3, 4		
	see poster programme		

NCR Days 2019 Conference Programme

Marinus Ruppert Building – Paars	
14:00 – 16:15	**Session 4 – Long-term river behavior** *Chairs: Hans Middelkoop/ Jasper Candel*
14:00 – 14:45	**Keynote:**
	The branches of the upper Rhine delta: channel incision and rapid bed surface coarsening
	Astrid Blom (Delft University of Technology)
14:45 – 15:00	**Declining fluvial sediment delivery to major deltas due to human activity**
	Frances Dunn (Southampton University/Utrecht University)
Marinus Ruppert Building – hallway	
15:00 – 15:30	Break
Marinus Ruppert Building – Paars	
15:30 – 15:45	**Reconstruction of differential formation and phasing of crevasses in the fluvial-tidal realm of the Old Rhine**
	Jelle Moree (Utrecht University)
15:45 – 16:00	**River delta floodplains: diffusive deposition, crevasse splays, or avulsions?**
	Jaap Nienhuis (Tulane University/Utrecht University)
16:00 – 16:15	**Depth-limiting resistant layers tune the shape of tidal bar pattern of Holocene alluvial estuaries**
	Harm Jan Pierik (Utrecht University)
16:15 – 16:30	**Wrap up & closing**
Marinus Ruppert Building – hallway	
16:30 – 17:30	*Drinks and awards*

NCR Days 2019 Conference Programme

Thursday, January 31

12:00 -14:00 | Marinus Ruppert Building – Hallway

Session 1 – Discharge Extremes

Poster

01	**Dike cover erosion by overtopping waves: an analytical model** Vera van Bergeijk (University of Twente)
02	**Incorporating subsurface heterogeneity in hydrological models for assessing dike stability** Teun van Woerkom (Utrecht University)
03	**Geological framework for representing subsurface heterogeneity relevant for piping** Tim Winkels (Utrecht University)
04	**The influence of subsurface heterogeneity on scour hole development in the Rhine-Meuse delta, the Netherlands** Bas Knaake (Utrecht University)
05	**Propagating main channel roughness uncertainty in the bifurcating Dutch Rhine system** Matthijs Gensen (University of Twente)
06	**Flow patterns for contrasting discharge conditions in a lowland sharp river bend: implications for backwater** Tjitske Geertsema (Wageningen University)
07	**The effects of Land reclamation along gravel-bed braided system: Mao River, Bhutan** Mahsa Ahmadpoor (IHE Delft)

Session 2 – Ecology and Morphology

08	**Empirical channel pattern predictors – why do they work?** Jasper Candel (Wageningen University)
09	**Impact of vegetation on braided river morphology under changing flood conditions in a physical model** Bas Bodewes (University of Hull)
10	**Estimating sediment travel distances in Alpine catchments through UAV based sediment shape indices** Alessandro Cattapan (IHE Delft)
11	**Mapping river bank erosion and morphology using drone imagery for the Buëch River in France** Steven de Jong (Utrecht University)
12	**Efficient vegetation management through remote sensing in small streams** Koen Berends (Univerity of Twente)
13	**Operational monitoring of floodplain vegetation using google earth engine** Gertjan Geerling (Deltares)
14	**Simulation of cross-sectional variations of the Pilcomayo River channel, Paraguay** Alberto Grissetti (IHE Delft)
15	**Cyclic steps on the Loess Plateau, China: Field Survey and Numerical modelling** Xin Zeng (Technical University Delft)
16	**Low-angle dune morphodynamics under shallow flow** Suleyman Naqshband (Wageningen University)
17	**Interaction of dunes and bars in the Dutch Waal River** Timo de Ruijsscher (Wageningen University)
18	**Examination of the declining trend in suspended sediment loads in the Rhine River in the period 1952-2016** Marcel van der Perk (Utrecht University)
19	**Estimating the attenuation of sound by fine sediment using a tilted ADCP transducer** Judith Poelman (Wageningen University)
20	**High frequency monitoring of suspended sediment properties to accurately quantify suspended sediment fluxes** Dhruv Sehgal (Wageningen University)
21	**Modelling the long term dynamics of the Mara wetland (Tanzania) using a 2D-hydromorphodynamic model** Ibrahim John Migadde (IHE Delft)

NCR Days 2019 Conference Programme

Friday, 1 February

12:30 -14:00|Marinus Ruppert Building – Hallway

Session 3 – River Management

22	**Development of a methodology to assess future functional performance of a river system** Koen Hiemstra (Technical University Delft)
23	**Developing a tangible gaming interface for Virtual River** Robert-Jan den Haan (University of Twente)
24	**Surface screens for maintenance of side channels** Thomas Oostdijk (Technical University Delft)
25	**Development of a new Rhine branches model with Delft3D-Flexible Mesh** Iris Niesten (Deltares)

Session 4 – Long-term River Behaviour

26	**Towards Best Practices for Mitigation of Channel Degradation** Matthew Czapiga (Technical University Delft)
27	**Can floodplain excavation help to mitigate bed erosion?** Ralph Schielen (University of Twente)
28	**Long term governance in the Noordwaard: matching physical features, social needs and economic revenues** Derk Jan Stobbelaar (University of Applied Sciences Van Hall Larenstein)
29	**Response of the upper Rhine-Meuse delta to climate change and sea-level rise** Clàudia Ylla Arbós (Technical University Delft)
30	**Long-term development of lowland rivers Rivers2Morrow – a research program** Matthijs Boersema (Rijkswaterstaat)

Keynote speakers

Menno Straatsma

A level playing field for intervention planning in lowland rivers

Adapting a densely populated delta to the combined impacts of climate change and socioeconomic developments presents a major challenge for the sustaining multiple functions throughout the 21st century. The primary function of flood conveyance requires interventions to convey higher discharges from upstream, while taking the rising sea level into account that determines the downstream boundary condition. The ecological function requires a divers natural wetland with suitable habitat for all taxonomic groups of species that are characteristic of the fluvial area, which contrasts with the agricultural function that thrives by dry meadows and agricultural fields. Lastly, navigation requires harbours and deep channels, and housing and industries also need additional space. The conflicting demands for space require evidence-based decisions making.

Decisions on the interventions require an overview of cost and benefits immediately after the implementation of the measure and a solid understanding of the temporal development regarding morphology, vegetation succession, biodiversity, and costs. An extensive overview of interventions and their development over time gives insight in the possibilities and limitations interventions. Therefore, the objective was to automate the intervention planning and evaluation to create an overview of costs and benefits of common landscaping measures within the context of increasing discharge and sea level rise. Seven intervention types were evaluated on their efficiency in flood hazard reduction, potential biodiversity, number of stakeholders as a proxy to governance complexity, and measure implementation cost. Clear trade-offs were revealed between evaluation parameters, but no single measure represented the optimal combination on all aspects. The multidimensional evaluation space provides the frame for the co-creation of adaption paths for future-proofing the delta and a level playing field of information and boundary conditions. This lecture calls for continued integration of scientific insights in decision making to maximize the accuracy of projections of landscape development.

Lotte Jensen, Radboud University Nijmegen
Dutch identity and water management: a cultural-historical perspective

The Netherlands has a strong international reputation in the field of water technology and management. This pioneering position comes with a sense of pride and imagery, which connects the (successful) struggle against water with Dutch national identity. Publications on water management, especially those which aim at a larger audience, often refer to this expertise as being typically Dutch, as if this expertise is part of the DNA of the Dutch.

The connection between water management and Dutch identity is rooted in a long history: already in the seventeenth century the struggle against water was perceived as a typical Dutch phenomenon. It reached a high point in the nineteenth and twentieth centuries, in particularly in times of disastrous floods (for instance in 1855, 1861 and 1916). Charity and the role of kings and queens played a pivotal role in the construction of a heroic self-image in the media.

This lecture calls for a cultural-historical turn in the study of water management. It is argued that the omnipresence of cultural discourses, spread through a wide variety of media, is key to understanding the complex relationship between flood narratives and the so called ‘Dutch identity’ in the past and the present. The media are not only providing people with information, they are also setting the agenda and serve as powerful tools in the political and ethical debates.

Astrid Blom, Delft University of Technology

The branches of the upper Rhine delta: channel incision and rapid bed surface coarsening

The fact that the upper Rhine delta is characterized by channel incision is fairly well known. This channel incision results from a decrease of the equilibrium channel slope. Only recently we have become aware that the bed surface sediment in the branches of the upper Rhine delta is coarsening with time rapidly. Within a period of only 20 years, the representative grain size of the bed surface sediment in the Bovenrijn has increased from 1 to 10 mm. This is an unprecedentedly rapid change. This bed surface coarsening appears to be the reason that the incising trend in the Bovenrijn stopped about 30 years ago. The effect of bed surface coarsening is expected to be slowly migrating downstream and to increasingly affect the downstream Rhine branches. In her presentation Astrid Blom will address the causes and implications of both the channel incision and the rapid bed surface coarsening, as well as the effects of climate change on the upper Rhine delta.

Session 1 - Discharge Extremes

Oral Presentations

Effect of upstream flooding on extreme discharge frequency estimations

Rita Lammersen[a*], Anke Becker[b], Mark Hegnauer[b]
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[b]*Deltares, P.O. box 177, 2600 MH Delft*

Keywords — Weather generator, inundation, flood frequency curve

Introduction

The Netherlands are situated in a lowland area. High discharges and possible inundations have been an important topic for a very long time. As a result a sophisticated system of flood defence measures has been developed during a long period of several centuries. In the past most flood defences along the Dutch Rhine branches are designed based on water levels corresponding to flood peaks with a defined return period of 1:1250 years. The Dutch standards are high, compared design standards for flood defences along the stretches of the river Rhine further upstream in Germany. New legislation in the Netherlands following a risk-based safety assessment asks for an even higher design standard and asks for flood statistics for discharges with even higher return periods up to 10.000 years. Therefore traditional ways of estimating flood frequency curves using relatively short (approximated 100 years) observed time series was not sufficient anymore, because with these methods it is very difficult to take into account system behaviour of the river for discharges higher than observed. Therefore a new method is developed for taking into account upstream flooding in the estimation of extreme discharge statistics. First results will be presented.

Method

A modelling instrument called GRADE (**G**enerator of **R**ain **A**nd **D**ischarge **E**xtremes) was developed for the Rivers Rhine and Meuse (Hegnauer et. al. 2014) to estimate extreme discharge statistics for Rhine and Meuse rivers, including the effect of upstream flooding

GRADE consists of three components:

1. A stochastic weather generator, producing synthetic time series of daily precipitation and temperature (50 000 year) for Rhine and Meuse catchments.
2. A rainfall runoff model (HBV), which calculates the runoff from the synthetic precipitation and temperature series for the main tributaries of Rhine and Meuse.
3. A hydrodynamic model, which routes the discharge generated by the rainfall runoff model through the main river stretch. The hydrodynamic model includes physical processes such as retention of water and flooding as result of dike overtopping. Recently the models for the German Lower Rhine (including also the upper parts of the Dutch Rhine branches) and the Belgian Meuse between Chooz and Borgharen that are used within GRADE were improved by coupling a 1D-model for the river with a 2D-model for the area behind the main dikes which are potentially prone to inundation (Becker, 2019; Gao, 2017) (Fig. 1).

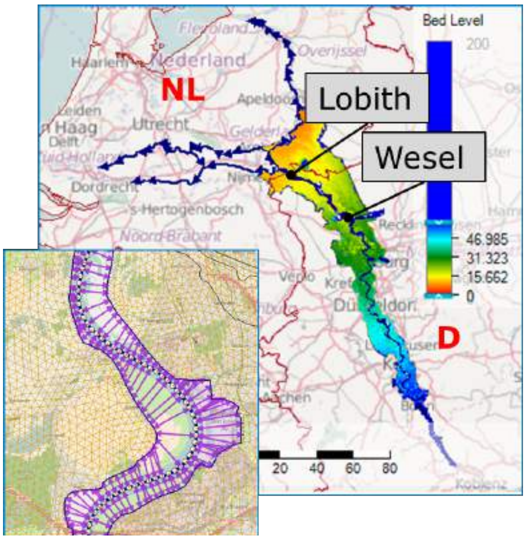

Figure 1. 1D-2D hydraulic model of the German Lower Rhine and Dutch Rhine branches in GRADE: bed elevation and coupling 1D-2D.

Results

Flood frequency curves were calculated for Lobith at the German-Dutch border and Wesel approximately 40 km upstream of Lobith by using GRADE to simulate 50,000 years of discharges for two situations: one with the assumption that dikes along the Rhine are high enough so that no flooding can take place and the more realistic one,

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that dikes can be overtopped, resulting in dike breaches and flooding. Both was done for current climate conditions, as well as for the situation with climate change.

For the situation under current climate conditions the discharge frequency curves with and without taking into account flooding are comparable for Wesel and Lobith, since no tributary enters the river Rhine between these locations and no water gets lost due to dike overtopping along this river stretch. However the effect of retention and flooding further upstream can clearly be observed at both locations.

For the situation under climate change conditions in general discharges at both locations are getting higher due to climate change and again the effect of upstream retention and flooding can be observed at both locations. It can also be seen that there is a clear reduction of extreme discharges between Wesel and Lobith due to overtopping of the dikes along the stretch between both locations.

The inundation pattern of a very extreme flood event under climate change conditions is shown in figure 2. It shows very large areas being inundated along the whole stretch of the German Lower Rhine including the stretch between Wesel and Lobith along the border between Germany and the Netherlands. In this area water that overtops the dikes along the German parts of the River Rhine between Wesel and Lobith flows into the Netherlands and reaches the dikes along the IJssel River, which is the Dutch Rhine-branch flowing to the North.

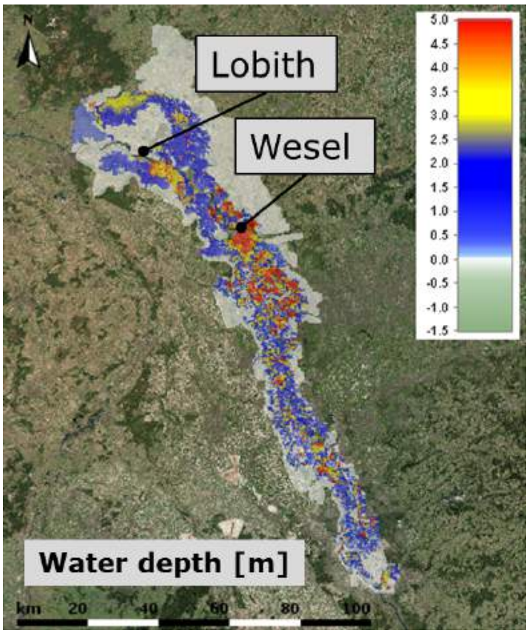

Figure 2. Inundation of large areas along the Lower Rhine in Germany under very extreme flood conditions.

Conclusions

Taking into account upstream flooding as result of dike overtopping and resulting dike breaches is essential for designing flood defence measures in the Netherlands to avoid over-dimensioning and investing too much money.

This makes flood management in the Netherlands strongly dependent on the activities upstream in the catchment. It is therefore of great importance to communicate on regular basis with partners in the Rhine basin to share plans and knowledge.

Of particular importance are the plans for the flood protection of the area between Wesel and Lobith. Any changes along this stretch of the river that will influence the conveyance capacity in the Rhine will directly impact the discharge at Lobith and locations further downstream. Since the discharge at Lobith is often used as design criteria for all levees along the Dutch Rhine branches, this can have large consequences and this should therefore be studied in more detail.

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The effect of dike breaches on downstream discharge partitioning

Anouk Bomers[a*], Ralph M. J. Schielen[a,b], Suzanne J. M. H. Hulscher[a]
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Keywords — Dike Breaches, Discharge Partitioning, Hydraulic Flood Modelling

Introduction

Flood frequency analyses (FFA) are widely used to estimate discharges associated with various recurrence times**.** The common procedure of a FFA is to select the annual extreme discharges of the measured data, which are then used to identify the parameters of a probability distribution. With this distribution, design discharges corresponding to any recurrence time can be computed.

However, a major drawback of the FFA is that the effects of overflow and dike breaches on the downstream discharge wave cannot be incorporated in the analysis unless such events have occurred during the measurement period.

Excluding overland flows from FFA results in an inaccurate prediction of design discharges since overland flows may alter downstream discharge partitioning. Water that left the river system may flow through the embanked areas towards another river or river branch, increasing the discharge of this specific river. The objective of this study is therefore to determine the effect of dike breaches on downstream discharge partitioning capturing the full dynamics of a river delta. The upstream part of the Rhine river delta is used as a case study.

Hydraulic model

A one dimensional-two dimensional (1D-2D) coupled hydraulic model is developed (Fig. 1) using the open source software HEC-RAS (Brunner, 2016) to simulate the discharges and flow velocities from Andernach (Germany) to the Dutch deltaic area. As upstream boundary condition a discharge wave is used whereas normal depths are used as downstream boundary conditions. The Manning's equation with a user entered energy slope (commonly equal to the slope of the river bed) produces a water level considered to be the normal depth.

The 1D profiles in the main channels and floodplains and the 2D grid cells in the embanked areas are coupled by a structure corresponding with the height of the dike that protects the embanked areas from flooding. If the computed water level of a 1D profile exceeds the dike crest, water starts to flow into the 2D grid cells resulting in inundations of the embanked areas.

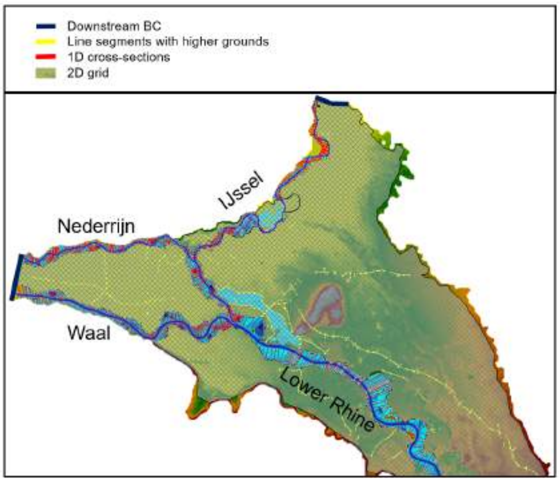

Figure 1. 1D-2D coupled hydraulic model used to perform the Monte Carlo analysis

Monte Carlo Analysis

A Monte Carlo analysis is performed to determine the effect of dike breaches on downstream discharge partitioning. In total 33 potential dike breach locations are included in the model that may change the downstream discharge partitioning as a result of large overland flows. The following input parameters are considered as random parameters in the Monte Carlo analysis:

- Upstream flood wave in terms of hydrograph shape and peak value
- Flood waves of the main tributaries (Sieg, Ruhr and Lippe rivers) dependent on the shape and peak value of the upstream flood wave
- Dike breach threshold in terms of critical water level (based on fragility curves) indicating when the

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dike starts to breach. Failure as a results of wave failure mechanisms wave overtopping, piping and macro-stability are considered (Diermanse et al., 2013).

- Dike breach formation time
- Final breach width

For each model run present in the Monte Carlo analysis, an upstream discharge wave and corresponding discharge waves of the three main tributaries are sampled. The 1D-2D coupled model computes the water levels along the river Rhine branches as a result of the upstream boundary condition and lateral inflows. If the simulated water level exceeds the dike crest, water starts to flow into the embanked area. Furthermore, the model evaluates at every time step and at each potential dike breach location whether the water level exceeds the dike breach threshold in terms of critical water level. If the critical water level is exceeded, the dike starts to breach based on the sampled dike breach formation time and final breach width. It is assumed that a dike breaches to the level of the natural terrain in case of failure (Daswon et al., 2005).

Results

During the Monte Carlo analysis, 375 runs were performed with a maximum discharge at Andernach ranging from 12,000 to 28,000 m^3/s.

In general terms, we found that dike breaches can significantly change the maximum discharges of downstream rivers. This effect is not only beneficial in terms of a reduction of the maximum discharge further downstream, as was found by Apel et al. (2009). Large overland flows may change the discharge partitioning of the Dutch river Rhine branches and hence the flood risk along these rivers.

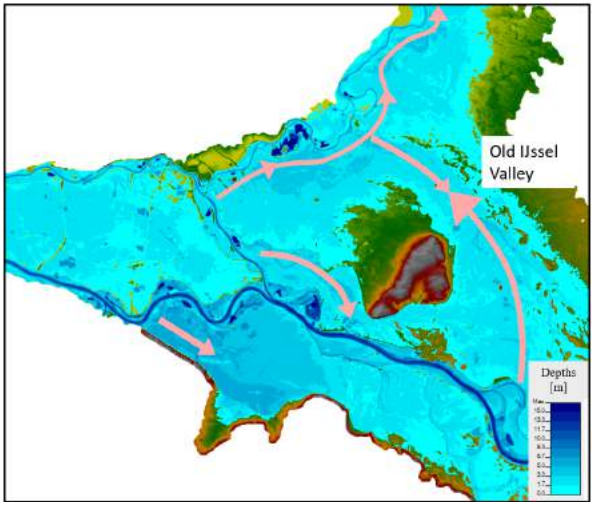

Figure 2. Most dominant flow patterns (pink arrows) present in the studied area. Specifically, the flow pattern through the Old IJssel Valley results in a change of the discharge partitioning of the Dutch river Rhine branches Waal, Pannerdensch Canal, Nederrijn and IJssel river.

Furthermore, a dike breach results in a sudden drop of the water level. This decrease of the water level propagates in upstream direction as a result of backwater effects. Consequently, the maximum discharge may increase upstream of the dike breach location.

For this specific case study, it was found that overflow and dike breaches along the Lower Rhine results in overland flows that consequently increase the maximum discharge at the downstream end of the IJssel river on average by 151% under the most extreme scenarios (Fig. 2: an example of potential flow pattern through the Old IJssel Valley). All other Rhine river branches were not affected by such overland flow patterns and hence only a reduction in maximum discharge as a result of upstream dike breaches was found for these branches.

Conclusions

We can conclude that dike breaches, resulting overland flow patterns and backwater effects must be included in the analysis of safety assessment since it may have a significant effect on downstream discharge partitioning and design discharges. This study shows that dike breaches may have a beneficial effect on some downstream river branches in terms of discharge reduction, while it may also cause severe problems along other river branches, especially if the discharge capacity of the specific river is relatively low compared to the discharge capacity of the other river branches.

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Should we build more side-channels?

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Keywords — Room for the River, river engineering, side-channels, uncertainty analysis

Introduction

Thirteen years ago, the Room for the River programme officially started (Wolbers et al., 2018). The Room for the River programme represented a paradigm shift in Dutch river management in moving from raising the dikes to increasing the conveyance capacity of the river corridor. The programme itself consisted of multiple projects, built around a limited number of intervention types: relocating the dikes, removing or lowering obstructions, reconstructing side-channels and excavating parts of the river or floodplain.

Any large-scale intervention in the river system affects water levels, short- and long-term morphology, ecosystems and social systems. Predicting what the response of the system to the intervention will be is therefore evidently important.

We recently concluded a large-scale study (Berends et al., 2018a) on the effect on water levels of these intervention types on one of the River Waal bottlenecks: the river bend at St. Andries. In this paper, we will argue why building side channels may be the most sensible option — from a statistical perspective.

A statistical perspective

From a statistical perspective, we treat predicted water levels as stochastic variables with an expected value and variance. In our study, these water levels are stochastic because of variability in measured vegetation parameters and vegetation distribution. This results in a 95% confidence interval of about 70 cm at design discharge.

Since water levels are stochastic, the expected effect of an intervention is stochastic as well. However, the variance of the effect is not directly predictable from the variance of the water levels and may vary wildly between different intervention types (Berends et al., 2018b). For this reason, Berends et al. (2018a) introduced the measure for relative uncertainty U_r, which is defined as the expected effect devided by the 90% confidence interval. It was found that interventions that do much to decrease flood levels, while affecting relatively little of the river system, have a low U_r. As we will see in the following examples, having a low U_r is beneficial for decision making.

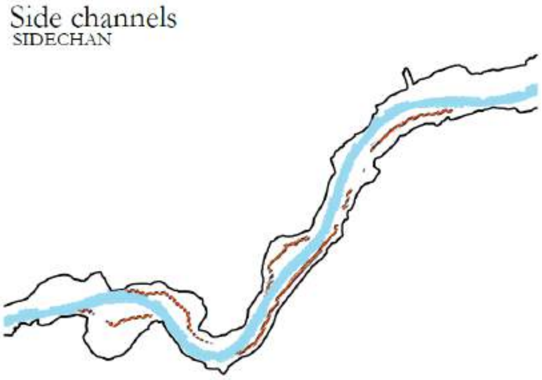

Figure 1: Large scale sidechannels in the River Waal at the St. Andries bend

Comparing two interventions

Here, we consider two possible intervention to lower the water levels. The first is the removal of a particular kind of obstacle to flow: vegetation. Over the course of the entire study area, we removed all types of vegetation and replaced it with the equivalent of a soccer field. This intervention is therefore aptly termed 'floodplain smoothing'. The second intervention is to dig a large number of side-channels in the floodplain (Figure 1).

Both interventions have similar expected effects: 28 cm for floodplain smoothing and 36 cm for side-channels. However, their relative uncertainty is quite different: 82% against 18%. This is immediately obvious from Figure 2, which displays the confidence bands for the water level decrease of both interventions.

Why side channels are preferable

We found that scaling the intervention, i.e. removing more or less original vegetation or dig-

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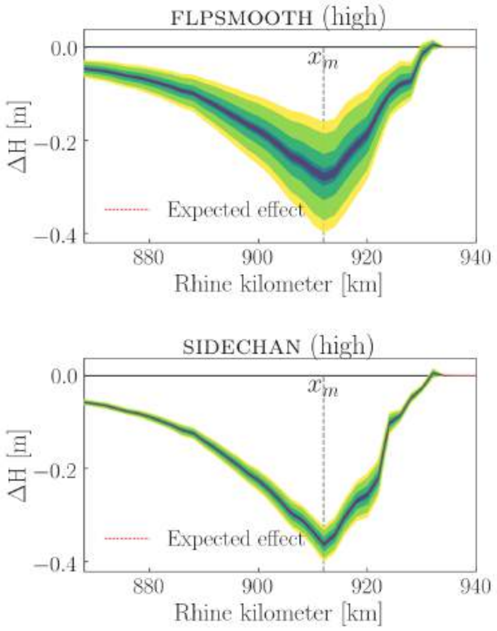

Figure 2: The effect of floodplain smoothing (up) and side channel construction (lower panel) on design water levels.

ging narrow or wide side channels, did affect the expected effect but not the relative uncertainty. This means that we could hypothetically scale down the side channels to an expected effect of 28 cm, similar to the floodplain smoothing intervention, with the same expected relative uncertainty. From a statistical perspective, the choice between the two interventions then boils down to the level of acceptable uncertainty.

There are several ways of dealing with uncertainty from a statistical point of view. One way is to compute the likelihood that a certain water level is reached. For the above example, the likelihood that the water level decrease is 28 cm is around 50% for both interventions. This likelihood may not be acceptable and a higher confidence is required. For example, floodplain smoothing with an expected effect of 28 cm is extremely likely (i.e. 95% probability) to reach a decrease in water level of at least 16 cm. So while the expected effect is 28 cm, there is a significant probability that the effect is much lower than this. Due to the much smaller relative uncertainty, for side channels with an expected effect of 28 cm, it is extremely likely that the effect is at least 25 cm.

Practically, this means that in order to be confident that a certain flood level decrease is reached, interventions with a high uncertainty need to be significantly over-designed.

This is why building side channels is attractive from a statistical perspective: due to low relative uncertainty compared to alternative measures (see Berends et al. (2018a) for a full list), a given water level reduction can be reached without extensive over-design.

Discussion

In this study we only considered the immediate hydraulic effect of interventions. In previous studies and project, this has been one of the most important parameters in designing interventions. However, looking beyond the immediate effect, other considerations need to be taking into account, such as biodiversity and costs (Straatsma et al., 2018). For side channels in particular, recent studies into the rate of sedimentation (van Denderen et al., 2019) may help predict how this diminishes the effect over time. These considerations, in combination with the statistical argument, will help to inform model-assisted decision making.

Acknowledgements

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Experiments on the relation between grain size distribution and the initiation of pipe erosion.

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Keywords — Piping, Heterogeneity, Backward erosion, Modelling, Dike stability

Nature of piping

One of the processes threatening the stability of embankments is piping. During a high water event, due to the steeper hydraulic gradient groundwater flow velocity increases. This may exceed the threshold at which soil particles can be mobilized and washed out, forming a preferential drainage path when there is a point for this flow to exit the subsurface. This pipe may widen and extend backward by suffusion or erosion and eventually lead to the collapse of the embankment (VNK, 2015). However, due to its subsurface nature, limited occurrence and the inherent feedback mechanisms, piping is still poorly understood (Richards and Reddy, 2007; Vrijling, 2010).

For this study, the main subsurface considered is the Dutch Rhine-Meuse delta, which has a complex past with many avulsions and changing sedimentary environments, giving rise to a highly heterogeneous subsurface (Weerts, 1996; Stouthamer, 2011), which is a determining factor in the likelihood that piping will occur considering the relationship between build-up of the subsurface and associated permeability. Heterogeneity thus needs to be considered in relation to the initiation of erosion at the particle scale.

Problem definition

Previous experiments already demonstrated that vertical layering increased the critical gradient required to initiate backward erosion (Negrinelli, 2016). However, currently piping risk is determined using only the d70 value to describe the sandy substrate (RWS, 2017), beyond that lacking any variables that account for heterogeneity, other than a saturated conductivity for the entire subsurface lumped together.

The overarching aim of the project is to connect the different scales from process scale to field scale, to create a probability model for piping at larger scale scenarios, to this end, the heterogeneity at the lower scales needs to be understood. Once enough results have been gathered to create an upscaled version of the experiments on the field scale these could potentially be combined with characterisations of the underground such as the pilot area studies being performed by T.G. Winkels (see this volume).

Project aims and approach

As a first step towards the identification of the influence of heterogeneity on the piping process, laboratory experiments have been performed on sandy soils with non-uniform grain size distributions. These experiments build on earlier experiments on samples with uniform grain size distributions (Van Beek, 2015). These will provide a first step towards a definition of the critical erosion threshold and a qualitative understanding on how this interferes with backward erosion under controlled hydraulic gradients.

Few experiments have been performed for measuring erosion on non-uniform sands under laminar flow conditions (Van Beek, 2015). So, the experiments that were performed for this study tested for differing and broader grain size distributions than the previous homogenous samples, mimicking grain size distributions that do occur close to the cover layer in the field. Thus, the goal of these experiments was not yet to classify heterogeneity in terms of the interactions between different soil textures, but to quantify the differences between homogenously prepared samples with differing grain size distributions.

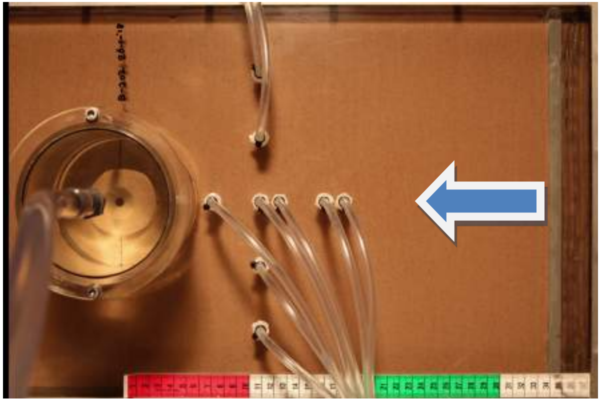

Figure 1: Top view of the experiment container. Inflow is from the right, on the left is the cilinder with the outflow point. Blue arrow indicates the general flow direction.

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To this end samples with similar d70 values but differing grain size distributions were mixed. These resulting samples were placed in a test container that forced piping through expulsion of the porous medium through a hole in the top of the test container. Thus, for initiation the first grains eroded in the backward erosion process had to be transported only vertically. This allowed to assess the impact of the differing grain size distributions on the initiation of backward erosion (See figure 1).

Results

The experiments showed an overall increase in hydraulic head gradient in order to initiate backward erosion in non-uniform samples. As the grain size distribution of the sample became less uniform the saturated conductivity decreased, in agreement with previous previous studies (Alyamani & Sen, 1993 ; Odong, 2007). Consequently, as shown in Figure 2 as the uniformity coefficient increased, the hydraulic head gradient required to initiate backward erosion became steeper.

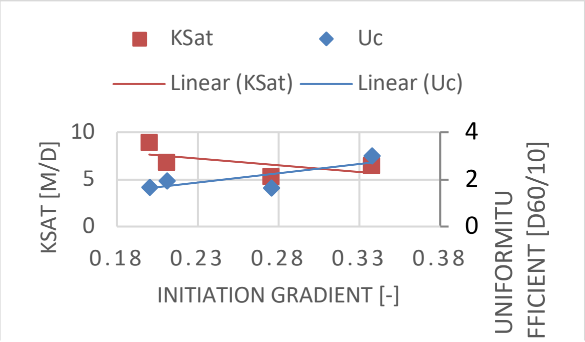

Figure 2: Initiation velocity in relation to saturated conductivity and uniformity coefficient.

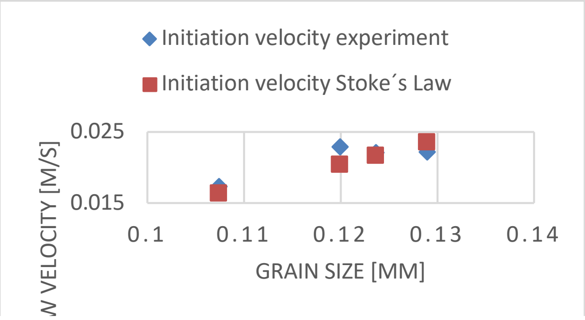

Figure 3: Initiation velocity for both the experiment and the calculated velocity through Stoke's law versus median grain size.

Analysis of the flow velocity required to initiate erosion in the vertical water column just under the outflow point was calculated using Stokes' law, which provided a good fit when using the median grain size (d50) (see figure 3). This indicates that the velocity required to initiate erosion did not change with the width of the grain size distribution. It changed with the median grain size, and the initiation gradient is thus mainly influenced by saturated conductivity.

Further research

The analysis of these results are preliminary and the data is still too scant to allow general conclusions. Still, they show a possible general trend and further experiments are needed to expand the empirical basis. At the same time, model simulations will be performed to develop hypotheses that may be falsified and refined by the experiments. Through this combined development of model and experiments, we will improve our understanding of the piping mechanism in heterogeneous soil. In the next phase, this knowledge will be linked to fluvial architecture which will allow us to transfer the model to the field scale where we can validate it against observations and give it regional application.

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Session 1 - Discharge Extremes

Poster Presentations

The effects of Land reclamation along gravel-bed braided system: Mao River, Bhutan

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Keywords — Floodable land reclamation, Gravel-bed braided rivers, Morphodynamic responses

Introduction

Braided rivers are known as highly dynamic systems characterized by several channels (Williams, et al., 2013) divided by unsteady bars (Egozi and Ashmore, 2009). Training is often a necessary action in order to either control their lateral expansion (Carolina Rogeliz, et al., 2006) and undesirable bank erosion, or for land reclamation (Jurina, 2017). The latter is usually associated with local channel narrowing which leads to vast changes in river morphology. According to the equilibrium theory developed by Jansen et al. (1979), narrowing leads to channel incision, local decrease in longitudinal bed slope, upstream erosion, opposite bank pushing and decrease in the braided degree of the river (Duro et.al, 2016). Moreover, during high flow condition, local channel narrowing creates backwaters that increase the upstream water level and risk of flooding in the areas adjacent to the river. Thus, land reclamation might deeply change braided river systems and cause undesirable hydraulic and morphodynamic alterations. Therefore, efficiency of different river training alternatives regarding to land reclamation should be examined.

Fracassi and Di Pietro (2018) presented some lateral land reclamation schemes that are floodable during high flows, which minimizes their hydraulic and morphological impacts. These interventions proved to be successful for farming along a few braided rivers of Bolivia. Agricultural land reclamation was obtained by constructing Gabions wall with openings to protect the land up to a specific flood and inundation level. In addition, the area was subdivided by screens perpendicular to the water flow to decrease the flow velocity during flood events and enhance deposition of fine material. Therefore, this type of interventions proved successful regrading to fertility rise in the new agricultural fields. However, there is no precise description of the river morphdynamic responses.

This work aims at evaluating the degree of success of this land reclamation technique considering the morphological adaptation of the river. The Mao River is chosen as case study (Fig. 1). This is a gravel-bed braided tributary of the Brahmaputra. The study area is located in Bhutan, where the river channel has high potential of agricultural land reclamation. The degree of success is here considered in terms of water level raise during floods which depends on the morphological changes induced by the land reclamation scheme.

Figure 1. Potential area for land reclamation in the Mao River.

Method

The main tool for the analysis is a 2D (depth-averaged) numerical model, built using the Delft3D software. Numerical modelling has been successful to simulate the morophodynamic behaviour of gravel-bed braided rivers and has the advantage of allowing for comparison of several different as scenarios (Nicholas, 2013, Schuurman, et al., 2018). This is one of the main advantages of numerical modelling in comparison to other solutions especially in morphodynamic studies (Schuurman, et al., 2018). Delft3D is based on

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the solution of the Navier Stokes equations considering the Boussinesq assumptions. Singh et.al (2017) proved that Delft3D can be used to model braided rivers having graded sediment, composed of gravel and sand.

Delft3D is therefore used to study several scenarios differing in size of land reclamation areas along the Mao River in Bhutan. Optimization is obtained by considering a balance between frequency of flooding of the reclaimed area and agriculture needs. This is related to how often and how fast and deep the reclaimed land would be inundated compared to the possibility to use the same land for agriculture.

Sediment transport is computed using the Ashida-Michiue (1974) formula for three different classes of bed material, including hiding and exposure of sediment particles. It should be noted that there is lack of data on the Mao River basin. Thus, SWAT modelling has been already conducted and calibrated based on the catchment rainfall data and few discharge measurements in order to generate the required flow time series for Delft3D modelling.

Next step is to implement floodable land reclamation in the model as a new feature in the braided system to see its short term and long term effects on the Mao River morphodynamic behaviour. As results of this study, the efficiency level of the technique proposed by Fracassi and Di Pietro (2018) in gravel-bed braided rivers is quantified.

This is an ongoing study and the preliminary results of morphodynamic modelling show the capability of the model to simulate dynamics of braided system. As it is shown, the model is perfectly able to model braided system (Fig.2).

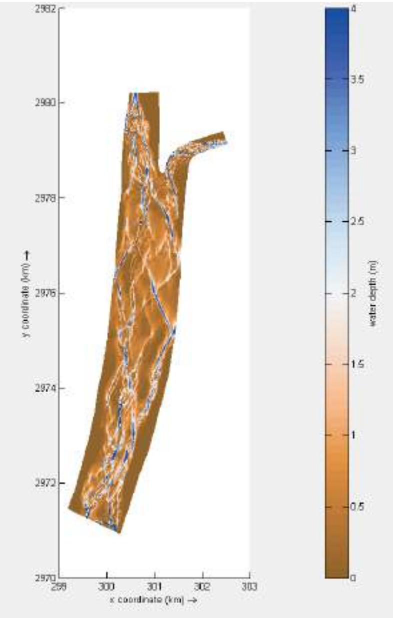

Figure 2. Preliminary results of Delft3d morphodynamic simulation.

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Flow patterns for contrasting discharge conditions in a lowland sharp river bend: implications for backwater

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Keywords — River Bends, Flow patterns, Backwater effects, River Hydraulics

Introduction

Most lowland rivers meander through the landscape. These meanders can become very sharp in the course of millennia (*Candel et al.*, in review). *Candel et al.* (in review) show that rivers constrain themselves with previously deposited fine sediments, which are almost impossible to erode and result in sharpening of the bends. These sharp bends are very stable in time (*Vermeulen et al.*, 2014). High discharge events are normally responsible for morphological change, but the previous studies show that high discharge does not affect the planform of these bends. It is unknown what the effects of discharge are on stable sharp bends. We question whether rivers with sharp bends are more prone to flooding and whether flow patterns influence the stability of sharp bends. We investigate the effects of a medium and a high discharge event on flow patterns and upstream water levels in a sharp bend in a lowland river.

Material and Methods

We studied a sharp bend in River Dommel between Liempde and Olland in the province of North Brabant in the Netherlands. We used five water level gauges, two upstream of the bend, one in the inner bend, one in the outer bend and one downstream of the bend during the winter season of 2017-2018 in a small lowland river. We also used discharge data with a measurement frequency of one hour over the same measuring period as the water level measurements. In addition, we performed two ADCP field campaigns to measure the flow patterns in the bend, and a field campaign to measure the water levels at the bank. One ADCP field campaign was during a medium discharge event of 9 m^3 s^{-1} and one during a high discharge event of 13 m^3 s^{-1} (Fig. 1).

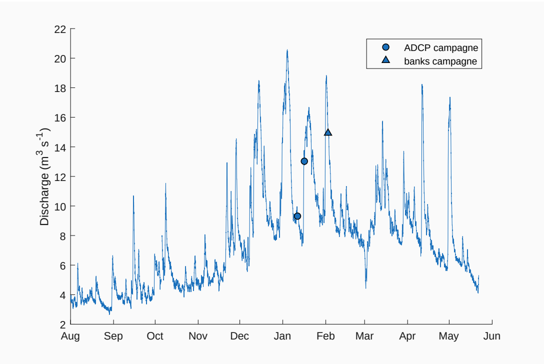

Figure 1: Discharge variation during the water level measurements and field campaigns. The ADCP campaigns were one time during a medium discharge event and one time during a high discharge event. The measurement of the water levels at the banks was also during a high discharge event.

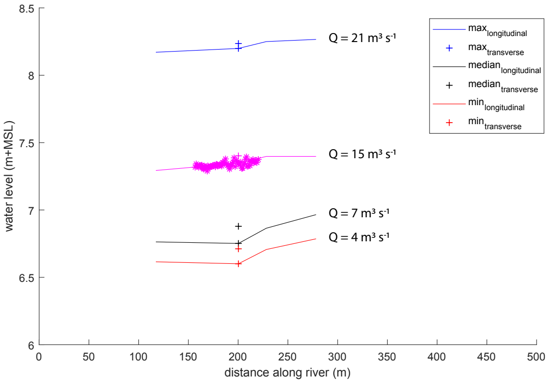

Figure 2: The longitudinal and transverse water profiles in the bend for the maximum, median and minimum measured water levels and with the measurments of the water levels at the bank.

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Results

Fig. 2 shows the measured water levels profiles in the bend during minimum, median and maximum measured discharge events. The water level profiles increase with discharge, however the water levels show little change in time and space in relation to each other. There are thus no significant local backwater effects caused by flow obstruction in the bends. Figure 3 shows the top view of the flow patterns in the bend during a medium discharge event (left) and a high discharge event (right). The flow pattern at the medium discharge event shows a reversed flow at the outer bank, while flow at high discharge shows hardly any flow recurrence. This means that the effective cross sectional area of medium and high discharge events are not only depending on the water level and the total cross sectional area, but also on the cross sectional area of the flow reversal zone. Figure 4 shows the cross sectional area of the reversed flow for the medium and high discharge events. The area of the flow reversal during the medium discharge event is 50% of the total cross section, while the area of the flow reversal during the high discharge event is 4% of the total cross section. The effective cross sectional area during high flow is 125% of the total cross section during the medium discharge event, because the cross section is 30 % larger during the high discharge event. The effective cross sectional area differs thus between 50% and 125% for a medium and high discharge event, respectively.

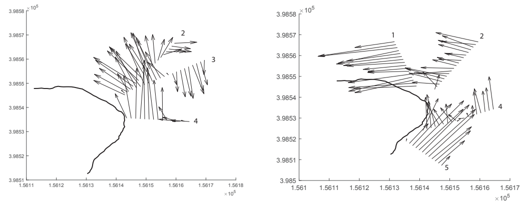

Figure 3: Top view of the flow pattern in the sharp bend during medium discharge event (left) and the high discharge event (right). The axis show the location in RD-coordinates

Conclusion

Medium and high discharge events in sharp bends show similarities in water level profiles, but differences in flow patterns. The water level profile for a high discharge event is naturally higher than for a medium discharge event. The water level profiles however do not change shape for a medium or high discharge event, which means that the water levels at different locations in the bend do not change in space and time in relation to each other. Thus, there are no local backwater effects in bends due to varying discharge. Meanwhile, the flow pattern in a medium discharge event shows a reversed flow, while this vanishes at the high discharge event. The effective cross sectional area is therefore influenced by the water level and the area of the flow reversal zone, which are both dependent on discharge. Discharge thus contributes to complexity and dynamics in morphologically stable sharp river bends.

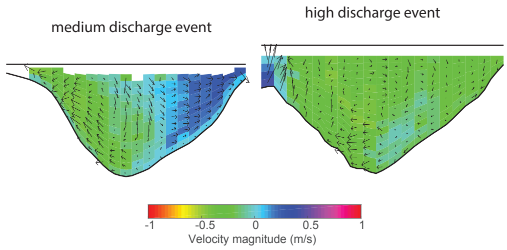

Figure 4: Flow patterns in cross section 2 (see Fig. 3) during a medium discharge event and a high discharge event. The negative velocity magnitude illustrates flow in the downstream direction and the positive velocity magnitude illustrates flow in the upstream direction

Acknowledgements

This research is part of the research program RiverCare, supported by the Dutch Technology Foundation STW, which is part of the Netherlands Organization for Scientific Research (NWO), and which is partly funded by the Ministry of Economic Affairs under grant number P12-14 (Perspective Programme). The authors furthermore would like to thank Dutch water boards De Dommel in collaboration with STOWA, Dutch Foundation of Applied Water Research, for providing discharge and help during the field campaigns.

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Propagating main channel roughness uncertainty in the bifurcating Dutch Rhine system

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Keywords — River bifurcation, Main channel roughness, Uncertainty analysis

Introduction

Bifurcating river systems around the world are complex and dynamically active systems. Natural processes and human interventions cause the system to change over time, which leads to variations in the discharge distribution over its branches. In the bifurcating river these changes cause changing water levels throughout the entire system.

The new Dutch flood risk framework requires the calculation of probabilities of water levels. Wherever possible uncertainties should be included in these probabilities. Generally, the upstream discharge and main channel roughness due to river bedforms are the dominant sources of uncertainty (Gensen, 2018; Warmink et al., 2013). This work aims to quantify the maximum effect of main channel roughness uncertainty on the range of possible water levels in the Dutch river Rhine system, including its two main bifurcation points.

Methods

Roughness scenarios

Roughness limit lines have been defined to represent the range of possible roughness values due to variations in bedform dimensions. For every branch (Waal, Pannerdensch Kanaal, Nederrijn/Lek and IJssel) a high and a low discharge-dependent limit line is estimated. These data points are based on available dune measurements and have been translated into roughness values using the roughness predictors of Van Rijn (1993) and Vanoni and Hwang (1967). The limit lines are then visually defined assuming a linear increase of the (Nikuradse) roughness with discharge. Figure 1 shows the roughness limit lines for the river Waal along with the roughness predictions. The combination of limit lines for every branch leads to 16 roughness scenarios, ranging from HHHH (high roughness on every branch) to LLLL (low roughness on every branch) in which the order is: Waal, Pannerdensch Kanaal, Nederrijn/Lek and IJssel.

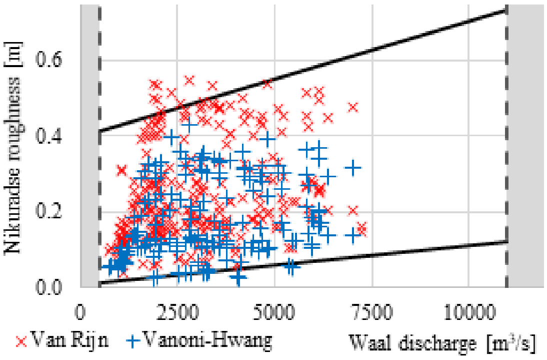

Figure 1: Roughness predictions in the river Waal. The black lines are the defined high and low discharge-dependent roughness scenarios.

Sobek model

An 1D Sobek-model of the Rhine Branches (Rijn-j16_5_v1) is applied to predict the water levels for each of the 16 roughness scenarios. The upstream boundary is a stationary discharge ranging from 1500 to 18,000 m^3/s.

Results

The effects of the varying roughness and the varying discharge distributions can be visualized in Qh-plots, in which the local water level is plotted versus Lobith (upstream) discharge (Figure 2). All scenarios in which the Waal has a large roughness result in an above-average water level. The spreading between these scenarios is caused by a changing discharge distribution at the Pannerdensche Kop. The highest and lowest water levels on the Waal are found for the scenarios in which all branches have a high and low roughness, respectively.

In Figure 3, the changes in local water levels are plotted against the changes in local discharges for all downstream branches (Nijmegen-haven for the Waal, De Steeg for the IJssel, Driel for the Nederrijn) for a Lobith discharge of 16,000 m^3/s. In this figure the roughness effect on the water level of the IJssel is indicated by Arrow 1, while the maximum discharge distribution effect for the IJssel is indicated by Arrows 2 and 3.

Figure 3 shows that the roughness effect is largest for the Waal and is smaller for the Nederrijn and IJssel. It is observed that for the

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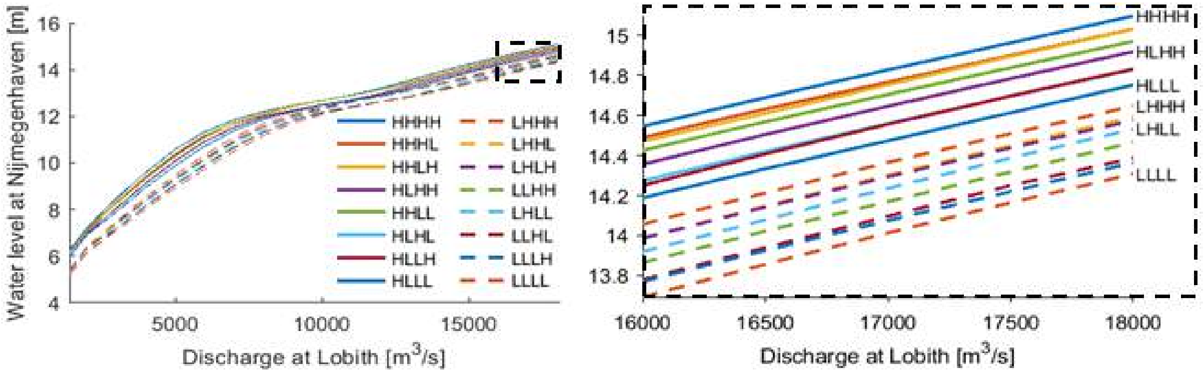

Figure 2: Stage at Nijmegen-haven plotted against upstream Lobith discharge for the 16 roughness scenarios. The right panel zooms in on the part of the stage-discharge relations at extreme discharges.

Waal the scenarios all plot in the upper left and lower right quadrant. This implies that for a high Waal roughness, the Waal discharge always decreases, regardless of the roughness on the other branches, thereby decreasing the water levels along the Waal. Scenarios exist for the Nederrijn and IJssel in which the discharge increases along with a simultaneous increase in local roughness (upper right quadrant). These scenarios generally correspond to scenarios with a high Waal roughness. Therefore, if the discharge distribution effect is included for these branches, the maximum water level increases. Concluding, the discharge distribution effect for the Waal thus causes a decreasing water level range, whereas the range increases for the IJssel and Nederrijn.

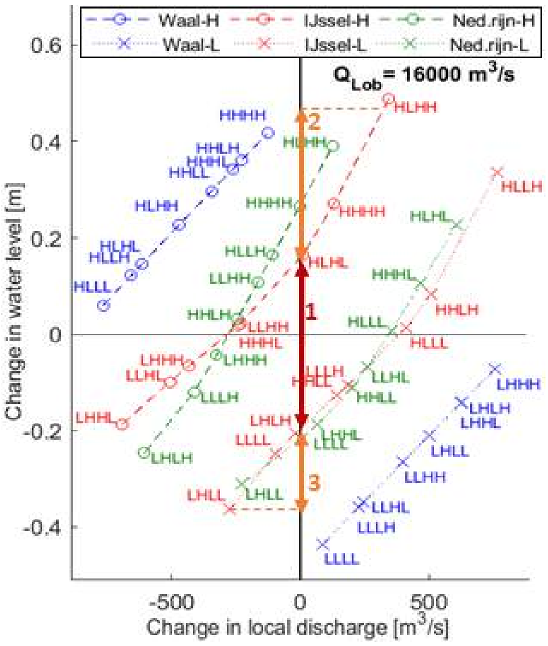

Figure 3: Local water level change versus local discharge change with respect to the average of all scenarios for a Lobith discharge of 16,000 m^3/s.

Conclusion

By propagating extreme roughness scenarios through the 1D Sobek model an estimation of the maximum effect of uncertain main channel roughness on the water levels in the bifurcating river Rhine was attained. It is concluded that the effect of varying discharge distributions decreases the range of water levels along the Waal, while it increases the range for the Nederrijn and IJssel. In this study extreme roughness scenarios were applied. Therefore, the water levels should not be taken as absolute, but they show the trends in water levels under roughness uncertainty in a bifurcating river. In future work, more realistic scenarios are tested to quantify the water level ranges. Additionally, the effect of regulation structures and river engineering works in the vicinity of the bifurcation points on the propagation of the uncertainty to water levels will be analyzed.

Acknowledgements

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The influence of subsurface heterogeneity on scour hole development in the Rhine-Meuse delta, the Netherlands

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Keywords – Scour hole, subsurface heterogeneity

Introduction

River dikes are the primary form of flood protection of the Rhine-Meuse delta in the Netherlands. The newly adopted risk approach for the management of flood defenses, requires quantification of multiple failure probabilities in dike stability assessments. The stability of dikes may be compromised where deep scour holes develop in the rivers nearby. Scour holes are a form of bed erosion that impose increased probability of channel bank instability (e.g. flow slides along steepened sides of the bed) and hence of dike failure. This is especially the case for scour holes in the lower reaches of the Rhine-Meuse delta, where most dikes are located close to the main channel (Fig. 1).

Moderately sized scour holes often occur around bridge piers and groynes. Larger and deeper scour holes are known to have developed at other places in the river bed, which in most cases indicates that the bed substrate was locally more erodible than its surroundings. Thus, the occurrence and development of scour holes reflects, besides channel morphology and local hydrodynamic conditions, heterogeneity of the subsurface. Previous research into the influence of subsurface heterogeneity on scour holes focused on variation in erodibility between geological layers making up the channel substrate at individual scour sites (Sloff et al., 2013; Huismans et al., 2016). Geological heterogeneity and variation of erodibility at the base of modern channels, however, is the result of past geological processes that operated regionally. So we might expect scour holes and their characteristics to reflect the local buildup of the subsurface and thus are linked to specific lithostratigraphic units and geologic sequences. Therefore, linking the occurrence and evolution of scour holes to 3D subsurface architecture will contribute to better understanding of geologic boundary conditions in which scour holes with a specific geometry, size and development rate occur. This study presents an inventory of scour holes and their relation to the large scale subsurface buildup of the whole delta. At a later stage, more detailed mappings and cross-sections will be used and made (cf. Stouthamer et al., 2011) to understand the geological influence at the local scale.

Methods

Our approach to study the link between the subsurface geology and scour holes and their characteristics follows several steps. Huismans et al. (2016) identified 120 scour holes in the western part of the delta (Fig. 2) which were analyzed by Koopmans (2017). We revisited this inventory and extended it to the central and upper delta. Time series of bathymetric data for all major river branches with a temporal resolution of one year were analyzed semi-automatically and visually inspected. Differing per river branch, bathymetry data is generally available from 1990 onwards. Scour holes (Fig. 1) are identified based on the following criteria:

- Local deepening, >1 m deeper than surrounding channel bed.
- Maximum length approximately 1 km.

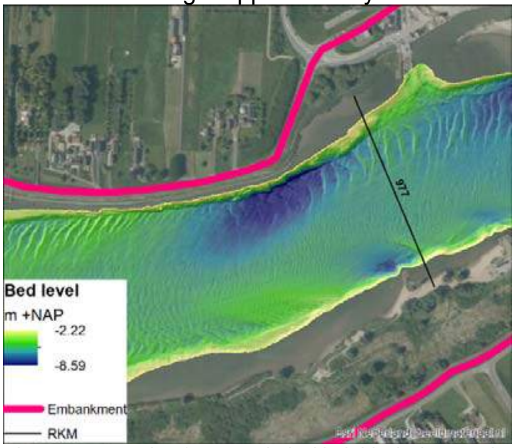

Figure 1. Example of a scour hole (dark blue) close to the upper embankment (pink) in the river Lek near Bergambacht downstream of river kilometer (rkm) 977.

We created a combined database with data from Koopmans (2017) and new identified scour holes with (1) location, (2) geometric attributes such as slope, maximum depth and area, and (3) additional conditions that may

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influence development such as local channel morphological setting (e.g. channel curvature, confluence/bifurcation) and proximity of engineering structures for the entire study area.

Geological data from different sources were compiled to characterize the regional subsurface build-up around scour holes. The data consists of the high-resolution channel belt mapping (UU: Cohen et al., 2012) and subsurface geological data and models (TNO DINO & GeoTop). We work towards identification and overview of the relevant lithostratigraphic subunits, strati-graphic sequences and characterization of their distribution and properties throughout the study area. At this stage of our study, showing and intercomparing the spatial availability of geologic data per region (and quality and resolution differences therein) is mainly relevant.

Preliminary results

Analysis of bathymetric data for the period 2014-2018 has resulted in 26 locations in the central and upper parts of the study area where potential new scour holes are identified (Fig. 2). Most of these objects have been relatively stable in their geometry and location during the last four years. Occurrence of channel scour features appear less common upstream in the delta than in the tidal downstream part. This appears not strictly a matter of hydrodynamic difference (unidirectional vs. bidirectional flow), but also of large scale trends in the substrate character of the study area (i.e. tidal/fluvial/peat vs. fluvial influence; Fig. 2).

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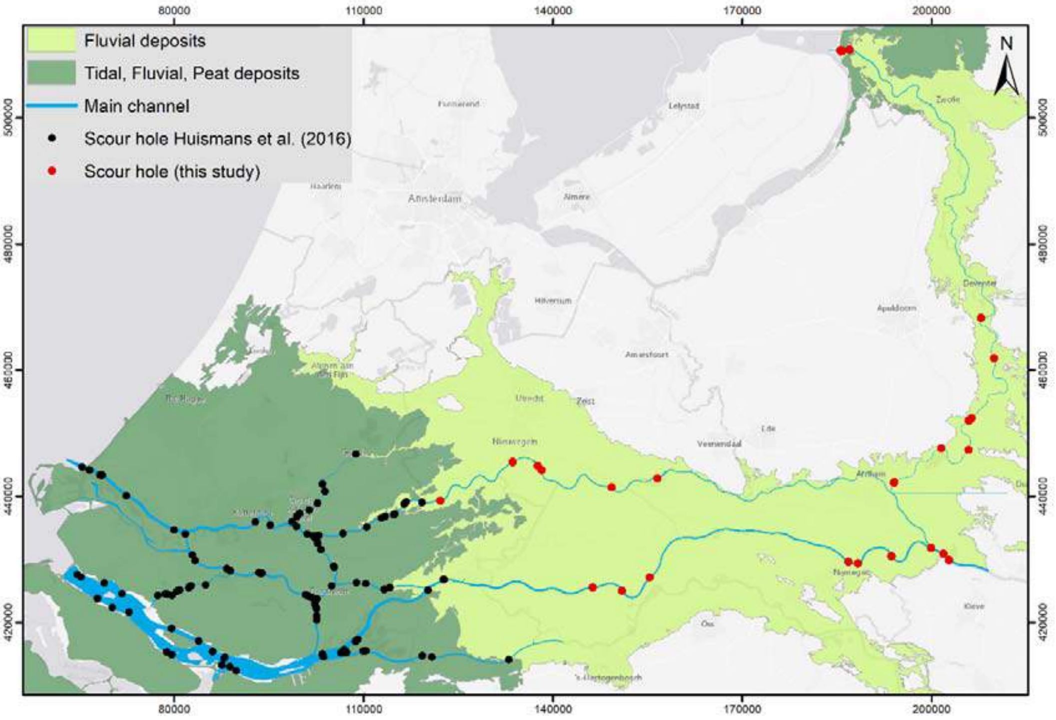

Figure 2. Locations of scour holes identified in the active channels in the study area in relation to the large scale buildup of the subsurface. The central and upper parts of the delta are dominated by fluvial deposits and the lower part is generally made up by an alternation of tidal, fluvial and peat deposits. Black dots (n=120) are lower (tidal) delta scour holes (Huismans et al., 2016). Yellow dots (n=26) are central and upper delta scour holes (this study).

Dike cover erosion by overtopping waves: an analytical model

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Keywords — Wave overtopping, Dike cover erosion, Turbulence parameter

Introduction

Climate change results in more extreme weather conditions such as storms and droughts. Droughts decrease the strength of the grass cover on dikes, which makes the dikes vulnerable to failure due to wave overtopping. During storms, waves overtop the dike and run down on the landward slope where the high flow velocities erode the dike cover. Experiments and numerical models have shown that erosion starts at the weak spots along the profile (Aguilar-López et al., 2018). One type of weak spots are transitions in dike geometry and cover type, for example the berm-road transition. These transitions decrease the strength of the dike cover while at the same time increasing the hydrodynamics load by creating extra turbulence (Bomers et al., 2018). In this study, three formulations for the turbulence in the erosion model are tested to determine the erosional effects of transitions due to turbulence.

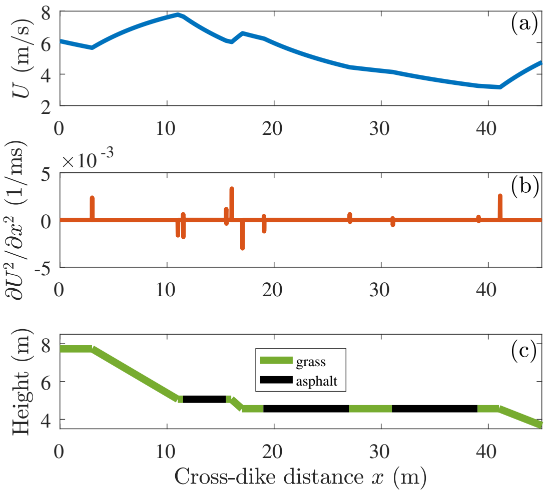

Figure 1: (a) The flow velocity U, (b) the flow velocity gradient $\partial U^2/\partial x^2$ and (c) the input profile of the lake IJssel side of the Afsluitdijk as a function of the cross-dike distance x.

Test case: the Afsluitdijk

The coupled hydrodynamic-erosion model is applied to the lake IJssel side(Fig. 1c), because the profile contains several transitions in geometry and cover type: a berm with a biking path ($x \approx 13$ m) and another berm with two roads ($x = 18 - 40$ m). The Afsluitdijk is designed for wave heights of 4 m resulting in overtopping waves with a maximum overtopping volume of 2700 l and maximum flow velocity of 6.1 m/s at the start of the dike crest. The analytical formulas for the flow velocity of Van Bergeijk et al. (2018) are applied to the test case. The calculated flow velocity decreases due to bottom friction on the horizontal parts and increases on the slope until a balance is reached between the gravitational acceleration and bottom friction (Fig. 1a).

Erosion model

The flow velocity U along the cross-dike profile is used to determine the dike cover erosion. The analytic erosion model of Hoffmans (2012) assumes that erosion only occurs if the flow velocity U exceeds the critical flow velocity U_C. In this case, the erosion depth z_d (mm/wave) is calculated as

$$z_d(x) = \left[(1.5 + 5.0\, r_0) U(x)^2 - U_C(x)^2\right] T_0 C_E \tag{1}$$

with the cross-dike coordinate x, the turbulence intensity r_0, the overtopping period T_0 and the strength parameter C_E. Assuming an average grass quality, the critical flow velocity U_C is 4.5 m/s and the strength parameter C_E is $2 \cdot 10^{-6}$ s/m (Hoffmans, 2012). Furthermore, it is assumed that the asphalt covers of the biking path and the roads do not erode and the overtopping period is set to 4.0 s.

Turbulence parameter

Three formulations for the turbulence intensity r_0 are tested to determine how transitions affect the turbulence intensity and the erosion depth. The turbulence intensity is determined using (A) a constant value, (B) the formulas of Hoffmans (2012) and (C) turbulence input based on the flow velocity gradient (Fig. 2a).

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Formulation A: Constant

In the first case, the turbulence intensity r_0 is assumed to be constant along the cross-dike profile. The value is set to 0.1 based on turbulence measurements on the slope of a river dike during overtopping tests (Bomers et al., 2018).

Formulations B: Hoffmans (2012)

Hoffmans (2012) derived two formulas for the turbulence intensity. On the horizontal parts of the dike profile, the turbulence intensity depends on the cover type as

$$r_0 = 0.85\sqrt{f} \tag{2}$$

with f the bottom friction coefficient. The bottom friction coefficient is 0.01 and 0.02 for grass covers and asphalt covers, respectively. On the slope, the turbulence intensity is calculated as

$$r_0 = \sqrt{\frac{g\,q\sin\varphi}{U_{max}^3}} \tag{3}$$

with the gravitational acceleration g, the discharge q, the slope angle φ and the maximum flow velocity U_{max} along the slope.

Formulation C: Velocity gradient

The flow velocity depends on the slope angle and the cover type, thus the double gradient of the flow velocity increases significantly at transitions (see Fig. 1b). The extra turbulence created by local acceleration and deceleration of the flow is simulated by increasing the turbulence intensity with 0.1 at locations where $\left|\partial U^2/\partial x^2\right| > 0$. The extra turbulence input is followed by a decrease in the turbulence intensity to 0.1 over a cross-dike distance of 1 m.

Results

The erosion depth along the cross-dike profile was determined for the three formulations of the turbulence intensity (Fig 2b). The difference in erosion depth between the methods is largest at the transitions ($x = 5, 11, 15-20$ m). The difference in erosion depth between a constant turbulence intensity and the formulas is very small. However, the erosion depth changes significantly using the velocity gradient method, especially around transitions. At the location of maximum erosion ($x \approx 11$ m), the erosion depth is 0.35 mm/wave larger in case of the velocity gradient method compared to the other two methods. Most erosion occurs around $x \approx 11$ m because the flow velocity is maximal (Fig. 1) and both the slope and the cover type change. The cover does not erode for $x > 20$ because the flow velocity does not exceed the critical flow velocity.

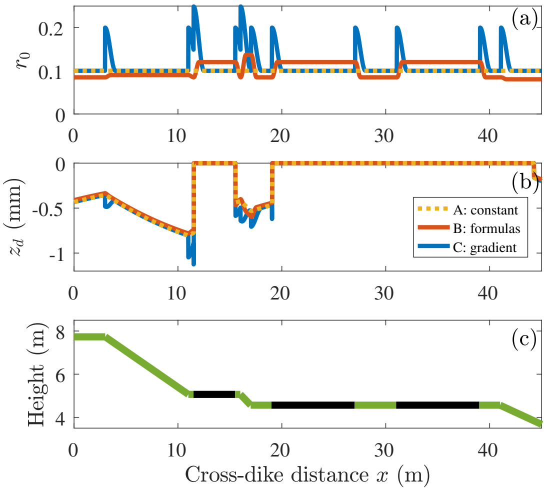

Figure 2: (a) The turbulence intensity r_0, (b) the erosion depth z_d and (c) the input profile of the lake IJssel side of the Afsluitdijk as a function of the cross-dike distance x.

Conclusions

Existing flow and erosion models need to be improved to understand the effect of climate change on the erosion resistance of transitions in dike covers. The load term in the dike cover erosion model of Hoffmans (2012) is adapted using three different formulations of the turbulence intensity. It was found that the turbulence intensity formulation at transitions significantly affects dike cover erosion. The analytical model proves useful as a first estimate to predict dike cover erosion. However, to create more realistic erosion profiles with smoother slopes, further testing of the turbulence formulation as well as formulations for the grass cover strength (U_C, T_0, C_E) are necessary.

Acknowledgements

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Incorporating subsurface heterogeneity in hydrological models for assessing dike stability

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Keywords — Dike stability, Extreme discharges, Pore pressure

Introduction

In 2017, a probabilistic risk approach for managing flood defenses as introduced by the Dutch Flood Protection program (Rijkswaterstaat, 2017), became law. In this approach, all possible failure mechanisms for a given dike stretch are taken into account, and combined into a flooding probability.

Link between groundwater and dike failure mechanisms

Often, overflowing and wave overtopping of the dike are the main dike failure mechanisms taken into account, resulting in a dike failure probability mostly based on the height of extreme river water levels. However, many failure mechanisms do not require water levels at or above the dike crest elevation. They occur due to high pore pressures, either within or underneath the dike body, that cause dike instability. Examples include slumping/liquefaction and piping/heave respectively (van Gerven, 2004). Towards the future, peak flows in the rivers are projected to increase due to earlier snow melt and an increase in extreme precipitation events in the river basins upstream of the Netherlands (IPCC, 2014). Under those circumstances, higher groundwater and river levels will pose adverse loading conditions that increase the risk of dike failure through multiple failure mechanisms. By gaining knowledge of the relative importance of specific failure mechanisms at different locations, more specific dike reinforcements can be made to cope with future changes, which is in line with the new probability-based approach.

Importance of subsurface heterogeneity

In- and sub-dike pore pressure will vary with subsurface heterogeneity, which varies across different scales. Both geological architectural units (Polanco and Rice, 2014) and intra-unit heterogeneity (Gardner et al., 2015) need to be taken into account in order to make representative model predictions of the evolution of pore water pressures and flow paths during high water levels. Due to the complex architecture of meandering river deposits, the currently used 2D subsurface characterizations are insufficient to capture the spatial variability of the subsurface. However, up to now, no three-dimensional (3D) groundwater flow studies involving realistic subsurface heterogeneity of both the dike core and the subsoil are available.

Project aims and approach

The aim of this research is therefore to couple 3D subsurface characteristics and groundwater flow to failure mechanisms. For some processes, the critical pore pressure to destabilize the dike can be calculated using static equilibrium as a first stability approximation. Subsequently, for many configurations of (sub)surface geometry and hydraulic conductivities, calculations can be carried out, to indicate a priori under which conditions the critical pore pressure is reached. The same method can be applied to actual dikes, where available databases (AHN, GeoTop, fieldwork data, GPR dike measurements) can be used to construct a hydrogeological model on the fly. Other processes (e.g. piping) are also highly dependent on subsurface characteristics and heterogeneity (Sellmeijer, 1989). However, they do not directly cause structural dike failure, and assessing their influence on dike stability requires more enhanced hydrological models, which are capable of simulating pore pressures under changing subsurface parameters following subsurface sediment displacement. When combining these processes in order to indicate the failure probability of many dike stretches on a regional scale, calculations need to be both quick and precise. These calculations will be incorporated in a final tool, which indicates the susceptibility of a dike (on sub-dikestretch scale) to various groundwater-related failure mechanisms and which can be used to better determine dike failure probability.

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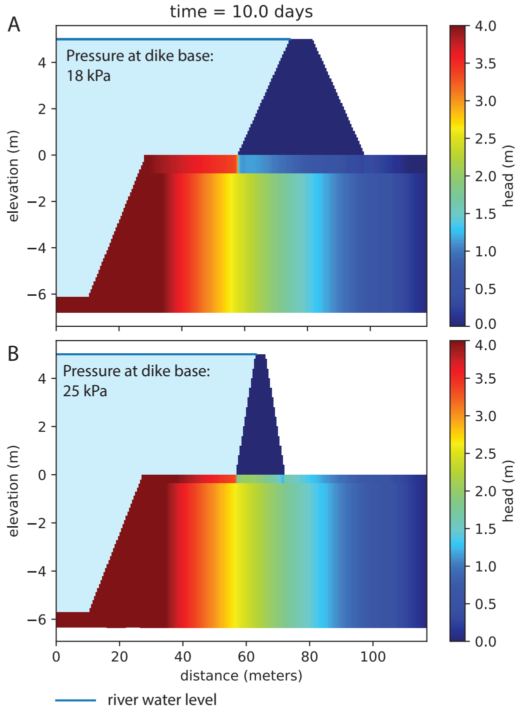

*Figure 1: First results: Differences in pore pressures as a result changes in (sub)surface geometries after a 10 day river water level rise of 0.5 m day^{-1}, with a low permeability dike and confining layer (k = 1*10^{-6} m day^{-1}). Note differences in confining layer pore pressure.*

Current work: Modelling pore pressure changes and dike stability

To be able to assess the effect of incorporating 3D subsurface geometries to hydrological dike stability models, first a 2D model is constructed. This model is capable of calculating within-dike and sub-dike pore pressure changes under transient conditions and given (sub)surface characteristics. Dike geometry, subsurface geometry, hydraulic conductivities and flood characteristics will be varied, resulting in a dataset with the sensitivity of pore pressures to different settings.

Similarly, an approximation of the dike probability to slumping and lateral displacement will be made using a deterministic threshold of the critical pore pressure from the static equilibrium analysis, based on the distribution of expected pore pressures and the related soil saturation.

First results

To examine differences in pore pressures due to geometry differences, two different configurations are compared: One where a wide dike is on top of a thick confining layer, and a second one where a narrower dike is on top of a thin confining layer. The flood characteristics and and conductivities are kept constant. The maximum pore pressure at the dike base is much higher in case of a thin confining layer (Fig. 1, B), as seepage through that layer occurs from the aquifer below. This simple example already shows the importance of incorporating heterogeneity in subsurface architecture in hydrological models assessing dike stability. It is expected that the importance of heterogeneity increases further when assessing pore pressure variability using 3D subsurface heterogeneity. In a later stage (indirect) hydromechanical failure mechanisms and fast undrained instabilities (e.g. piping, liquefaction) will also be incorporated in this analysis.

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Geological framework for representing subsurface heterogeneity relevant for piping

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Keywords — Piping, Fluvial deposits, Geological framework

Introduction

Piping is seen as a key failure mechanism of river dikes threatening the polder areas in the Netherlands (VNK, 2015). Substrate characteristics play a key role in the occurrence of piping. Especially where embankments overlie a permeable sand body, seepage-pathways can emerge during flood periods, initiating backward erosion and thus the creation of small pipes (Van Beek et al., 2013). Localization of potential weak spots remains challenging because the scale on which the piping process occurs is much smaller than the scale of any available subsurface information.

Current assessments use a probabilistic approach in setting up multiple subsurface scenarios to represent the subsurface architecture types beneath embankments (e.g. WTI-SOS). These subsurface scenarios form the starting point for local subsurface reconstructions and assessments of piping hazard (Hijma, 2015) Temporal trends, during the Holocene, in transported river sediments and variations in dimensions of fluvial deposits on both delta and local scale, are not directly incorporated into the set-up up of these stochastic subsurface scenarios.

Within this project we aim to summarize and provide a theoretical background for these variations (dimensions, composition) across the fluvially dominated part of the Rhine-Meuse delta.

Geological framework

The Rhine-Meuse delta in the Netherlands is one of the most extensively studied deltas in the world. Over the past decades multiple studies have shown the large variation in dimension and composition within fluvial deposits across the delta (e.g. Erkens et al., 2009; Gouw & Berendsen, 2007; Pierik et al., 2017; Stouthamer & Berendsen, 2000; Toonen et al., 2012; Weerts, 1996). The sandy substrate forms the starting point for defining the occurring architectures and sequences forming the subsurface scenarios of the study area as this is the substrate in which the backward erosion process forming pipes takes place. We identify four major sandy depositional units: 1) channel belt deposits, 2) cover sand deposits, 3) aoelian river dune deposits and 4) older Pleistocene fluvial deposits. The channel belt deposits are subdivided into four different generations based on changes in sediment supply and depositional setting; >5000yr BP, 5000-3000 yr BP, 3000-800 yr BP, <800 yr BP (Berendsen & Stouthamer, 2000; Cohen & Stouthamer, 2012). These changes are due to changes in rate of sea-level rise, sediment supply and embankment of rivers. The occurrence of all sandy depositional units are combined to create a substrate map showing the genesis of the upper sand units of >0.5 m thick preserved in the subsurface sequence (Fig. 1).

The next step is to reconstruct the thickness and composition of the cover layer of overbank deposits on top of the sandy substrate. At present, both the composition (*saturated volume weight*) and the thickness of the (semi)impermeable cover layer are used as input variables for piping calculations.

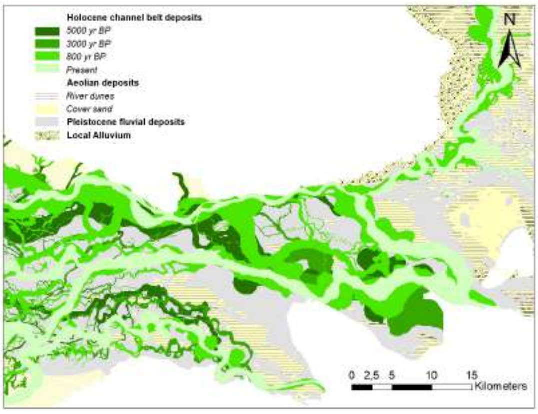

Fig 1. Subsection of the (sandy) substrate map showing the genesis of the upper sand units of >0.5 m thick preserved in the subsurface.

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The difference in composition is mainly caused by changes and transition in depositional environment. Therefore, overbank deposits are sub-divided and mapped according to the following three sub-units: natural levee deposits, crevasse splay deposits and flood basin deposits.

The resulting maps (substrate and cover layer) provide a tool for the regional subdivision of the Rhine-Meuse delta's subsurface with per area distinct fluvial sequences and help in better understanding the build-up of the geological subsurface and its potential for piping beneath river embankments.

Incorporating local variability

It is widely recognized that - at local scale - the internal build-up and dimensions of channel belts are highly variable (Bridge, 2002; Toonen et al., 2012; Miall, 1996; Weerts, 1996; Van de Lageweg et al., 2016). Given the complexity involved, we first attempt to make local reconstructions for representative areas of the study area to refine the lithological detail of the existing geological subsurface models by using existing and new collected data (coring, CPT, geophysics).

Future incorporation of this lithological variability would be a significant step to more functional hydrological characterization of channel belts in 3D numeric subsurface flow and piping calculations.

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Session 2 - Ecology and Morphology

Oral Presentations

Modelling degradational rivers

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Keywords — Ill-posedness, Mixed-size sediment, Regularization

Introduction

Throughout the last two centuries engineers have intervened large rivers for the sake of, among others, improving navigability and preventing flooding (Lonnquest et al., 2014). These interventions have induced morphodynamic changes that we still face nowadays. One if the consequences of past interventions is the ongoing bed degradation occurring in several large rivers including the Rhine River in the Netherlands (Blom, 2016).

Measures aimed at preventing further degradation require predicting the effects of such interventions using morphodynamic models. A problem arises when using a morphodynamic model to predict degradational conditions of a river: the model may become ill-posed. An ill-posed model becomes useless in practice, as unphysical oscillations appear in the results. The origin of the oscillations lays in the unsuitability of the model to represent the physical processes under consideration and for this reason the emergence of oscillations is independent of the numerical solver. The most striking feature of an ill-posed model is that the result does not converge when the numerical grid is refined. Worded differently, when using smaller grid cells unphysical oscillations grow faster leading to ever changing results.

In this paper we present two alternative strategies to prevent ill-posedness in morphodynamic modelling.

Two Alternative Models

Modelling of bed elevation and bed surface texture changes typically combines a set of equations accounting for the flow with the Exner equation accounting for bed elevation changes and the active layer equation accounting for changes in the bed surface grains size distribution. This model may become ill-posed particularly under degradational conditions into a substrate finer than the active layer (Chavarrías et al., 2018).

The first alternative aims at preventing ill-posedness while introducing minimal changes to the model (Chavarrías et al., b). The regularization strategy consists of artificially modifying the time scale associated with mixing processes when and where the active layer model is ill-posed, guaranteeing in this manner that the resulting model is well-posed.

The second alternative yields a well-posed model by improving the description of the physical processes related to sediment transport and change of the bed surface texture (Chavarrías et al., a). This alternative consists of combining the active layer equation with an equation that conserves the sediment in transport. This new mass conservation model achieves a better description of the physics at the expense of a more complex system of equations.

Results

In this section we compare the original active layer model to the regularization strategy and the new mass conservation model. To this end we run simulations of an idealized degradational case using the three models. The domain is one-dimensional and it initially is under equilibrium conditions. The sediment mixture is characterized by two sediment sizes. The mean bed surface is coarser than the substrate as typically found in the field. The causes of the long term degradation are simplified and it is imposed by a decrease of the upstream sediment load.

Figure 1a shows the bed elevation predicted using the original active layer model. Nonphysical oscillations appear over the entire domain from the start. The most upstream oscillation is largest, as it is enhanced by the imposed change in upstream boundary condition. A mesh-convergence test (not presented here) shows that the growth rate and amplitude of the oscillations grow with decreasing cell size, as it is expected from unphysical oscillations. The results of the regularized model do not display any oscillations (Figure 1). Degradation progresses smoothly. The new model captures the formation of a large degradational wave due to the sudden reduction of the upstream load superimposed to the overall degradational trend. As opposed to the original active layer model this wave is not physically unrealistic. The wave requires a certain space and time to form, and regardless of the grid size, the wave speed, amplitude, and position remains

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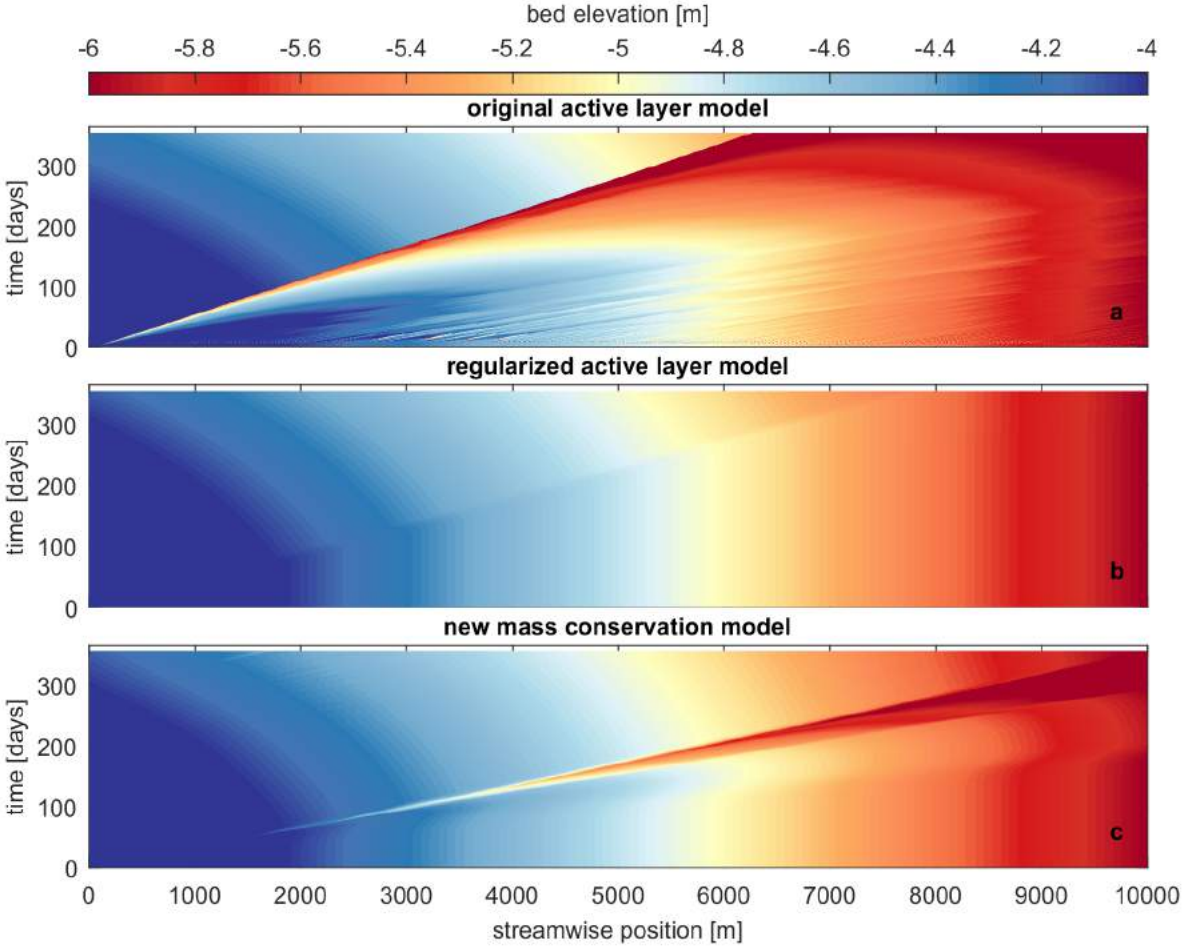

Figure 1: Simulated bed elevation of a degradational case.

constant, which is a standard requirement to a numerical run.

Conclusions

We present two alternative strategies that allow modelling of river bed degradation under conditions in which the original active layer model is not applicable as it becomes ill-posed. The advantages of the regularization strategy are that it keeps the fundamentals of the active layer model and is relatively cheap in computational terms. The disadvantage is that it does not capture the formation of a degradational wave superimposed to the overall degradational trend. The new model captures both the trend and the wave at the expense of a costly numerical solution. Our analysis highlights the necessity of implementing the alternative(s) to allow for the assessment of future interventions in degrading rivers.

Acknowledgements

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Monitoring flow and sediment transport at strongly asymmetric bifurcations of a large sand-bedded river

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Keywords — large river, river delta, river bifurcation, sediment transport, discharge division, ADCP

Introduction

Bifurcations are a key element of river deltas, as the division of water and sediment greatly influences the hydrodynamics and morphology of the downstream branches. This division can change over time so that one branch silts up and the other widens. This can risk downstream settlements and infrastructure. The division of sediment is complex, as it strongly depends on the planform and bathymetry of the bifurcation. In particular, bifurcations, at which one branch takes off to the side, are considered as unstable, as secondary currents divert an excess of sediment into the side branch, leading to its demise. Despite its relevance and complexity, few field studies have been conducted on bifurcations of large sand-bedded rivers. To fill this gap, we present here the discharge and sediment division of two mayor bifurcations of the Kapuas, a large sand-bedded river in West Kalimantan, Indonesia. Both bifurcations are highly asymmetric, with the side branches turning to the side at an angle that exceeds 90°. Despite their particular shape, which implies a rapid siltation of the side branches, the branch dimension did not change over the last century. With our measurements, we want to identify the processes that govern the sediment division and stabilize the bifurcations.

Field Site

The discharge of the Kapuas varies seasonally with the monsoon. In 2014 the discharge ranged between 1 000 m^3/s in the dry season and 10 000 m^3/s in the wet season (Kästner et al., 2018). The tide is mixed, mostly diurnal with a root mean square spring tidal range of 1.5 m. Along the alluvial plain three distributaries branch off the Kapuas River (Figure 1). The distributaries terminate in short tidal funnels and upstream of which their width remains constant (Kästner et al., 2017). This study focusses on the two most downstream bifurcations, where the Kapuas Kecil and Kubu channel branch off. The bifurcations are located 45 and 90 km from the sea. While the Kapuas Kecil branches off in an outer bend, the approach of the Kubu bifurcation is straight. The flow reverses at the bifurcation only when the river flow is very low, and salt water reaches only the downstream bifurcation during low flow extremes.

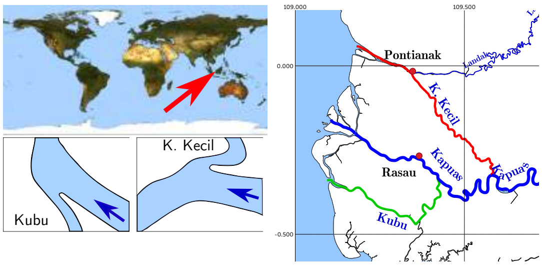

Figure 1: Location of the Kapuas Delta, Map of the Kapuas Delta, and bird view of the bifurcations

Measurement

We measured the discharge and sediment division at each bifurcation for one full diurnal cycles during spring tide, and one full semidiurnal cycle during neap tide, during March and April 2014. We measured with two boats in parallel. Both boats were equipped with a 1200 kHz ADCP and a GPS receiver mounted above the instrument. The first boat measured the discharge and successively crossed the approaching channel and downstream branches. The second boat followed the same route but took water samples on its way. Water samples were taken with a Niskin bottle at up to four points along the water column, at three locations in the main branch and two locations in the side branches. Suspended sand transport was inferred from the ADCP backscatter (Kästner and Hoitink, 2019).

Result

During the measurements the river flow was lower than expected for the season, and ranged only between 3 000 and 4 000 m^3/s. The measurements show, that 18% of the approaching discharge is diverted at the Kapuas Kecil bifurcation, and 10% at the Kubu bifurcation respectively. Even though the river flow was low, the tidal discharge was lower than the river discharge during all measurements. The flow between the Kapuas main branch and the Kapuas Kecil is nearly in phase, while the flow into the Kubu channel is considerably

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Email address: `karl.kastner@wur.nl` (Karl Kästner) delayed with respect to that along the main branch. This is likely caused by the considerably smaller depth and longer distance to the sea of the Kubu channel.

The division of the suspended sand differs from that of the discharge. Only 7% of the approaching sand is diverted into the Kapuas Kecil, while 18% is diverted into the Kubu channel. Relatively less sediment than water is therefore diverted into the Kapuas Kecil, while relatively more sediment than water is diverted into the Kubu branch. The spatial distribution of the suspended sediment reveals, that most sediment is transported in the side of the channel that is opposite to the side from which the Kapuas Kecil branches off (Figure 2). This is not the case at the Kubu channel, which explains the different division of sediment at both bifurcations.

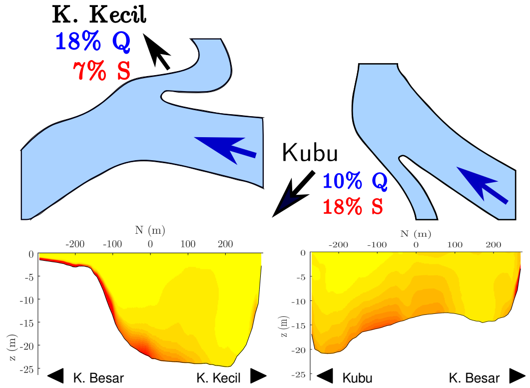

Figure 2: Discharge and sediment division at the Kapuas Kecil (top left) and Kubu (top right) bifurcation, the different division of sediment is reflected in the sediment concentration within the approaching channels (bottom), owing to the main channel curvature

Discussion

Small-scale laboratory experiments show that bifurcation branches that take off to the side receive most of the approaching sediment (Bulle, 1926; Herrero et al., 2015). However, at both Kapuas bifurcations, the majority of the sediment remains in the main branch. Scale experiments with small aspect ratios are thus not necessarily representative for the sediment division in large sand-bedded rivers.

Differences between the sediment division at the Kapuas Kecil and Kubu bifurcation are likely related to their location within the meander bend. The importance of the curvature of the approaching channel for the division of the sediment has been shown before (Kleinhans et al., 2008). However, the lower diversion of sediment to the outer bend branch does not be the direct result of the secondary flow in the main channel branch, as the secondary circulation in the immediate approach of the bifurcation is annihilated by the diverting flow (Figure **??**). Rather, the meandering seems to exert its influence indirectly by means of coarsening the bed material towards the outer bank. Such sorting has also been shown to be relevant for the division of sediment at the Rhine bifurcations (Sloff and Mosselman, 2012).

Conclusion and Outlook

The Kapuas bifurcations give an unprecedented insight into the sediment transport division at bifurcations of large suspended load dominated rivers. Overall, a much smaller fraction of sediment is diverted to the side branches compared to scale experiments with small aspect ratios. The relatively large inlet area of the side branches seems to reduce secondary currents of the diverted flow and thus the amount of the diverted sediment. Differences in the division between the bifurcations are caused by the curvature of the main channel.

As the measurements merely take a snapshot of the long life of river bifurcations, further work is necessary to understand the long-term morphodynamic. Currently, we investigate the role of the inlet area by means of an idealized mathematical model and the long-term morphology with a detailed Delft3D simulation.

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Measuring and modeling the development of side channels

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Keywords — Side channels, Bifurcation, River morphology

Introduction

Side channel construction is a common intervention to reduce the flood risk of the river or to increase the river's ecological value. In the Netherlands, over 20 side channels have been constructed since 1996. Such artificial side channels generally aggrade (e.g., Van Denderen et al., 2019), which in most cases is undesired and therefore, regular maintenance is required. A better understanding of the mechanisms that lead to morphodynamic changes in a side channel can improve its design, operation and maintenance. We evaluate the development of side channels using measurements of the side channel system at Gameren in the river Waal and numerical computations.

System description

The side channel system at Gameren in the river Waal (the Netherlands) is an example of an artificial side channel system (Fig. 1). The three side channels were constructed between 1996 and 1999, and their objective is to compensate a water level increase that was a result of a levee relocation. At the upstream side of the East channel and the West channel, weirs were constructed to control the discharge in the channels such that the East channel flows 100 d/yr and the West channel flows 265 d/yr. The Large channel is much longer compared to the other two channels and is permanently connected to the main channel.

Method

Data analysis

In the first few years after the construction of the channels, regular bed level measurements are available. Unfortunately, from 2003 the main source of bed level data is LIDAR measurements, which only gives the bed level data of the East channel because the other channels are permanently inundated. In addition, we collected sediment samples in 2017 in the three side channels of the deposited sediment to analyze and to characterize the development of the side channels.

Hydrodynamic and morphodynamic model

We use a hydrodynamic model (Delft3D Flexible Mesh) to estimate the flow conditions in the side channels. Using the model results we estimate the variation of the bed shear stress and the streamlines as a function of the discharge in the river. The morphodynamic model is used to get more insight into the temporal development of a side channel system. We use a two-dimensional depth-averaged version of Delft3D in combination with the mixed-sediment morphodynamic module (Sloff et al., 2001). We look at an idealized version of a side channel system in which we neglect the effect of the floodplains. The discharge at the upstream boundary is given by a repeated averaged yearly hydrograph. We use four sediment-size classes and we compute the sediment transport for bed load transport and for suspended bed-material load transport separately. Using the model, we study the effect of varying hydrodynamic conditions on the bed level development and on the sediment that is deposited in the side channel.

Results

Data analysis

Here, we focus mainly on the bed level development of the East channel. The East channel has reached a bed level at which vegetation is able to grow and at which wash load is deposited in the channel (Fig. 2). Therefore, the channel seems to have become part of the floodplain. The bed level measurements show a clear relation with the hydrodynamic regime of the river (Fig. 2B). With increasing flow frequency of the channel, the aggradation rate of the bed reduces. A similar relation is found between the cumulative discharge conveyed by the side channel and the aggradation rate. The more the side channel flows, the less aggradation occurs. This explains partly why the aggradation rate of the West channel is much smaller.

Hydrodynamic and morphodynamic model

The hydrodynamic model gives insight into the spatial and temporal variation of the transport capacity in the side channels at Gameren. Furthermore, the streamlines give valuable information on the flow patterns and thereby, give

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Figure 1: An aerial image of the West, East and Large side channel at Gameren in the river Waal. The three side channels were constructed between 1996 and 1999. (After images of Rijkswaterstaat)

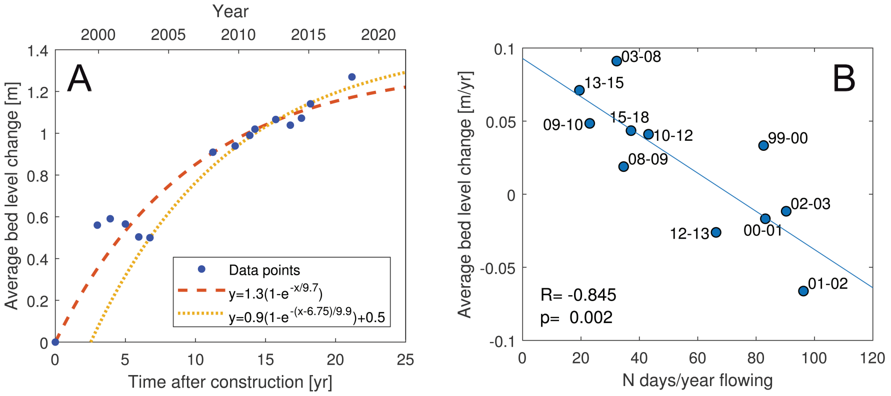

Figure 2: (A) The average bed level change in the East channel of Gameren from its construction in 1996. (B) The average bed level change per year related to the yearly-average flow frequency of the East channel. The correlation is computed using Spearman's rank correlation and a first-order fit is shown.

an indication of the temporal and spatial variation of the sediment supply to the side channels. The morphodynamic model confirms that varying hydrodynamic conditions have a large effect on the aggradation rate of the side channel. We computed the bed level development using a repeated hydrograph and found that at lower bed levels the largest bed level increase occurs at bankfull discharge. With increasing bed level, the peak flow becomes more important for the continuing aggradation of the side channel. The sediment that is deposited in the side channel also varies in time. During low flow conditions mainly the fine sediment classes are deposited in the side channel and during peak flow mainly the coarse sediment classes. With increasing bed level, the supply of coarser sediment classes to the side channel reduces.

Discussion and conclusions

The analysis of the side channel system at Gameren is valuable to better understand the development and the temporal variation in development of side channels in general. Unfortunately the measuring frequency is too low to study the effect of single flood events on the side channel development. The numerical model is used to fill in these knowledge gaps. We find that both the aggradation rate and the sediment that is deposited in the channel, show a relation with the bed level of the side channel and the hydrodynamic conditions of the river.

Acknowledgements

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Upstream perturbation and floodplain formation effects on meandering river pattern and dynamics

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Keywords — fluvial morphodynamics, floodplain formation, perturbation

Problem definition

A sustained dynamic inflow perturbation and bar-floodplain conversion are considered key to dynamic meandering. Past experiments have demonstrated that the initiation and persistence of dynamic chute cutoff-dominated meandering requires a periodic transverse motion of the inflow position (Van Dijk et al., 2012). This finding is supported by theory (Lanzoni and Seminara, 2006) and one-dimensional models (Weiss, 2016), but it remains unclear whether the period of the inflow perturbation affects self-formed meander dynamics.

Furthermore, most currently available models that are used to study meander dynamics are either one-dimensional or apply a two-dimensional grid that reshapes as the channel migrates (a practice that is also known as regridding) (e.g. Weiss, 2016; Schuurman et al., 2016). A drawback of such models is that they invariably lead to some form of neck cutoff-dominated meandering, even when river pattern predictors suggest a different river pattern given the imposed discharge and grain size (Kleinhans and Van den Berg, 2011). Since we are interested in modelling a chute cutoff-dominated river, a two-dimensional grid that includes floodplain is required, in which former self-formed floodplain topography can influence the location of future cutoffs.

Objective and methodology

The objective of this study is to test numerically the effect of the inflow perturbation period on the development and meander dynamics of a chute cutoff-dominated river. To this end, we modelled a dynamic meandering river on a laboratory scale using the morphodynamic model Nays2D, starting from a straight channel. Nays2D is a physics-based numerical model that solves the depth-averaged nonlinear shallow water equations and computes sediment transport and bed level change (see Shimizu et al., 2013, for equations and numerical implementation). We extended Nays2D with colonisation and mortality rules of static vegetation to allow for floodplain formation, and included a laterally moving inflow boundary with a constant displacement rate, similar to Van Dijk et al. (2012).

We varied vegetation density to determine its effect on channel pattern and dynamics, with the objective to select a run with a sustained dynamic meandering river for the inflow perturbation tests. Next, we tested the effects of a transversely migrating inflow boundary by varying the perturbation period between runs over an order of magnitude around typical modelled meander periods. Finally, we ran three characteristic scenarios on a finer grid to test the effect of grid size.

Results

All runs with sufficient vegetation show series of growing meanders terminated by chute cutoffs (Fig. 1). This generates an intricate channel belt topography with point bar complexes truncated by chutes, oxbow lakes, and scroll-bar related vegetation age patterns. These patterns appear better defined on a finer grid but are generally present at a lower grid resolution as well. Occasionally, the river changes into a weakly braided network due to a cascade of cutoffs, but it always tends back to a single thread with moderate sinuosity.

Sinuosity, braiding index and meander period emerge from the inherent biomorphological feedback loops in the model and are therefore greatly influenced by the degree of bar-floodplain conversion (Fig. 2); the denser the vegetation on the bars, the more flow is channelised into a single sinuous channel. In contrast, the inflow perturbation period has an insignificant effect on the overall channel pattern and dynamics; its direct influence only extends to the first bend, while all other migrated uncoupled from the upstream boundary. This is attributed to perturbations migrating in downstream direction and dampening out within a few channel widths. Also, the spin-up to dynamic equilibrium takes

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a longer time and distance for weak and absent inflow perturbations.

Conclusion

A dynamic inflow perturbation and bar-floodplain conversion are necessary and sufficient conditions to model dynamic chute cutoff-dominated meandering in numerical hydromorphodynamic models and in landscape laboratory experiments with a domain of limited length. This insight extends to many more fluvial, estuarine and coastal systems in morphological models and experiments, which require sustained dynamic perturbations to form complex patterns and develop natural dynamics.

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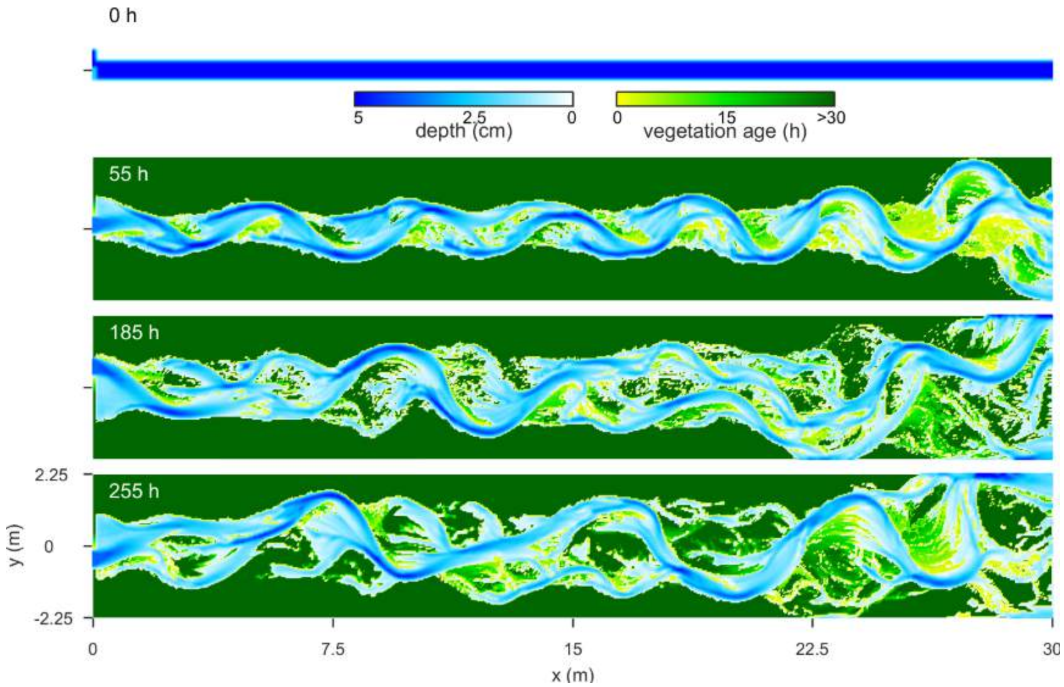

Figure 1. Development of river morphology, here shown as water depth overlain by vegetation age. Flow is from left to right.

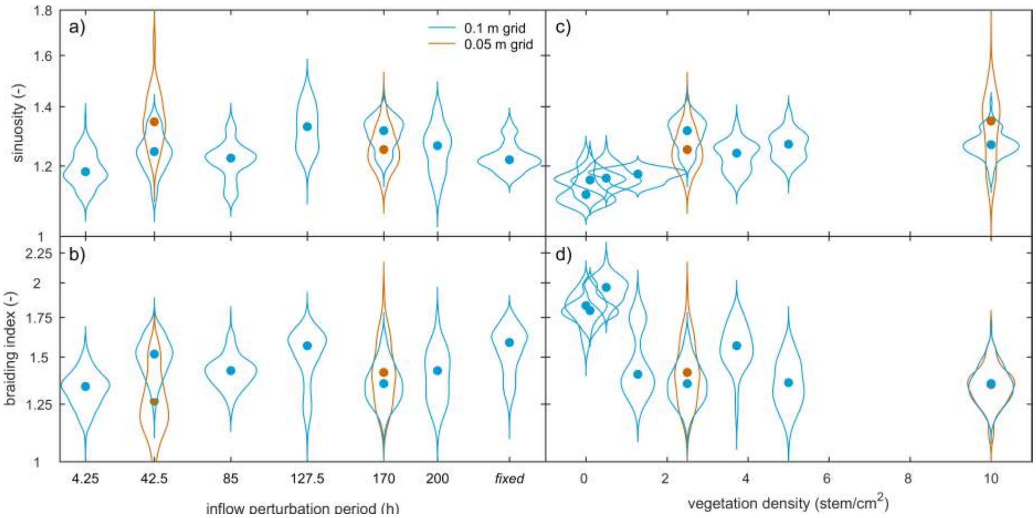

Figure 2.Violin plots showing spatially averaged sinuosity and braiding index as function of (a-b) inflow perturbation period and (c-d) vegetation density, sampled from t=100 h until the end of each model run.

Levee morphology and evolution in the fluvial-tidal realm

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Keywords — Levees, morphology, fluvial-tidal realm

Introduction

Natural levees are sloping deposits of sand, silt and/or mud that are build up along the sides of a channel. They are common and pronounced geomorphological features in river and delta landscapes in which they form elevated areas in further low-relief floodplains (Adams et al., 2004). The along channel position of levees and their morphology influences hydraulics and the distribution of water and sediment within river and delta systems (Brierly et al., 1997). Despite its relevance on delta evolution, research on levees is sparse and commonly limited to case-studies (e.g. Cazanacli and Smith, 1998; Adams et al., 2004; Filgueira-River et al., 2007) losing the general understanding and implications of levee development on a larger scale. The need for a comprehensive understanding was underlined by Pierik et al. (2007) who found that levee dimensions vary throughout the delta over space and time, driven by changes in hydraulic and sedimentary processes. Their field based method focussed on the comparison of purely fluvial levees in the Rhine/Meuse delta, excluding the lower tidal rivers and estuaries as well as different boundary conditions that occur in other deltas and river systems. Therefore, the objective of this study is to assess the influence of boundary conditions on levee morphology and evolution.

Methods

To assess the influence of boundary conditions a systematic study was conducted with morphodynamic numerical modelling in Delft3D. The model enclosed 4 sand sediment fractions (300/250/125/75μm) as well as silt and clay while the initial bathymetry resembled the lower Old Rhine system during the early-mid Holocene. In addition, field data from this system was collected for comparison. The influence of three different boundary conditions was tested, aiming to cover distinct hydraulic regimes where levees can be formed: 1. Constant fluvial discharge without tides (Q=700 m^3/s), 2. Varying fluvial discharge without tides (Q=690-1000 m^3/s), 3. Constant fluvial discharge with tides (Q=700 m^3/s, M2=0.50 m).

Results

Levee development is simulated in all three contrasting models, see morphologic results in Figure 1. In general, higher discharge magnitudes and larger tidal amplitudes cause the maximum levee height to increase (not visualised). Yet, an increase in tidal amplitude has a larger influence on maximum levee height than an increase in fluvial discharge.

In all model runs levee evolution can be divided into several phases. These phases are caused by the morphologic evolution of the levee itself and by the development of crevasses in the levees. In general, three phases of levee evolution can be distinguished (Figure 2): 1. A heightening phase, in which the levee grows in height; resulting in a triangle shape cross-section. 2. A widening phase, in which the levee starts to widen significantly while continuing to grow in height. 3. A phase linked to the crevasse channels, in which the crevasse channels evolve more and create their own levees in the larger complex. In the lithological cross-sections of the Old Rhine river system multiple phases of levee formation can be found as well (Figure 3).

The overall morphology of the levee-complexes becomes more complex when water fluctuations are induced. In the model without water level fluctuations (Figure 1a), smooth levees form. When water fluctuations are introduced (Figure 1b,c) crevasses form that breach the levees. In the case of the tidal water level fluctuations the crevasses form simultaneously with the origination of the levee complex. With variable discharge crevasses seem to originate when the levee complex is already established.

Conclusions

Levees form as the result of differential sedimentation of fine sand, silt and clay as water and sediment flow over the edges of a channel. The maximum height of levees is controlled by the maximum water level, determined by discharge magnitude and tidal amplitude.

Undisturbed levees form when fluctuating water levels are absent during formation (Figure 1a). When water fluctuations are relatively small and occur on a yearly basis, relatively smooth levees are still able to form. These levees are only breached by a small amount of crevasses after a significant amount of time (Figure 1b). However, when larger water level fluctuations occur on a daily basis (e.g. by tides) intricate levee-crevasse complexes evolve where levees and crevasses develop simultaneously (Figure 1c). In general, the evolution of levees consists of multiple phases that are induced by feedbacks between accommodation space (max. water level), evolving morphology (heightening, widening and crevasse formation) and hydrodynamics. This demonstrates that multi-phase levee deposits do not have to be initiated by extreme up- or downstream events but can simply form due to the evolution of the levee itself. Aforementioned findings will help in unravelling the causes of levee phases in natural systems.

Acknowledgements

We would like to thank Jelle Moree and Tim Winkels for their help in collecting the field data presented in this abstract. This research is supported by the European Research Council (ERC Consolidator grant 647570 to MGK).

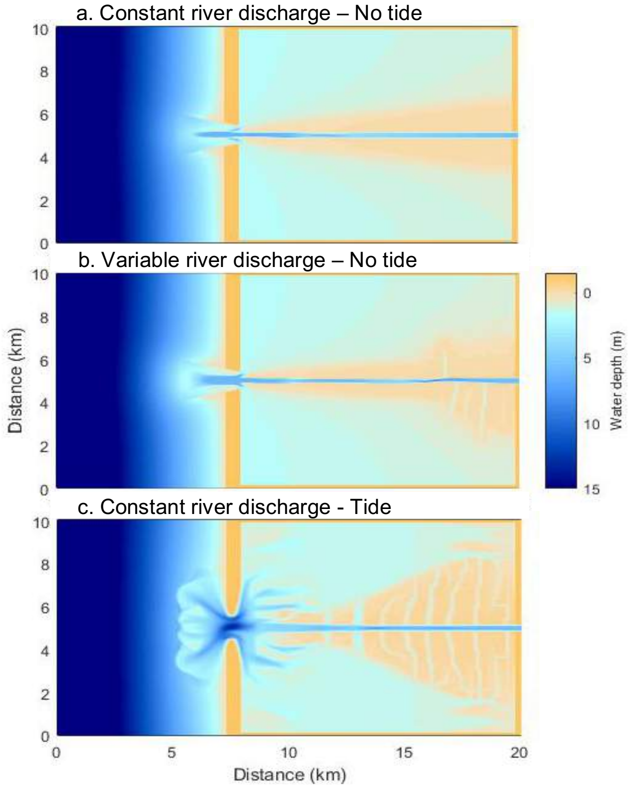

Figure 1. Morphological development after 100 years. a. Constant river discharge (700 m^3/s) without tides. b. Variable discharge (691-1000 m^3/s) without tides c. Constant river discharge (700 m^3/s) and tide (M2=0.50 m).

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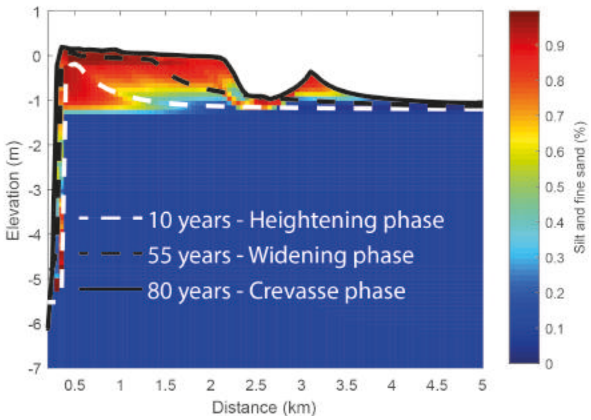

Figure 2. Cross-section over the southern levee at 18.4 km displaying the combined percentage of silt and fine sand from the model with fluctuating discharge without tides (b. in Figure 1). Lines represent bathymetry at three moments in time representing the three key phases in levee development: heightening (dashed white), widening (dashed black) and crevasse evolution (black).

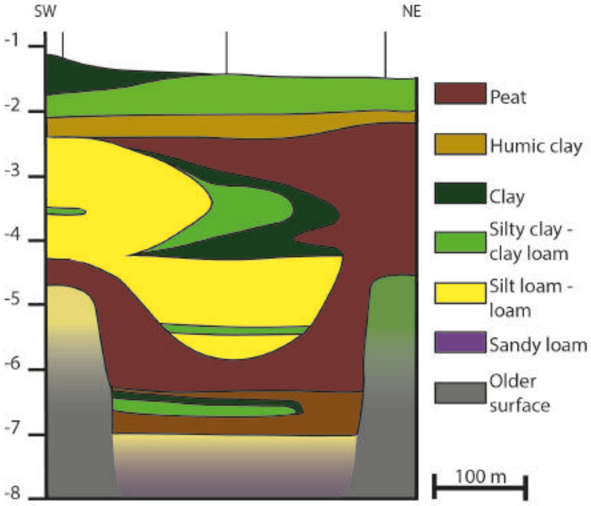

Figure 3. Lithological cross-section of overbank deposits of the Old Rhine river system east of Alphen aan den Rijn. The cross-section shows two levee phases. The oldest levee phase is preceded by a crevasse system. Depth is below NAP. Vertical lines indicate location of boreholes.

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Removal of bank protection to ecologically improve the River Meuse

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Keywords — Meuse, Restoration, Semi-Natural Shorelines, Ecology, Morphology, Water Framework Directive (WFD)

Introduction

Most of the shorelines of the impounded Meuse have protected with riprap. These enforced shorelines do have little ecological value. Starting in 1995 and accelerated by the Water Framework Directive (WFD), Rijkswaterstaat (RWS) decided to improve the ecological quality of shoreline habitats (Rijkswaterstaat, 1995). RWS commissioned to develop a 'Leitbild' for nature-friendly riverbanks in which the core notion for free eroding riverbanks was foreseen (Peters, 2005). Nowadays the greater part of these projects has been finished totalling over 80 km along the impounded stretch of the Meuse, which is unprecedented for a navigable river.

An overview of the sites where bank protection has been removed along the river Meuse can be found at: http://www.rws.nl/maasoevers.

To assess the morphological and ecological development of these so-called 'nature-friendly' shorelines, a 10 year monitoring programme (2008-2017) started in 2008 (Rijkswaterstaat Waterdienst, 2009) including baseline and reference sites. Such a duration for project monitoring is rather exceptional.

This study briefly presents the evaluation of 10 years of hydromorphological and ecological data for 21 river banks of five types: 2 types of bank removal, 2 protected types and unintended eroding riverbanks.

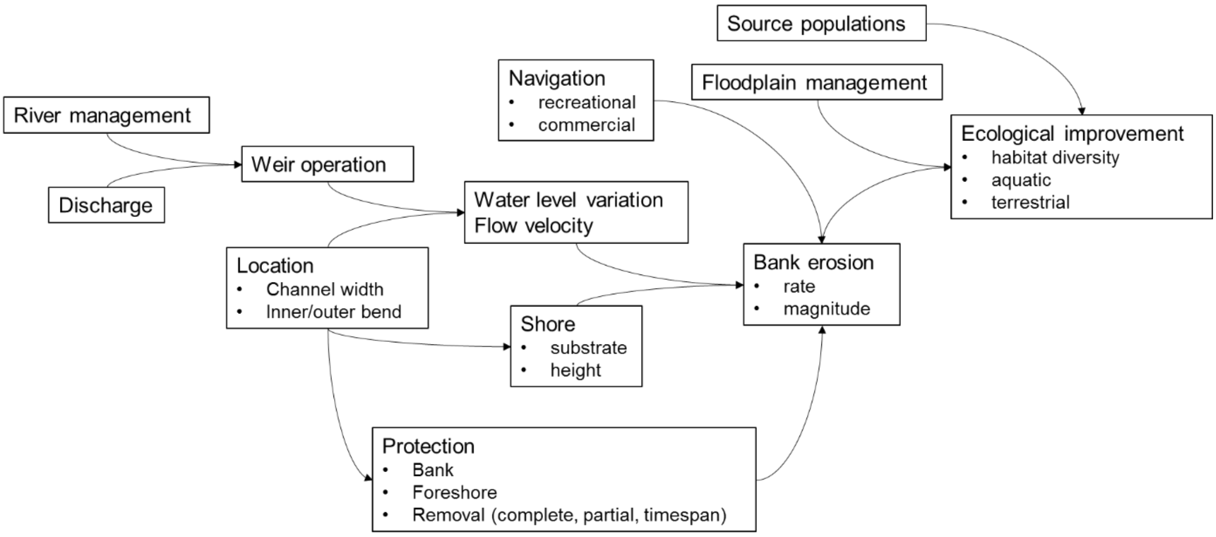

Figure 1 Conceptual model of factors influencing bank erosion and ecological development along the impounded river Meuse

Methods

Various factors have been identified to influence morphological and ecological development of river banks (Figure 1). Depending on the location and river management, removal of riverbank protection accelerates bank erosion resulting in improved ecological habitats for riverine species. Aerial surveys, laser altimetry, bathymetry were carried out for morphological monitoring. The ecological monitoring including macrophytes, macroinvertebrates, fish and terrestrial flora and fauna took place every other year on either the left or right bank.

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Results

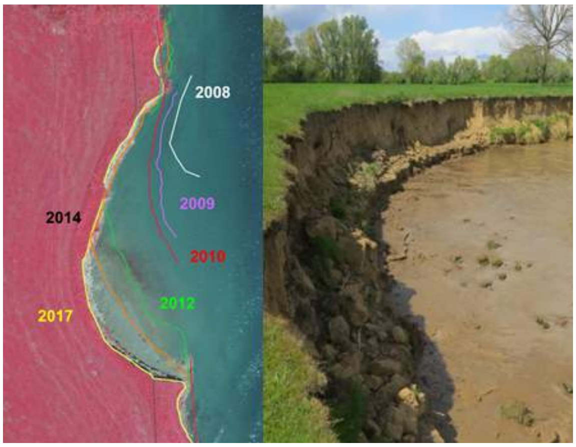

Figure 2 Erosion on riverbank Noordereiland near Beugen from 2008 - 2017 (left) and situation in 2017 (right)

Removal of riverbank protection results in increased erosion rates. In general the total length of eroding river banks increased. On some locations the banks eroded locally up to 20 meters into the floodplain (Figure 2 & Figure 3).

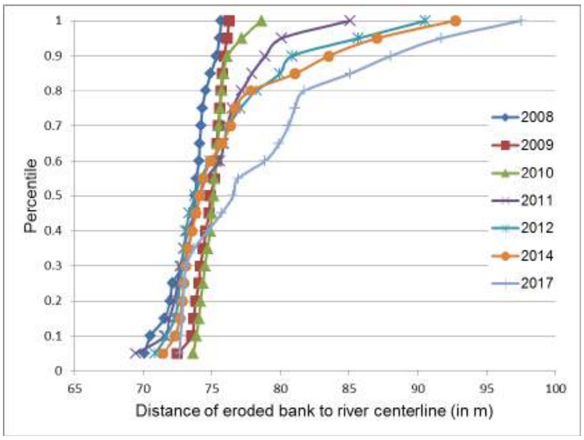

Figure 3 Erosion lines based on interpretation of aerial pictures

The monitored riverbanks have been classified in different succession phases according to Peters (2005). Most of the riverbanks where the protection is removed are currently in the 2nd and 3rd stage (Figure 4). Water level fluctuation, flow velocity, channel width, riverbank height, inner/outer bend, substrate and intensity of navigation play crucial roles for the degree of erosion (Figure 1).

Shoreline restoration has an obvious impact on fish population. The response is fast and removal of bank protection is beneficial for indigenous species. Macroinvertebrates monitoring indicates a strong relationship with the local substrate. In general the macroinvertebrates diversity near restored shores appears to increase with time.

The response of macrophytes has a time lag and coverage and species diversity increased throughout the monitoring period. More complex shorelines such as stage 4 and 5 are more suitable for macrophytes. The terrestrial flora and fauna is much influenced by floodplain management. The number of sand martin has increased due creation of high and steep river banks with an alteration of clay and sand layers forming an ideal nesting habitat.

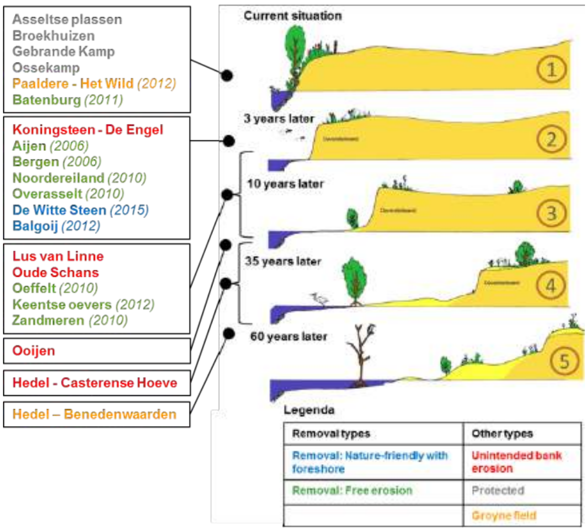

Figure 4 Successional stages according to Peters (2005) of the different riverbank types by 2017. The year of removal of bank protection is given within brackets.

Conclusion and recommendation

The removal of riverbank protection in the Meuse has led to a greater variety of shoreline habitats that are favourable for all biological quality elements of the WFD. The fact that the Meuse is impounded has a great influence.

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Session 2 - Ecology and Morphology

Poster Presentations

Efficient vegetation management through remote sensing in small streams

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Keywords — Remote sensing, aquatic vegetation, roughness, vegetation management, mowing

Introduction

Vegetation development can be a challenge for managers that aspire to decrease mowing intensity as a 'building-with-nature' measure. Particularly in unshaded low gradient streams with nutrient rich water aquatic plants can completely and very rapidly clog the stream channel, severely hindering its drainage function and increasing the risk of flooding the adjacent lands. For this reason, the instream vegetation is mowed frequently using crane or boat operated mowing-baskets. While seemingly an effective way to solve the problem, mowing is both expensive and has a considerable impact on the stream ecosystem.

Instead of waging a costly war on vegetation, our aim is to only selectively remove the vegetation that is most problematic in terms of flood risk. To reach this goal, we need to be able to (i) detect the spatial distribution of vegetation and (ii) assess the hydraulic impact of that vegetation. Progress in both fields has been made in previous small-scale pilot studies (Penning et al., 2018; Van den Eertwegh et al., 2017). In this paper, we report the findings of a larger scale study in the Leijgraaf stream, managed by regional water authority *Waterschap Aa en Maas*.

Spatial distribution of vegetation

The most common method to determine vegetation patches from remote sensing is multispectral analysis. In contrast to our eyes, and most commercial cameras, multi- or hyperspectral cameras capture not only the visible spectrum (wavelengths of 380nm – 750nm), but also near infrared (NIR, 750-1400 nm) and infrared (> 1400 nm). This allows us to detect things that the eye cannot by combining several wavelengths from both the visual spectrum, as well as the (near) infrared spectra.

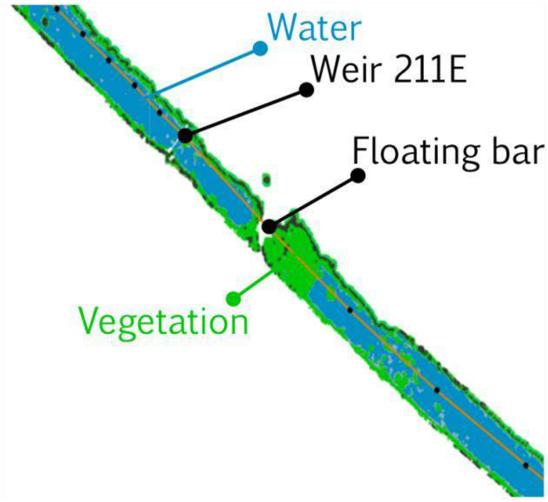

Figure 1. Vegetation (green) detected through multispectral analysis up- and downstream of weir 211E in the Leijgraaf stream.

Unfortunately, the resolution of multispectral free satellite imagery is currently not high enough to detect vegetation in small streams. To obtain these images for small stream stretches, a multispectral camera can be attached to a drone. However, a drone-based approach does not easily scale up to entire streams. Therefore, in this study we used an airplane to obtain the images for the entire 20 km of the Leijgraaf stream with a resolution of 0.25 m.

We use a combination of spectral indices like the Normalized Vegetation Density Index (NDVI) and the Normalized Difference Water Index (NDWI), to differentiate water, trees and aquatic vegetation in various stages of submergence. In general, results suggest a high level of non-uniformity along the stream: aquatic vegetation has a very patchy distribution. A close-up near one of the weirs (211E) in the Leijgraaf system shows that there is a concentration of vegetation just upstream of the weir (Figure 1). This might be explained by mowing activities; after mowing vegetation is often left to drift downstream and to be collected at a floating bar at the downstream end.

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To improve and validate the classification of the vegetation from spectral imagery, in-situ measurements of the vegetation were taken. For structurally homogenous patches of the dominant aquatic plant species present, stem density, submerged and emergent biomass were determined. These analyses are still ongoing.

Hydraulic impact of vegetation

The hydraulic impact of vegetation on flow is superficially easy to understand: vegetation increases flow resistance and will increase water levels. However, it is not straightforward to determine to what extent the vegetation increases roughness. The contribution of artificial vegetation (e.g. rigid cylinders) to roughness is reasonably well understood and adequately modelled by various (semi-empirical) formulas. However, there are severe technical challenges for predictive use of those models in the field. These include unknown plant composition, plant species specific traits, spatial non-uniformity, dynamic reconfiguration, seasonal variability and the effect of human-induced changes (i.e. mowing).

Therefore, we used an inverse, data-based approach. Based on fifteen years of hydraulic data, we computed the Manning's roughness coefficient with a 1D-hydrodynamic model for every other day. This resulted in a high-resolution dataset for multiple sections along the Leijgraaf stream. Results show two main factors explaining the roughness in the system. First, the Manning coefficient is highly dependent on discharge (Figure 2), which is in line with the general conception that vegetation dynamically reconfigures depending on the flow velocity in the system. The second explaining factor is seasonal variability. Even after accounting for discharge dependency (discharge tends to be lower in summer) roughness values were significantly higher in summer compared to winter, which suggest vegetation growth. Surprisingly, human-induced events (i.e. mowing) did not seem to be a major explanatory variable. We have two hypotheses which might explain the latter. First, it could have been caused by a time lag between the mowing event and the removal of vegetation biomass from the system, which complicates attribution of an effect on roughness to a specific event. Second, not all (local) mowing events will be effective for decreasing the impact that the vegetation has on the overall roughness in the entire stream section.

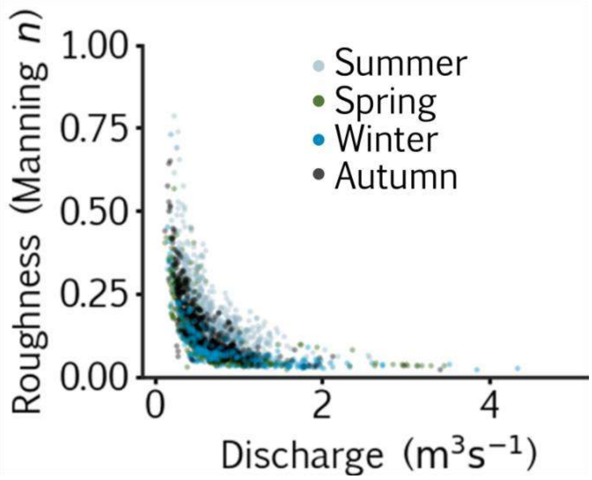

Figure 2. Result show that roughness has a high dependency on discharge.

Conclusion and future work

In order to be able to selectively remove vegetation, we need to detect the vegetation and we need to assess what effect removal will have on management goals. The results of this study contribute to both of these goals. Future work focusses on automation, generalisation and upscaling the temporal resolution of remote imagery, and to create a practical predictive system for vegetation management guided by remote sensing of the spatial distribution of vegetation within the stream.

Acknowledgement

This work was commissioned by Waterschap Aa en Maas within the Lumbricus research programme.

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Impact of vegetation on braided river morphology under changing flood conditions in a physical model

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Keywords — Braided Rivers, Vegetation, Physical Models

Under present day climate change predictions, with both higher magnitude and altered frequencies of flood events, uncertainties exist in how the behaviour of river systems will change in the future. This uncertainty is greater when considering the impact on river systems with vegetation, which may also vary because of climate change.

Physical modelling can be a valuable tool to understand the processes on a smaller scale, in particular by simulating the effects of vegetation using surrogates that can grow rapidly mimicking the forcing induced by vegetation growth. Previous studies using surrogate vegetation in flume experiments on braided rivers (e.g. Tal and Paola, 2007; Bertoldi *et al.*, 2015), have shown the potential for this modelling approach, but did not investigate the impact of vegetation growth under different flood sequences.

In a 2.5 m wide by 10 m long flume, a braided river system evolved under constant conditions. Once equilibrium conditions were reached Alfalfa was periodically seeded and allowed to germinate and grow for different time periods. After each period of growth, we used a sequence of low and high magnitude flood events in order to capture the change in morphology due to different sequences of events.

DEMs captured from these experiments indicate the impact surrogate vegetation has on stabilizing the river system and changing the pattern of erosion and deposition in the braided river system. The distinct patterns of erosion (and deposition) allow us to explain the effect of a range of flood sequences and vegetation growth have on the braided system. It also allows us to pinpoint these effects on morphology and the evolution of important individual morphologic features like bars and banks, e.g. bank erosion rates. Ultimately, this can give an indication how different flood events induce changes on vegetated and non-vegetated (braided) river system as well how to effectively introduce these into a physical model.

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Empirical channel pattern predictors – why do they work?

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Keywords — River channel patterns, bank strength

Introduction

Rivers worldwide exhibit a wide range of channel patterns, such as braiding and meandering (Leopold and Wolman, 1957). The type of channel pattern results from the balance of floodplain erosion and floodplain formation (Kleinhans, 2010), which is determined by the shear stress (i.e. stream power), calibre and quantity of sediment load, and bank strength (Nanson and Croke, 1992; Kleinhans, 2010). However, Leopold and Wolman (1957) suggested to empirically distinguish meandering and braiding rivers with just two controlling variables; bankfull discharge and channel slope, fully excluding the floodplain properties. Since their efforts, many attempts of channel pattern predictions applying a similar empirical approach have been made (Ferguson, 1987; Van den Berg, 1995).

Similarly, Kleinhans and Van den Berg (2011) developed empirical discriminators to distinguish between different styles of meandering and braiding by classifying bar pattern (Fig. 1). Although quite successful in predicting the channel pattern, the physical explanation behind their success remains unknown, and floodplain properties are still excluded. Towards this goal, a better understanding is needed of the physical meaning behind the empirical relations found by Kleinhans and Van den Berg (2011), and a plausible explanation is needed why certain rivers plot in a higher energetic regime than their actual morphology and dynamics suggest, e.g. rivers that have the energetic potential for meandering and development of scroll bars, may in fact be laterally stable (Fig. 1).

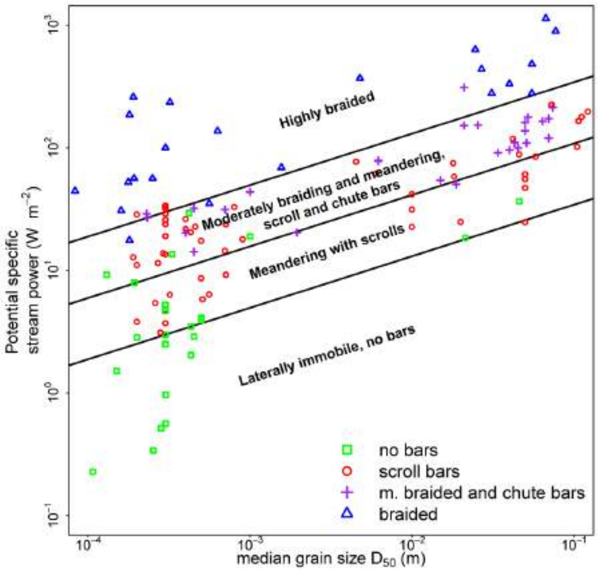

Figure 1. Empirical channel pattern prediction after Kleinhans and Van den Berg (2011). River patterns of alluvial rivers plotted according to their potential specific stream power (Eq. 1) and D_{50} of their bed material. Discriminators indicate the lower limit of channel pattern fields, defined by Eq. 2. .

Original channel-pattern prediction

The potential specific stream power was suggested to be a suitable independent measure of river energy as proposed by Van den Berg (1995); Kleinhans and Van den Berg (2011) following Eq. 1:

$$\omega_{pv} = \frac{\rho g Q S_v}{W_r} \qquad (1)$$

where ω_{pv} is the potential specific stream power (W m^{-2}), ρ is the water density (kg m^{-3}), g is the gravitational acceleration (m s^{-2}), Q is the effective channel-forming discharge (m^3 s^{-1}), S_v is the valley slope (-), and W_r is the reference channel width (m) (see definition by Kleinhans and Van den Berg (2011)). The original discriminators as presented in Fig. 1 are defined as:

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$$\omega = f(D_{50}^{0.42}) \qquad (2)$$

where D_{50} refers to the median bed grainsize.

Physical interpretation

The physical explanation of the success of the current empirical channel pattern prediction follows from several analyses. Firstly, we recalculated the slope of Eq. 2 from the Shields diagram (Li et al., 2015), and found that the current slope can be explained from the natural organization of rivers. Secondly, we found that the reference width (Eq. 1) indirectly includes the effect of width-depth ratio at which a river changes to a less stable bar regime (Crosato and Mosselman, 2009), which differs between sand-bed and gravel-bed rivers. Thirdly, we found that the relative difference between the discriminators (Fig. 1) can be explained from the differences in shear stress acting on the river bank, because of differences in actual width-depth ratio between the channel patterns.

Bank strength

Here we use the average silt-plus-clay fraction of river banks as a proxy for bank strength, which was available in literature for 71 rivers of the original dataset. We derived Eq. 3:

$$\omega_{pv} = \frac{(0.1SC)^{1.5}C}{\sqrt{\rho g}} \qquad (3)$$

where SC is the silt-plus-clay fraction of river banks, and C is the Chézy coefficient ($m^{0.5}$ s^{-1}). We further defined the discriminators in 3D by including Eq. 3 (Fig. 2), and found that the channel pattern prediction significantly improved, especially in discriminating between laterally stable and meandering rivers. We also applied Eq. 3 to the other discriminators using the same factor difference as used for the original discriminators (Fig. 1 and 2).

Conclusions

We physically explain the success of the empirical channel pattern prediction by Kleinhans and Van den Berg (2011), and further develop this prediction by including bank strength.

Acknowledgments

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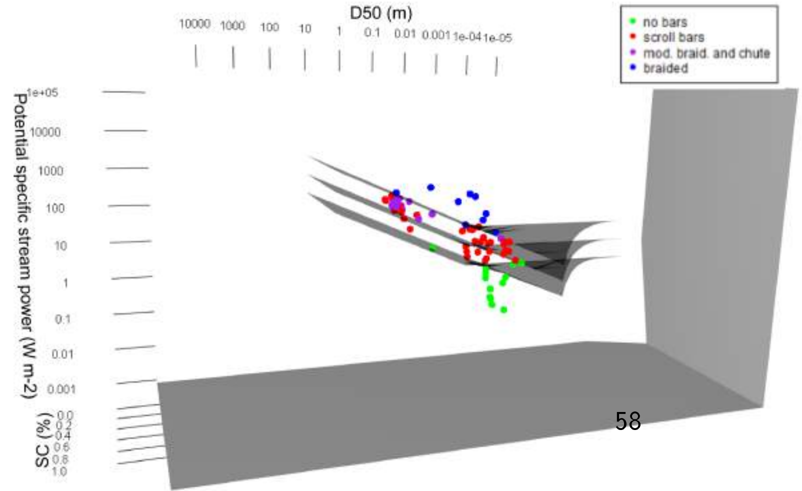

Figure 2. Empirical channel pattern prediction as in Fig. 1, now including the bank strength on the third axis expressed as the silt-plus-clay fraction of the river banks (SC, %). Graph is shown from an angle in which the data-points can be seen best.

Estimating sediment travel distances in Alpine catchments through UAV based sediment shape indices

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Keywords — Sediment Connectivity, Abrasion, UAVs

Within river basins, humans require infrastructures to cover a series of water needs. The impacts of these infrastructures on natural and anthropogenic systems is difficult (if not still impossible) to estimate and therefore medium to long term effects are only partially considered in planning and management decisions.

Sediment transport in rivers is a complex process for many reasons and our ability to model it in detail is still limited therefore, in many areas of the World, the development and management of river structures rarely considers their effect at basin scale. Available morphodynamics models aim at reproducing natural forms as consequences of changes in sediment transport rates, rather than to capture the dynamics of individual particles within the river network. These models are also often calibrated and validated using sediment transport rates measured in specific locations. These measures are affected by a number of drawbacks: they are expensive, affected by low accuracy, limited in terms of the range of sediment sizes they can collect, among others.

Recent studies on abrasion claim the existence of a "universal" relation between mass loss and specific shape indices (Novák-Szabó et al., 2018). Once the universality of this relationship will be confirmed by extensive testing in different real litho-morpho-climatic settings, it will become possible to link measurable properties of sediments (e.g. size, shape and lithology) to their travel distance (Cassel et al., 2018). This will represent a fundamental step towards a deeper understanding of sediment transport in mountain/piedmont rivers.

This research aims at the assessment of the applicability of this relationship to estimate sediment travel distance. In order to test the hypothesis of "universality" of the relation between relative mass loss due to attrition and particle shape, we will compare the shape indices of natural sediment characterized by different litho-morphological settings at different distances from their sources.

The selected case study is the Cordevole River basin in North-East Italy. Within this watershed, a small tributary, the Sarzana River, is characterized by the presence of localized outcrops of arenite and metabasalts which, given their very localized sources, will be considered as tracers.

The methodology that will be applied is based on the analyses of field data collected using UAVs. In the field, samples of sediments including the mentioned tracers will be collected at different distances from their sources and their size and shape will be estimated using digital image processing tools. The data collected during the field campaign will allow the assessment of the relation between shape change and distance travelled for each of the selected lithologies, which will be presented and discussed.

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Mapping river bank erosion and morphology using drone imagery for the Buëch River in France

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Keywords — Bank erosion, UAV-images, SfM Image processing, DEM difference

Introduction

River bank erosion, channel displacement and changing morphology are important processes that can do potentially damage to infrastructure such as bridges, roads and building and are important information for river managers. Remote sensing observations by drones are suitable tools to monitor these three processes. Using drones typically hundreds of images are collected by flying by manual control or by auto-pilot. These individual images must be processed for each time step of image acquisition into OrthoMosaics and Digital Elevation Models (DEMs) to study and evaluate the dynamics of river channels.

Here we present a study using temporal sets of drone images acquired in the visual wavelengths red, green and blue for local monitoring of the Buëch river system in the Hautes Alps in France. Discharges of this river are characterized by a major peak during spring (snow melt and rain) and a second peak in autumn (Sandre, 2018). The objectives of our study are to demonstrate the usefulness of time-series of drone images to map river bank erosion and channel displacement and we evaluate the obtained accuracy of UAV image products and erosion and displacement results.

Data and Methods

Drone images were collected in June 2014 and June 2015 along two stretches of the Buech river. The two sites are referred to as Chabastan and Labatie and cover each an area of approximately 400 by 1000 meters (Hemmelder, 2016). The drone used is a manually-controlled fixed wing aircraft with a consumer grade Canon Powershot D10 RGB camera aboard (figure 1). Flight altitude was around 130m. Forty markers with an identifiable dot in the centre were laid out for reference purposes and their exact location was measured using a Real Time Kinematic GPS system (Trimble R8 GNSS).

The structure form motion (SfM) algorithm (Smith et al, 2014) was used to process the images into DEMs of 10 cm pixel size and OrthoMosaics of 5 cm pixel size. SfM identifies millions of common points ('identical features') in the individual drone photos and these points are used to match the hundreds of individual photos. Next, SfM builts point clouds on the basis of these common features and very accurate OrthoMosics and DEMs can be computed.

Figure 1. Fixed wing aircraft with aboard a Canon Powershot D10 RGB camera. The drone is manually controlled and flown at an elevation of ~ 130m.

The positional accuracy was evaluated for the OrthoMosaics for both years using the DGPS positions of the laid out markers. Reference sites (locations) for river bank erosion were measured in the field using DGPS measurements along the edges of the river banks at a number of known erosion sites (figure 2). River bank erosion was determined in a quantitative way by comparing (subtracting the two DEMs acquired in 2015 and 2014. Channel displacement and gravel bank displacements in the flood plain were evaluated

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by comparing the two Orthomosaics and measuring the 'centre of channel' displacement at various locations.

Results and conclusion

Evaluation of the positional accuracy by comparing the locations of the 40 markers measured in the field using a DPS and their position in the images revealed that the XY accuracy was approximately 34 cm and the Z-direction around 2 cm.

Channel displacements for this braided (and sometimes meandering river) were ranging up to 70 m between 2014 and 2015 and at some location the channel has crossed the entire floodplain. Bank erosion was as expected very variable from location to location but could be mapped at centimetre to decimetre detail. Mapping efforts were sometimes hampered by overhanging vegetation, water glitter and shadows. At the Labatie site a significant erosive event took place in between the image acquisitions of 2014 and 2015 where an area of around 70 by 150 m was eroded. Volume estimates using the DEM difference revealed a displaced volume of around 6000 m^3.

This study showed that time-series of UAV images are suitable for monitoring river dynamics and for deriving quantitative information for a number of processes such volume estimates of bank erosion and channel displacements. Processing of the images into mosaics and DEMs is straightforward and reaches accuracies of centimetres to decimetres. The use of UAVs is easy, flexible and cheap. Users do not depend for their images on satellite overpasses and spatial resolution is so far much better. It is uncertain how legislation of using drones will develop in the coming years as rules tend to become stricter and stricter which unfortunately hampers the operational use of drones for scientific applications.

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Figure 2. Areas of active bank erosion illustrated by the tumbling trees. At these locations the erosion between 2014 and 2015 was measured using DGPS and used as reference for UAV image assessment of bank erosion.

Interaction of dunes and bars in the Dutch Waal River

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Keywords — River Dunes, Hybrid Bars, Waal River

Introduction

For decades bed forms have been studied in detail, amongst others for their effect on bed roughness. In this context, the main focus has always been on river dunes, with flow separation at the lee side (Best, 2005). In large-scale numerical models, dunes are generally not resolved, and an empirical bed roughness formulation is used (e.g. van Rijn, 1984) with a spatially homogeneous roughness coefficient.

Yet dunes are not the only bed forms present in rivers, and the question arises whether interaction with bed forms on other spatial scales might influence dune dynamics, contradicting the assumption of a spatially homogeneous roughness coefficient. Larger scale bed forms like bars are mainly studied separate from dunes, in a separate community.

In the present study, the aim is to test the assumption that migrating dunes and non-migrating hybrid bars (Duró et al., 2016) can be treated separately and hardly interact. To do so, a temporally and spatially extensive dataset of bed levels in the Dutch Waal River is used.

Methods

The bed level in the fairway of the river is monitored fortnightly as part of a regular maintenance programme of the river authorities, using Multi-Beam Echo-Sounding (MBES). This is an acoustic technique based on the reflection of emitted sound pulses on the river bed. The dataset was gridded to a regular grid of 1×1 m^2, with at least 95% of the cells containing at least 10 data points. In order to analyse bed form profiles in a 2-D way, profiles parallel to the river axis were defined (Fig. 1).

To distinguish between different spatial scales, a LOcally weighted regrESSion (LOESS) procedure was applied (Cleveland and Devlin, 1988; Vermeulen, 2016). To determine the optimal span for filtering dunes and bars, a spectral decomposition was performed. Individual dunes and their characteristics were detected and determined using the bed form detection tool by van der Mark and Blom (2007), based on a zero-crossing method. To test whether dunes are significantly influenced by hybrid bars, a cross-correlation analysis between specific dune characteristics and the bar profile height was performed.

Figure 1: Bed level on a 2 km trajectory of the Waal River on 23 March 2011, downstream of the city of Tiel. The river axis and two profiles to the left and right are indicated. The three lines are 41 m apart.

Results

Fig. 2 shows the hydrograph of the Rhine River at Lobith and the temporal evolution of the measured bed profiles over a stretch of 2 km. Although the temporal resolution is on average only two weeks, still individual dunes can be identified in subsequent profiles. From dune tracking, the dune celerity appears to vary between 50 and 200 m/month. Therefore our assumption that dunes are able to adapt to

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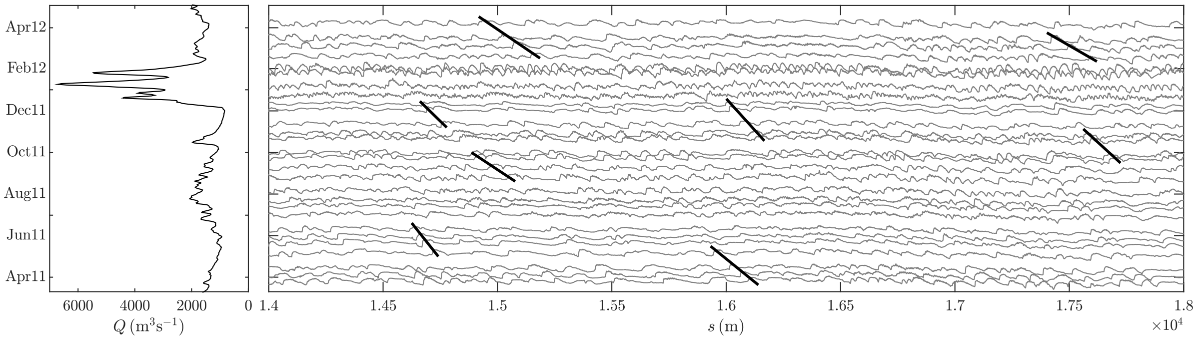

Figure 2: Left: the discharge at Lobith, where the Rhine River enters the Netherlands. Right: fortnightly bed level profiles for a stretch of 2 km in the Waal River. Dunes migrate from right to left. Several lines indicate dune celerities by tracking individual dune crests.

local hydraulic changes when migrating over bars (length of several km's) seems reasonable. During discharge peaks, however, the dominant dune length decreases and individual dunes are no longer traceable.

To assess whether dunes and bars are clearly separable, a spectral decomposition of the bed level profiles after LOESS filtering was performed. The peak bed form length after detrending with different spans was determined for a 20 km long stretch of the bed profile (Fig. 3). Four main length scales are detected, of which the lowest corresponds to dunes (144 m) and the highest to bars (8190 m). However, also two intermediate wavelength are present, corresponding to bed forms larger than dunes, but smaller than hybrid bars, which wavelength is dictated by the river curvature.

Conclusions and ongoing research

From a spatially and temporally extensive morphological dataset of the Waal River, it is concluded that dunes are able to adapt to local hydraulic changes when migrating over hybrid bars. In the spectral domain, dunes and bars are clearly separated, but also two intermediate wavelengths are observed.

Ongoing research focusses on cross-correlation analysis of dune characteristics and bar profile height. Preliminary results show that dune height and bar profile height are correlated, but that lag and significance depend on discharge regime and location. Correlation for dune length seems to be insignificant, probably because of the dominant effect of discharge.

Acknowledgements

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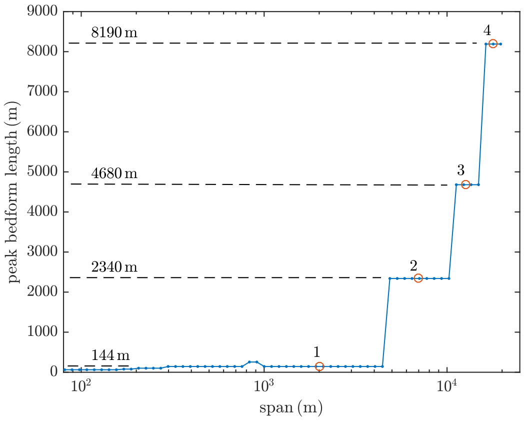

Figure 3: Peak bed form length after detrending a 20 km long bed level profile using different LOESS spans. Red circles indicate 40% of each sill width, following van der Mark and Blom (2007).

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High frequency monitoring of suspended sediment properties to accurately quantify suspended sediment fluxes

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Keywords – Suspended sediment, Flocs, *In-situ* measurements

Introduction

Suspended sediment transport is a continuous, natural and interactive phenomenon in geophysical surface flows. Pickup and settling of suspended sediment effects the geomorphology of rivers, deltas and coasts. Also, they carry contaminants possessing a threat to ecological health of river. Deposition of these sediments creates a source of contamination inside the river (Owens et al., 2005). This motivates the need to better understand and quantify the riverine transport of fine suspended sediments. However, the interdependence of suspended sediment properties and in-channel processes present a challenge in the quantification of suspended sediment fluxes. This association of properties is not well understood, as suspended sediment constitutes of variety of micro components in the form of primary particles (clay and silt), organic content, contaminants and pores. The large surface area of these fine primary particles act as a site for contaminants and organic matter, which get attached and develop empty and water-filled pores. Mutual co-existence of these fine components results in the formation of flocs (Droppo, 2001). Suspended sediments in the form of flocs are influenced by riverine conditions (salinity, temperature, turbulence). These conditions directly affect some measurable properties of suspended sediments, as for example turbidity, which is often used as a proxy to estimate suspended sediment concentration (Druine et al., 2018).

The relation between turbidity and suspended sediment concentration is ambiguous due to various factors. For instance, the presence of organic content lowers the density of flocs and increases the floc size. On the other hand, floc size can be increased or decreased under the influence of flow conditions (Droppo et al., 2014; Garcia-Aragon et al., 2011), effecting floc size distribution and eventually exerting an impact on turbidity. In this study, we therefore intend to develop methods to measure factors controlling floc formation at high frequency using in-situ sensors, with the ultimate aim to better quantify suspended sediment concentration, and model suspended sediment transport under changing hydrodynamic conditions.

Methods

In-situ measurements may capture the complexity involved in reproducing various chemical, physical and biological processes involved in suspended sediments at the laboratory scale (Druine et al., 2018). The sensors used for in-situ measurements may avoid the sampling error generated due to the transformation or breaking of flocs, which can occur during transportation and refrigeration of sediments before an actual measurement is to be carried (Gałuszka et al., 2015).

In this study, we will use the following in-situ sensors. The laser diffraction technology of LISST (Laser In-situ Scattering and Transmissometry) provides the particle size distribution and volume concentration for suspended sediments. It detects the scattered laser light through concentric ring detectors. These rings are sub-divided according to a size class or size range (2.5 – 500 µm). In this, the inner concentric ring detect the particles with the largest size, whereas the outer ring corresponds to smallest particle of the classified size range (Agrawal and Pottsmith, 2000; Druine et al., 2018).

In addition, we will use spectrometry originally developed to measure waste water parameters to quantify contaminants and organic content associated with sediments (Martínez-Carreras et al., 2016). We will measure the organic content and color, which helps to better characterize the relation between turbidity and suspended sediment fluxes (Blöthe et al., 2018; Sutherland et al., 2000).

Research Gaps

The following two research gaps will be addressed during the project, which each lead to an objective as follows.

i) The joint presence of organic and mineral content in suspended sediments in the form of flocs generates variability in densities and size distribution of suspended sediments (Blöthe et al., 2018). In turn, this variability develops uncertainty in formulating the relation of turbidity and suspended sediment concentration (Druine et al., 2018). Objective 1 is to quantify the impacts of organic and mineral content on turbidity and estimates of suspended sediment concentration.

ii) Changes in riverine conditions hamper the quantification of suspended sediment fluxes, where salinity causes integration and dissolution of floc components (contaminants, organic content) (Bainbridge et al., 2012; Druine et al., 2018). On the other hand, hydrodynamic forces exert a strong impact on floc size distributions (Droppo, 2001; Droppo et al., 2014; Garcia-Aragon et al., 2011; Stone and Krishnappan, 2003; Tsai et al., 1987). Therefore, objective 2 is to establish the influence of micro components on floc size under dynamic discharge conditions, and to improve the representation of floc formation and breakup in sediment transport models.

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Operational monitoring of floodplain vegetation using google earth engine

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Keywords — monitoring, floodplain vegetation, remote sensing, google earth engine

Introduction

The National Water Authority (Rijkswaterstaat or RWS) has the task to ensure an efficient discharge of water (from the Rhine and Meuse) at high water levels. The floodplains and their vegetation partly determine the water levels at high discharges; therefore maintenance of the floodplain's morphology and vegetation is essential.

The floodplain configuration at which a safe water level is guaranteed (at a designated water level) is mapped into the "vegetatie legger" and part of the legal framework for the watermanager called "waterwet". The 'vegetatie legger' consists of a map of the floodplains in which the vegetation is summarised into 6 classes. If the current state of the floodplains is different and the local hydraulic roughness exceeds that of the locally allowed vegetation type, vegetation maintenance is needed.

To compare a current state of floodplain vegetation to the 'vegetatie-legger', RWS needs a map of the current state. The current mapping procedure (ecotope maps) is a proven and robust method, but the production of the ecotope maps has a processing time of one year and its mapping cycle is every 6 years. Six years is to long for timely vegetation management, optimally one would like the information from within the same year for the whole management area comprising of Meuse and Rhine.

System Idea and basic methods of the monitoring application

The initial idea was to create an application that gives insight in the current state of a selected floodplain or river section and compares that state to the 'vegetatie legger'. It was decided that the developed application should allow all landowners in the floodplain to be able to check their 'vegetation status', so a web-based interface was chosen. Sentinel-2 satellite images were chosen as principal data source because of the high temporal coverage (every 5 days), free availability and resolution (10x10m). Using Google Earth Engine (GEE, https://earthengine.google.com/) makes it possible to implement an on-the-fly classification for areas of interest. The random forest classifier is trained using existing vegetation structure maps with about 200 points for each 'vegetatie legger' class.

Result

The vegetation monitor front-end is shown in Figure 1. You can visit https://www.openearth.nl/vegetatiemonitor/ to test the application. The user can zoom to an area of interest, look at the original vegetatie-legger and flow paths with highest flow, then select sentinel images by date, classify an selected image, and calculate the difference with the 'vegetatie legger'. Additionally, classified images can be downloaded (geotiff). Per land owner polygon a PDF summary comparing the 'vegetatie legger' vegetation distribution (% surface area of types) with a classified image is made available for downloading. The back-end is rooted in python, MapBox and the maps and computations are performed in Google Earth Engine (GEE).

The classification results vary per area of interest and selected image. The best results were obtained using August or September images, when vegetation types are optimally developed, and reach 71% total accuracy based on training and testing with vegetation structure maps from 2017. Field trials showed the maps provided sufficient detail to be able to recognise past vegetation management activities by end-users.

Figure 1. Screenshot of the web-interface of the vegetation-monitor application. On the left side you see the various spatial layers, including "classificatie" which contains the classification. The right side shows the area of interest, in the screenshot a classified image is drawn on top of a true-color version of the satellite image.

Application experiences

The vegetation monitoring tool is the first tool that gives up to date information of the current status of floodplain vegetation in the Rhine and Meuse floodplain areas. The revisiting time of sentinel is much higher than the annual aerial photograph survey (which is still used for verification). Comparing the 'vegetatie legger' with the current state allows an indication of how much "maintenance space" is available before interventions must be carried out (such as throwback of vegetation succession). Experiences of RWS show that the monitoring tool helps a lot in the discussion with nature organizations who are responsible for the maintenance of the vegetation in large parts of the floodplains. During the annual field check-ups the tool was used on tablets during field visits to areas which were classified as being rougher than the vegetatie legger. There were several reasons why spots were classified rougher: during the hot summer, the river dried up which had consequences for the shore areas going from water to sand. Quick developments of willow storage along the shore or at dried up gullies were identified quickly and efficiently. Although the classification of the tool was not always correct, given the fact that this is a first version; the reactions and feedback from RWS was very positive and the tool has been widely accepted by other end users such as Staatsbosbeheer, Natuurmonumenten, and other cultural and landscape foundations.

Outlook 2019

In 2019 the vegetation monitor will be further developed to improve the classification algorithms and explore if vegetation prediction can be added. The user experience will be enhanced by continued dialog between users and developers. Classification improvements under consideration are refining the training set by eliminating outliers in the training data and testing additional data such as newer LiDAR and Radar (Sentinel-1). A first version of a vegetation-prediction module was prototyped in 2018, but needs more 'vegetation succession rules' and validation using Landsat time-series for hind-casting to validate the vegetation succession rate as currently estimated by experts.

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Modelling the long term dynamics of the Mara wetland (Tanzania) using a 2D-hydromorphydynamic model

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Key words - Wetland, Vegetation, Suspended Sediment, Dam Operations, Delft3D

Introduction

In wetlands, water is the primary factor controlling the environment and the associated plant and animal life (Ramsar Convention Secretariat, 2006). Wetlands not only provide diverse ecosystem services but also contribute to the improvement of surface water. In tropical Africa, their supportive role has become progressively highlighted in ongoing studies, but less scientific research has been carried out as compared to other ecosystem forms and wetlands in other parts of the world (Kabii, 2017). This is largely due to the difficulty in field or insitu monitoring owed to their remote locations (Gallant, 2015), with those accessible during periods of low flow, totally cut off during high flows. The lack of timely and reliable information on the status and evolution of tropical African wetlands impedes efforts to sustainably manage and develop them.

This study focuses on utilisation of numerical modelling techniques to examine the factors influencing the dynamics of wetlands in tropical climatic conditions, specifically investigating the role of the interaction between sediment and vegetation on wetland dynamics. The research approach is centred on the Mara Wetland, a selected case study located in the lower Mara Basin, Tanzania, experiencing tropical climatic conditions. The study sets out to define, calibrate, validate and implement a 2D Hydromorphodynamic (2DH) numerical model of the wetland. The model focuses on the dynamics and fate of suspended sediment.

The Mara wetland is formed by the Mara River before it discharges its waters into Lake Victoria. As a natural filter, the wetland sinks nearly 90% of the river's total suspended sediment input (Bregoli et al., 2018), releasing clear water to the lake. The wetland's sediment and nutrient trapping capacity, and water purification function is influenced by the presence of vegetation, predominantly papyrus (Bogers, 2007). Vegetation enhances hydraulic roughness significantly reducing flow velocity and inducing sedimentation. However, the current vegetation cover and its spatial distribution is heavily endangered by human activities such as forest fires, intense farming and grazing activity (Bregoli et al., 2018). This poses a threat to the stability of the wetland system given the increasing suspended sediment loads originating from intense land use changes in the upper catchment (Defersha et al., 2012).

Another concern is the proposed dam construction across the Mara River, 30km upstream, purposed for water storage for irrigation, water supply and small hydropower production (Tuyishimire, 2014). The resulting effects envisaged include: significant changes in both the river, and wetland morphodynamics due to the regulation of flow and sediment input by dam operations (Bregoli et al., 2018).

Study Objectives

This study seeks to determine:

a) how vegetation and its spatial distribution affect sedimentation in the Mara Wetland;
b) the effects of dam operations on the wetland inundation times and frequency, water levels and sedimentation patterns; and
c) whether the results of the study on the Mara Wetland can be used to represent the sediment dynamics for wetlands in similar climatic zones.

Material and Methods

A 2DH numerical model of Lower Mara River and Wetland is currently under development using Delft3D-FLOW, a multidimensional hydrodynamic software module that computes the Navier Stokes equations for incompressible free surface flow considering Boussinesq and shallow water assumptions (Deltares, 2014).

The key data inventory required for the study include: wetland and river bed topography, Mara River channel geometry, discharge data, suspended sediment concentrations, bedload granulometry and vegetation types and spatial distribution.

The low bed slopes of the Lower Mara River and wetland make it a highly complex system characterised by several meanders and secondary streams created within the wetland (Fig.2). This aspect makes it difficult to generate the model computational grid as a curvilinear one, with the necessity for higher grid resolution at specific locations. The solution is to generate a computational net (Fig.1) using the new Delft3D Flexible Mesh package that allows generation and merging of several unstructured grids to better represent the domain requirements and optimize the model computational time. However, preliminary runs will be performed with both grid forms to check the level of consistence of the results.

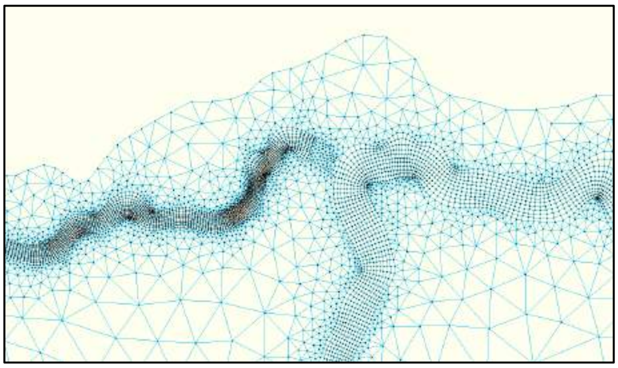

Figure 1: The Computational net generated by merging several unstructured grids

Sediment transport computations shall be based on the advection diffusion and Exner approaches for suspended and bed load, respectively. Effects of vegetation on flow shall be incorporated into the model according to Baptist's approach (Baptist, 2005), a method in which an additional flow resistance term depending on local water depth is included in the simulation (Deltares, 2014).

The model will be used to simulate several scenarios, including: the current situation, changes in vegetation and sediment concentration, and dam operations. With a simulation time of 1 hydrological year, the model will allow accounting for effects seasonal hydrological changes on vegetation dynamics. The ability to simulate several complex scenarios in relatively short durations resulting vital information makes the numerical modelling approach an indispensable tool for typical cases such as this.

Expected study results

The study is specifically expected to demonstrate the: (i) influence of seasonal vegetation cover changes on the wetland dynamics; (ii) the wetland areas more prone to sedimentation; potentially indicating the accumulation of heavy metals transported with sediment; (iii) expected effects of dam operations on the Mara Wetland dynamics; and (iv) the future morphometry and morphological changes. The insight on wetland inundation times, frequency, water levels and wetted area changes in time could be vital for forecasting the impacts on ecology and on the wetland life cycle. Based on scenarios, the results will be generalized for applications to other wetlands in similar tropical climates.

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Figure 2: Map of the study domain with land boundaries delineating the main river channel, the prominent stream and the wetland extent.

Low-angle dune morphodynamics under shallow flow

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Keywords — River Dunes, Turbulent Flow, Sediment Transport

Introduction

River bedforms arise from the interaction between flow and the underlying sandy river bed. Dunes are the most common bedforms observed in rivers. Due to their large dimensions relative to flow depth and the formation of turbulent flow separation zones, dunes are the main source of flow roughness and they are the essential ingredient for accurate predictions of water levels during floods (Warmink, 2014). Particularly under increasing river discharges, dunes grow rapidly and reach heights up to several meters, resulting in a significant rise of water levels and, consequently, increase flood risk.

Dunes are traditionally studied in sand-bedded flumes, in which Froude numbers are relatively high due to limited flow depths (e.g. Naqshband et al., 2017). Dunes under these conditions are asymmetric and possess lee-side angels at the angle of repose of sand (~30°). Consequently, most of our understanding of dune morphodynamics, kinematics, flow resistance, and sediment transport originates from shallow flows with high Froude numbers. However, field studies over the past decades have illustrated that dunes in natural rivers are predominantly symmetric with much lower lee-side angles (~10°) and more complex lee-side morphology (Hendershot et al., 2016). These low-angle dunes (LADs) are associated with intermittent flow separation zones, whereas laboratory generated, high-angle dunes (HADs) show a permanent zone of flow separation (Kwoll et al., 2016). Such difference in dune morphology and lee-side flow separation zone has major implications for flow resistance and water levels.

Using light-weight polystyrene particles as a substrate, in this study, we were able to generate low-angle dunes under shallow laboratory flow conditions. By limiting the Froude number, low-angle dune morphodynamics were studied for a wide range of flow and sediment conditions.

Flume experiments

Experiments were conducted in the Kraijenhoff van de Leur laboratory for Water and Sediment dynamics of Wageningen University & Research. A tilting flume of 14.4 m long and 1.20 m wide was used. At the downstream end of the flume, a sediment trap is connected to a sediment recirculation pump. At the upstream point where the sediment-rich water re-enters the flume, a diffuser is placed to distribute the inflow over the full width of the flume. Furthermore, turbulence is suppressed by a laminator located at the upstream end of the flume.

A 15 cm thick layer of light-weight polystyrene particles was installed at the flume bed with a D_{50} of 2.1 mm and a D_{90} of 2.9 mm, and a specific gravity of 1.1. A filter was installed at the end of the flume to prevent loss of polystyrene particles over the flume edge and to make sure that all particles were fully recirculated. Flow conditions were chosen such to represent the natural variability of observed suspension numbers and Froude numbers in large rivers (u_*/w_s range of 0.50 to 3.2, Fr number up to 0.15).

Flow discharge was measured continuously with an electromagnetic flow meter. Flow depths along the entire flume were measured using stilling wells. Water levels in the stilling wells were continuously recorded using magnetostrictive linear position sensors. Bed morphology was measured during certain phases of the experiment, being the initial dry-bed condition, the initial submerged condition and after reaching dynamic dune equilibrium. A line laser scanner mounted on a semi-automatic carriage was used for this purpose (for details see de Ruijsscher et al., 2018). The entire flume bed was scanned with a streamwise resolution of 2 mm and a crosswise resolution of 3 mm, in four parallel partly-overlapping swipes,

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within a period of 2 minutes. Three transects, evenly distributed from the centre of the flume towards both side walls, were selected to monitor dune morphology (height and length statistics, together with lee-side angles) using bedform tracking tool developed by van der Mark et al., 2008. Average and standard deviations of dune height and length were determined over the effective measurement section of the flume.

Flume experiments with light-weight polystyrene particles show that dune lee-side angles considerably vary across the width of a dune, and also between successive dunes downstream as recently observed in world's large rivers, including the Amazon, Mississippi, Parana, Mekong, Columbia and Jamuna rivers. Furthermore, for a wide range of flow and sediment conditions, dune lee-side angles are predominantly lower than the 30° angle of repose found under traditional flume experiments with sand.

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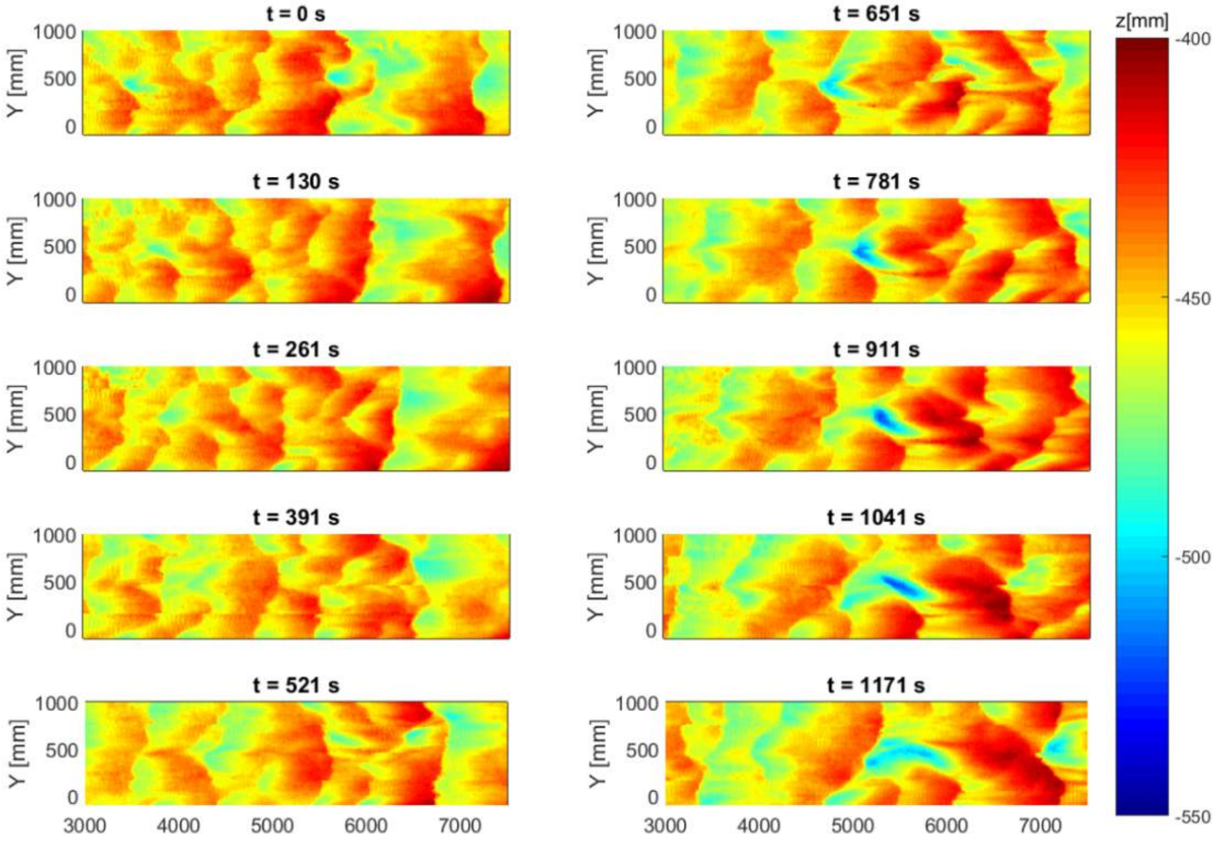

Figure 1. Sequence of dune development over time for the suspended load dominant experimental condition ($u_*/w_s = 2.5$). X is the streamwise direction, Y is the cross-stream direction, and z is the vertical distance with respect to the mean bed elevation.

Examination of the declining trend in suspended sediment loads in the Rhine River in the period 1952-2016

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Keywords — Suspended sediment, Rhine River

Introduction

It has widely been reported that sediment loads have decreased drastically in rivers worldwide during the past decades due to human intervention in the upstream river system. These interventions include the construction of rivers and dams, sediment mining, and flood protection and soil conservation measures. The decreased sediment loads to the downstream deltas and coasts are a major cause of loss of land in deltas due to coastal erosion and uncompensated land subsidence and sea level rise. The Rhine River is no exception and also conforms this global trend of declining sediment load.

To quantify this declining trend of suspended sediment loads in the Rhine River, we have built on the preliminary work of Asselman (1997) and De Boois (2013), and re-examined the annual suspended loads at the Lobith monitoring station near the Dutch-German border for the period since the start of the start of regular monitoring of suspended sediment concentrations (SSC) in 1952 until present (2016).

Methods

We combined the measured discharge and suspended sediment concentrations from the Rijkswaterstaat WaterInfo website (Rijkswaterstaat, 2018) to estimate daily sediment loads. Since 1989, measurements of both discharge and SSC are available at a daily time interval. For the pre-1989 period, only bi-weekly SSC measurements are available. Here, we estimated daily suspended sediment concentrations based on daily discharge measurements using the rating curve method. The sediment rating curve was assumed to take the form of a power-law function:

$$SSC = a\,Q^{b} \qquad (1)$$

Where *SSC* is the daily suspended sediment concentration (mg l^{-1}), *Q* is the daily discharge (m^3 s^{-1}), and *a* and *b* are power-law parameters, which were estimated using log-log regression with a bias-correction of parameter *a*. The rating curves were fitted for periods of about 5 years and the fitted parameters were subsequently used to estimate daily SSC for the pre-1989 period. The estimated daily suspended sediment loads were summed for each year to obtain annual loads. Annual discharge-weighted average SSC were calculated by dividing the annual suspended sediment loads by the total annual water discharge.

Results

The suspended sediment loads (Fig. 1) show a declining trend from about 4×10^6 t y^{-1} in the early 1950s to about 1.2×10^6 t y^{-1} in the late 2000s. This corresponds to a decrease by 70%. Since about 2005, the sediment load seems to have stabilised around this value. The peaks in the load during the late 1960s-1970 are likely the result of high-discharge events in this period. The peaks in suspended sediment loads due to high-discharge events are absent or tempered in the discharge-weighted average suspended sediment concentration graph (Fig. 2). This graph also shows a similar, but more consistently declining trend between 1960 and 2005. Furthermore, it also shows a remarkable step-wise increase in weighted SSC around 1960.

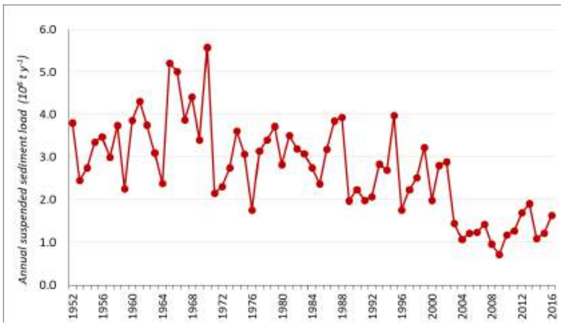

Figure 1. Annual suspended sediment loads in the Rhine River at Lobith in the period 1952-2016.

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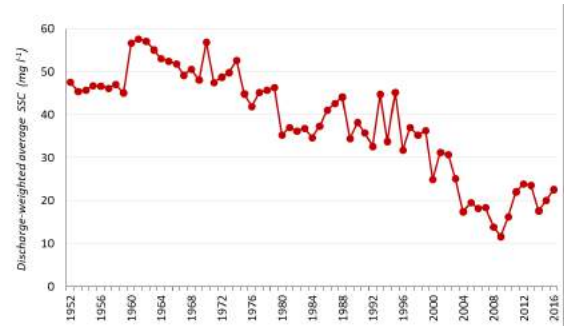

Figure 2. Annual discharge-weighted average suspended sediment concentrations in the Rhine River at Lobith in the period 1952-2016.

A closer inspection of the fitted 5-year rating curves (Fig. 3) reveals the decline in average SSC becomes particularly manifest at low discharges: SSC at low flow have decreased from about 40-50 mg/l to less than 20 mg/l in recent years. The steep rating curve for the period 1995-1999 can be attributed to the high SSC observed during the major 1995 flood event. The rating curves can roughly be classified into three groups indicated by the different colour groups. Major shifts in the sediment rating curves occurred around 1980 and around 2000. Although the annual average SSC seem at first sight to have gradually declined since 1960, the stepwise reductions of SSC and suspended sediment loads around 1980 and 2003 can also visually be recognized in Figs. 1 and 2.

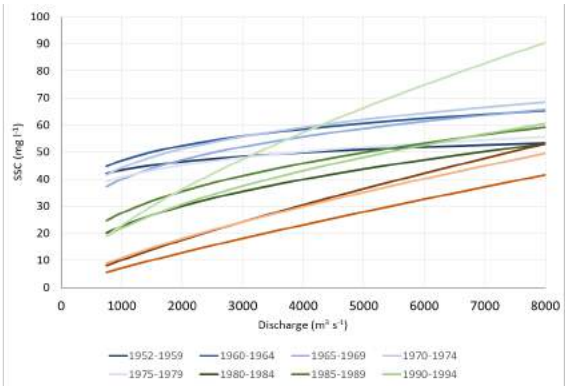

Figure 3. Fitted 5-year sediment rating curves for the Rhine River at Lobith.

Discussion and outlook

The substantial lowering of the rating curve between the 1975-1979 and 1980-1984 periods may probably be attributed to the construction of the upstream Iffezheim weir in 1977. The cause of the reduction of the rating curve around 1980 has not been identified yet. Considering the changes in the rating curves, the cause must likely be sought in an enhanced retention in the river channel network during low flow periods rather than in increased sediment trapping in floodplains or decreased sediment supply during hydrologic events. The identification of the precise cause will be subject of future study.

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Simulation of cross-sectional variations of the Pilcomayo River channel, Paraguay

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Keywords — River cross-section, sand-bed river, Delft 3D.

Introduction

The Pilcomayo is a very active sand-bed river located in South America, where during the last decades, quick changes in cross-sectional shape and dimensions have been observed. The total amount of sediment transported by the river is around 140 millions of tons per year, being one of the largest in the world (Martín-Vide et al., 2014).

Due to hydrological regime, the flood season is from January to March, with a maximum discharge around 4600 m^3/s. However, the monthly average flow during floods is 650 m^3/s. During the dry season, the river is almost dry, with the minimum measured discharge being 1.5 m^3/s.

The bed is formed by fine sand (Fig. 1), with a median size D_{50} equal to 100 μm. Wash load is formed mostly by silt and clay and represents the 89% of the total amount of sediment transported by the river. The high variability of flows and the presence of a highly erodible bed made of fine sand makes the Pilcomayo a very active river with cross-sections responding very fast to the flow.

Fig.2 shows the differences in planform of the river through the years, while Fig. 3 presents different cross-sections at the same location for different discharges in the same hydrological year.

There are some studies done in the Pilcomayo River, nevertheless, most of them are only hydrodynamic simulations, without taking into account the changes or adaptations in cross-section and bathymetry.

Objective

The cross-sectional adaptation in a river depends on different types of forcing, including climate change, river management, imposed hydrological changes and river engineering. The problem is to find the adaptation of the river cross-section and to predict how the river can respond to a different situation.

Figure 1. Photography of the Pilcomayo River.

In this context, the goal for this research is understanding the morphodynamic behaviour of the Pilcomayo River, in response to different scenarios by implementing a morphodynamic model using the software Delft 3D. First this research aims at establishing whether this morphodynamic model can properly represent the dynamics of the river.

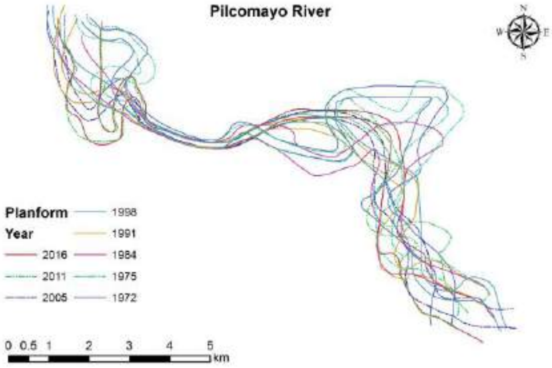

Figure 2. Planform of the Pilcomayo River in different years, from 1972 to 2016.

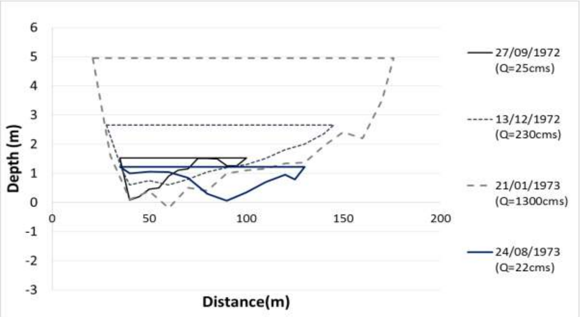

Figure 3. Example of cross-sectional variation in the Pilcomayo River. The measurements have been taken at the same location.

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Methodology

For this purpose, an approximately 10km-long reach of the Pilcomayo River, between Paraguay and Argentina is studied, and after assembling the available data from discharge measurements and topography surveys, a morphodynamic model is constructed, calibrated and validated. The software Delft 3D is implemented for this study since it is already being successfully used to simulate sand bed rivers, in addition, according to Schuurman et al. (2016), Delft 3D is a reliable and accurate model, widely used in the demanding practice of river engineering.

The model requires a bathymetry of the river as an initial condition, for this, a reconstruction of the channel including its floodplains is done using available DEMs, satellite images and survey measurements.

Regarding the hydrodynamic component, a time series from 1960 to 2017 was statistically analysed and by using the flow duration curve of the discharges, a representative yearly hydrograph is derived and included in the model as upstream boundary condition. For the downstream boundary condition, an open boundary is considered by adopting the normal depth assumption due to the lack of data.

For the sediments characteristics, one fraction is considered with a median size D_{50} equal to 100 μm.

In addition, the model takes into account the presence vegetation on floodplains, and its impacts on the hydrodynamics and morphodynamics of the river. This element is important, since in vegetated areas, the flow resistance is composed by the resistance exerted by the soil and the resistance exerted by the plants. The vegetation model adopted in Delft 3D was developed by Baptist (2005). It distinguishes between fully and partially submerged vegetation. In this way, the model represents correctly the decrease in bed shear and transport capacity (Crosato and Saleh, 2011). An example of this approach was done by Arroyave and Crosato (2010) in the Meuse River.

The work is ongoing, model calibration and validation being the first next steps. Then, several scenarios will be defined to simulate human interventions and climate changes (e.g. more dry, more wet).

Fig. 4 presents some preliminary results of water depth in the river, it can be appreciated that there are some areas of erosion and deposition. Natural channel narrowing and widening can be seen as well. Fig. 5 shows an example of a general cross-section of the river generated by the model. The adapted cross section is presented in blue, while the initial cross-section is shown in colour brown.

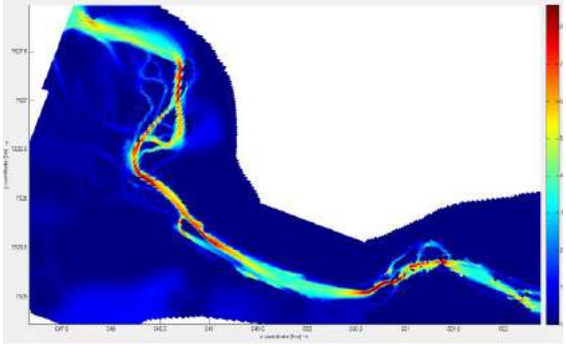

Figure 4. Preliminary results of water depth of the Pilcomayo River in Delft 3D.

Expected Results

If Delft 3D proves successful in representing the dynamics of the Pilcomayo River, the first (general) results are the new bathymetries generated by Delft 3D, where the cross-sections adapt to the corresponding changes in the input hydrograph or in vegetation. The results of the scenarios will illustrate how a highly dynamic sand-bed river channel adapts to different forcing. Second, if the model can successfully simulate the cross-sectional adaptation of the river, to variable flow, this research aims at showing the river response to different hydrological forcing, simulating the effects of human intervention (damming, water extraction) and climate changes.

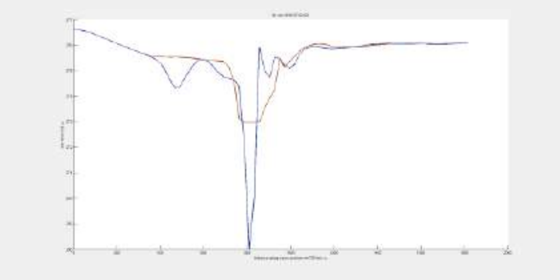

Figure 5. Preliminary results of the cross-sectional variation. Blue: generated cross-section, brown: initial bathymetry.

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Cyclic steps on the Loess Plateau, China: Field Survey and Numerical modelling

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Keywords — Cyclic steps, Morphodynamic model, Field survey

Introduction

Cyclic steps are long-wave bedforms that migrate upstream and are bounded by sustained internal hydraulic jumps. Each step has a gentle Froude-subcritical slope in the upstream and a steep slope related to supercritical flow in the downstream (Sun and Fagherazzi, 2003). A hydraulic jump connects two contiguous steps. Cyclic steps can be divided into three categories: purely-erosional cyclic steps, transportational cyclic steps and purely-depositional cyclic steps (Fildani et al., 2006). In purely erosional steps, that usually occur in bedrock or cohesive beds, sediment eroded from the bed is not redeposited again. Transportational steps are formed from a combination of erosion and deposition. In purely-depositional case, that can exist in deep-sea settings, deposition dominates and no sediment entrains from the bed.

Cyclic steps can exist in diverse settings with various sizes. They were also observed on the Loess Plateau, China where sediment are weakly cohesive silty loess, which can be easily eroded. The D_{50} median grainsize is about 30 microns. Our study sties contain two small basins on the Loess Plateau: Qiaogou basin and Wangmaogou basin. There are many check dams constructed in Wangmaogou basin but in Qiaogou basin there is no Impact of human interference. Fig. 1 shows 20 steps in a 600m reach of the Qiaogou basin on the Loess Plateau. The Loess Plateau, China is one of the most severe soil and water loss areas in the world, which causes a decrease in agricultural land productivity. It is characterized by a typical monsoon climate that rainfall is concentrated in July and August. Both flow discharge and sediment supply can show very high variability in mountain gullies on the Loess Plateau. This unexpected phenomenon inspired our interests in studying their effect on sediment transport and the key factors that control their formation and evolution.

Several theoretical models were proposed to shed lights on the formation and evolution of cyclic steps(e.g. Parker and Izumi, 2000). However, many analyses were based on shallow water equations with the quasi-steady approximation and there was little consensus in regard to the unsteady and variable flow. Thus far, no study has looked at the effect of steps on sediment flux exiting the channel (e.g. Sun and Fagherazzi, 2003).

Therefore, the objective of this research is to explore the role of cyclic steps on sediment transport and clarify the dominant factors that affect cyclic step formation and evolution with unsteady flow equations and variable discharge.

Methodology

Field survey

We obtained detailed 3D topographic data of the gullies with steps via terrestrial laser scanning(TLS) and Uninhabited Aerial Vehicle(UAV). In addition, Real-time kinematic(RTK) was also used to extract bed profiles with higher resolution. By comparing the results obtained by RTK and laser scanning, we can understand whether the resolution of TLS and UAV is acceptable. We found that TLS and UAV can be used as efficient access to topographic data with acceptable resolution. We also sampled sediment along the channel to analyze grain size distribution and the dry density of sediment.

Numerical model

Apart from the field survey, we also implemented a 1D river morphodynamic model to study the formation and evolution of cyclic steps. The governing equations we used to describe formation and evolution of cyclic steps included 1D shallow water equations, the mass conservation of suspended bed-material load,

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and the Exner equation. A shock-capturing method was applied here to simulate the transition between subcritical flow and supercritical flow. The numerical flux was calculated with the HLL approximate Riemann solver.

I confirmed the model with a case similar to that in the paper of Sun and Fagherazzi (2003). This test case started with an initial flat-bed with a small perturbation.

Preliminary results

Field survey

Fig.1 shows the bed profile of the main stream in the Qiaogou basin on the Loess Plateau. We obtained the ratio of wave-length to wave-height of each step and the relation between the local bed slope and the ratio of wave-length to wave-height was detected. The ratio of wave-length to wave-height decreased with the increase of local bed slope, which means the steps are both more frequent and higher in a steeper gully (Fig.2).

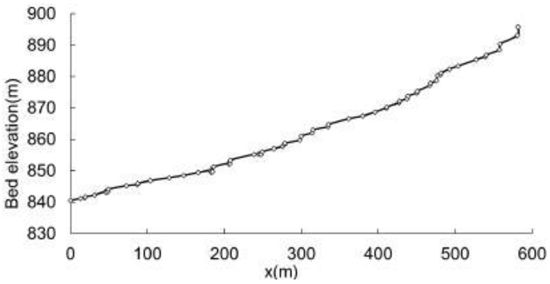

Figure 1. The longitudinal bed profile of the main stream in the Qiaogou basin on the Loess Plateau, China.

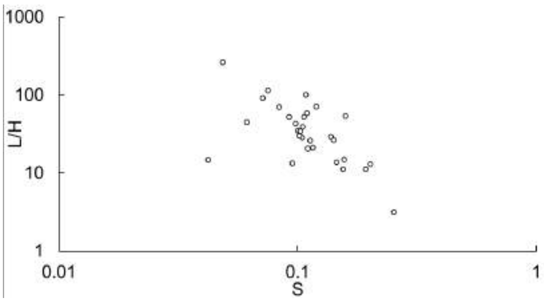

Figure 2. Variation of the ratio of wave-length to wave-height with the local slope in the main stream of the Qiaogou basin on the Loess Plateau, China.

Numerical simulation

In the numerical simulation, firstly we set up a case with an initial single step to study the key factors that control steps evolution and formation. We found that the initiation of cyclic steps is closely related to transcritical flow conditions. With very fine sediment, convection of bed wave dominates over dissipation, which could lead to a self preserving step. The resistance coefficient was a key factor that controls the formation of steps. In the case with a small resistant coefficient, a series of steps form downstream of an initial headcut. We found that purely-erosional case and transportational case illustrated different patterns of steps evolution. A self-preserving headcut can coexist with cyclic steps under purely-erosional conditions. More scenarios with other initial conditions will be implemented in the future.

Future work

In the future, more scenarios with different initial conditions will be implemented to study the dominant factors of step formation and evolution. To study the effect of variable discharge on step formation and evolution, various hydrograph scenarios are considered. The intensity and duration of flood events in Qiaogou gully are estimated to determine the intermittency factor and flow discharge in the case of constant discharge. To analyse the effect of cyclic steps on sediment transport, we also start from the case of a single step and then extend to the case of a series of steps.

Acknowledgments

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Session 3 - River Management

Oral Presentations

The added value of Nature-Based Solutions

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Keywords — Nature Based Solutions, Evaluation Framework

Introduction

In order to value Nature-Based Solutions (NBS) in a systematic way, a qualitative evaluation framework is proposed to assure that essential elements relating to efficiency, effectiveness, flexibility and social support are included in NBS projects. Literature on NBS reveals that to evaluate NBS it is sensible to make a distinction between design and implementation aspects that relate to these elements. Thereby, the extent to which outputs and outcomes are achieved can be assessed.

It is a key challenge in many NBS to define and apply suitable indicators to monitor progress and success of the project. Additionally, by keeping track of performance indicators of the NBS also more advantage can be taken of the flexibility of the NBS by alerting for and guiding of possible measures (interventions) if needed. For this purpose, in the design phase the choice for a particular intervention needs to be clearly justified, uncertainties must be addressed and comparisons to the projected null-situation (do nothing), alternative grey solutions or otherwise undesired impacts must be made. These considerations help to define the crucial indicators that allow to keep track of and adequately respond to the management and performance of the NBS during the implementation and operation phase.

Existing frameworks and guidelines

From existing works on the broad theme of NBS we observed that the focus of studies and approaches can broadly be subdivided into three categories: (i) setting up NBS (design), (ii) putting NBS to practice (implementation) and (iii) assuring an effective and efficient process and to achieve social support. In our exploration of the existing literature on definitions, frameworks and guidelines on NBS we therefore distinguish three main aspects to group recommended practices:

- Design: setting up and choosing a suitable NBS
- Implementation: putting NBS into practice
- Process: making sure NBS are (socially) accepted, and that they are efficient and effective.

We extracted commonalities of existing approaches, frameworks, guidelines and, next, compiled essential elements that should be considered in an evaluation framework for NBS.

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Proposed Evaluation Framework

The general framework outlined here and summarized in Figure 1 is inspired by the framework that the Netherlands Environmental Assessment Agency has designed for the Dutch Delta Programme to monitor and evaluate future measures to climate proof the Netherlands (NL PBL, 2016). That framework includes projects that, just like NBS, are associated with a system wide approach, a central role for environmental aspects and long-term visions.

In the framework we separate design from implementation steps. In the design step the challenge, the objectives and goals must be clearly defined and co-benefits must be listed. This step includes the process of stakeholder participation (internal dynamics) and taking into account flexibility with respect to external dynamics. The process should be such that wide stakeholder involvement is assured to make sure that co-benefits (and trade-offs) are known and considered throughout the project. The outputs and outcomes (implementation) must be characterized by measurable indicators that can be monitored and evaluated to show efficiency and effectiveness of the NBS, to reveal co-benefits and to see if adaptation actions are needed.

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The essential elements of an evaluation framework for Nature-based solutions are then:

1. Output indicators that describe whether the solution satisfies the specifications and principles of the design process. A positive score gives an impression of the efficiency of the implementation phase (to what extent has been delivered what was promised)
2. Outcome indicators that describe whether the solution adequately answers the social challenge at the base of this measure. A positive score gives an impression of the effectiveness of the solution (to what extent is the solution an answer to the social challenge).
3. Process indicators that describe whether all the right steps have been taken to ensure that the solution addresses all envisaged co-benefits. A positive score indicates that the solution is based on the social support of relevant stakeholders.
4. Flexibility (or adaptation) indicators that describe how easy (and at low cost) the solution can be adjusted in view of the internal and external dynamics of the social challenge, and how to deal with uncertainties.

The indicators (also called essential framework elements) summarized above should be defined such that by monitoring and evaluating them, the success of the NBS in reaching these objectives and co-benefits can be judged.

Conclusion

We argue that, by using the proposed NBS evaluation framework and its essential elements, it is possible to qualitatively and, potentially, quantitatively evaluate the value of NBS and make explicit their advantages over traditional "grey" solutions. These types of qualifications are necessary to unambiguously show when and where NBS are the suitable way forward. Besides, they help to make sure that in the future full advantage is taken of the various opportunities that NBS provide.

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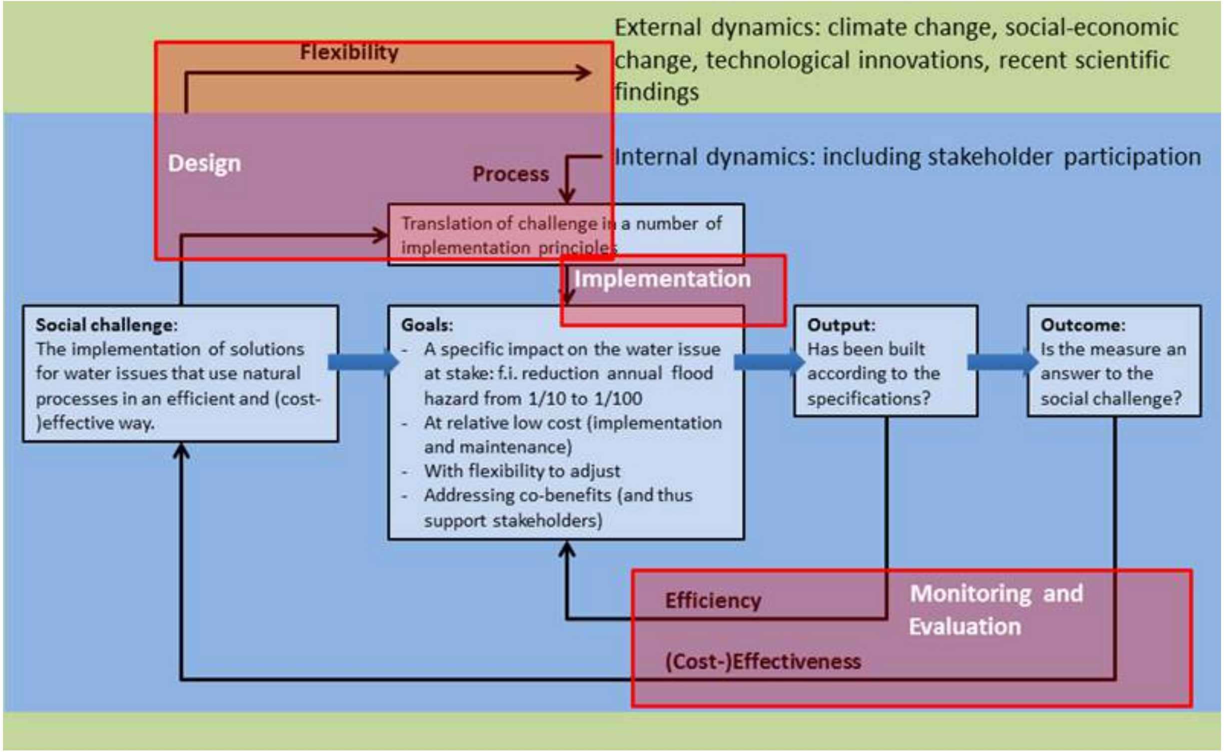

Figure 1. Summary of essential elements for an evaluation framework of NBS.

Controls of renewed sediment trapping in low-lying polders of the Bangladesh Delta

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Keywords — Sediment dynamics, sediment accumulation, sea level rise, flow control, polder, sinking delta

Introduction

The Bangladesh delta, built with the sediment carried by Ganges-Brahmaputra-Meghna rivers, is one of the largest deltas in the world. These three rivers cumulatively carry about 1 billion tons of sediments per year (Islam *et al.*, 1999). The Bangladesh delta is one of the most vulnerable deltas to sea level rise (Ali *et al.*, 2012) as the area is flat and low-lying. The rate of sea level rise would potentially be counteracted by capturing these fluvial sediments efficiently and spreading uniformly throughout the delta as under natural conditions. However, polder dikes constructed in 1960s hamper sediment flow from the rivers to the coastal flood plain (van Staveren *et al.*, 2017). Local practice of breaching the dikes of the polders to flood the lands inside intended to keep the tidal rivers alive demonstrated that land alleviation by flooding the polders is feasible (van Staveren *et al.*, 2017). Still, lack of knowledge on the sediment dynamics, improper operation and management have prevented effective re-sedimentation through re-connecting polder areas to the river (Gain *et al.*, 2017). Although sediment management is a major issue for the coastal regions of Bangladesh, the governing parameters of the sediment dynamics inside the polders have not been explored yet. To raise the land through controlled flooding efficiently, the sediment dynamics inside the polders after opening the dike need to be understood. This research aims to quantitatively analyse sediment deposition in polder areas, depending on tidal ranges, number of dike openings, seasonality of water and sediment flow, and operational flow control through the connecting gates. With this knowledge, designs for new polder-river connections may be developed that effectively result in sediment accumulation in low polders, allowing the land to rise along with sea level. This contributes also to assessments of controlled flooding to raise the land surface to combat sea level rise, which is primary concern for the sinking deltas worldwide.

The low-lying coastal areas of Bangladesh receive a large fluvial or marine sediment load potentially available to raise the land by sediment accumulation. The Beel Pakhimara of Satkhira District (southern Bangladesh) was selected as study area (Figure 1). Beels are saucer-like depressions within polders, caused by land erosion and subsidence (Chakraborty, 2009). Beel Pakhimara is currently being used as tidal retention basin to manage the sediment of the adjacent tidal river (Kobadak River) to trap its sediment and so to maintain drainage capacity and navigability of the main channel (IWM, 2017). Beel Pakhimara has an area of about 700 ha (IWM, 2017). To ensure the river flow into the Beel Pakhimara, a canal was constructed between the river and the Beel (IWM, 2017). Flow though this connecting canal is not regulated. A temporary dam was constructed across the river (IWM, 2017).

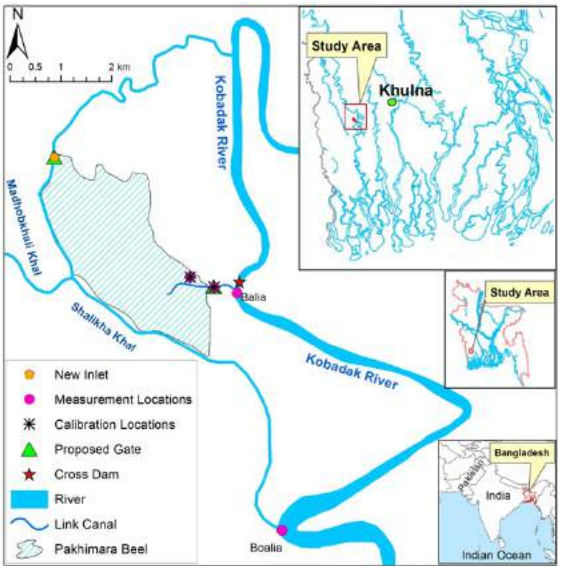

Figure 1. Study area (Beel Pakhimara) in southwest region of Bangladesh

Method

To understand the sediment dynamics inside the Beel Pakhimara a two-dimensional (2D) morphodynamic model was developed (Figure 2) using Mike-21FM developed by DHI (Danish Hydraulic Institute), with a flexible mesh base (different cell size). Mike 21FM simulates sediment dynamics implicitly by updating the bathymetry prior to every time step. A

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sensitivity analysis was conducted to identify the most significant parameters. The 2D model was calibrated for water level, water discharge and suspended sediment concentration using observed data from the beel, by adjusting the significant parameters. Multiple scenarios were developed considering the seasonality of water and sediment flow, tidal ranges, flow control and number of river-beel connections. We simulated sediment deposition during the three key hydrological seasons: dry (Jan), pre-monsoon (April) and monsoon (July), along with unregulated and regulated flow with gates. For regulated flow, static and dynamic gate operations were defined. For 'static gates' situations, all gates move (open or close) simultaneously, whereas for dynamic operation, the gates move alternatively. To capture the effect of spring and neap tide, all the simulation were carried out for 14 consecutive days. The developed scenarios were simulated using the calibrated 2D model and results were analysed. To compare the results and to determine the relationship between the sediment accumulation rate and, seasonality of water and sediment flow, tidal ranges, flow control and number of dike breach, total sediment accumulation for each scenario was calculated. To identify the most effective operation of tidal basin for sediment accumulation, the trapping efficiency was calculated using the following equation:

The difference between the sediment delivered inside the Beel and sediment returned back to the river was calculated for residual sediment.

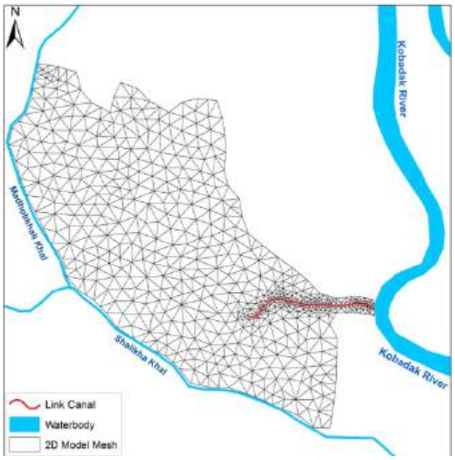

Figure 2. 2D morphodynamic model setup and mesh

Results

The analysis of the results from 2D morphodynamic model simulations are presented in figure 3 and figure 4. Fig 3 indicates that the sediment deposition varies seasonally with pro-monsoon having the highest. Tidal ranges vary with season. Therefore, the sediment deposition varies with tides as well. Moreover, Fig 3 indicates that the sediment deposition increases with increasing number of inlets and regulated flow. Fig.4 shows that the flow regulation increases the sediment trapping efficiency as well.

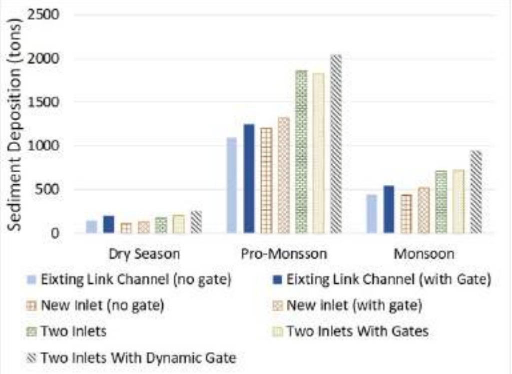

Figure 3. Sediment deposition for different scenarios

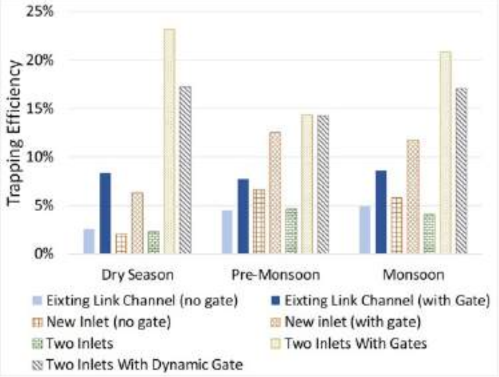

Figure 4. Sediment trapping efficiency for different scenarios

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Improving accuracy of weir/groyne discharge formulations for highly sub-critical (submerged) conditions

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Keywords — Weirs, Groynes, Discharge formulas

Introduction

This study proposes an improved discharge formulation for weirs, to be used within the context of 2D or 3D computational models. It is based on elementary conservation laws for volume, energy and momentum and yields improved accuracy in case of sub-critical weir flow. This feature may prove to be useful for larger-scale groyne modelling in rivers during (highly) submerged conditions.

In large-scale numerical river models, the effect of groynes is often parametrized by the use of weir formulations, which reduce the local groyne to a sub-grid phenomenon. Some of these weir formulations apply a form of quadratic friction law or prescribed energy loss (e.g. Delft3D), whereas other weir formula types directly relate the discharge over the weir crest to the piezometric or energy levels on both sides of the weir (e.g. WAQUA, FINEL).

As pointed out by Yossef (personal communication) among others, it is known that such discharge formulations for weirs – though usually accurate for critical or nearly critical weir flow – may exhibit inaccuracies for strongly sub-critical flow; in general, the total discharge over the weir during sub-critical flow is often underpredicted. When applied to submerged groyne flow in rivers, this underprediction may give rise to a relative overprediction of the over-all flow resistance.

Based upon elementary physical conservation laws for a schematized broad-crested weir, this study shows that the origin of the inaccuracy is related to unjustified simplifications within the flow expansion region behind the weir. A consistent application of momentum conservation in this deceleration region yields a practical combined Carnot-/Villemonte-type discharge formulation, which is valid for all Froude numbers and especially shows improved behaviour for sub-critical flow. Eventually, additional (empirical) coefficients should be added to this elementary discharge formulation in order to account for the influence of geometrical parameters like weir shape and roughness (e.g. Sieben, 2011).

Exact solution and WAQUA approach

The core analysis in this study is based on application of basic conservation laws on a schematized (long-crested) weir, with many geometrical complexity parameters omitted (Battjes and Labeur, 2017). Figure 1 depicts the schematized weir and associated variable nomenclature. The upstream energy level is denoted as E_1, the downstream piezometric level is denoted h_4. A "critical h_4" is defined as the value of h_4 for which the discharge q above the weir crest, at given E_1, reaches its maximum (critical flow).

Application of energy conservation upstream and momentum conservation downstream of the weir yields a known cubic equation for h_2 (water level above the crest) or q (discharge), which can be solved analytically or iteratively. We compare this exact solution with two approaches for q that are present in the flow model WAQUA: the approach by Van Prooijen and Busnelli (2006) and by Sieben (2011).

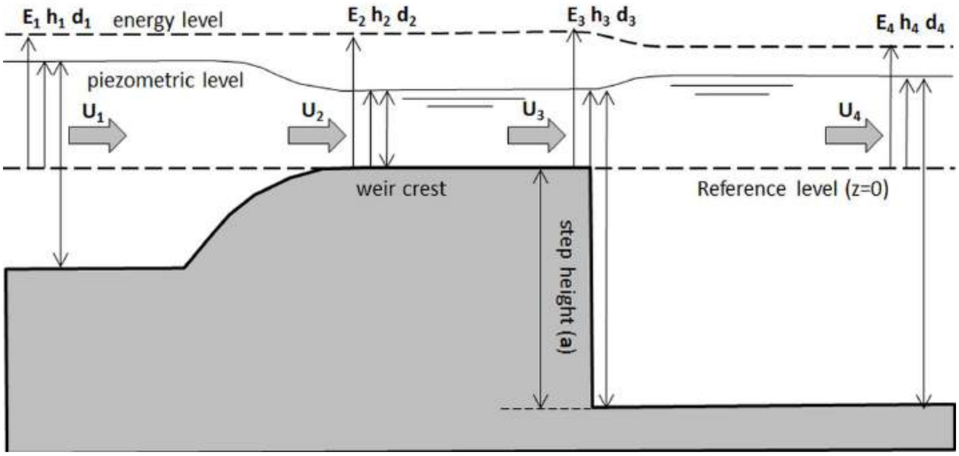

Figure 1. Overview of basic (long-crested) weir schematisation.

Both approaches for the discharge *q* within WAQUA differ on details; however, in essence their behaviour in the sub-critical limit reads:

$$q = h_4\sqrt{2g(E_1 - h_4)} \qquad (1)$$

Conceptually, this approach implies *h*₂ = *h*₄, which basically neglects all dynamics related to momentum conservation downstream of the weir, and the associated water level set-up. Figure 2 shows that this neglect of downstream-weir physics yields a systematic underprediction of discharge *q* compared to the exact solution in the sub-critical limit. (In the critical limit, Van Prooijen and Busnelli (2006) apply the exact solution for critical *q*, whereas Sieben (2011) applies an empirical Villemonte-type fit to connect the sub-critical and critical regimes.)

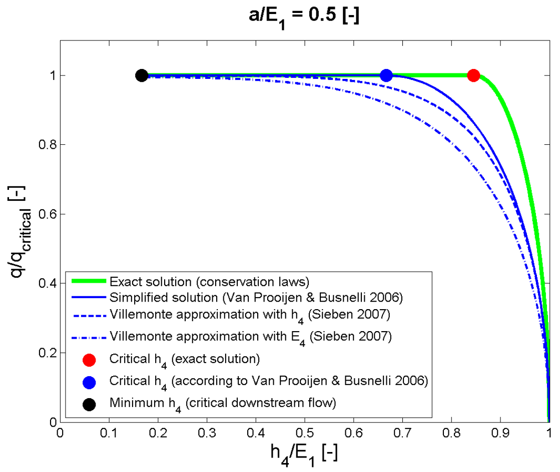

Figure 2. Weir discharge: exact solution vs. approaches by Van Prooijen and Busnelli (2006) and Sieben (2011).

Improved discharge formula; results

Our aim is to present an improved prediction for *q* in the sub-critical regime, yet the formulation must be significantly simpler and more practical than the theoretical exact solution. This is achieved by applying a "rigid-lid approximation" to the region downstream of the weir, which is equivalent to a Carnot-type energy loss equation. This approach guarantees a good convergence toward the exact solution in the sub-critical limit. It reads:

$$q = h_4\sqrt{2g(E_1 - h_4)\cdot f}, \quad \text{with} \quad f = \frac{(h_4+a)^2}{h_4^2+a^2} \qquad (2)$$

Furthermore, it is possible to adjust the scaling of the Villemonte-type fitting equation that is applied by Sieben (2011) in order to improve its behaviour in the critical flow limit. In this way, we can fit together the approaches for *q* for all Froude numbers in a single formulation. The result is:

$$q=\left(\frac{2}{3}E_1\sqrt{\frac{2}{3}gE_1}\right)\cdot\sqrt{1-\max\left(\frac{3h_4-2E_1}{E_1},0\right)^{\left(\frac{9}{4}\right)\frac{(E_1+a)^2}{E_1^2+a^2}}} \qquad (3)$$

Figure 3 compares this combined Carnot-/Villemonte approach with the exact solution.

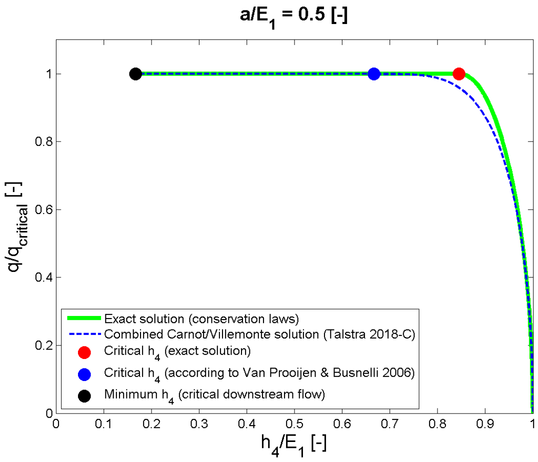

Figure 3. Weir discharge: exact solution vs. improved combined Carnot-/Villemonte approach.

Conclusion and recommendation

It has been shown that the sub-critical flow behaviour of weir discharge formulations can be made much more accurate by taking into account the proper downstream physics. The improved formula uses the same input as existing formulae in computational models like WAQUA, TRIWAQ, Delft3D and FINEL, and hence can be implemented straightforwardly, also in combination with additional (empirical) factors to account for the influence of geometrical complexities like weir shape and roughness, such like those by Sieben (2011).

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Community of Practice Lowland River Systems

A platform for developing, sharing and imbedding knowledge for river engineering and management

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Keywords — River engineering and management, Knowledge management

Introduction

Rijkswaterstaat (RWS) is responsible for the design, construction, management and maintenance of the low-land river systems in the Netherlands. These systems need to reconcile a number of functions, such as protection against floods and provision of safe and efficient navigation, floodplain agriculture, ecology and recreation. Understanding fluvial processes and knowledge about the physical functioning of river systems is essential to make this possible, to design effective river engineering works, for operational forecasting and for maintenance of the river system. Therefore, RWS recognizes the importance of knowledge about the system behavior and strengthened his knowledge position by starting the Community of Practice (CoP) Lowland River Systems at the end of 2017. This CoP is responsible for developing, sharing and imbedding knowledge for river engineering and management practice in the Netherlands. Experts of both Rijkswaterstaat and knowledge institutes take part in the community.

The CoP consists of two functionalities:

- demand-driven knowledge development
- strategic advisory and vision development based on the physical functioning of river systems

We elaborate on the scope in the next section. The two functionalities will be explained in de next sections, including the results of the first year of operation.

Scope

The focus of the community is to develop and provide knowledge about the dynamic physical behaviour of river systems Rhine and Meuse to assist river engineers and managers at various scale levels viz. in planning and design, in operational forecasting and in maintenance. The scope is limited to the area between the high dikes: the main channel, low levees ('summer dikes') that protect floodplains from frequent flooding and silted up flat floodplains. More over the following river functions are within the scope: (1) enabling a safe discharge of water, ice and sediment and providing protection against flooding, (2) ensuring safe and efficient navigability (improving navigation conditions and minimising hindrance), (3) provision of sufficient quantities of clean freshwater (sufficient volume, flow and level, with sufficiently low salt concentrations and temperature), and (4) maintaining and improving nature values in ecosystems in riverine areas.

Demand-driven knowledge development

This part of the CoP focusses on demand driver knowledge development. Main activities are to

- identify knowledge questions
- line up a programme/agenda per year and for multiple years
- share, publish & develop knowledge
- provide and anchor knowledge to tackle societal issues in Dutch river basin areas

Knowledge questions are periodically identified followed by the programming of research. All research questions are organized and classified in classes viz. policy preparation, implementation and asset management. They are prioritized and linked to existing projects. These projects have their own means (capacity and budgets) to execute the knowledge questions. The community provides an overview, helps with the programming of knowledge questions and identifies the knowledge gaps. A close relation with the scientific institutes and university is required. The Community monitors if knowledge products are shared and published in an accessible manner such that research outcomes find their way in daily engineering and maintenance practice.

In 2018 for the first time knowledge questions were collected, combined and programed together, instead of being programmed in individual projects. The result is a worthwhile overview of all relevant knowledge questions and a bundling of questions that are close-related to ensure an efficient approach (for instance efficiency in resources (capacity and budgets)).

A number of topics that will be addressed in coming year(s):

- contribute to a better understanding of sediment transport and system dynamics of the river Meuse
- improve the prediction of large scale bed level changes
- provide insight in the effect of sea level rise on the hydrodynamics and morphology of rivers Lek and Waal
- contribute to a better understanding of the dynamics and interaction of side channels with the main channel
- better prediction of the storage and conveyance capacity of floodplain areas along the Meuse and their impact on flood wave propagation

Strategic advisory and vision development based on the physical functioning of river systems

An expert pool is responsible for this part of the CoP and focusses on strategic advisory and vision development based on the physical functioning of river systems. It addresses also knowledge gaps regarding the physical system behaviour. Main activities are to

- provide an actual description of the river system behaviour
- provide transparent and integral assessment framework
- identify bottlenecks and challenges
- advise and respond to societal issues in river basin areas

By having an up-to-date description of the functioning of the system of the main rivers, the CoP can provide strategic advisory (pros and cons) and visions with respect to the design of river engineering works and the maintenance of the river system.

The Community of Practice stimulates that the river is investigated as an integral system in which all functions have their place. To do so the community collects and combines all the available system knowledge. Besides that the community gives advice in cases where a system wide advice is needed in order to make decisions on maintenance and development of the river.

Last year existing knowledge of the river Rhine, river Meuse and the Estuary of the Rhine and the Meuse are enclosed in three ‘Stories of the River’.

Het Verhaal van de
Rivier
een eerste versie

The Stories of the river are stories of experts and express their opinion on the past and future development of the rivers. The stories are used by Rijkswaterstaat to develop a vision on the river, and are used in policy developing on river management. A number of generic statements following from the Stories are:

- acknowledge the river system behaviour when designing and maintaining river systems.
- maintain or even increase the storage and conveyance capacity along the Rhine and Meuse with respect to a safe discharge of water, ice and sediment.
- stop the ongoing autonomous erosion of the main river bed and the gradual silting-up process in the floodplain areas. Consider sediment management and increasing the river’s flood conveyance capacity over the (entire) eroding river stretches as a means to do this.
- create opportunities to counterbalance the effects of a less strict maintenance of the nature in floodplain regions, large scale sediment management and other developments in the river area.

The statements fulfill an important role in the development of the integral river management program by the Deltaprogram. Besides that the stories identify gaps in the present knowledge. Knowledge gaps and related questions will be communicated with the demand driven knowledge development functionality of the community.

Connecting with researchers

The ambition of community is to link the CoP community with the NCR community, so we can contribute together to robust and livable river area, now and in the future.

Session 3 - River Management

Poster Presentations

Developing a tangible gaming interface for Virtual River

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Keywords — River management, Serious gaming, Interaction design

Introduction

Achieving sustainable river management is generally complex as any issues addressed are multi-scale, concern inherent uncertainty, and affect multiple actors and agencies. To address river management issues, it is important that decision-making processes are adaptive to deal with the uncertainties and include the diversity of knowledge and values of all affected actors. Learning-by-doing—active experimentation and continuous evaluation—has been advocated in natural resources management to facilitate collaboration between and learning among actors.

Serious gaming

Serious games, games with a primary purpose other than entertainment, are increasingly explored in the context of integrated water resources management as facilitation tools in such social learning processes. In the context of multi-actor decision-making, serious games can be defined as "experi(m)ent(i)al, rule-based, interactive environments, where players learn by taking actions and by experiencing their effects through feedback mechanisms that are deliberately built into and around the game" (Mayer, 2009, p. 825). The strength of using such serious games lies in the ability to include both the techno-physical complexity—the river system and its uncertainties—with the socio-political complexity—the strategic interactions in the policy arena—by combining role-play with in-game feedback mechanisms in the safe experimentation environment of a game (Mayer, 2009).

Virtual River serious game

As part of the RiverCare research programme, we are developing a serious game titled Virtual River. Virtual River aims for participants to experience how the river system functions and what the implications of choices are, in particular in regard to spatial riverine measures as executed in the Room for the River programme. By playing Virtual River, participants learn about the socio-political complexity as they engage in active collaborations and negotiations with other participants playing different river basin management roles. On the techno-physical complexity, participants learn about how management measures affect the system and how such measures impact indicators like flood safety, biodiversity, and costs. Moreover, participants learn about the trade-offs that measures present between these indicators.

Formative evaluations—evaluations focused on improving a design—of a board game prototype show that participants found the game engaging and insightful, and that participants understood the link to reality (Den Haan et al., 2018). However, participants, both laymen and river management researchers, also found the game complex and perceived the in-game indicator calculations as a black box, preventing participants from gaining the techno-physical insights into how a river system responds to changes. For further development, the goal therefore became to lower or help navigate the complexity and to remove the black box.

Tangible user interface

The pursued solution is the development of a tangible gaming interface based on the SandBox; a collaborative modeling tool developed by Deltares based on augmented reality that contributes to system understanding and enhanced communication between actors (Ottevanger et al., 2017). The SandBox is, quite literally, a box of sand, which represents the geometry of a river section that can be changed by users. By reshaping the sand, an updated geometry is sent to the hydrodynamic model. Visualizations of the results—e.g water level and flow magnitude—are projected back onto the sand by a beamer (figure 1).

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The SandBox can be classified as a tangible user interface; an interface that provides physical forms to digital information (Ishii, 2008). The physical forms serve as both control and representations for their digital counterpart. Using tangible interaction for Virtual River therefore uses the participants' ability to grab, move, and change physical objects as an easy, intuitive, and low-threshold way to interact with digital information.

Figure 1. SandBox setup and interface (photo from Ottevanger et al., 2017)

3D game board

The tangible gaming interface is based on replacing the sand in the existing SandBox framework with a 3D game board. Based on a hexagonal board design, the arrangement of a limited number of 3D game pieces form the basic geometry of a river basin stretch that includes—based on a Dutch perspective—the main channel, the floodplains, and the dikes (figure 2). Additional 3D game pieces are used to construct spatial measures in the game board—e.g. side-channels, longitudinal training dams, and dike relocations. The integration therefore takes the SandBox's easy and low-threshold interaction with a hydrodynamic model and adds structure to the Virtual River by providing structure through a limited number of options to facilitate gameplay.

At the time of writing, an alternative detection for the 3D game board geometry is explored over the existing SandBox's detection based on a Kinect measuring the distance of the geometry (figure 1). The alternative detection would be based on directly detecting the insertion of game pieces in the game board's hexagonal grid using for example RFID tags. This approach would remove the necessity to calibrate the Kinect at each game session. In addition, it removes the necessity to create 3D game pieces that are smooth and interconnected as shown in figure 2. In this approach, it would be possible to instead use a single standardized game piece. Stacking this game piece raises evaluation and can therefore be used to create the geometry of the 3D game board. Interpolation can be used to smoothen the sharp changes in elevation for the hydrodynamic model. An additional benefit of this approach is that it makes building the geometry universal; game pieces do not necessarily represent the Dutch river system. Next steps include developing and testing this 3D board game approach. This alternative to the game board's design therefore increases its flexibility which is potentially beneficial for when adapting and deploying Virtual River in a non-Dutch setting.

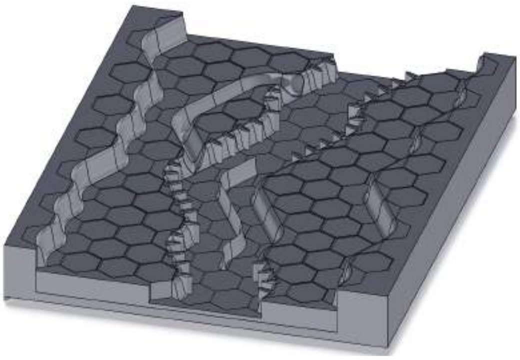

Figure 2. Virtual River hexagon-based 3D game board

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Development of a methodology to assess future functional performance of a river system

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Keywords — river functional performance, shipping, nature, flood protection, bed degradation, climate change, integrated river management

Introduction

The summer and autumn of 2018 showed the negative drawback of both low-flow conditions and bed degradation over the last century in the Dutch Rhine. This resulted in record-breaking low water levels, extreme low navigation depth and subsequently nautical problems. The Rhine's long-term bed degradation is the response to river training of the last centuries focused on improvement of navigation and flood protection. Over the past hundred years the river bed of the Upper Dutch Rhine branches degraded 1 to 1.5 m, while a current trend of 1 to 2 cm per year is observed (Blom, 2016). The ongoing bed degradation is problematic since it induces (i) a reduction of navigation depths due to the existence of non-erodible layers, (ii) lowering of ground water levels and dehydration of nature, (iii) lowering of coverage rates of infrastructure (e.g. cables in subsoil, bridges and groynes) and (iv) a gradual shift in discharge distribution at the bifurcation points. As climate change will increase the inter-annual variability of the Rhine's discharge pattern, low-flow conditions are likely to occur more often, reinforcing the abovementioned impacts on nature and navigation (Sperna Weiland et al., 2015).

Rijkswaterstaat is preparing for an integrated approach to mitigate the impact of bed degradation. Sediment management is considered as a sustainable way to counteract the bed degradation. Nourishment partly restores the deficit of sediment, while it also (temporarily) elevates the river bed increasing water levels. As the assignment of climate change and bed degradation are strongly connected, an integrated solution has to be found to guarantee a future multi-functional river system. To justify an investment in large scale nourishments, the impact of a nourishment on the river functions has to be compared with the result of a reference situation without nourishments. Also the cost-effectiveness of nourishments counteracting the bed degradation should be assessed.

This study aims to develop a methodology that evaluates the future performance of rivers functions accounting for the autonomous trends (bed level and climate changes) and provides insights in the cost effectiveness of river interventions. By means of a simplified 1D hydrodynamic model, the impact of these trends and the effectiveness of nourishment strategies on the performance of three functions (navigability, nature and flood protection) has been assessed. This was done for a river section of the Waal.

Methodology

This methodology consist of a two main blocks: (i) a model describing river conditions incorporating river processes and (ii) a model that quantifies the functional performance based on river conditions. A feedback loop between the river function performance and river intervention measures enables the assessment of measures on the performance of the river system.

In the first block "modelling river processes"', the hydrodynamic conditions are analysed by applying an 1D semi-analytical model that describes the system behaviour based on simplified equations. Bed trends are imposed on the river profile with a fixed rate. The bed erosion rate was varied per river section depending on observed trends. In addition, two extra scenarios for bed degradation rate were considered: a minimum (stabilization) and a maximum (doubled observed trends). This enables the assessment of uncertainty in the bed trends. Daily discharge records are imposed at the inflow boundary. Discharge time series adapted by Mens & Kramer (2016) are used to account for future climate scenarios ($W_{H,dry}$ (dry) and G_L (wet), KNMI'14). The climate scenarios have been linearly interpolated between the present and 2050 to define a bandwidth accounting for climate change uncertainty.

The assessment of the river's performance follows from sub-models per function. For the assessment of the ***navigability*** we used the model of Jonkeren (2009) relating navigation depth restrictions with the welfare loss for navigation. This model requires the navigation depth as input in order to

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determine the loading factor of vessels. To come up with the navigation depth and the corresponding loading factor, the water level information was combined with the width-averaged bed level that was corrected for transverse slope effects in river bends and bed forms. In addition, the agreed low water level (ALW) is obtained by simulating the future agreed low discharge for two climate scenarios. A navigation channel of 2.80 m deep by 150 m wide should be guaranteed. If these dimensions are not met, dredging is required. Dredging is only undertaken in alluvial parts of the river bed. The river function ***nature*** is assessed by analysing the inundation frequency of 'objects' contributing to nature, such as side channels or floodplains. For the "performance of nature" the amount and frequency of inundation is important since it says something about (i) the interaction between the river channel and the tranquil water bodies in the floodplain, and (ii) dehydration. The impact on nature has not been translated in economic values. Finally, the impact of autonomous processes and nourishment strategies on ***flood levels*** during design discharge conditions has been assessed. We did not account for a potential change in discharge distribution. As an increase in flood levels requires heightening of the flood defence, the impact on dike heightening costs has been assessed.

Application of the methodology

In the reference situation all three functions are affected by autonomous bed level degradation and climate change. Navigation depths drop. During ALW conditions, the water depth is most critical at the fixed layer of Nijmegen and responds almost one-to-one to the bed degradation. Due to bed degradation with the actual ALW, already in 2040 the depth requirements during ALW are not met. When considering the most extreme bed degradation scenario in combination with a dry clime change scenario this could be even the fact already in 2024, see Fig 1.

The autonomous changes also reduce the loading capacity of vessels. As water levels drop, the inundation frequency of side channels decreases from 300 days per year (start condition) up to 260 days per year in 2050. Whereas the combined effect of $W_{H,dry}$ and a doubling of the bed degradation rate results in an inundation frequency of even 150 days per year in 2050. Considering flood protection it is shown that future flood levels during design conditions drop with a rate of 3 mm per year due to bed degradation (11 cm in 2050), whereas more extreme flood discharges in climate scenarios result in an increase in flood levels with approx. 25-30 cm in 2050.

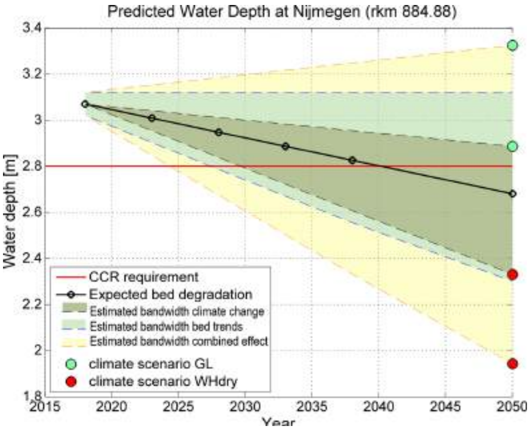

Figure 1. The effect of bed degradation and climate change on depth requirements at the fixed layer near Nijmegen during Agreed Low Water.

The impact of two nourishment strategies has been assessed: a strategy restoring and maintaining the bed level to its state in 2010 and in 1997. The navigability and the inundation frequency of floodplains and side channels improve for each strategy. The flood levels increase. An indicative cost-benefit analysis shows that the costs of nourishing and flood level compensation are lower than the future navigational losses due to reduced loading capacity. This implies that a nourishment strategy could be considered cost-effective.

Conclusions

Preliminary results show that the approach is a promising way to obtain insight in (i) the impact of bed level degradation and climate change on the river's performance, and (ii) the effectiveness of nourishment strategies. It is recommended to extent the methodology to the remaining part of the Rhine system, and also evaluate other measures than nourishments. The results revealed the importance of an accurate prediction of the bed degradation.

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Development of a new Rhine branches model with Delft3D-Flexible Mesh

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Keywords — Hydrodynamic modelling, Delft3D Flexible Mesh, Rhine

Introduction

With the development of the D-HYDRO suite, RWS has decided to make the transition from the 5th to the 6th generation models for WBI-applications (calculation of expected water levels due to measures). The planning is to have a 6th-generation model for all Dutch large-scale water systems by 2020. For this aim, we have started the generation of a new model in Delft3D-Flexible Mesh for the Rhine branches-system in 2018.

The main application of the newly developed models will be WBI, which requires an accurate reproduction of water levels. Next to that, the computation time needs to be reasonably short. Morphology will not (yet) be included in these models.

The transition to a new generation models offers the chance to alter (numerical) methods, such as determination of later inflows, implementation and control of hydraulic structures and a new calibration strategy. In this study we aim to explain the methods and choices we used in the set-up of the new Rhine branches model.

Area description

The Rhine branches include all branches that bifurcate from the German Rhine as it enters the Netherlands at Lobith (Figure 1). The three main branches are the river Waal, the IJssel and the Neder-Rijn – Lek. The annual average discharge at Lobith is around 2200 $m^3 s^{-1}$, of which 2/3rd is discharged through the Waal. Together, the branches have a length of over 300 km. The Waal and IJssel are free-flowing branches. The discharge through the Neder-Rijn – Lek is controlled by three hydraulic gates, thereby also influencing the discharge distribution through the other branches.

Methods

Grid design

The first step in model set-up is the creation of a new computational grid. We choose to use a curvilinear grid where possible, and triangles where needed. Quads are preferred over triangles because this results in 1) less numerical diffusion and 2) a larger possible time step, due to the larger volume of quads compared to triangles (De Jong, 2017). Furthermore, the grid is aligned to predominant streamlines and local features, while on the other hand orthogonality and smoothness should be maintained.

Figure 1. Overview of the model area

Implementation of hydraulic structures

Different types of structures are present within the Rhine branches area. Small (subgrid) weirs such as groynes and embankments are implemented as fixed weirs. When overtopped, the energy loss is calculated with the Villemonte approach (Yossef & Visser, 2018).

As a typical Dutch river, there is a clear distinction between the main channel and flood plains. Some of the flood plains cover a large area and determine the high-flow storage capacity to a large extent, while inflow is determined by a small diver or coupure. These structures are typically smaller than the resolution of a grid cell, and these are implemented as "gates", to allow for both through-flow and over-flow.

Larger hydraulic structures such as the hydraulic gates in the Neder-Rijn – Lek are taken into account in the grid design and implemented as gates or weirs.

Control of hydraulic structures

For control of the hydraulic structures, D-Flow is coupled to the real-time control module (D-RTC). The coupling between D-Flow and D-RTC is made for the three gates in the Neder-

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Rijn – Lek, the inlet of the bypass Veessen-Wapenveld and control structures in the Betuwepand (connection between the river Waal and Neder-Rijn – Lek). These structures are controlled using a PID-controller, which determines the difference between the upstream water level and the desired water level (setpoint). Based on this difference (*e(t)*), the gateheight at the next timestep (*f(t)*) is determined as:

$$f(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_e \frac{de(t)}{dt}, \qquad (1)$$

where K_p, K_i, and K_e are calibration factors (Deltares, 2018).

Boundary conditions

The model has four open boundaries. The upstream boundary at Emmerich is the only discharge boundary, of which the discharge is iteratively determined from the measurements at Lobith. The three downstream boundaries (one for every branch) are qh-relations, which remain unchanged with respect to the 5th generation-model.

Furthermore, the model knows several lateral inflows, which are mainly located at the IJssel. Compared to the 5th-generation model, more lateral inflow location are taken into account. Since measurements of the small lateral inflow are hardly available, the magnitude of these inflows is based on measurements at the two lateral inflows Oude IJssel and Twentekanaal, by a Qf-relation.

Calibration strategy

Calibration of the main channel roughness is based on water levels during different discharge periods. We distinguish five approximate discharge levels from extremely low (1000 $m^3 s^{-1}$ at Lobith) to extremely high (around 12.000 $m^3 s^{-1}$ at Lobith). For every discharge level, a period is defined for calibration and one for validation. Before starting calibration, a main channel background roughness is determined based on a combination of available dune height and grain size measurements and roughness fields from the DVR-model. The calibration is performed not directly on the roughness, but using a calibration factor. The flood plain roughness is not calibrated, but based on vegetation maps.

Results

The Rhine branches model (as well as other 6th generation models) is still under development. Preliminary results show realistic water level calculations and a realistic behaviour of the controlled hydraulic structures. We expect that the calibrated model roughness will be lower compared to the 5th generation models, due to better grid alignment with the flow.

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Surface screens for maintenance of side channels

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Keywords — River morphology, Surface screens, IJssel River

Introduction

Since the dawn of civilization, engineers have adapted rivers to societal needs by implementing training works such as bank revetments, groynes, dams, and excavated new courses. They designed training works to protect land against erosion, but also to let the rivers erode and deposit sediment of the river bed into a desired morphology, making use of the energy of the river. Traditional river training works are often large and expensive, but the principle of using energy of the river to obtain a desired morphological effect can also be used with smaller devices such as vanes and screens. When placed under an angle with the flow, these vanes or screens generate vortices and transverse flows that move sediment sideward.

The classical examples of these devices are bandals (from “bundles”) in former British India (Spring, 1903), still routinely used in South Asia, and Potapov vanes in the former Soviet Union (Potapov and Pyshkin, 1947). Two types can be distinguished: bottom vanes (Odgaard, 2009) and surface screens, the latter either fixed on stakes or floating. In the Netherlands, extensive research has been carried out on bottom vanes in laboratory experiments (e.g. Struiksma and De Groot, 1997), numerical models (e.g. Flokstra et al, 2003) and a field experiment (Asmerom and Jörissen, 2003). Surface screens received less attention, notwithstanding some experimental work by Filarski (1966) and Troost (2010). Floating surface screens were tested in Bangladesh in the 1990s (Mosselman, 2006).

We propose that floating surface screens could offer an attractive method for sediment management in the numerous side channels that have been created along the Dutch Rhine branches under the Room for the River programme (Mosselman, 2003). The screens would allow removal of undesired sedimentation or mitigation of bank erosion without having to deploy heavy machinery that might disrupt the local ecosystem.

Against this background we carried out a field experiment with a floating surface screen in a side channel in the Welsumerwaard along the IJssel River. We briefly present this experiment here. Oostdijk (2018) provides more complete information.

Method

The first author designed and constructed a floating surface screen with adjustable penetration depth into the water (Fig. 1). The screen was 2 m long and had an adjustable height up to a maximum of 1 m. It was mounted between two barges that were attached to the banks using chains. We varied the penetration of the screen (50% and 70% of the water depth), the angle with respect to the main flow direction (25° and 45°) and the position of the screen within the channel (in the centre or close to the bank). We measured the bed topography manually using a GPS on a pole. The flow was measured using a current meter for the velocity upstream and a frame with small flags for the local direction of the flow at different depths downstream.

Figure 1. Surface screen mounted between two barges and attached to the banks using chains.

We carried out 8 experimental runs from June 18 to June 28, 2018. Table 1 shows the corresponding settings.

Results

Table 2 shows the conditions during the experiments. Unfortunately the river discharge declined to values at which the sediment transport was small. Nonetheless, we obtained useful results for a proof of concept. Figure 2 shows the differences between channel bed elevations downstream of the screen before and after Run 5. Moreover, we obtained insights in practical aspects of floating-screen deployment and operation.

Table 1. Settings of experimental runs.

Run	Penetration (%)	Angle (deg)	Position
1	30	+20	centre
2	70	+25	centre
3	75	+40	centre
4	75	-40	centre
5	70	-45	centre
6	50	-45	centre
7	50	-45	centre
8	50	-45	bank

Table 2. Conditions of experimental runs.

Run	Duration (h)	IJssel discharge (m^3/s)	Channel depth (m)
1	16.0	370	1.30
2	14.5	363	1.25
3	16.3	350	1.10
4	16.8	348	1.06
5	18.8	324	0.88
6	16.1	312	0.82
7	29.1	303	0.76
8	18.0	292	0.71

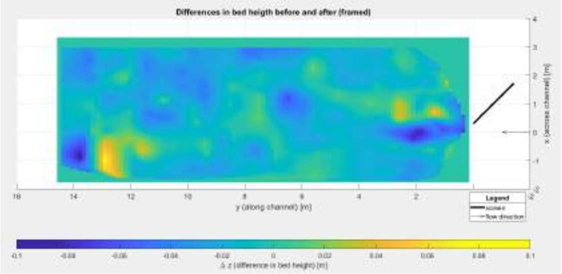

Figure 2. Differences between channel bed elevations downstream of the screen before and after Run 5.

Conclusions

Although the conditions became unfavourable during the experiment, effects on flow and bed topography could be assessed. We also came to the conclusion that further upscaling should be sought in a larger number of screens with longer durations, rather than in larger screens. Deployment and operation of larger screens would require heavier machinery, reducing the expected benefits for the local ecosystem.

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Recommendation

We recommend carrying out a field experiment with a larger number of screens, with longer durations. It should be designed in a way to meet a predefined channel maintenance objective.

Acknowledgements

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Session 4 - Long Term River Behaviour

Oral Presentations

Declining fluvial sediment delivery to major deltas due to human activity

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Keywords — River deltas, Hydrogeomorphic modelling, WBMsed, Fluvial sediment

Introduction

Deltas are home to over half a billion people worldwide, and are vulnerable due to being low-lying coastal climate change hot spots. Deltas lose elevation relative to sea level due to subsidence and eustatic sea level rise, both of which are increased by anthropogenic activities, and aggradation is the only process by which deltas can maintain elevation relative to sea level. The prediction of rates of delta aggradation is therefore critical to assessments of delta sustainability by contributing to the understanding of the extent to which sedimentation can potentially offset sea level rise. The ability to make predictions of aggradation potential is limited by a lack of insight into future trends of fluvial sediment fluxes delivered to deltas by their catchments. To address this gap we investigate fluvial sediment fluxes under future environmental change for 47 of the world's major river deltas.

Methods

We employed the spatially explicit hydrogeomorphic model WBMsed (Cohen et al. 2013, 2014) to project future variations in mean annual fluvial sediment delivery under 12 environmental change scenarios that include changes in climate, socioeconomics (as an indicator of land use and engineering), and reservoir construction. The 12 scenarios (see Methods) were constructed based on combinations of four climate pathways (Representative Concentration Pathways (RCP) 2.6, 4.5, 6.0, and 8.5, Jones et al. 2011), three population and GDP pathways (Shared Socioeconomic Pathways (SSP) 1, 2, and 3, Murakami and Yamagata 2016), and one projection of future global trends in large dam construction (Lehner et al. 2001a, b, Zarfl et al. 2015). The results presented are the changes in average fluvial sediment delivery to the 47 deltas between the years 1990-2019 and 2070-2099.

Results

The results (Figure 1) indicate a decrease in fluvial sediment delivery in total to the 47 deltas by 34-41% by the end of the 21st century depending on the specific scenario. Most of the 47 deltas also show a decrease in fluvial sediment fluxes with the reductions driven primarily by reservoir construction globally, however other anthropogenic changes such as land use can be equally influential for those delta catchments which experience significant socioeconomic change over the 21st century. In contrast, climate changes drive generally small increases in sediment delivery to most of the deltas which are overwhelmed by the effects of anthropogenic river engineering and land management in the river catchments.

Conclusion

The projections show the extent of major declines in fluvial sediment load over the 21st century to many of the world's major deltas. The implications of the declines in sediment load for future rates of relative sea-level rise in specific deltas depend on the rates of change of other key controlling factors, such as subsidence and eustatic sea level rise. The declines in future sediment load projected here are sufficiently pronounced and consistent, despite uncertainties inherent in projecting future rates of relative sea level change, that there is an strong rational to mitigate declining sediment loads if the major adverse impacts of such reductions, such as 'delta drowning', are to be minimised or prevented. Importantly for such mitigation efforts, our research highlights that anthropogenic climate change is the least

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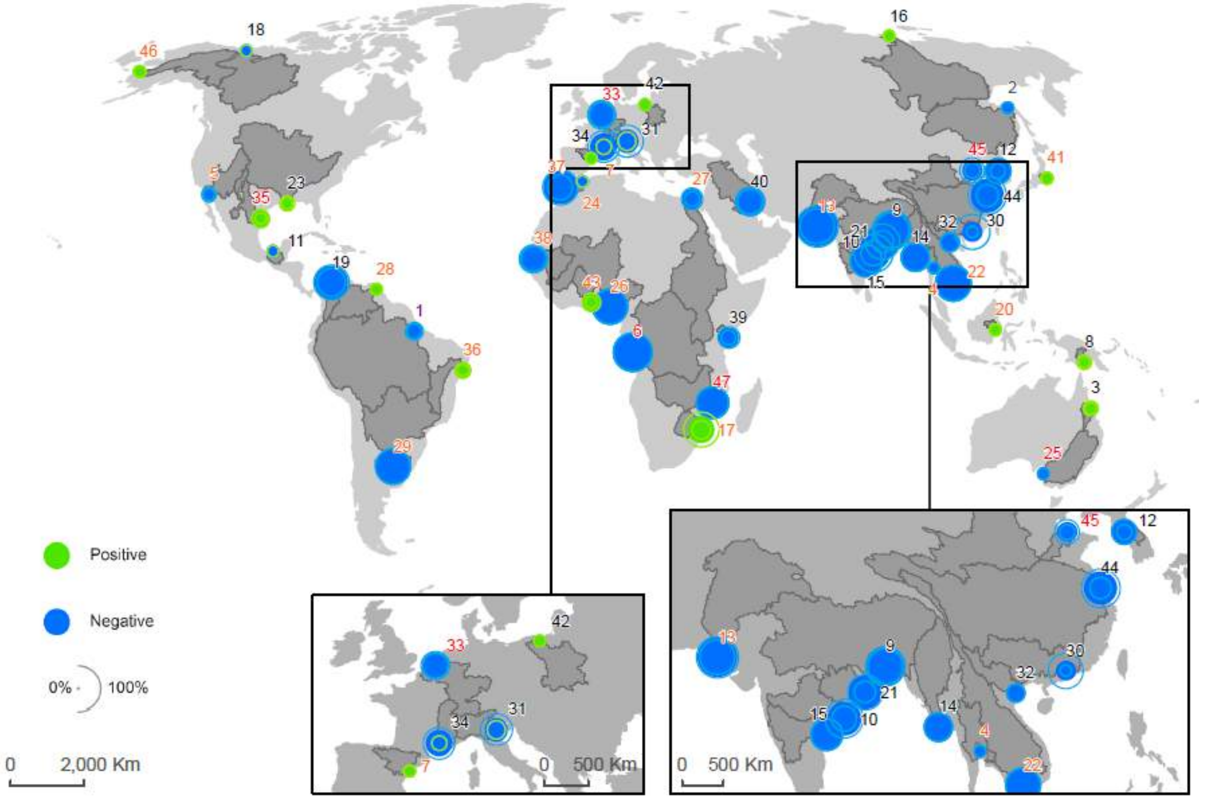

Figure 1. Projected percentage change in simulated mean annual fluvial sediment flux between 1990-2019 and 2070-2099 to 47 major deltas. The green (increase in sediment flux) and blue (decrease in sediment flux) circles are scaled to represent the mean annual sediment flux across all 12 model scenarios, with the outer (maximum sediment flux) and inner rings (minimum sediment flux) around each filled circle representing the extremes of the ensemble of 12 scenarios. The numbers of the deltas are coloured to indicate the confidence in the projection of each delta where error < a factor of 2 gives high confidence (black, 22 deltas), a factor of 2-10 gives medium confidence (orange, 19 deltas), and > a factor of 10 gives low confidence (red, 6 deltas). The dark grey outlines are the catchment boundaries of the feeder basins for each delta.

influential driver of sediment flux change investigated here, and the key drivers of reduced sediment loads are anthropogenic activities taking place within each of the delta's catchments. While the scale of the challenge is great, this means that nations hosting the world's deltas and their catchments should consider sediment management including measures designed to minimise sediment flux changes detrimental to downstream deltas.

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Reconstruction of differential formation and phasing of crevasses in the fluvial-tidal realm of the Old Rhine

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Keywords — Crevasses, fluvial-tidal realm

Introduction

Crevasses splay complexes can be found in many different river systems around the world, both in the purely fluvial as well as the tidal-fluvial (estuarine) realm. They originate at a breakthrough in the natural levee during peak discharges, forming a lobate landform with multiple interconnected shallow channels proximal to the river channel belt. In some cases crevasses extend several kilometres into the distal floodplain as a single deeper channel (e.g. the crevasse channels branching of the channel belt of the Old Rhine in Figure 1).

Combined field and modelling studies (e.g. Kleinhans et al. 2012; Millard et al., 2017) found that these extensive crevasses can evolve from the small proximal ones during a prolonged period of frequent peak discharge events when sufficient (i.e. not too much) supply of coarse silt to fine sand suspended sediment from the parent river channel is available. Too coarse and too much suspended sediment increases crevasse channel bed aggradation, which leads to healing, whereas coarse silts and fine sands promote levee build-up during overbank sedimentation, causing flow confinement, incision and progradation. However, the influence of tidal and other marine processes on crevasse formation, evolution and persistence has not been studied on a river scale yet. For example, both above mentioned studies did not include these in their models or analysis.

The Old Rhine provides an excellent area to study the interplay between tidal and fluvial processes and how they affect the formation and evolution of extensive single-channel crevasses, since many of these are well preserved (see Figure 1). Moreover, sufficient literature has been published about the spatio-temporal development of the system and its boundary conditions (affecting the tidal and fluvial processes) (cf. De Haas et al., 2018).

We hypothesize that extensive crevasses within the tidal-fluvial realm of a river system have different phases of activity and various origins of formation under continuously changing boundary conditions. The aim of this study is to test whether this hypothesis is true for the crevasses of the Old Rhine.

Methods

We gathered hand-augered borehole data of four single-channel crevasse splay complexes of the Old Rhine during a field campaign in early September 2018 (see Figure 1 for locations). The corings were performed along transects perpendicular to the crevasse channel belts, at roughly similar distances along each crevasse from the Old Rhine channel belt to enable fair comparison between crevasses. Sedimentary characteristics were logged, based on which lithological cross-sections were made. Additionally, we will obtain ^{14}C-dates of the formation and abandonment phases of the crevasses from peat samples.

Results and preliminary conclusions

Figure 2 and Figure 3 show the lithological cross-sections of the Zwiet crevasse and a crevasse South of present-day Alphen aan den Rijn (henceforward Alphen crevasse) respectively.

For the Zwiet crevasse, at least three different phases can be distinguished: an early purely tidal creek phase, and two younger tidal-fluvial crevasse phases. The three phases can be distinguished from each other through intermittent peat layers. We argue that the crevasse adopted the pre-existing course of the older tidal creek, which we infer from the depth of channel deposits and the presence of laminated silty clay deposits directly underneath crevasse levee deposits (Figure 2).

On the other hand, for the Alphen crevasse only one crevasse phase could be recognized, which dates after the first peat had formed here on top of older tidal deposits (see Figure 3). This crevasse did not take on the course of an earlier tidal creek (like the Zwiet), but progradated into the floodplain as a novel channel.

We presume that, pending ^{14}C-dates, the Alphen crevasse formed between roughly 3000 to 2000 years BP and that during this period also the initiation of the 1st tidal-fluvial crevasse phase of the Zwiet took place. This period is characterized by an increase in suspended sediment load, due to anthropogenic deforestation upstream since the Bronze Age (Erkens and Cohen, 2009), a relatively high frequency of intense storms in North-Western Europe from 3350 to 1550 BP (Pierik et al., 2017), and the occurrence of relatively many large flood events (especially around ca. 3300 years BP) between 4000 and 3000 BP compared to 3000 and 1500 BP (Cohen et al., 2016). The combined effects of the relatively high frequency of storm surges and large floods in this period led to a breach in the natural levee of the Old Rhine, initiating the formation of the Alphen crevasse. The contemporaneous increase in suspended sediment load facilitated the Alphen crevasse to extend far into the floodplains, and the Zwiet to build up relatively high natural levees along its already existing course.

Furthermore, we argue that ebb and flood flows flowed through the Zwiet on a daily basis, whereas the Alphen crevasse seems to have been active infrequently, i.e. only during peak discharge events. We base this on the fact that the Zwiet's natural levee deposits show very regular laminations, and that abundant smaller-sized tidal creeks branch off from its main channel, as identified on AHN imagery. Contrastingly, the natural levees of the Alphen crevasse lack laminations and its more distal floodplain deposits are more humic. Apparently tidal flows did not reach this far upstream, despite the estimation that the tidal backwater effect reached up to ca. 30 km inland from the apex of the estuary (Van Dinter, 2013). This might have to do with the shape of the course of the Old Rhine, effectively blocking the tidal wave at some point.

Our comparison of two crevasses at different locations from the Old Rhine mouth thus shows that tidal processes can play an important role in determining the course, extent, planform shape and sedimentary characteristics of extensive crevasse channels. This can be used to further refine theories about crevasse formation and evolution.

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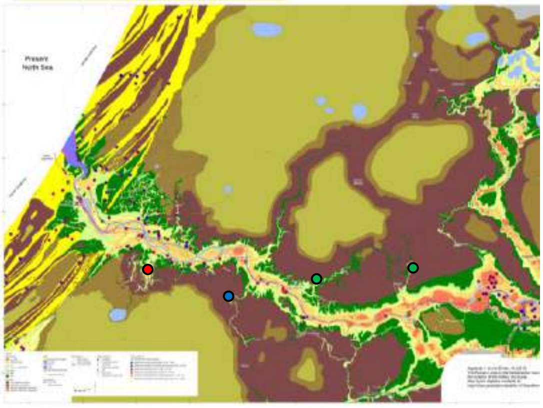

Figure 1 Palaeogeographic map of the Old Rhine in Roman times. Blue dot indicates the location of Zwiet lithological cross-section in figure 2, red dot indicates the location of that in figure 3, and green dots indicate locations of other coring locations. Modified after Appendix 1 of Van Dinter (2013).

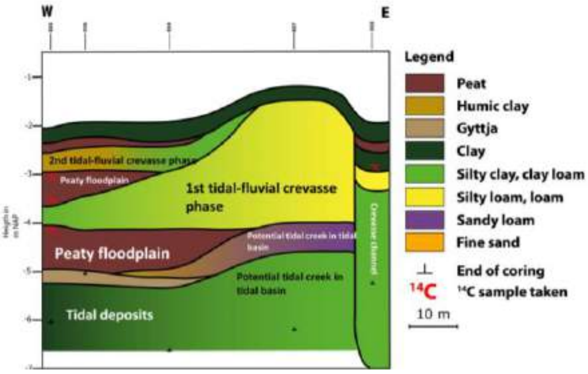

Figure 2 Lithological cross-section of the Zwiet crevasse with annotations on the lithogenesis and different phases of the Zwiet.

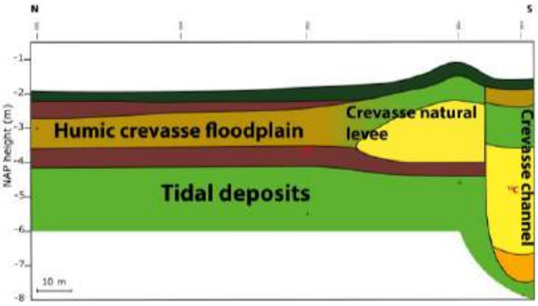

Figure 3 Lithological cross-section of the Alphen crevasse with annotations on the lithogenesis. Legend as in figure 2.

River delta floodplains: diffusive deposition, crevasse splays, or avulsions?

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Keywords — Floodplains, Avulsions, Crevasse Splays

Introduction

During floods, rivers can deposit sediments on their floodplains, but can also erode new channels that later heal (crevasse splays) or form an entirely new channel (avulsions). Close to the coast, in deltaic floodplains, the style of flooding is highly heterogeneous, yet carries important implications for the timescales, length scales, and styles of delta growth.

In deltas, avulsions do not occur until some distance upstream from the river mouth, called the avulsion length (Mohrig et al., 2000; Slingerland & Smith, 2004; Jerolmack & Swenson, 2007). Despite significant recent interest (Kleinhans et al., 2008; Chatanantavet et al., 2012; Hajek & Edmonds, 2014; Toonen et al., 2016; Moran et al., 2017; Chamberlain et al., 2018), avulsion mechanisms and their implications for avulsion lengths and delta size are still poorly understood.

Here we hypothesize that levee breaches result in river delta avulsions depending on two competing controls: floodplain roughness and the water level head between the channel and the floodplain. If the channel-to-floodplain water level head gradually increases away from the river mouth, this would set a preferential minimum distance for river delta avulsions at a location with a critical water level difference.

Methods

Here we use Delft3D to investigate channel-floodplain interactions, and simulate responses from crevasse splays to avulsions including the effects of vegetation and soil consolidation (Nienhuis et al., 2018). We compare these responses to observed floodplain features from the Lafourche lobe of the Mississippi River Delta.

Results

Model simulations show that crevasse splays heal because floodplain aggradation reduces the water surface slope, decreasing water discharge into the flood basin (Nienhuis et al., 2018). Easily erodible and unvegetated floodplains increase the likelihood for channel avulsions. Denser vegetation and less potential for soil consolidation results in small crevasse splays that are efficient sediment traps but that are also short-lived.

We also find a strong dependence of avulsion occurrence on water level head. A high water level head between the channel and the floodplain increases avulsion likelihood. Here, the flow velocities exceed a threshold and erosion dominates floodplain deposition. A low water level head on the other hand tends to heal crevasses and leave only small splays.

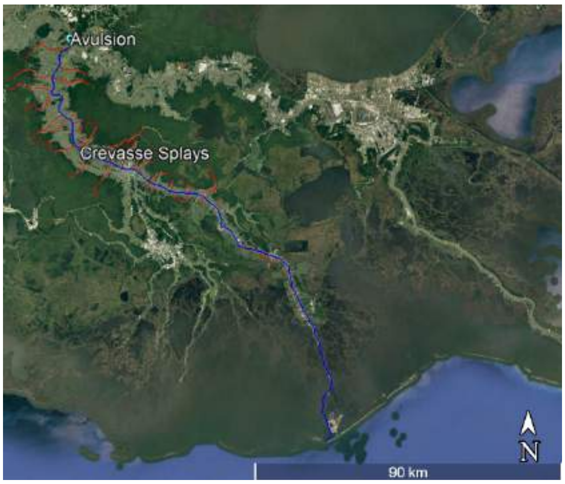

Figure 1. Crevasse Splays (in red) along the Lafourche lobe (in blue) of the Mississippi River Delta. The Avulsion node is marked in green.

We compare these simulated floodplain features to observed the Lafourche lobe of the Mississippi River Delta (Fig. 1). Here the avulsion length is approximately 125 km (Chamberlain et al., 2018).

From the mouth (at 125 km) up to the avulsion node (at 0 km), we find that the elevation difference between the natural levee and the adjacent floodplain increases upstream (Fig. 2). Assuming most floodplains form at or near flood water levels, this would indicate gradually increasing water level heads with distance upstream. We analyzed crevasse splays and found that crevasse splay length also generally increases with distance from the mouth (at 125 km) (Fig. 2). Because river avulse when conditions for crevasse splays are exceeded, it is likely that the Lafourche avulsion formed by a critical water level head that occurred during flood.

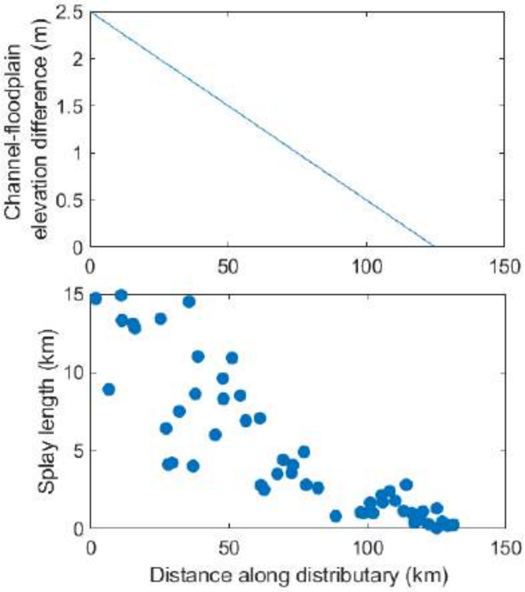

Figure 2. Crevasse Splay Length as a function of distance from the avulsion node (at 0 km) up to the modern river mouth (at 125 km).

Conclusions

Preliminary analysis of the Lafourche lobe of the Mississippi River Delta suggests that crevasse splay size and avulsion locations are dependent on the channel-floodplain water level head, in accordance with our Delft3D simulations. Combined, these investigations will help us understand river delta avulsions and provide critical new insights into controls on large-scale delta morphology and small-scale floodplain and fluvial sedimentology.

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Depth-limiting resistant layers tune the shape and tidal bar pattern of Holocene alluvial estuaries

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Keywords — Estuary, resistant geology, channel-bar pattern

Holocene fluvial and estuarine systems are commonly assumed to be entirely alluviated, which means that channels freely move in erodible substrates. This implies that the shape and tidal bar patterns are self-formed. Data analysis for estuaries and deltas worldwide, however, proves presence geological depth constraints in many, if not most systems. This potentially constrains estuary channel dimensions and planform shape. In this study we compare detailed historical bathymetry maps of the last two centuries and depths of resistant Pleistocene clays and tills in the Eems-Dollard estuary, located on the Dutch-German border. Based on this new historical and geological data we show how resistant layers forced bar patterns and channel dimensions in an estuary that was hitherto considered autogenically-formed. Resistant layers limit channel depth and consequently cause widening and mid-channel bar formation, increasing channel curvature over at least one bar length in both seaward and landward direction (Figure 1). Furthermore, channel confluences preferentially form where resistant layers are absent. These combined effects determine the position of confluences and bars on the scale of the entire estuary; they are tuned to the presence of the resistant layers. Our results challenge the view that bar-filled estuaries are predominantly self-formed. They show that apparently local obstacles have estuary-wide implications: they can, for example, force bar formation and increased channel curvature that may favor the stability a two channel system. Future sea-level rise may cause tidal prisms and consequently the channel volumes to increase. As a result, the resistant layers are expected to be more exposed on the bases and edges of estuary channels, leading to potentially unexpected channel behavior when their effects are not taken into account. This strongly highlights the need to incorporate inherited resistant layers into morphological models.

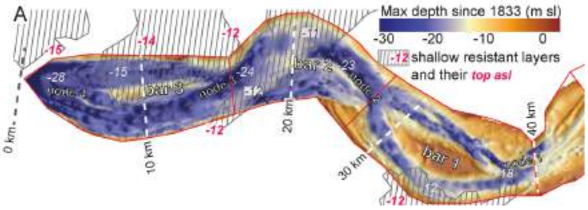

Figure 1. Maximal channel depth over 200 years. Where shallow resistant layers occur (hatching), channels are persistently shallower and bars occur here preferentially.

Session 4 - Long Term River Behaviour

Poster Presentations

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

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

Introduction

The lowland rivers of the Netherlands -- Rhine, Meuse, Ems and Scheldt -- play a vital role in the Dutch society. Although these rivers are relatively small on a worldwide scale, their watersheds are highly industrialized and densely populate, making their protection and development very important.

As an entity responsible for river policies and management in the Netherlands, the Ministry of Infrastructure and Water Management has the duty to maintain, and facilitate the sustainable development of four river's functionalities that are beneficial to the society at large. These functionalities are: (1) flood risk management (safely discharging water and sediments), (2) providing sufficient amount of fresh water to end users, (3) access to water that is ecologically clean and poses no health hazards, and (4) river navigation. Other river-related functions, such as energy production, cooling-off, fishing, construction materials, agriculture, and so on, are accepted as long the main four river functionalities are not under threat [1].

Since the last decade it is becoming clear that maintaining and developing the four river functions for the longer term, is becoming increasingly challenging and costly. Taking care of local bottlenecks without taking into account the long-term river development is not sufficient. The paragraph below describes the complexity of various factors at stake, both coming from nature and induced by men.

Changing conditions

The large-scale geomorphology of river systems is adapting quite slowly to the changing boundary conditions. For lowland rivers these conditions are: (1) the upstream discharge, (2) the down-stream sea level, (3) the upstream sediment inflow, (4) the stability of bifurcation point, and (5) the present material composition of the river bed. The hydraulic boundary conditions are changing due to the climate change; the sea level is rising and we observe a more extreme water discharge pattern. At the same time, the construction of dams (the upstream part), straightening of the navigation channel, meander cut-offs, construction of groynes, executed in the period 1850-1940, give rise to an imbalance between sediment transport capacity and sediment supply. This causes rapid erosion of the river bed. Measurements in Dutch part of the river Rhine show an erosion rate of 2 cm/year over de last 50 years. This causes problems with navigation depth around places with non-erodible layers, stability of infrastructure, covering depth of river crossing pipelines, lowering of groundwater tables and the impact on nature development, etc. In the river delta we see issues related to the development of erosion holes in the riverbed. Secondly the salt intrusion, especially during low discharge, is an increasing problem.

This combination of changing boundary conditions, past and present human activities makes it unclear what the new equilibrium state on the longer term will be. For new large scale measure in the river system, we would like to know and predict the impact on the river morphology. This is only possible when we understand the current long-term development.

Rivers2Morrow
Working on the Future of our Rivers

The program

To develop deeper insight in the long-term development of the Dutch river systems, and provide new information for adaptive strategies, the Ministry has started in 2017 a research program called Rivers2Morrow [2]. This program will have a duration of six years and will be part of the larger NKWK program, which addresses fourteen themes related to climate adaption issues [3].

This program focuses on geomorphology, hydraulics, and ecology. We would like to find out how lowland rivers respond to climate change, sea level rise and changing river discharge. The sediment supply at the upstream boundary will most probably change, not only as a result of climate change, but also as a result of anthropogenic interference. Furthermore, in many river systems (including the Dutch Rhine branches and the Meuse River), many measures to reduce flood risk have been applied in the past thirty years. Although every individual measure has been designed so as to minimize the morphological changes, the combined morphological effects in the next few decades are still highly uncertain. Also the assessment of ecological changes --succession of vegetation -- and its effects on hydrology and morphology remain challenging.

Rivers2Morrow can be seen as the successor of the research program RiverCare [4]. which in its turn was inspired by the program Room for the River, which among other things explored the morphological and ecological consequences of longitudinal dams, side channels and other restoration measures.

Research questions

The overall research question that we intend to answer is how a lowland river system in general responds to changes, in the course of its evolution towards a new (dynamical) equilibrium. Rhine and Meuse rivers act as case studies and living labs to test a number of theories.

Rivers2Morrow addresses the following six research questions:

1. What is the long-term response of Rhine and Meuse to the sea-level rise and other changing external conditions, and how can we predict that response.
2. How do interactions between water, silt, sand, salt and vegetation determine the long-term development of the deltaic area of lowland river systems, and how can we apply this knowledge .
3. How will the sediment supply towards the delta, the partitioning and spread of sediment within the delta and the composition of the river bed change as a result of changing climate, changing land use, constructions of measures and other influence of other anthropogenic developments.
4. How do the changing boundary conditions, influence the anticipated development of nature and what strategy is increasing the ecological opportunities.
5. What are the hydro-morphological effects of the heterogeneity of the subsoil of lowland rivers on the formation of bedforms (bars and dunes) and bed features (e.g. scour holes) and what is the influence of changing boundary conditions?
6. How can we improve hydraulic, ecological, and morphological models in order to improve their predictive value and expand their predictive horizon?

Progress

Three PhD-candidates will work on research question 1. One PhD-student at Utrecht University has already started addressing the question of sediment management in the deltaic area. A second PhD-student at the TU Delft will start in December 2018 to work on sediment issues in the upper delta. At Wageningen University, a third PhD-student has started her research in the second part of 2018, working on research question 3. She explores new methods to predict sediment transport. Early 2019, a PhD candidate will start working on bifurcation points at the University of Twente, contributing to research question 1 and 3.

Rivers2Morrow is funded by the Ministry of Infrastructure and Water Management and its executive organization Rijkswaterstaat for the period 2017-2022. Consultancy companies and Deltares, participated in the setup of the program.

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[3] https://waterenklimaat.nl/en/research-tracks/
[4] http://www.rivercare.nl/

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Towards Best Practices for Mitigation of Channel Degradation

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Keywords — River Degradation, Engineered Rivers, Sediment Nourishments

Introduction

The Rhine River, like many highly-engineered channels throughout the world, has experienced a long history of human-made modifications to suit stakeholders. While the implementations have changed over time, the goal has been generally consistent – to ensure flood safety and navigation while limiting environmental effects.

Historical modification to the Rhine include: channel straightening, cross-section normalizations, construction of dams, and construction of groynes *Van Heezik* (2008). In comparison to natural conditions, the modern Rhine has narrower, deeper channels Blom (2016). Patterns of degradation in Dutch Rhine are shown in Fig. 1.

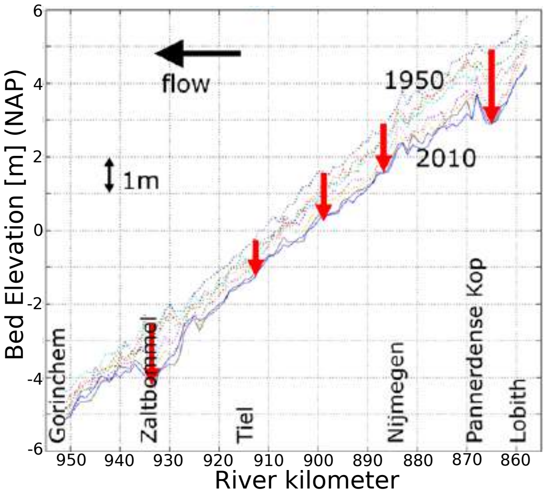

Figure 1: Temporal bed degradation of Rhine/Waal River from 1950 - 2010. Reproduced from Blom (2016); source: Rijkswaterstaat Oost-Nederland.

Channel degradation relates to a transition towards a lower-slope equilibrium state. Incision is expected to continue until a new equilibrium state is achieved.

Risks of Channel Degradation

Channel deepening initially decreases flood risk by increasing in-channel storage. However, numerous secondary effects may affect long-term changes to navigation and flood risk. Unequal degradation due to presence of less-erodible material in the channel substrate may hamper navigation. Scouring around the foundation of channel structures, e.g. groynes, increases the risk of failure.

Goals for Mitigation

We focus here on implementations to reduce or eliminate the degradation process rather than the many causes of degradation. This implies two possible goals for remediation to:

A restore the river to a semi-natural state with steeper bed slope

B reduce degradation by maintaining a selected slope

Each goal requires different strategies, so goal selection should be discussed with the associated stakeholders.

Mitigation Measures

We identify and evaluate three measures to mitigate channel degradation:

1. side channels
2. longitudinal dams
3. sediment nourishments

Our tests use generalized conditions of the Rhine River. The findings, however, are relevant for evaluation of mitigation strategies against channel degradation in any other highly-engineered river.

Methodology

The Elv 1D mixed-grain size, morphodynamic numerical research code is used to evaluate the effectiveness of these three measures for restoring the river to a steeper bed slope. To evaluate goal (A), we establish a base case that assumes constant inflow of water Q_w and sediment flux (sand Q_s and gravel Q_g) estimated from modern Rhine River conditions

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with grain size classes for 1 mm sand and 10 mm gravel Rudolph (2018) (via measurements of Hillenbrand and Frings (2017)). Note that this is not representative of the current conditions, but rather the projected equilibrium state given a measured sediment feed rate. Goal (B) will be tested in future work.

For all cases, the measures are implemented separately. Both side channels and longitudinal dams relate to distribution of water and sediment flux to secondary channels. However, we only model changes in the main channel and do not dynamically model the distribution of water and sediment flux between main and secondary channels. For example, if we assume longitudinal dams split 20% of total water flow and sediment flux to the secondary channel, then we model the main channel with 80% of the total water flow and sediment flux.

Parameterization of Implementations

A system of side channels adjacent to the river are parameterized as to reduce Q_w and Q_s throughout the entire reach.

Longitudinal dams act as an internal bifurcation with temporally and spatially static splits for water and sediment (sand and gravel) load between the main and secondary channel; this is parameterized by modeling a narrower channel width B with reduced Q_w, Q_s, and Q_g.

Coarse sediment nourishments are modeled by increasing the volume of gravel introduced into the river. The gravel feed rate can be increased as $Q_g = Q_{g,0} + Q_{g,n}$, where *0* denotes the original gravel load and *n* denotes a nourished quantity. We also model the effect of mid-reach nourishments. For these runs, $Q_g = Q_{g,0}$ and the extra gravel, i.e. $Q_{g,n}$, is distributed throughout the river in a variety of ways and at different frequencies. These nourishments are placed in the model as an instantaneous bed aggradation with volume V_n:

$$V_n = (1 - \lambda_p)\Delta t_n Q_{g,n} \qquad (1)$$

where λ_p = porosity of bed sediment and Δt_n = the time between nourishments.

Preliminary Results

First, all three implementations are tested to understand the magnitude of change needed to attain a specified slope change. For sediment nourishments, coarse material is included as additional feed rate into the system. For example, if we seek to increase the base case bed slope by 25%, the following changes are required to fluxes in the main channel:

- Side channels: $0.8Q_w, 0.9Q_s$
- Long. Dams: $0.7Q_w, 0.8Q_s, 0.95Q_g, 0.9B$
- Sediment Nourishments: $2Q_g$

The ratios listed above are a proportion of the base case value. For example, the system of side channels adjacent to the main channel must account for 20% of water discharge and 10% of sand load to increase bed slope in the main channel by 25%. Values are replicated from Rudolph (2018). This analysis can be useful to understand the scale and practicality of necessary changes to achieve a selected condition (bed slope).

Future Work

In the future, these implementations will be tested for mid-reach applications; this may include, for example, sequential application of sediment nourishments and longitudinal dams. Future modeling efforts will also aim towards addressing Goal (B) through maintenance of a specified slope.

Acknowledgments

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Can floodplain excavation help to mitigate bed erosion?

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Keywords — morphology, bed erosion

Introduction

In October 2018, the water level in the Dutch Rhine reached an all time low-record. At Lobith, a water level of 6.50 m.+MSL was measured, which was approximately 3.5 meters lower than the average water level and more than 10 meters lower than the all-time high water level (16.93m.+MSL, recorded in 1926). This situation of low water levels lasted from May 2018 until December 2018, which is very exceptional. Due to this, shipping on the Rhine was seriously hindered. Low water levels by itself hinder navigation, but along the Waal River this hindrance was increased because ships encountered obstacles in the navigation channel: apart from natural rock formations in Germany, there are man-made training works in some of the outer bends, fixating the bed level by boulders. As a result, the bed level in the inner bend gets lower and the navigational width is increased. This so called ‘fixed layer’ is stable, while the surrounding stretches experience bed erosion of several cm’s per year. It is kind of ironic that a measure which was intentionally meant to help navigation, now has an opposite effect.

At this moment, bed erosion is one of the most serious problems that Rijkswaterstaat (the executive organization of the Ministry of Infrastructure and Water Management) encounters. Besides its negative impact on navigability, it has also severe consequences for biodiversity and ecosystems in the floodplains due to lower ground water levels, it endangers the stability of sluices and bridges, cables and pipelines might get exposed, it interrupts the intake from fresh water during low flows and finally, the entrance to harbours (which is often provided by sills) becomes more difficult. Therefore, it is obvious that Rijkswaterstaat is interested in mitigating measures to counteract this bed erosion. As erosion and sedimentation is basically caused by an imbalance between the sediment supply and the transport capacity of the river, there are essentially two ways to counteract erosion: increase the supply (e.g. sediment nourishments) or lower the transport capacity of the river. As the transport capacity of the river is a function of the slope, width, sediment properties and flow velocity, those are the parameters that one might try to alter to decrease the transport capacity and reduce or stop the erosion (see also Lane, 1955).

The World Wide Fund for Nature (WWF) is the founding father of the Living Rivers concept, which was an important source of inspiration for the Room for the River program. Now that Room for the River is almost finished, WWF wants to further explore the Living River concept, and introduced Room for *Living* Rivers. Their vision is to create more space for climate-proof rivers, where nature can flourish and people live, work and recreate safely.. A way to do this is to reconnect the floodplains to the main river, for instance by creating a chain of side channels along long river stretches. This means that essentially, the river is widened. Hence, the same measure serves multiple goals: nature development and floodplain restoration, as well as sediment management to create a sustainable river system.

Recently, Rijkswaterstaat also adopted the concept of Integral River Management. This means that apart from creating and maintaining a safe river system, also other functions in the river system (e.g. nature, navigation, agriculture, extraction of drinking and industry water) play an essential role. That is where RWS and WWF meet and work jointly on a more sustainable river.

Method

To test the hypotheses whether large floodplain widening indeed reduces bed erosion, we use a 1D-SOBEK model of the Waal, in which we implement a 2-meter integral excavation of the floodplain. We assume that every section of the floodplain is lowered, side channels and objects within the floodplain included. Only a small zone at the toe of the dike is excluded for dike-

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stability reasons and a small levee-like structure at the boundary of the navigational channel and the floodplain is maintained, such that there is still a threshold discharge before the floodplains get inundated. As upstream hydrodynamic boundary condition, we assume a historically averaged annual regime, which we repeat every year. We assume a sediment supply from Germany such that the annual bed erosion of 2cm/a continues for the next 100 years. We model a sediment mixture with 17 sediment classes.

Results

In Figure 1, we plotted the mean bed level for the reference situation after 100 years of simulation. The bed erosion in the most upstream reach is approximately 2 meters. In downstream direction, the erosion decreases. Approximately 35-50 km downstream, there is a stretch where there is almost no erosion or sedimentation. Going further downstream, we see increased sedimentation, up to 3 m at the downstream end with respect to the initial situation. This simulation is in accordance with present erosion and sedimentation trends in the Waal River.

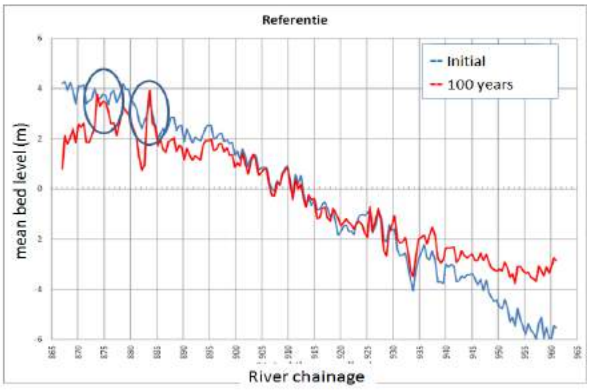

Figure 1. Mean bed level for the reference, as initial state and after 100 years. The two ellipses indicate the location of the bottom groynes and the man made fixed layer at Nijmegen

Note also that at the locations where the bed is fixed by human interventions there is no erosion (see blue ellipses in Figure 1).

We also calculated the reduction in water level for the highest discharges, which appears to be more than 2 m. at the upstream boundary. In Figure 2, we plotted the effects of the variant with respect to the reference. Note that in the most upstream part of the river stretch, it seems that the bed erosion continues at a rate which is even larger compared to the reference. This might be due to the effect that in that part, also the reduction in the flood water level is the most. Apparently, the water level is reduced to such an extent that at moderate discharges, the floodplains no longer inundate and erosion in the main channel is even increased. Further downstream, we indeed see reduction of the erosion trends. As in this variant all floodplains are lowered uniformly by 2 meters, existing irregularities in discharge distribution between main channel and floodplains may be maintained or increased, depending on the reduction in water level. Alternating local erosion and sedimentation is the result.

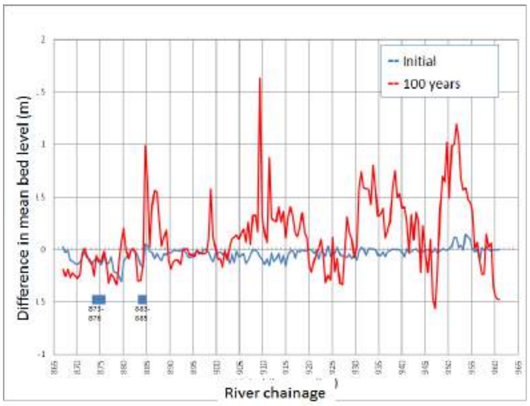

Figure 2. Difference in mean bed level between the reference and the variant. Positive values mean that there is less erosion in the variant. The two blue rectangles indicate the location of the non-erodible stretches.

Conclusion

We studied the effect of large scale floodplain excavation on the reduction of erosion in the upstream part of the Waal River. Simulations with a 1D numerical morphological model indicate that this measure indeed has the potential to reduce the erosion. However, applying the measure uniformly on the whole stretch does not give clear results. This might be due to the large reduction of flood water levels, because of which the effects of the excavation are not everywhere evenly effective. This means that the measure should be designed tailor made to have maximal effect. The results can also be used to get insight in the necessary sediment supply at the upstream boundary for stabilizing the river bed.

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Long term governance in the Noordwaard: matching physical features, social needs and economic revenues

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Keywords: Noordwaard, survey, network analysis, governance, place keeping

Introduction

The Noordwaard is a recently realised high water floodplain near Dordrecht. The design plan of the Noordwaard is an answer to the increasing river discharge extremes, combining water safety, agriculture, recreation and nature management (Stobbelaar & Schoenmakers, 2018). However, in terms of governance a gap has emerged. The Department of Water management and Public Works (RWS) had been the main driver in this redevelopment project, being both landowner and project developer. However, there was no plan for the governance of the area after completion (Van Buren, 2017), while institutional settings are required to maintain the floodplain in an integrated way (Fliervoet and Van den Born, 2016). The area has a high potential for the development of different ecosystem services, thus it has the potential to stimulate economic growth in the area. Which leads us to the following question: to what extent does the layout comply with the recreational wishes of the inhabitants and other stakeholders in the area?

Method

Through the platform of the Kenniscentrum Natuur en Leefomgeving (KCNL) a triple helix research project was developed to assess the integral development of the Noordwaard. Our research question was addressed as part of this project. A power/interest matrix was made on the basis of 17 stakeholder interviews about governance, qualities and bottlenecks of the area (Van Buren, 2017). Recreationists were interviewed on their perception of natural areas and how they view the developments within the Noordwaard (Hendriks, 2017). The same was done for the inhabitants (Bromberg, in prep).

Qualities and bottlenecks

Local residents mention the following qualities of the area: natural (fish eagle) and landscape qualities (open area), showing the historic struggle against flooding, and management by large grazers. Recreational possibilities like biking, walking, bird spotting, canoeing (Figure 1) are also highly appreciated. This was in line with the preferences of the recreationists (Hendriks, 2017).

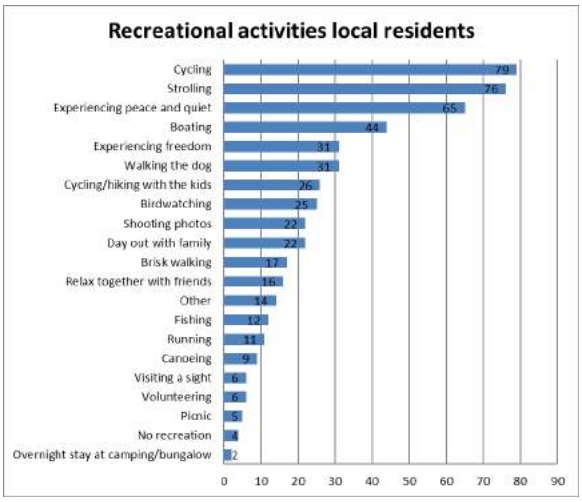

Figure 1. Recreation motives of inhabitants (Bromberg in prep).

The area is easy to access for cyclists. Although, they also point out some bottlenecks like the use of the Bandijk (the main dyke). Here conflicts occur between different user groups, for instance between inhabitants driving to their homes and bird watchers blocking the route. There are only a few accessible footpaths and there is no regular bus line. Some of the stakeholders would like to expand recreational possibilities, while others would keep it small, protecting nature qualities

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and/or Sunday rest (Hendriks, 2017; Bromberg, in prep).

Among the interviewed recreationist the desire to visit the Noordwaard repeatedly when more recreational activities would be developed, correlated with their reason for visiting. Those who visited the area for recreation have the intention to return *(r_2= 0.335; $p<0.05$)* than those who visited for the natural value *(r_2= -0.335; $p<0.05$)* and relaxation *(r_2= -0.285; $p<0.05$)* (Hendriks, 2017).

Governance

As written in the former section, the stakeholders are satisfied with the changes made in the area, but they also see possibilities for improvement. However, a clear governance structure is lacking and more cooperation is wanted to neutralize bottlenecks and to seize opportunities. Several stakeholders, like the municipality of Werkendam and recreational organizations want to cooperate with Free Nature (owner of the large grazers) because their management is very important for the image of the area and recreational possibilities.

According to the power/interest matrix, the five most important stakeholders need to be encouraged and influenced to actively take a role in the development of the area (Figure 2). They should take care that especially stakeholders with little power but high stakes (farmers and recreational entrepreneurs) could/should be more involved in the governance process.

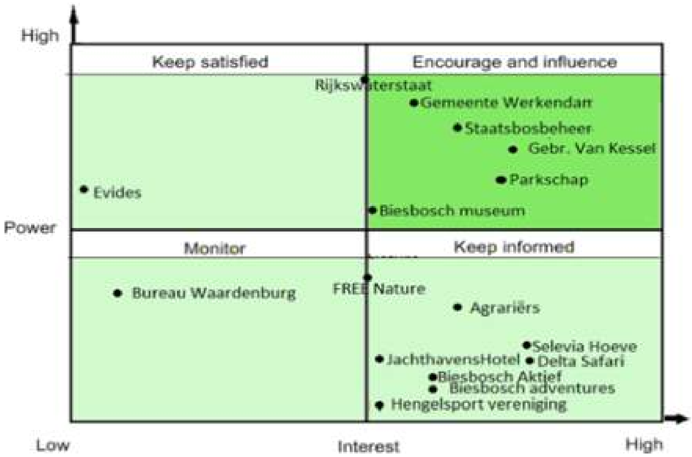

Figure 2. Power/interest matrix of the stakeholders in the Noordwaard and their preferred method of participation (Van Buren, 2017).

Conclusions and discussion

The Noordwaard is a typical example of a project with emphasis on placemaking, somehow disregarding place keeping aspects (Dempsey & Burton, 2011). Especially a recreational vision is necessary to keep developing the area, because most of the stakeholders have opinions about and / or interest in recreation. This recreational vision should determine what sort of recreationists will be attracted to the area, which will influence both the natural value and the economic progress of the area. Strongly related to this and very important for place keeping is to secure funding over the long term for managing the area for recreation, livelihood and nature quality, which therefore should be an important element of the new vision. Therefore it is vital for the landowner (RWS) to involve the main stakeholders in writing this vision, in order to balance their wishes with the physical features of the area and the economic revenues from the area. Fortunately RWS has become aware of the lack in governance structure and has appointed a new internal coordinator for the Noordwaard. More in general the Noordwaard learns us that organizing a governance structure in large scale spatial projects from the start on is essential to keep stakeholders attached and the area in continues development.

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Response of the upper Rhine-Meuse delta to climate change and sea-level rise

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Introduction

The Rhine River is the most important inland waterway in Europe, with over 300 million tons of cargo transported annually over its waters (Blom, 2016). The river also serves as a water supply for households, industry and agriculture, evacuates wastewater and is part of several nature conservation areas (Frings et al., 2014). Additionally, its waters create a main ecological corridor and host several hydropower plants (Middelkoop et al., 2001). The proper fulfilment of these functions can be hindered due to human intervention and climate change, which both impact the river morphodynamics.

In the Rhine-Meuse delta, which is the most densely populated and intensively used region of the Netherlands (Huismans et al., 2017), bed degradation and aggradation patterns can already be observed, at rates of 2 cm/yr and 2-3 mm/yr respectively (Blom, 2016). Sea-level rise has been associated with bed aggradation, whereas bed degradation is known to be a consequence of historic river training works. Yet other factors such as coarsening of the upstream sediment supply, climate-change induced variations in the probability distribution of the flow rate, and adaptation to implemented and foreseen engineering interventions can also have an important effect on these dynamics.

The river response to changes in the boundary conditions typically takes tens to hundreds of years. In this context, the National Knowledge and Innovation program on Water and Climate (NKWK) has been set up by Rijkswaterstaat in order to ensure that the Dutch river system remains stable in the long term, both in terms of navigation and flood protection. This project is part of Rivers2Morrow, a research program within the NKWK initiative that aims at gaining understanding on the long-term response of lowland river systems to climate change and human impact.

Methodology

The studied area is the upper Rhine-Meuse delta in the Netherlands, with a possible extension to the German Rhine (Fig. 1).

Figure 1. Area of interest

Four main factors influencing long-term river behavior will be addressed in this project:

1. Sea level rise
2. Climate-change induced variations in discharge probability distributions
3. Coarsening of the upstream sediment supply
4. Effects of undertaken and foreseen engineering measures (for instance those of the Room for the River program)

For each of these controls, the past trends will be investigated, and scenarios for future behaviour will be set. A scenario approach is chosen due to the high uncertainty of the field data (e.g. data on the sediment supply) and predictions for long-term changes of boundary conditions.

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A 1D morphodynamic model is set up to investigate the long-term river response (50-250 years) to the changes in boundary conditions. In some specific areas of interest, 2D modelling will be used. The outcomes of the model will be used to assess how the river response affects the river functions over time, and if possible, advise on sediment management practices in the upper Rhine-Meuse delta.

Preliminary investigations

Some preliminary studies have been conducted.

A range of scenarios has been defined for the rate of sea-level rise, probability distribution of flow rates, and upstream sediment supply for the Dutch Rhine (Van Tets, 2017). These scenarios were used in a 1D model of a simplified branch of the Waal river, and analysed individually (i.e., considering a change in one control at a time, leaving the others in the current state) for a period of 300 years (Van Hamel, 2018). Similar analysis of a larger reach of the Dutch Rhine have also been carried out for periods of 400 years (Soci, 2018).

These studies provide early insight on the general trends of the river response to changes of its controls. Sea-level rise results in a higher water depth at the river, with a consequent decrease in flow velocity that produces bed aggradation. The aggradational wave migrates upstream, further than the backwater zone.

Due to climate change, the probability distribution of the flow rate is expected to change. The water discharge will be higher in the winter season and lower in the summer. The former has a dominant effect, implying that the average flow rate will increase. Higher discharges result in higher flow velocities and thus higher sediment transport rates, causing important bed incision in the long term. The degradational wave travels from the upper boundary in the downstream direction.

The gravel share of the Rhine has increased in the past years. Coarsening of the sediment supply locally reduces the transport capacity and thus the sediment supply to the downstream part of the river. This causes degradation of the river bed and eventually an increase of the bed slope. This coarsening effect migrates downstream.

Future work

The previous preliminary studies serve as a tool to identify research needs for the project.

The input data will be revised in the future, in order to consider the most up-to-date field measurements and long-term predictions for changes in the boundary conditions. Particular attention will be brought to the estimation of discharge distribution at bifurcation points. The effects of undertaken and foreseen engineering measures will equally be included.

Since changes in river controls can result into opposite trends, the combined effect of the variation of different boundary conditions will also be studied.

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