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Ylla Arbos, C.

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Clàudia Ylla Arbós

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Proefschrift

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Clàudia YLLA ARBÓS

Enginyera Civil, Universitat Politècnica de Catalunya, Barcelona, Spanje
Master of Science in Civil Engineering (Water and Energy),
Ecole Polytechnique Fédérale de Lausanne, Lausanne, Zwitserland,
geboren te Barcelona, Spanje.

Dit proefschrift is goedgekeurd door de

promotor: Dr. ir. A. Blom
copromotor: Dr. R.M.J. Schielen

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Dr. R.M.J. Schielen	Rijkswaterstaat, Technische Universiteit Delft

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I would love to live like a river flows,
carried by the surprise of its own unfolding.

John O'Donohue

Contents

Summary

Humans have intervened in rivers for centuries. River engineering measures have aimed at protecting populations against flooding, ensuring reliable and safe navigation, providing freshwater for drinking, domestic and industrial use, irrigation, and energy supply, and providing opportunities for recreation. All around the world, measures such as channelization (i.e., channel narrowing and shortening), dam construction, or channel diversion have allowed for the proliferation of human settlements, technological progress, and an improved quality of life.

Despite the various socio-economic benefits of human intervention in rivers, engineering measures have side effects, often unaccounted for, or simply unknown before they manifest. This is because, by modifying the channel characteristics (geometry, planform, size of the bed surface sediment), or its controls (water discharge, sediment supply, base level), engineering measures alter the equilibrium state of a river. In response, rivers adjust toward the new equilibrium state through bed incision or aggradation, changes in channel width or sinuosity, or changes in the bed surface grain size distribution. This response may extend over hundreds of kilometers, and develop during decades to centuries.

Besides direct human intervention, climate change continuously and increasingly affects the river controls. This is because climate change modifies the hydrograph through changes in precipitation, ice-, and snowmelt, and the base level through sea level rise or base level lowering. Such changes alter the equilibrium state of the river, thereby prompting channel adjustment. Channel adjustment in rivers is, therefore, influenced by both human intervention and climate change.

Understanding how channels respond to human intervention and climate change is highly important, as channel adjustments are known to affect flood risk, hinder navigation and freshwater extraction, and compromise the ecological quality of rivers. Insight on the physics behind channel adjustment allows to, on the one hand, anticipate how climate change may affect river systems, and, on the other hand, plan interventions with minimal side effects. This knowledge can be gained through a combination of methods, including the collection and analysis of field data, numerical modeling, laboratory experiments, and remote sensing. Very often, however, data are not available over sufficiently large spatio-temporal scales to understand and model channel response at centennial timescales and over hundreds of kilometers.

This dissertation aims to understand how engineered rivers respond to climate change and human intervention at centennial timescales. To this end, we focus on the lower Rhine River, which we define as the stretch of the Rhine River between Bonn (Germany) and Gorinchem (the Netherlands). The lower Rhine River flows through the most densely populated region in Europe, and is the most transited inland waterway in the continent. As such, it has been heavily intervened for centuries, and is intensely monitored, making it a valuable case study to investigate centennial channel response at (sub-)basin scales.

To this end, we first delve into the history of human intervention in the lower Rhine

River since the 18th century, and analyze the resulting channel adjustment, in terms of change in bed elevation and bed surface grain size. We do this using measured bed elevation and bed surface grain size data from the period 1898-2020. We see that domain-wide channelization measures have caused generalized channel bed incision (by up to 5 m over 100 years), resulting in increased channel concavity. In other words, the channel slope has increased in the upstream part of the river, and decreased in the downstream part. The downstream slope decrease is an expected response to channelization measures, as a smaller equilibrium channel slope suffices to transport the sediment supplied from the upstream part of the basin. The upstream slope increase, however, is unexpected. This behavior seems to be largely influenced by the presence of bedrock in the upstream end of the river. We additionally observe that, since the 1980s, the bed surface has coarsened over the entire domain, and that the Rhine River's gravel-sand transition has migrated 30-40 km downstream and flattened (i.e., it has become about 40 km longer). The changes of the gravel-sand transition follow natural processes, although its downstream migration has likely been enhanced by the nourishment of coarse sediment. As a result, the Dutch Rhine, which used to be a sand-bed reach, has become a gravel-bed reach.

Subsequently, we explore how climate change may alter the river controls and how the river channel responds to these changes. This necessitates new methods to translate climate change scenarios into scenarios for control change in the lower Rhine River. To assess how the changes in the river controls affect channel response (i.e., changes in bed level and bed surface grain size) over the 21th century, we set up a schematized one-dimensional numerical model, and subject it to different scenarios of control change. Our results suggest that human intervention continues to dominate channel response over the next century, in the form of channel bed incision. Climate change may enhance this incision by up to 30% mostly due to changes in water discharge. The effects of sea level rise, and changes in the sediment flux, are comparatively smaller. While channel response to human intervention slows down as the river reaches a new equilibrium state, channel response to climate change accelerates with time, as the rate of change of the river controls accelerates.

Finally, we focus on adaptation measures used to cope with the consequences of channel adjustment, specifically erosion control measures. These measures aim to mitigate channel bed incision or to increase the navigable width in sharp river bends. We investigate the large-scale channel response to such measures, using a combination of measured bed elevation over the period 1980-2020 and an idealized numerical model. While erosion control measures succeed in achieving their intended purpose at the local scale, we show that they lead to downstream-migrating waves of additional incision that may extend over tens of kilometers. This is because the measures reduce the sediment flux at their downstream end due to sediment trapping upstream of the measure and lack of erosion over the measure, which results in downstream-migrating incision waves. The additional incision caused by erosion control measures is more pronounced for increased lengths of the measure, and for decreased spacing between measures.

This dissertation highlights the role of human intervention in channel response, warns about an accelerating response to climate change, and highlights the need to incorporate large-scale channel response studies in river management.

Samenvatting

Mensen hebben eeuwenlang ingegrepen in rivieren. Deze ingrepen zijn gericht op bescherming tegen overstromingen, het garanderen van betrouwbare en veilige vaarwegen, zoetwaterbeschikbaarheid voor drinkwater en irrigatie, energievoorziening, en recreatieve activiteiten. Over de hele wereld hebben maatregelen zoals rivierversmalling (via de aanleg van kribben), de afsnijding van rivierbochten, en de aanleg van dammen en irrigatiekanalen de ontwikkeling van nederzettingen, technologische vooruitgang en een verbeterde levenskwaliteit mogelijk gemaakt.

Ondanks de verschillende sociaal-economische voordelen van menselijk ingrijpen in rivieren, hebben dergelijke ingrepen neveneffecten die vaak onbekend zijn voordat ze zich manifesteren. Dit komt doordat maatregelen de evenwichtstoestand van een rivier veranderen, bijvoorbeeld door de ligging van de rivier, het dwarsprofiel of de hydrograaf te wijzigen. Als reactie hierop passen rivieren zich aan in de richting van die nieuwe evenwichtssituatie. Dit gebeurt via bodemerosie of sedimentatie, veranderingen in rivierbreedte of sinuositeit, of veranderingen in de samenstelling van de rivierbedding. Deze reactie kan zich over honderden kilometers uitstrekken en zich gedurende decennia tot eeuwen ontwikkelen.

Naast direct menselijk ingrijpen heeft klimaatverandering voortdurend en in toenemende mate invloed op de rivier. Klimaatverandering wijzigt bijvoorbeeld de hydrograaf, als gevolg van veranderingen in neerslag het smelten van ijs en sneeuw. Daarnaast stijgt de zeespiegel. Deze veranderingen beïnvloeden de evenwichtstoestand van de rivier, waardoor de rivier zich geleidelijk in de richting van deze nieuwe evenwichtssituatie ontwikkelt. De aanpassing van riviersystemen wordt dus veroorzaakt door zowel menselijk ingrijpen als klimaatverandering.

Begrijpen hoe rivieren zich aanpassen aan menselijk ingrijpen en klimaatverandering is van groot belang, omdat veranderingen in bodemligging en de samenstelling van de rivierbedding het overstromingsrisico beïnvloeden, scheepvaart en zoetwaterwinning kunnen belemmeren en de ecologische kwaliteit van rivieren in gevaar kunnen brengen. Door ons inzicht in de fysica achter deze veranderingen te vergroten, kunnen we enerzijds anticiperen op de manier waarop klimaatverandering rivieren beïnvloedt en anderzijds interventies plannen met zo min mogelijk ongewenste neveneffecten. Deze kennis kan worden verkregen door een combinatie van methoden, waaronder het verzamelen en analyseren van veldmetingen, numerieke modellering, laboratoriumexperimenten en remote sensing. Vaak zijn er echter geen gegevens beschikbaar op voldoende grote schaal en over een voldoende lange periode om de rivierontwikkeling op honderdjarige tijdschaal en over honderden kilometers te begrijpen en te modelleren.

Dit onderzoek heeft tot doel te begrijpen hoe rivieren waarin al veel ingrepen zoals versmalling hebben plaatsgevonden reageren op klimaatverandering en menselijk ingrijpen over de komende 100 jaar. Daartoe richten wij ons op een deel van de Duits-Nederlandse Rijn, en meer specifiek het gedeelte van de Rijn tussen Bonn (Duitsland) en Gorinchem (Nederland). Dit deel van de Rijn noemen we hier simpelweg Duits-Nederlandse Rijn en

stroomt door het dichtstbevolkte gebied van Europa en is de drukste binnenvaarweg van het continent. De rivier is al eeuwenlang in hoge mate aangepast en intensief gemonitord, en daardoor een waardevol studiegebied om systeemveranderingen op de schaal van eeuwen en over honderden kilometers te onderzoeken.

Allereerst hebben we ons verdiept in de geschiedenis van menselijke ingrepen in de Duits-Nederlandse Rijn sinds de 18e eeuw en analyseren we de systeemontwikkelingen wat betreft veranderingen in de bodemhoogte en de samenstelling van het bodemoppervlak. Dit doen we met meetgegevens verzameld over de periode 1898-2020. We zien dat de grootschalige normalisatiemaatregelen uit het verleden (dat wil zeggen versmalling en verkorting van het riviersysteem) hebben geleid tot algemene bodemerosie van het zomerbed (tot 5 m over een periode van 100 jaar), resulterend in een meer concaaf langsprofiel. Met andere woorden: het verhang van het zomerbed is in het bovenstroomse deel van de rivier toegenomen en in het benedenstroomse deel afgenomen. De benedenstroomse afname van het bodemverhang is een te verwachten reactie op normalisatiemaatregelen, aangezien in geval van versmalling een kleiner evenwichtsverhang voldoende is om het van bovenstrooms aangevoerde sediment te transporteren. De toename van het bovenstroomse verhang met de tijd is echter onverwacht. Dit gedrag lijkt grotendeels te worden beïnvloed door de aanwezigheid van een rotsige ondergerond in het stroomopwaartse deel van de rivier. Daarnaast stellen we vast dat het bodemoppervlak sinds de jaren tachtig over het gehele studiegebied grover is geworden en dat de grind-zandovergang van de Rijn in de afgelopen 25 jaar geleidelijker is geworden (ongeveer 40 km langer) en zich stroomafwaarts heeft verplaatst (30-40 km). Langzame stroomafwaartse migratie van een grind-zandovergang is een natuurlijk proces, maar hier is de migratie en afvlakking relatief snel en zijn deze processen waarschijnlijk versterkt door bovenstroomse grove sedimentsuppleties. Als gevolg hiervan is de Nederlandse Rijn, die vroeger een zandrivier was, over grote afstand een grindrivier geworden. Naar verwachting zet dit proces zich voort. Vervolgens onderzoeken we hoe klimaatverandering de rivier beïnvloedt en hoe het zomerbed op deze veranderingen reageert. Dit vereist nieuwe methoden om klimaatscenario's te vertalen naar scenario's voor onder andere de verandering van de hydrograaf in de Duits-Nederlandse Rijn. Om te beoordelen hoe deze veranderingen de bodemhoogte en de samenstelling van het bodemoppervlak beïnvloeden gedurende de 21e eeuw, hebben we een schematisch ééndimensionaal numeriek model opgezet en hiermee verschillende scenario's voor de klimaateffecten doorgerekend. Onze resultaten suggereren dat menselijk ingrijpen de komende eeuw de dominante factor zal blijven wat betreft verwachte systeemverandering, en dat dit zich vooral uitdrukt in de vorm van versterkte bodemerosie. Klimaatverandering kan de verwachte bodemerosie met wel 30% vergroten, vooral als gevolg van veranderingen in de hydrograaf. De effecten van zeespiegelstijging en veranderingen in de sedimentaanvoer (vanuit het bovenstroomse deel van het stroomgebied) zijn daarmee vergeleken significant kleiner en beperken zich ook tot een beperkter deel van het studiegebied. Een belangrijke bevinding is de volgende: terwijl de rivierrespons op menselijke ingrepen uit het verleden vertraagt naarmate de rivier dichter bij de nieuwe evenwichtstoestand komt, versnelt de rivierrespons op klimaatverandering met de tijd. Met andere woorden, de relatieve invloed van klimaatverandering op de bodemligging en -samenstelling neemt snel toe.

Ten slotte richten we ons op klimaatadaptatie, dat wil zeggen adaptatieve maatregelen die ingezet kunnen worden om met de gevolgen van klimaatverandering om te gaan, in het bijzonder erosie-beperkende en vaarweg-vergrotende maatregelen (hierna aangeduid met de term erosiemaatregelen). Deze erosiemaatregelen zijn er op gericht de bodemerosie te verminderen of de vaargeulbreedte in scherpe rivierbochten te vergroten. We onderzoeken de rivierrespons op dergelijke erosiemaatregelen op een grote schaal, via analyse van bodemligging gemeten over de periode 1980-2020 en een geïdealiseerd numeriek model. Hoewel erosiemaatregelen hun beoogde doel op lokale schaal bereiken, laten we zien dat ze leiden tot stroomafwaarts migrerende erosiegolven die zich over tientallen kilometers kunnen uitstrekken. Over het algemeen creëren erosiemaatregelen namelijk niet-erodeerbare riviergedeeltes van enkele kilometers (vaste lagen en bodemkribben) en leiden deze maatregelen via een bovenstroomse stuwkromme tot aanzanding aan de bovenstroomse zijde en een afgenomen sedimentflux aan de benedenstroomse zijde. Deze benedenstroomse extra erosie is sterker naarmate de erosiemaatregelen langer zijn en hun onderlinge afstand afneemt.

Dit proefschrift benadrukt de rol die menselijk ingrijpen speelt in de ontwikkeling van riviersystemen, waarschuwt voor een steeds snellere respons van rivieren op klimaatverandering en benadrukt de noodzaak om onderzoek te doen naar hoe we de grootschalige rivierresponse integreren in het beheer van rivieren.

Summary for Policymakers

This research project investigates how the lower Rhine River between Bonn (Germany) and Gorinchem (the Netherlands) responds to climate change and human intervention at centennial timescales. Our objective is to (1) gain insight on channel response in the lower Rhine River, and (2) conceptualize the physics behind the observed behavior, such that similar analysis and methods can be used in other engineered rivers. To this end, we first examine how human intervention since the 18th century has modified the channel bed level and the bed surface grain size distribution, using measured data over the period 1898-2020. We then explore how different climate scenarios may alter the river controls (i.e., the water discharge, sediment flux, and sea level), and assess how these changes affect bed elevation and bed surface grain size distribution over the 21th century, using a numerical model. Finally, we focus on modern interventions (specifically, erosion control measures implemented since the 1980s), and analyze how they induce large-scale bed level change at multi-decadal timescales, by means of measured data and numerical modeling.

Our findings can be used to assist river managers and policymakers to develop more efficient and effective operations and maintenance strategies, and to support policy decisions on river management.

Main Findings

1. Past channelization works carried out between the 18th-20th centuries have resulted in domain-wide channel bed incision, reaching up to 5 m over 100 years. This incision has resulted in an increased channel bed slope in the upper part of the system (approximately Bonn-Xanten), and a decreased slope in the lower part (Xanten-Gorinchem). This means that, while both the German and Dutch Rhine are incisive, incision rates are highly variable in space.

2. While channel bed incision rates in the Niederrhein have largely decreased over the past 35 years, channel bed incision in the Waal continues at rates of 0-1.8 cm/a. This seems to be due to a combination of factors, including a relatively coarser bed surface and sediment nourishment in the Niederrhein, and potential instability of the Pannerden bifurcation.

3. The lower Rhine River has experienced domain-wide bed surface coarsening since at least the 1960s. This is reflected by the downstream migration and flattening of the Rhine River's gravel-sand transition (from river km 820-870 in the late 1990s to river km 840-930 in 2020). As a result, the Waal, which used to be a sand-bed river, has become a gravel-bed river down to Tiel.

4. Climate change modifies the hydrograph, sediment flux, and sea level, and may cause up to 1 m of additional incision over the 21th century. This is mostly due to increased moderate-to-high discharges. The effects of sea level rise and changes in sediment flux are smaller and extend over smaller spatial scales.

5. Since at least the early 1900s, channel response has been governed by human intervention. Channel response over the 21th century will likely remain dominated by human intervention rather than climate change. However, while channel response to past channelization works slows down as the river approaches its equilibrium state, channel response to climate change accelerates, as the rate of change of the river controls accelerates. For instance, channelization-related channel bed incision reaches up to 1.25 m over the period 2000-2050, and up to 1.75 m by 2100. On the other hand, additional incision due to climate change reaches up to 0.35 m by 2050, and 1 m by 2100.

6. Erosion control measures such as scour filling, bendway weirs, and fixed beds, are successful at mitigating channel bed incision or increasing the navigable width at local scales. However, they lead to downstream-migrating incision waves (at about 1.5-2 km/a) that may enhance the problem of large-scale channel bed incision.

When Will Channel Bed Incision Stop?

Past channelization works constituted a domain-wide modification of the channel characteristics. In particular, the main channel width was reduced by up to 40%. A narrower river strives toward a situation with a smaller equilibrium channel slope, as a smaller slope suffices to transport the same amount of sediment supplied by the upstream part of the basin. This smaller slope is achieved by means of channel bed incision. Such adjustment takes place over centuries. In the absence of any other changes, this incision is expected to continue beyond the 21st century.

Besides the incision caused by past channelization, incision is enhanced by climate change, as it modifies the hydrograph, sediment flux, and sea level. Specifically, increasingly larger moderate-to-high discharges enhance the ongoing channel bed incision. This is because, for a larger discharge, the system strives toward a smaller equilibrium channel slope, which is achieved through channel bed incision. As the rates of climate change accelerate, the incision related to increased discharges is expected to increase over the next centuries. In addition, extreme flows may lead to sudden alterations of the water and sediment partitioning at bifurcation points, resulting in a larger fraction of water discharge flowing into one branch, thereby causing enhanced incision and possible disruption of discharge partitioning at the bifurcation points.

While sea level rise may mildly reduce channel bed incision in the lower Waal, such effect is substantially smaller than the enhanced incision resulting from hydrograph changes.

In short, channel bed incision is not expected to stop in the foreseeable future.

Can We Stop Channel Bed Incision with Sediment Nourishments?

Successful erosion-mitigation experiences in the Niederrhein suggest the possibility to mitigate channel bed incision in the Waal by means of sediment nourishments. Such an endeavor requires careful consideration, as the comparison between the Niederrhein and the Waal is not straightforward.

In the first place, channel incision rates in the Niederrhein have been largely reduced since the 1960s, which is prior to the first sediment nourishments in the late 1980s. This may be due by the coarser bed surface in the Niederrhein, which is associated with a larger equilibrium channel slope, as well as to earlier implementation of channelization measures in the Niederrhein (starting in the 1770s, while in the Waal implementation began in the 1850s), which implies that the Niederrhein has adjusted to past channelization works for a longer period. In addition, channel bed incision in the Waal may be enhanced by bifurcation dynamics at the Pannerden bifurcation point.

When considering nourishments in the Waal, large-scale slope-change trends need to be taken into account. Current river management initiatives (i.e., the Integrated River Management program) have considered restoring the bed level to the profile of a certain year. Such measure could be unsustainable if large-scale channel response trends are ignored, as both the current channel characteristics and increased discharges due to climate change are associated with a smaller equilibrium channel slope. While optimized choices of the size and frequency of the nourished sediment may help temporarily reduce channel bed incision, there is a risk that nourishments enhance (rather than reduce) channel bed incision if not carefully designed. In addition, more research is needed to understand the implications of such a measure on sediment delivery to the delta.

Other policy options within the Integrated River Management program consider halting the ongoing channel bed incision, that is, preventing further incision, rather than reverting the river bed profile to the one of a certain year in the past. Such option would require nourishing hundreds of thousands of cubic meters of sediment every year. This raises the question of whether such amounts of sediment are available, whether such large campaigns are logistically feasible, and whether such a strategy is sustainable, both economically and in terms of carbon footprint.

Recommendations for Managers of Engineered Rivers

The large spatio-temporal scales of channel adjustment, as well as the magnitude of the associated changes in bed level and bed surface grain size, require incorporating a large-scale, long-term perspective in river management. While the design and implementation of specific interventions needs detailed studies at the local scale, simplified models can readily provide valuable information on large-scale channel response at a low cost. The large-scale physics of channel response should systematically be considered in intervention planning.

In the face of a changing climate and a constantly-adjusting river system, frequent and spatially-dense monitoring of the river system becomes ever more important. For monitoring data to be valuable, such data need to be open, centralized, and easily accessible. In addition, with increasing knowledge and modeling capabilities, scenarios for change of the river controls need to be updated when new information on climate change impact becomes available.

Finally, the large uncertainty associated with climate change requires an open mindset regarding climate adaptation. This means that it is necessary to challenge some of the common assumptions we have on river management (e.g., "channel bed erosion needs to be stopped"), and to consider and adopt adaptive policy pathways (i.e., policy that considers future uncertainty, and that considers adaptation alternatives as new information becomes available). Some questions to be asked in this regard include "Why do we want to stop river bed incision?", "Can we realistically halt channel bed incision, or are other paths more feasible and sustainable?", "Which river functions are we ready to compromise when planning adaptation measures?", or "Are there alternative ways to tackle the issues related to river bed incision, other than stopping large-scale channel bed incision?".

Samenvatting voor Beleidsmakers

Dit onderzoeksproject bestudeert hoe de Rijn tussen Bonn (Duitsland) en Gorinchem (Nederland) (hierna aangeduid met 'de Rijn') reageert op klimaatverandering en menselijke ingrepen, over één tot meerdere eeuwen. Het doel van het onderzoek is om (1) inzicht te krijgen in de hydraulisch-morfologische respons van het riviersysteem en (2) het duiden van de fysica die daarvoor verantwoordelijk is, zodat soortgelijke analyse en methodes gebruikt kunnen worden in de analyse van andere gekanaliseerde rivieren. Om dit te bereiken onderzoeken we eerst hoe menselijke ingrepen sinds de 18de eeuw de bodemligging en -samenstelling hebben veranderd. Dit doen we aan de hand van gemeten data van de periode 1898-2020. Daarna verkennen we hoe de verschillende klimaatscenario's de randvoorwaarden van de rivier (afvoer, sedimentflux en zeespiegel) veranderen en hoe die veranderingen doorwerken in de bodemligging en -samenstelling in de 21ste en 22ste eeuw. Dat doen we met behulp van een geschematiseerd numeriek model. Tenslotte beschouwen we maatregelen die sinds 1980 geïmplementeerd zijn en de bodemerosie beïnvloeden, en analyseren we of en hoe deze maatregelen bodemveranderingen teweegbrengen op een tijdschaal van meerdere decennia. Ook dit doen we met behulp van gemeten data en numerieke modellen.

Voornaamste Bevindingen

1. Maatregelen uit het verleden (die de rivier min of meer gekanaliseerd hebben), uitgevoerd in de 18de tot en met de 20ste eeuw, hebben geresulteerd in een grootschalige bodemerosie (ook wel insnijding genoemd), tot 5 m over een periode van 100 jaar. Deze bodemerosie heeft geleid tot een versteiling van het verhang in het bovenstroomse deel van het domein (ongeveer het traject Bonn-Xanten), en een verflauwing van het verhang in het benedenstroomse deel van het domein (Xanten-Gorinchem). Dit betekent dat het beschouwde Nederlandse en het Duitse deel van de Rijn grotendeels erodeert, maart dat de mate van erosie varieert over het domein.

2. Daar waar de bodemerosie in de Niederrhein grotendeels is afgenomen over de afgelopen 35 jaar, gaat de bodemerosie in de Waal door met een snelheid van 0-1.8 cm per jaar. De oorzaak ligt in een combinatie van factoren, onder andere de aanwezigheid van een relatief grove bodem en sedimentsuppleties in de Niederrhein en mogelijk een instabiel splitsingspunt (Pannerdense Kop).

3. Het bodemoppervlak van de Rijn is sinds de jaren 60 (en wellicht al ervoor) over het hele domein steeds grover (qua verhouding zand-grind) geworden. Dit blijkt uit de verplaatsing van de grind-zandovergang richting benedenstrooms, en die overgang wordt ook minder scherp. De overgang bevindt zich in 2020 zo rond km 840-930, terwijl die zich eind jaren 90 nog rond km 820-870 bevond.

4. Klimaatverandering verandert ook de hydrograaf en de sedimentflux, en zorgt voor zeespiegelstijging. Hierdoor erodeert de rivierbodem in de 21ste eeuw op plaatsen

tot 1 meter bovenop bovengenoemde bodemerosie. Dit komt voornamelijk door toenemende hogere tot hoge afvoeren, aangezien die zorgen voor een afname van het evenwichtsverhang. De effecten van zeespiegelstijging en veranderingen in de sedimentflux zijn milder en spelen zich af over een beperkt ruimtelijk gebied.

5. Sinds tenminste het begin van de 20ste eeuw is de reactie van de rivierbodem (bodemerosie) te wijten aan menselijke ingrepen. Het gevolg van deze ingrepen (doorgaande bodemerosie) zal nog merkbaar zijn tot ver in de 21ste eeuw. Dit effect is sterker dan het effect van klimaatverandering (aanvullende erosie). Wel is het zo dat het effect van de menselijke ingrepen langzaam aan minder zal worden, omdat de rivier een evenwichtsprofiel nadert. Het effect van de klimaatverandering zal echter versnellen, omdat de snelheid van klimaatverandering met de tijd groter wordt. Als voorbeeld: erosie door menselijke ingrepen uit het verleden over de periode 2000-2050 zal ongeveer 1.25 m bedragen, en zal toenemen tot 1.75 m in 2100. Maar de aanvullende bodemerosie door klimaatverandering zal in 2050 ongeveer 35 cm en 1 m in 2100 zijn.

6. Maatregelen zoals het opvullen van erosiekuilen en de aanleg van bodemkribben en vaste lagen beperken lokaal de bodemerosie of leiden lokaal tot een bredere vaarweg. Tegelijkertijd genereren deze interventies erosiegolven die zich verplaatsen in benedenstroomse richting met een snelheid van ongeveer 1.5-2 km per jaar. Deze bodemerosie kan problemen gerelateerd aan de grootschalige bodemerosie verergeren.

Wanneer Stopt de Bodemerosie?

De maatregelen uit het verleden hebben geleid tot grootschalige veranderingen van het riviersysteem. De rivierbreedte is bijvoorbeeld op plaatsen met 40% gereduceerd. Een smallere rivier streeft naar een minder groot verhang bij dezelfde hydrograaf en sedimentaanvoer: dit uit zich via bodemerosie. Deze aanpassingen vergen eeuwen en zullen voorlopig doorgaan.

De bodemerosie wordt verergerd door klimaatverandering via veranderingen in de hydrograaf en mogelijk de sedimentflux. Met name de extremere middelhoge en hoge afvoeren verkleinen het evenwichtsverhang en versterken daarmee de bodemerosie. Als de klimaatverandering versnelt, zal de aanvullende bodemerosie door deze versnelling ook toenemen. We zien ook dat extreem hoge afvoeren kunnen leiden tot een verandering in de verdeling van water en sediment over het splitsingspunt Pannerdense Kop. De Waal ontvangt nu een toenemend aandeel van de rivierafvoer dan voorheen, samen met een versterkte bodemerosie in deze tak. Dit betekent dat het splitsingspunt instabiel is.

Zeespiegelstijging zal leiden tot een afname van de erosie, allereerst in het benedenstroomse deel van de Waal. Dit effect is echter substantieel kleiner dan de versterkte erosie door de veranderingen in de hydrograaf.

Kort samengevat zal de bodemerosie in de nabije toekomst (over de komende 100 jaar) niet stoppen.

Kunnen we de Bodemerosie via Sedimentsuppleties Stoppen?

In de Niederrhein zijn sinds de late jaren 80 erosie-mitigerende maatregelen in de vorm van sedimentsuppleties uitgevoerd. Deze maatregelen lijken succes te hebben. We moeten oppassen om dit als voorbeeld te hanteren voor erosie-mitigatie in het Nederlandse deel van de Rijn omdat de laatste van het Duitse deel van de Rijn verschilt.

Ten eerste zien we dat de erosiesnelheden in de Niederrhein sinds het begin van de jaren zestig van de vorige eeuw al zijn afgenomen. Dit is dus vóór het begin van de sedimentsuppleties in de late jaren 80. Deze afname kan te maken hebben met de grovere bodem in de Niederrhein, en het daarmee gepaard gaande steilere verhang. Het kan ook te maken hebben met het feit dat de menselijke ingrepen in de Niederrhein eerder startten (vanaf rond 1770) dan de maatregelen in de Waal (rond 1850). De Niederrhein heeft zich dus langer kunnen aanpassen aan die veranderende omstandigheden. Daarnaast lijkt de bodemerosie in de Waal sterk beïnvloed door de aanwezigheid van het splitsingspunt Pannerdense Kop en de daarmee samenhangende instabiliteit.

Als we sedimentsuppleties in de Waal willen overwegen, dan moeten we rekening houden met de optredende grootschalige veranderingen in het bodemverhang. Huidige rivierbeheerprogramma's (zoals Integraal Riviermanagement, IRM) overwegen om het niveau van de rivierbodem terug te brengen naar een niveau dat in het verleden ligt. Als bij deze overwegingen onvoldoende rekening wordt gehouden met de huidige bodemerosietrends, dan zijn dergelijke inspanningen waarschijnlijk niet duurzaam. Immers, zowel de maatregelen uit het verleden en de klimaatverandering wijzen op toenemende en doorgaande bodemerosie via afname van het bodemverhang. Sedimentsuppleties van een geoptimaliseerde samenstelling, en aangebracht met de juiste ruimtelijke dichtheid en frequentie kunnen tot een afname van de bodemerosie leiden. Maar bij een onjuist ontwerp ten aanzien van samenstelling en frequentie kunnen suppleties leiden tot extra bodemerosie in plaats van minder. Er is meer onderzoek nodig om de gevolgen van sedimentsuppleties goed te begrijpen, en om inzicht te krijgen in de sedimenttoevoer naar de Nederlandse delta.

Een andere optie die IRM overweegt is om de bodemerosie te stoppen. Om dit te bereiken zijn jaarlijkse suppleties met vele honderdduizenden kubieke meters sediment nodig. Dit werpt de vraag op of dergelijke hoeveelheden sediment van de juiste samenstelling wel beschikbaar zijn, of de suppleties logistiek mogelijk zijn en of een dergelijke strategie duurzaam is vanuit het oogpunt van CO_2-uitstoot en financiële overwegingen.

Aanbevelingen voor Rivierbeheerders

Grootschalige aanpassingen van het riviersysteem maken het noodzakelijk dat de rivierbeheerder een strategie heeft voor diezelfde ruimte- en tijdschaal . Het ontwerp en de implementatie van specifieke interventies vereisen gedetailleerde studies op een lokale schaal, maar geschematiseerde modellen kunnen inzicht geven in de grootschalige effecten van voorgenomen maatregelen, en dit tegen geringe kosten. De grootschalige rivierrespons zou niet uit het oog verloren moeten worden bij het plannen van interventies.

Het klimaat verandert en de rivier past zich daar voortdurend aan aan. In dit licht wordt ook het monitoren (van de juiste parameters met de juiste frequentie) van het systeem steeds belangrijker. Om door iedereen gebruikt te kunnen worden moeten deze data open en eenvoudig toegankelijk (via een gecentraliseerd systeem) zijn. Daarnaast moeten de scenario's voor de randvoorwaarden van het riviersysteem geactualiseerd blijven worden wanneer nieuwe informatie beschikbaar komt ten aanzien van klimaatscenario's.

Tenslotte vereist de grote onzekerheid ten aanzien van klimaatverandering een open houding ten aanzien van klimaatadaptatie. Dit betekent dat het noodzakelijk is om aannames ten aanzien van rivierbeheer ter discussie te durven stellen (bijvoorbeeld de uitspraak: "we moeten de bodemerosie stoppen") en adaptieve beleidspaden te overwegen en aan te nemen. Zo'n alternatief beleidsplan moet rekening houden met een onzekere toekomst, en kan alternatieven ten aanzien van adaptatie overwegen als nieuwe informatie beschikbaar komt. Vragen die in dit verband gesteld kunnen worden zijn: "Waarom willen we rivierbodemerosie stoppen?", "Kunnen we de rivierbodemerosie überhaupt stoppen?", "Zijn er andere, meer haalbare en duurzame paden?" of "Zijn er alternatieve manieren om de problemen ten gevolge van de rivierbodemerosie op te lossen, zonder dat we de grootschalige bodemerosie zelf oplossen?".

Preface

I am pleased to be writing this preface, as it means that I the work I have carried out over the past five years will be soon getting to you. While this is a scientific document, I have tried to write it with you in mind.

If you are reading this dissertation for its scientific content, by all means, go ahead and go through Chapters 2-4. These chapters include (the content of) the journal articles that I have written during my PhD. You can read them independently, although they build up on each other, so I would suggest you read them in the order they are presented.

If you are a river manager, I invite you to read the summary for policymakers, the introduction, and the synthesis. I have put special attention into translating the scientific findings into content that you can use, or learn from. I will feel fulfilled if that is the case.

If you are family, or a friend, you can go straight to the acknowledgments: I would not have completed this project without you, and I am incredibly grateful for that. But do not stop there. I have done my best to write an accessible introduction, as well as short introductory paragraphs for each of the content chapters (Chapters 2-4).

And for all of you, whoever you are, I have a small surprise. While a PhD is very much about research, there is so much more than that. During my time at Delft University of Technology, I have had the immense privilege to travel the world and exchange knowledge and experiences with incredible people. There have also been difficult times, and a pandemic in the middle. I would like to take you with me in this journey-beyond-research through photos and side notes in-between chapters.

Please enjoy.

Clàudia YLLA ARBÓS
Delft, October 2023

In late November 2018, I moved from Lausanne to Delft. I was instantly charmed by this tiny fairy-tale city full of canals, cozy houses with large windows to peek through, and warm winter lights. I had the feeling that this marked the beginning of a new creative chapter of my life.
Moving to a new country is hard, but I was very warmly welcomed by the whole Waterlab group. For what was probably the first time in my life, I met a community where I felt I was like everybody else. These perks compensated for the desolating lack of mountains and the even-worse-than-I-had-imagined weather.

1

Introduction

Aucun philosophe n'a pu lever par ses propres forces ce voile que la nature a étendu sur tous les premiers principes des choses; ils disputent, et la nature agit.

Voltaire

"No philosopher has been able with his own strength to lift this veil stretched by nature over all the first principles of things. Men argue, nature acts."

1.1. Rivers Adjust to Natural and Anthropogenic Change

Rivers are the lifelines of Earth. They provide populations with freshwater and drain floodwater away; they are home to thousands of plant and animal species, as well as arteries of inland transport and a source of energy. Not only do rivers satisfy many of our essential needs, but they are also natural recreation spots, fulfilling the important task of bringing humans closer to nature. In short, much of life on Earth depends on rivers.

Like all living things, rivers come in many shapes and sizes, which change in time. This is because rivers respond to triggers, and adjust to the continuous changes in their environment, both natural (e.g., tectonics or floods) and anthropogenic (e.g., channelization, dam construction, diversions). In turn, the environment and riparian populations are affected by changes in the river. Understanding the interactions between rivers and their environment, including humans, is vital to ensure that we and future generations can continue to benefit from and enjoy them.

Human intervention in rivers started thousands of years ago (*Dalton et al.*, 2023; *Alizadeh et al.*, 2004). As humans have settled around rivers, they have modified them through engineering, with the aim to enhance the services that they provide, as well as to remain safe from flooding (*Best*, 2019; *Marsh*, 1864). Most commonly, engineering measures consist of channelization for flood protection and improved navigability, dam construction for hydropower generation, flood retention, and freshwater supply, channel diversion for water supply, irrigation and flood protection, and a wide range of sediment management measures for erosion control.

A notorious example of a river modified by humans is the Colorado River in the United States. In the late 19th century, colonists carried out multiple diversion and irrigation works that both extracted water from the river and modified its course (*Williams*, 1937). Despite creating fertile land, excess water extraction led to an increasingly dry river. Conflict over rights to water use between the different states in the Colorado River basin, led to the Colorado River Compact, an agreement on the allocation of water rights among states, which included the construction of two reservoirs (*Hundley*, 2009). The reservoirs controlled the amount of water flowing down the river, allowing for proliferation of human settlements around the river. A larger population, however, meant more demand for water and increased conflicts over water use, generally to the detriment of indigenous populations and poorer regions. Today, water management laws allocate more water to the states than there is available (*Hundley*, 2009). This puts extreme pressure on freshwater availability, especially in the current times of unprecedented drought (*Williams et al.*, 2020).

The above changes to the Colorado River course and water discharge combined with worsened droughts have largely decreased the sediment flowing down the river. This sediment is needed for delta construction at the river mouth (*Meckel*, 1975), and its deficit leads to degradation of the delta (*Carriquiry and Sánchez*, 1999). In fact, the Colorado River only reaches the sea during very high tides and unusually wet years (*Zamora et al.*, 2013) which threatens deltaic ecosystems and leads to dramatic habitat loss.

Besides direct human intervention and natural change (e.g., tectonics such as uplift and subsidence), the river controls (i.e., hydrograph, sediment flux, and downstream base level) are modified by climate-related changes to the precipitation regime, ice- and snowmelt, and sea level rise. Such climate-related changes in the river controls lead to large variations in the amount of water and sediment flowing down the rivers, which modifies their shape and course, and affects the extent to which deltas can grow.

In contrast to the Colorado River, the Brahmaputra-Jamuna River in Bangladesh is relatively undisturbed and characterized by vast amounts of water and sediment (*Coleman*, 1969). Natural triggers, mostly related to tectonics, shifts in the course of tributaries, and major floods, led to a major westward shift in the course of the Old Brahmaputra River between the 18th and 19th centuries, which gave rise to its current Jamuna name (*Bristow*, 1999). In the 19th and 20th centuries, floods and tectonic activity led to continued westward migration of the river, changes in planimetric shape, and doubling of the river width (*Sarker et al.*, 2014). All these processes have affected millions of people, which have lost crops, houses, infrastructure, and lives (*Best et al.*, 2007). Stronger floods due to climate change and tectonic activity will continue to alter the Jamuna river in the future (*Goodbred Jr et al.*, 2003; *Yu et al.*, 2010; *Sarker et al.*, 2014).

1.2. Channel Adjustment in Engineered Rivers

We define engineered rivers as rivers that are largely modified by humans. Human intervention in rivers serves water-related purposes, although the associated effects go far beyond water. This is because engineering measures directly alter the river planform, geometry and/or the river controls. Rivers respond to anthropogenic and natural changes to their controls by adjusting (1) the channel width, through narrowing and widening, (2) the channel slope, through erosion and deposition, and through changes in sinuosity, and (3) the bed surface grain size distribution, through coarsening or fining of the bed surface. In channelized rivers where the planform is fixed, rivers only adjust through erosion and deposition, and through changes in the bed surface grain size distribution.

Human intervention in rivers often has side or unwanted effects (e.g., *Galay*, 1983; *Habersack et al.*, 2013; *De Vriend*, 2015; *Wyżga et al.*, 2016). For example, channel bed incision reduces the stability of in-river structure foundations (*Habersack et al.*, 2013), and exposes river-crossing cables and pipelines (*Hiemstra et al.*, 2020). Furthermore, as the channel bed and water level lower, the water table lowers. As a result, water intakes are exposed (*Wyżga et al.*, 2016), hampering freshwater extraction, and the main channel becomes increasingly disconnected from the floodplains, compromising the ecology of riparian areas (e.g., *Bravard et al.*, 1997).

Besides the above issues, channel bed erosion is problematic for navigation. Specifically, the spatial variation of erosion results in navigation bottlenecks in non-erodible reaches. This can be due to the presence of bedrock, as reported in the Mississippi River (*Olson and Wright Morton*, 2014), the Elbe River (*Pusch et al.*, 2022), or the Umpqua River (*Wallick et al.*, 2011), or due to artificial non-erodible layers, as reported in the Danube River (*Goda et al.*, 2007) and the Rhine River (*Havinga*, 2020). The navigation bottlenecks appear because, as the surrounding river bed erodes, the water level drops, resulting in locally reduced water depths over the non-erodible reaches, especially during low flows. In these situations, ships can transport less cargo, as the maximum weight on ships depends on water depth. As a result, either more ships are used to transport the same amount of goods, or the stocks of goods decrease, which disrupts the supply chain and drives inflation.

Channel adjustment to interventions and control change may extend over hundreds of kilometers, and develop on timescales of decades to centuries (*De Vriend*, 2015). Considering the side effects of channel adjustment, and the large amount of people living close to rivers, this means that human intervention and climate change can affect societies over multiple generations, and in multiple ways, from navigation, to flood risk, ecology and general well-being. All the more so because the demands of an ever-growing population translate into increased river engineering and higher rates of climate change, posing difficult challenges to river managers.

1.3. The Need for Predictions of River Channel Adjustment

As populations concentrate around rivers and deltas, they are vulnerable to the processes and adjustments that rivers undergo. The issues related to channel adjustment, therefore, need to be understood and addressed in a sustainable way (i.e., with reasonable costs, without the need for constant repair and maintenance over time, and without leading to unwanted side effects). Lack of knowledge, or limited capacity and resources, can lead to measures with short-term benefits but dramatic side effects in the long run, as the example from the Colorado River illustrates. In other words, sustainable river management can only happen with a long-term perspective of channel adjustment. This also means that it is necessary to understand past and current river behavior, as it allows us to better predict how rivers may respond to potential changes in the future.

To understand how rivers have adjusted to past natural and anthropogenic change, we need data on channel characteristics over large scales and decadal timescales. This is a major limitation, as most rivers do not have measurement records of that duration. A next step is having an understanding of the laws of physics underlying channel adjustment. This is a second limitation, as any representation of reality remains an approximation, and many physical processes are not yet fully understood (*Siviglia and Crosato*, 2016).

With enough data and good-enough understanding of the physics, it is possible to simulate river behavior with computer (numerical) models. Such models can help us to better understand past river behavior. In principle, when a model satisfactorily represents past and current behavior, it can also provide information on future river behavior. This information is very useful to river managers, as it helps to identify appropriate river management measures, so that resources can be allocated efficiently.

Models can have very different levels of detail regarding the density of input data (i.e., channel geometry, number of represented sediment sizes, variability of water discharge, etc.). In addition, models can also have varying degrees of complexity depending on the number of physical processes they can account for, and the dimensions over which these processes are simulated (one, two, or three).

Depending on the type of information we need from a model, the latter will require a different level of detail. To plan and implement specific interventions (e.g., the construction of a water intake), river managers typically use what we call “detailed” models of a river reach. In these detailed models, the channel characteristics closely resemble the characteristics in the field (Figure 1.1a). These models are often quite complex in terms of represented physical processes. The outcome of these models is often used to assess the benefits of a certain measure at a specific location, and/or to choose between different design alternatives.

Very often, data is insufficiently available to create a detailed model. In these cases, we use “schematized” models, which are models that loosely represent a certain river (Figure 1.1b). As such, schematized models can capture the main components of river channel adjustment, but are not able to provide details on small-scale and short-term dynamics.

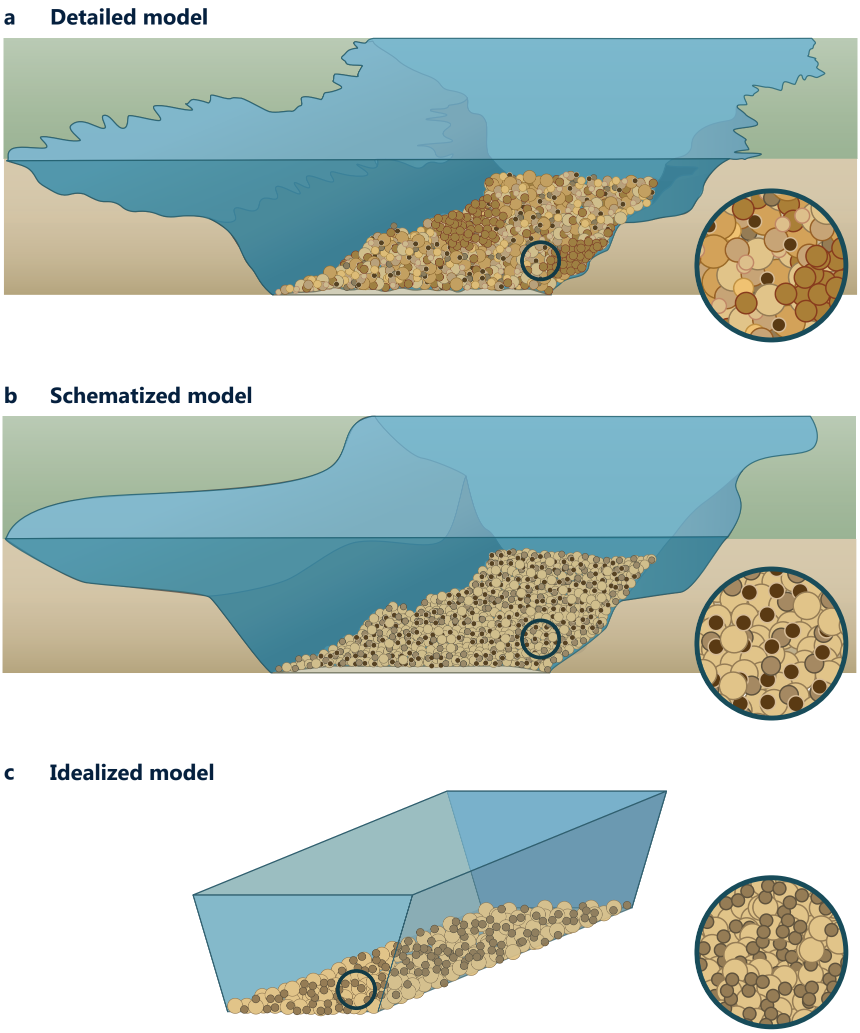


Figure 1.1: Schematic of different types of models based on the density of input data: (a) Detailed models, which closely follow the conditions in the field; (b) schematized models, which loosely represent the conditions in the field; and (c) idealized models, which represent theoretical cases.

The intermediate level of detail of schematized models makes them very useful to answer questions on a more conceptual, large-scale level (e.g., how would a certain river respond, in general terms, to the removal of a series of dams?). In such cases, a detailed model may not be the best choice, as it is difficult to separate the large-scale trends from the local, small-scale natural variability of the system.

Sometimes, we want to better understand the physics behind a certain phenomenon, from a theoretical perspective (e.g., how do rivers respond to sediment additions of different characteristics?). In this case, we may want to use "idealized" models (Figure 1.1c). These are highly simplified models that do not represent a specific river. In general, they simulate river channels that are very homogeneous in space. This allows us to focus on the more fundamental physical mechanisms of channel adjustment.

The more detailed computer models are, the more data is required to calibrate and validate them, and the more computer power they need. The choice for a certain type of model is often driven by the availability of time and resources.

1.4. Accounting for Climate Change in Predictions of River Channel Adjustment

As sustainable river management requires a long-term perspective, it becomes evermore important to account for climate change in modeling future channel adjustment. To do so, we need information on how the river controls may change in the future, which, by definition, is uncertain. To deal with future uncertainty, we work with a set of scenarios.

The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body in charge of assessing climate change, and is considered the main authority in terms of climate scenarios. The IPCC defines a scenario as "a plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships" (*IPCC*, 2023). By using a set of scenarios, we aim to reflect the range of uncertainty regarding the future state of the world. As our knowledge on the climate system increases, the IPCC scenarios are updated, the last set of scenarios being that of *IPCC* (2023).

The *IPCC* (2023) climate scenarios do not directly provide information on potential changes of the river controls. Instead, different models are used to translate the *IPCC* (2023) climate scenarios into scenarios for change of the river controls. Eventually, we can carry out multiple simulations of future channel adjustment, based on a range of scenarios of change of the river controls. The outcome of each of these simulations will be a projection of future channel adjustment (i.e., a description of the future state of the river and the pathway leading to it).

An accurate prediction of future channel response is, at present, utopia. Yet with enough data, scenarios of control change, and simplified models, we can get closer to understanding channel response to climate change and human intervention.

1.5. Channel Adjustment in the Lower Rhine River

In this thesis we consider the Rhine River, as it is a paradigmatic example of an engineered river, and one of the few intensely-monitored rivers, both in time and space, making it a real-life laboratory to investigate channel response. From the Swiss Alps to the North Sea, the Rhine flows along 1230 km through nine of the most densely-populated countries in Europe (Figure 1.2), the whole basin hosting about 60 million people (*Yang et al.*, 2019).

The oldest records of human intervention in the Rhine date back to 1150, when dikes were constructed for flood protection (*Hudson et al.*, 2008). Today the Rhine River is the most transited inland waterway in Europe, with over 300 million tons of cargo being transported annually in its waters (*Christodoulou et al.*, 2020).

We focus on the lower Rhine River, which we define as the 300-kilometer stretch of the Rhine between Bonn (Germany) and Gorinchem (the Netherlands). The lower Rhine River has been heavily engineered for centuries, and the effects of climate change are increasingly felt through wetter winters, drier summers, and a rising sea level (*IPCC*, 2022). The current characteristics of the lower Rhine River are largely related to the large-scale channelization measures carried out in the 18-20th centuries. Since then, a number of additional engineering measures have been implemented to ensure navigability and to increase protection against floods (e.g., the *Room for the River* program), including several pilot projects (such as sediment nourishments) whose potential will be more clearly revealed in the future.

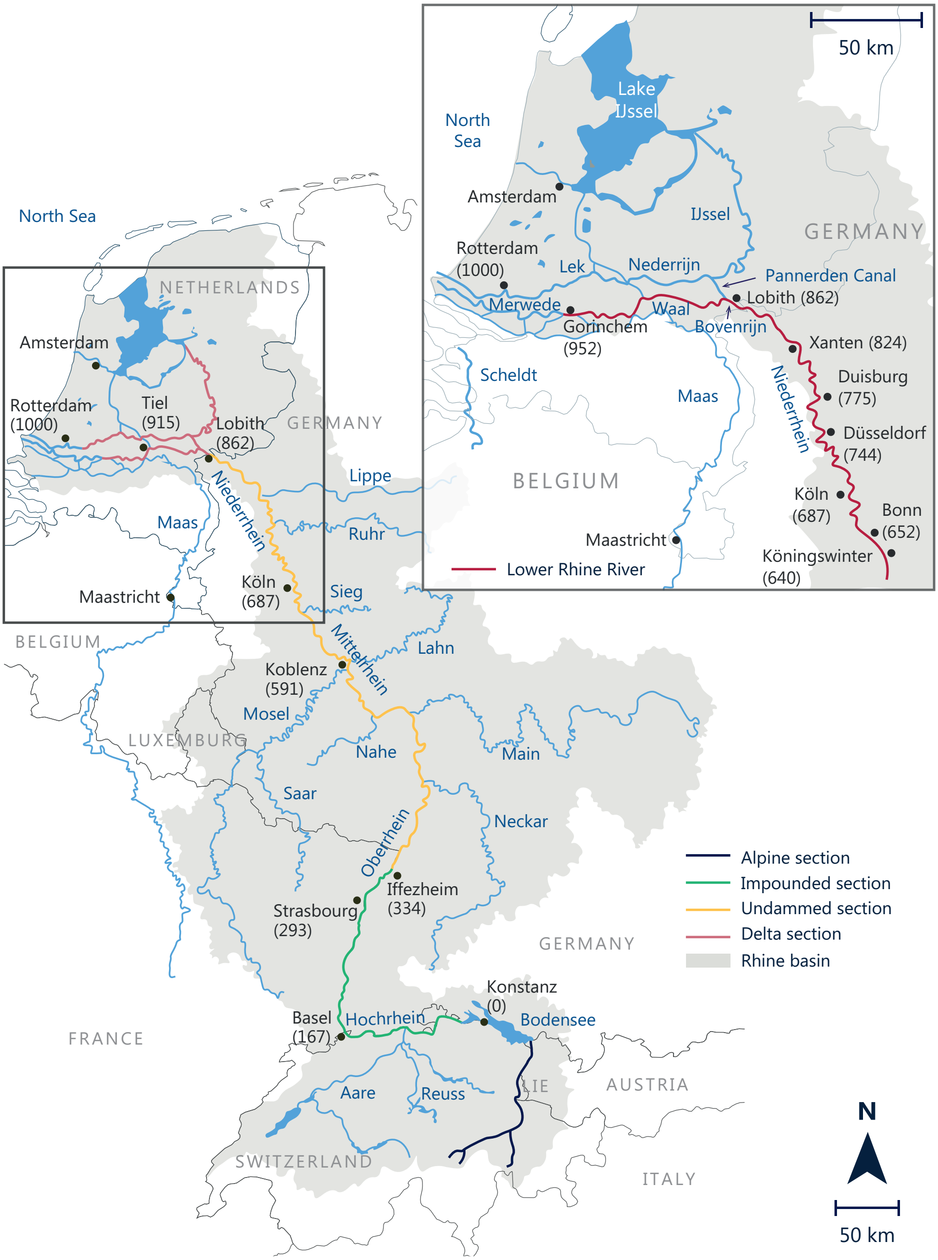


Figure 1.2: The Rhine basin, including the different sections of the Rhine, with inset on the lower Rhine River. Numbers in parentheses indicate river kilometer, with origin at Konstanz (Bodensee).

1.6. Objective, Research Questions, and Approach

With the aim to support sustainable river management in the Netherlands with scientific insights, the Rivers2Morrow program was initiated by the Dutch Directorate General of Water and Soil (DGWB) and the Directorate General Rijkswaterstaat. The goal of this program is to better understand the long-term development of lowland rivers, in terms of hydraulics, channel adjustment, and ecology. This PhD research project is part of the Rivers2Morrow program and addresses the following research question:

How does the lower Rhine River adjust to human intervention and climate change at centennial timescales?

We subdivide this question into three subquestions:

1. How has the lower Rhine River adjusted to past human intervention over the 20th century, in terms of change in bed level and bed surface grain size?

2. How does the lower Rhine River adjust to climate change over the 21st century, in terms of change in bed level and bed surface grain size?

3. How do erosion control measures affect large-scale channel adjustment in terms of change in bed level and bed surface grain size?

Each of these questions is addressed in a different chapter of this thesis. Chapter 2 investigates past channel adjustment to domain-wide human intervention through analysis of measured bed elevation and bed surface grain size data, covering the period 1898-2020. We introduce a conceptual model explaining the physics of the observed channel response.

Chapter 3 addresses future channel response to different climate change scenarios over the period 2000-2100. To this end, we first study how climate change affects the river controls, considering a set of climate scenarios. We then set up a highly schematized one-dimensional numerical model (Figure 1.1b) that is able to represent channel response over large spatial scales and centennial timescales, which we calibrate and verify using measured data. Finally, we assess how the river responds to climate-related change of the river controls, in terms of change in bed level and bed surface grain size. We detail the approach followed in this chapter in a framework for numerical assessment of channel response to climate change (Figure 1.3).

Chapter 4 examines the large-scale channel response to erosion control measures. This is done through (1) the analysis of detailed measured bed level and bed surface grain size data around different types of erosion control measures in the lower Rhine River; and (2) idealized numerical modeling (Figure 1.1c) of the large-scale effects of erosion control measures.

The dissertation concludes with a synthesis of the answers to the above research questions, possibilities for application, implications for river management, opportunities for further research, and a general outlook on the future of river science and policy (Chapter 5).

Framework for numerical assessment of channel response to climate change

1. Define and characterize domain
2. Quantify current rates of channel response
3. Identify controls and interventions relevant to channel response
4. Define the desired accuracy of model results
5. Select a model coherent with the desired accuracy
6. Define and schematize the reference case (initial and boundary conditions)
7. Calibrate
8. Verify
9. Define and schematize scenarios of control change
10. Model channel response to scenarios
11. Analyze results and uncertainty

Figure 1.3: Framework for numerical assessment of channel response to climate change, defined in a series of steps.

Barely one year into the PhD I got the immense privilege to travel to New Zealand for the RCEM 2019 conference. This trip remains one of the highlights of my PhD. RCEM is a nice community (I even got to catch up with a former professor from Barcelona, who had also helped me with my application to EPFL) , and New Zealand is breathtaking. It is full of 'big nature', wild rivers, and it even has its own Alps. This was the trip where we bonded with Ana and Jill, who has become my official Dutch hiking partner since. I am lucky to call them friends now.

2

Response of the Lower Rhine River to Human Intervention since the 18th Century

Key Points

- Channel narrowing has unexpectedly led to a slope increase rather than a slope decrease in the upper part of the incising lower Rhine River.
- This slope increase is associated with the presence of bedrock in the upper part of the considered domain.
- The Rhine River's gravel-sand transition has advanced and flattened, suggesting its gradual fading.

This chapter has been published in *Geophysical Research Letters*:

Ylla Arbós, C., A. Blom, E. Viparelli, M. Reneerkens, R.M. Frings, & R.M.J. Schielen (2021). River response to anthropogenic modication: channel steepening and gravel front fading in an incising river. *Geophysical Research Letters*, 48 (4), e2020GL091338, doi: 10.1029/2020GL091338.

In this chapter, we make an inventory of the most important engineering measures carried out in the lower Rhine River since the 18th century, and we investigate how the channel has adjusted to these measures. To do so, we analyze field data on bed elevation and bed surface grain size collected since 1898 and 1966, respectively. The data show unexpected behavior: while channelization measures in the Rhine are expected to decrease the equilibrium channel slope, we see that the latter has increased over time. We introduce a conceptual model to explain this behavior, which seems to be influenced by the presence of bedrock in the upstream end of our domain. In addition, we explain how and why the gravel-sand transition has migrated downstream and flattened, and the extent to which this phenomenon relates to human intervention.

Abstract

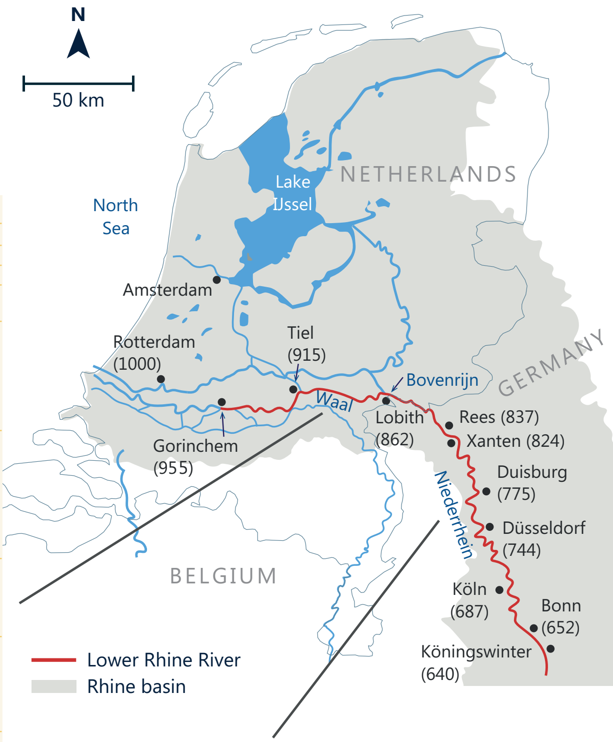
While most of the world's large rivers are heavily engineered, channel response to engineering measures on decadal-to-century timescales and several 100 km scales is scarcely documented. We investigate the response of the lower Rhine River (Germany-Netherlands) to engineering measures, in terms of changes in channel slope and bed surface grain size distribution. Field data show domain-wide incision, primarily associated with extensive channel narrowing. Remarkably, the channel slope has increased in the upstream end, which is uncommon under degradational conditions. We attribute the observed response to two competing mechanisms: bedrock at the upstream boundary increases the channel slope over the upstream part of the alluvial reach to compensate for the reduction of net annual sediment mobility, and extensive channel narrowing reduces the equilibrium slope. Another striking feature is the advance and flattening of the gravel-sand transition, suggesting its gradual fading due to an increasingly reduced slope difference between the gravel and sand reaches.

2.1. Introduction

Lowland rivers have been heavily engineered for centuries to protect the land against floods, improve navigability, irrigate crops, and provide populations with freshwater and energy (*Marsh*, 1864; *Thomas*, 1956; *Downs and Gergory*, 2004; *Best*, 2019). Measures such as dam construction, installation of weirs, levees, and groynes, channelization, diversion, sediment mining, and dredging, have transformed meandering, braiding and anabranching rivers into straighter and shorter single-thread rivers with a fixed planform. The Rhine, Missouri and Danube are examples of such heavily engineered rivers (*Alexander et al.*, 2012; *Hohensinner et al.*, 2011; *Uehlinger et al.*, 2009).

Due to its fixed planform and width, an engineered river can only respond to such human intervention by changing (1) channel slope, through channel bed incision or aggradation, and (2) bed surface texture (i.e., the grain size distribution of the bed surface sediment). Significant incision has been documented in many engineered rivers (*Quick et al.*, 2019; *Harmar et al.*, 2005; *Surian and Rinaldi*, 2003; *Habersack et al.*, 2016). Channelization measures tend to narrow the channel, increase flow velocity, and hence increase sediment transport capacity (*De Vriend*, 2015; *Blom et al.*, 2016). A smaller alluvial equilibrium channel slope then suffices to transport the sediment flux downstream (*Mackin*, 1948; *Blom et al.*, 2016, 2017a), and the channel bed incises to approach this new equilibrium state. Channel bed incision may severely impact navigation due to draught reduction in non-erodible reaches. This is because water level lowering generally follows bed level lowering, which results in a locally reduced flow depth at non-erodible or barely erodible reaches. Furthermore, channel bed incision may enhance flood risk due to foundation weakening of in-river structures and compromise riparian ecology due to increased channel-floodplain disconnection and groundwater level lowering (*Habersack et al.*, 2013; *Hiemstra et al.*, 2020; *Buijse et al.*, 2002).

Despite the abundance of engineered rivers, examples of monitored large-scale channel response to engineering measures on century timescales are scarce. Here we consider the Rhine River, which flows from the Swiss Alps to the North Sea (Netherlands), as it is a paradigmatic example of an engineered river with records of levee construction for flood protection since 1150 (*Berendsen and Stouthamer*, 2001), and has been monitored over the past century. We focus on the lower Rhine River, here defined as the 300-km-long reach comprising the Niederrhein (Germany), Bovenrijn and Waal (Netherlands), where major engineering measures have occurred since the 1700s (Figure 2.1). Field data collected since the late 1800s show that the lower Rhine River has been incising with a surprising increase (instead of the expected decrease) in channel bed slope in the upper part of the domain, and flattening of the gravel-sand transition, located near the German-Dutch border (Figure 2.1). To explain these unexpected river adjustments, we analyze field data of bed elevation and bed surface grain size, collected since 1898 and 1966, respectively.



Period	River km	Intervention
1639	928-931	Meander cutoff
1649	875-883	Meander cutoff
1655	930-935	Meander cutoff
1775-1776	860-880	Meander cutoffs (net shortening since 1600 ~10%)
1850-1870	858-952	Training works for flood protection: - Channel narrowing (Bovenrijn: from 500 to 440 m; Waal: from 500 to 360 m), embankment construction
1870-1890	858-952	Training works for improvement of navigation: - Channel narrowing (Bovenrijn: from 440 to 360 m; Waal: from 360 to 310-320 m), groyne construction
1900-1916	858-952	Extension of training works: - Channel narrowing (from 310-320 to 265-300 m), groyne lengthening
1900-	858-952	Dredging for navigation and construction purposes, volumes reaching 1’500’000 m^3/a. Since 1992, dredge sediment is reallocated.
1985-1988	858-861	Fixed bed installation
1996-1999	925-928	Fixed bed installation
1996-1999	925-928	Bottom vanes installation
2009-2020	858-952	Room for The River measures to increase conveyance capacity, mostly dike relocation and floodplain lowering
2014	858-861	Fixed bed installation
2016	862-864	Nourishment of a 30 cm thick layer of gravel
2019	862-864	Nourishment of 70’000m^3 of gravel

Period	River km	Intervention
1770-1790	640-858	Training works for flood protection - Channel narrowing, groyne construction - Meander cutoffs - Connection of islands with banks - Installation of bank revetments
1880-1900	640-858	Training works for improvement of navigation: - Channel narrowing (from 475-500 to 325-285 m) - Meander cutoffs (net shortening ~10% relative to 1770) - Embankment reinforcement and heightening
1870-	640-858	Dredging for navigation and construction purposes. Since the late 1970s dredged sediment is reallocated elsewhere in the river.
1900-	640-858	Dam construction in tributaries
1920-	640-858	Several local engineering and flood protection works
1920-	775-824	Coal and salt mining cause river bed subsidence. Since 1976 subsidence pits are filled with mining waste.
1985-	665-860	Sediment nourishments to mitigate bed degradation. 2Mt of fine gravel, and 6.4Mt of coarse gravel and cobbles supplied between 1991-2010 along the entire reach. Largest quantities supplied between river km 815-855.

Figure 2.1: Geographical setting and history of human intervention of the lower Rhine River since the 17^{th} century (after *Schwab and Becker*, 1986; *Bolle and Kühn*, 1975; *Jasmund*, 1901; *Van Til*, 1979; *Visser*, 2000; *Kalweit et al.*, 1993; *Frings et al.*, 2009; *Probos*, 2009; *Overmars*, 2020; *Uehlinger et al.*, 2009; *Frings et al.*, 2009; *Ten Brinke*, 2005). Numbers between parentheses in the lower Rhine River map indicate river km, with origin at Konstanz (Bodensee).

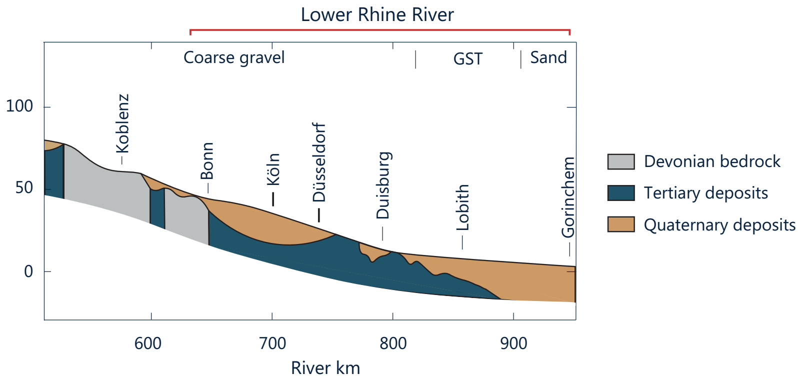


Figure 2.2: Schematic lithological cut of the Rhine River between river km 520-952 (after *Gölz*, 1994; *Gouw*, 2008), comprising the domain of interest of the lower Rhine River (Tertiary and Quaternary alluvial deposits, river km 640-952) as well as a 120 km long bedrock reach at its upstream end (river km 520-640).

2.2. The Lower Rhine River

The hydrologic regime of the lower Rhine River is controlled by snow-melt and rainfall. The mean discharge at Rees (Germany, Figure 2.1) is 2310 m^3/s, and the mean annual peak discharge at Lobith (Netherlands, Figure 2.1) is 6780 m^3/s (*Frings et al.*, 2014a; *Te Linde et al.*, 2010). Over a 120-km-long reach upstream of Bonn (Germany, Figure 2.1) the channel bed consists of Devonian bedrock (Figure 2.2). Downstream of Bonn, the channel bed is composed of Tertiary (fine sand) and Quaternary (gravel and coarse sand) alluvial deposits (*Gölz*, 1994; *Frings et al.*, 2014a). The bed surface primarily consists of coarse gravel in the Niederrhein, and coarse sand in the lower part of the Waal, with a gravel-sand transition zone in between.

The history of human intervention is summarized in Figure 2.1. Between 1600 and the 1930s, the river was narrowed and straightened for flood protection and navigability (*Schwab and Becker*, 1986; *Bolle and Kühn*, 1975; *Jasmund*, 1901; *Van Til*, 1979; *Visser*, 2000; *Kalweit et al.*, 1993). Islands were removed, groynes were constructed, bank revetments were installed, and bends were cut off. As a result, the river became a single-thread channel with a fixed planform, straighter, narrower, and shorter than the natural river. Net channel narrowing was 30 to 40% of the original main channel width (*Van Til*, 1979; *Visser*, 2000; *Overmars*, 2020; *Probos*, 2009). Net shortening was about 10% of the pre-1770 length (*Uehlinger et al.*, 2009; *Visser*, 2000; *Frings et al.*, 2009). Additionally, coal and salt mining since the 1920s between Duisburg and Xanten (Germany, Figure 2.1) caused channel bed subsidence (*Kalweit et al.*, 1993; *Uehlinger et al.*, 2009). Intensive dredging and sediment mining in the main channel carried out for navigation and construction purposes enhanced channel bed incision (*Ten Brinke*, 2005). Reported dredged volumes reach up to 1.5 million m^3/a over the past century, though the actual volumes are likely higher, due to non-declared dredging activities. This prompted river managers to enforce reallocation of dredged sediment, from 1976 in the Niederrhein (*Frings et al.*, 2014a), and from 1992 in the Bovenrijn and Waal (*Visser*, 2000). In order to mitigate channel bed degradation, sediment has been nourished in the Niederrhein since 1989, especially at the downstream end (*Frings et al.*, 2014a). A total of 8.4 Mt of sediment was supplied in the Niederrhein between 1990-2010. In the Bovenrijn, field tests of sediment nourishment were conducted in 2016 and 2019. The most recent intervention program (*Room for the River*) has been carried out over the period 2007-2018 in the Netherlands, where the river has been extensively modified to increase the flood conveyance capacity. Interventions included floodplain lowering, side-channel construction, dyke relocation, river bed excavation, groyne lowering, and obstacle removal.

2.3. Slope Increase in an Incising Reach

Bed elevation data show that the response of the lower Rhine River to engineering measures over the last century mainly comprises domain-wide channel bed incision (Figure 2.3a). Details on data collection and treatment are provided in Appendix A. Incision rates were highest in the early 1900s (reaching 2-3 cm/a in river km 760-870) and have decreased with time. Since the 1990s, bed level has been stable in the Niederrhein and Bovenrijn, and incision rates have decreased in the largest part of the Waal down to 0.5-1.5 cm/a. In the lowermost 30 km of the Waal, the channel bed has been stable or aggraded.

The total bed elevation change in the Niederrhein and Bovenrijn (river km 640-870) over the past century increases in the downstream direction. The most prominent bed incision within this reach is observed between Düsseldorf and Lobith (river km 740-860), reaching up to 5 m over the past century. Conversely, incision rates decrease in the downstream direction in the Waal (river km 860-950), as the branch approaches the estuary.

This spatial distribution of channel bed incision is associated with a slope steepening over the upstream part of the domain, versus a slope decrease over the downstream part of the domain, which is indicated by the two arrows in Figure 2.3a. In other words, the channel slope has remarkably increased in the upper part of the Niederrhein, and decreased in the Waal (Figure 2.3b).

Channel bed incision has been accompanied by bed surface coarsening in the largest part of the domain (Figure 2.3c). In the Niederrhein, the median bed surface grain size, D_{50}, has increased from about 12 mm to about 16 mm between the early 1980s and 2010. This bed surface coarsening is related to sediment nourishments carried out since the 1990s. The coarse outliers observed at river km 700-750, and 855-859 in the period 2012-2017 are likely associated with nourishment campaigns. Downstream from river km 820, D_{50} gradually decreases, reaching values of 1 mm at the downstream end of the Waal (river km 950). The gravel-sand transition (GST) is visible between river km 840-915 (Figure 2.3c). In this reach, the bed surface has coarsened over the past decades, and the Waal has transformed from a sand-bed river into a gravel-bed river up to Tiel (river km 915, Figure 2.3c).

Channel slope increase is an unexpected response to domain-wide channel narrowing, as a narrower channel requires a smaller equilibrium channel slope to transport the same sediment flux (*Blom et al.*, 2017a, 2016; *De Vriend*, 2015; *Jansen et al.*, 1994; *Mackin*, 1948). Such a smaller equilibrium slope is achieved through channel bed incision. This large scale slope-reduction does not exclude the possibility that, locally, a spatial gradient in channel width gives rise to a localized slope increase (*Bolla Pittaluga et al.*, 2014; *Ferrer-Boix et al.*, 2016). Our hypotheses on the response of the lower Rhine River (from Figure 2.4a to 2.4b) is described in the subsequent paragraphs, considering the following assumptions and sim-

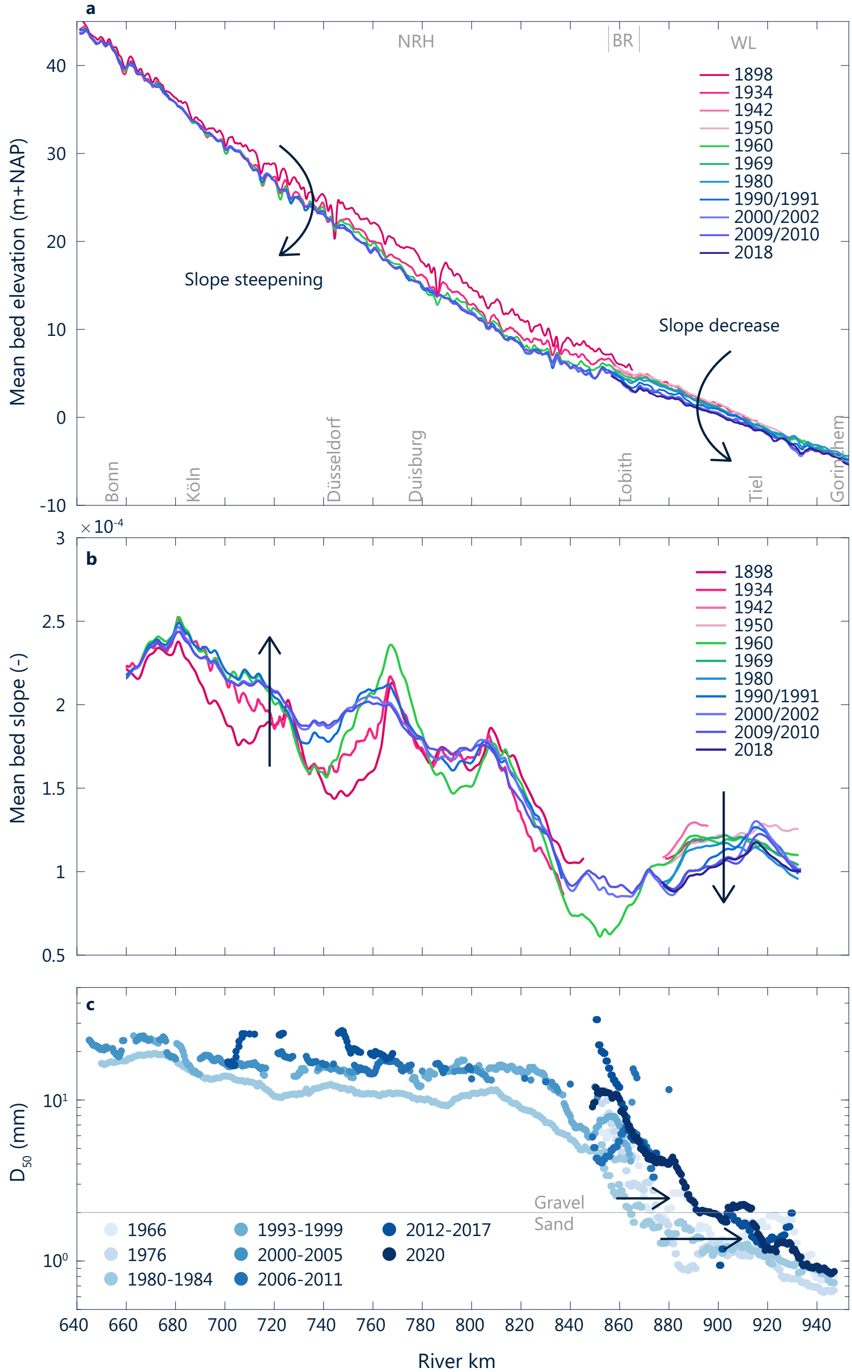


Figure 2.3: Bed elevation, bed slope and bed surface grain size in the lower Rhine River over the past century: (a) bed elevation, moving average with window size 2 km; (b) bed slope, moving average with window size 40 km; (c) median bed surface grain size D_{50}, moving average with window size 10 km. The Niederrhein, Bovenrijn, and Waal reaches are indicated with labels NRH, BR, and WL, respectively.

plifications. The lower Rhine River is delimited by an upstream bedrock reach (river km 520-650) and the North Sea (Figures 2.1 and 2.2). We assume the sediment flux over the bedrock reach to be more or less constant with time. The longitudinal profile is concave upward due to gravel particle abrasion (*Blom et al.*, 2016). The bedrock reach is uplifting at a rate of about 2 mm/a (*Frings et al.*, 2014b), and relative sea-level rise at the downstream end is about 1-4 mm/a (*Wahl et al.*, 2013). As these rates are an order of magnitude smaller than the channel incision rate (up to 1.5 cm/a), we assume the bedrock reach and the downstream base level (sea level) to be fixed points in the below reasoning.

In response to domain-wide channel narrowing, the alluvial equilibrium channel slope decreases, which results in the formation of a downstream-migrating incision wave originating at the downstream end of the bedrock reach (Figure 2.4c1). This decrease in bed elevation downstream from the bedrock reach results in an M2-backwater curve over the bedrock reach (Figure 2.4c2). As a result, the flow expands and flow velocity decreases at the downstream end of the bedrock reach. The relative flow deceleration is larger for small and medium flow rates than for peak flow rates, as the ratio of bed level step to flow depth is larger for small and mean flow rates than for high flow rates. This effect results in a reduction of the net annual sediment mobility (sediment is transported less effectively), and the channel slope increases to compensate for this. This mechanism is similar to the reason for the streamwise decrease of net sediment mobility in a backwater segment, which is compensated for by a streamwise increase of channel slope (*Arkesteijn et al.*, 2019). The slope increase in the upstream part of our alluvial domain competes with the effect of narrowing that tends to reduce the equilibrium slope (Figure 2.4c3). Here we recognize an analogy with the two competing mechanisms that govern Gilbert delta progradation under conditions of base level change (*Chavarrías et al.*, 2018).

The observed incision has been likely intensified by the exposed fine Tertiary deposits (Figure 2.2; *Gölz*, 1994; *Frings et al.*, 2014b), by channel shortening in the 18th-20th centuries, and by extensive removal dredging in the 20th century. By multiplying the length of the shortened reach by the channel slope, we estimate shortening to have caused, roughly, up to 3.5 m and 1 m of channel bed incision in the Niederrhein and the Waal, respectively. Part of this incision has been achieved before 1900 and is not visible in Figure 2.3a. The contribution of coal and salt mining-induced subsidence to bed level lowering over the period 1934-1975 is estimated to be up to 1.5 m, between river kms 787-797 (*Rommel*, 2005). While the magnitude of bed level change is considerable, mining-induced subsidence appears to be a local phenomenon. We therefore suggest that its influence on large-scale bed elevation change is minor. Since 1976, subsidence pits have been refilled with mining waste, even though the refilling has not completely compensated the subsidence (*Frings et al.*, 2014a).

Figure 2.4 considers the transient response of a bedrock-alluvium channel to channel narrowing, and does not elaborate on the morphodynamic equilibrium state of the reach. Further research is needed to shed light on (the dynamics of) this equilibrium state.

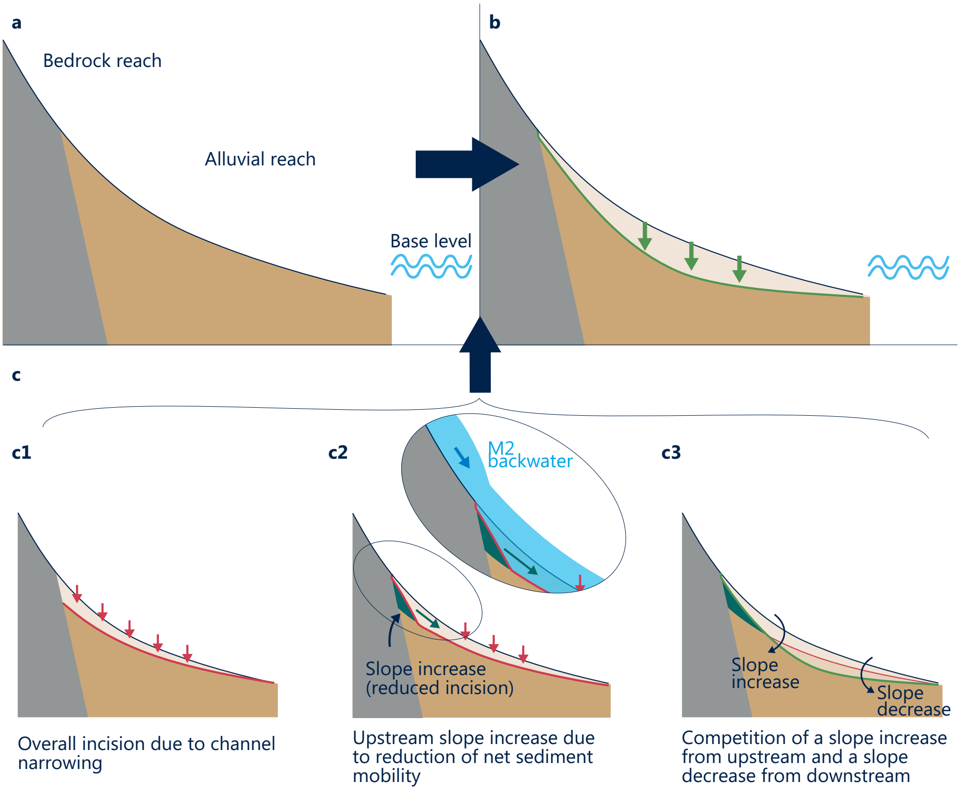


Figure 2.4: Schematic of hypothesized large scale channel response of the lower Rhine River to the normalization works from the 18th until the 20th century: (a) initial state with two fixed points (the bedrock at the upstream end of the alluvial reach and the downstream base level); (b) current state with an increased slope over the upstream part of the alluvial reach, and a reduced slope over the downstream part of the alluvial reach; (c1) channel narrowing reduces the alluvial equilibrium channel slope; (c2) flow expansion at the downstream end of the bedrock reach affects low and mean flows more strongly than peak flows, which results in a decrease of the net annual sediment mobility and an increase of the equilibrium slope over the upstream part of the alluvial reach; (c3) the slope increase at the upstream part of the alluvial reach competes with the slope decrease associated with channel narrowing.

2.4. A Migrating and Fading Gravel-Sand Transition

Besides the striking increase in channel slope in an incising reach, Figure 2.3c shows a significant advance (30 to 40 km) and flattening of the Rhine River's gravel-sand transition (GST). The flattening is expressed as an increase of the length of the GST zone from about 50 km (river kms 820-870) in 1997 (*Frings*, 2011) to about 90 km (river kms 840-930) in 2020.

GST advance is a natural process that does not require a change in the boundary conditions (*Blom et al.*, 2017b). As such, GST advance is not necessarily related to human intervention. GST advance in the Rhine River, however, has likely been enhanced by coarse sediment nourishments. These nourishments are expected to further enhance GST advance in the future.

In general, as a GST advances, the gravel reach becomes longer, and gravel particle abrasion reduces gravel size at the downstream end of the gravel reach with time. This effect very slowly reduces the slope difference between the gravel reach and sand reach with time. Eventually, the change in slope over the gravel front becomes so small that gravel particles are no longer trapped at the front and remain mobile in the sand reach due to the enhanced mobility of gravel in presence of sand (*Venditti et al.*, 2015; *Blom et al.*, 2017b) (Figure 2.5). This mechanism flattens a GST and reduces GST abruptness (*Blom et al.*, 2017b). Gravel particles overtaking the gravel front further reduce the slope difference over the front. It is therefore a self-reinforcing effect (*Blom et al.*, 2017b). We expect this mechanism to be the cause of the observed lengthening of the Rhine River's GST.

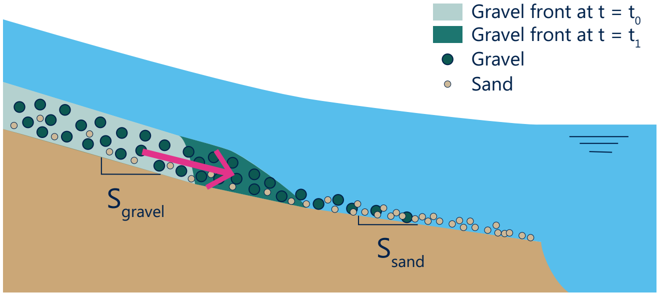


Figure 2.5: Schematic of the migration and flattening of a gravel front. With time, the gravel front migrates downstream and the slope difference between the gravel reach and the sand reach decreases. Eventually, this slope difference becomes so small that gravel particles overtake the gravel front and remain mobile in the sand reach, which flattens the gravel-sand transition.

2.5. Discussion

The present study contributes to understanding channel response in engineered river systems. In this regard, it is interesting to compare the response of the lower Rhine River to that of other engineered river systems, though making such comparisons is a challenging task, because long records of data on river channel response are not available for most river systems. An exception is the Arno River in Italy (*Billi and Rinaldi*, 1997). The Arno River system is slightly smaller than the lower Rhine River, but has a similar history of human intervention and is delimited by a bedrock reach upstream and the Thyrrenian Sea downstream. Bed elevation profiles measured over a century show similar behavior to that observed in the lower Rhine River: a slope increase downstream from a bedrock reach, with downstream from this reach a slope decrease. Such behavior matches with our conceptual model, and is primarily attributed to the presence of bedrock at the upstream end of the domain. The conceptual model of channel adjustment in Figure 2.4 will be helpful in explaining channel response in other bedrock-alluvium engineered river systems, and shall motivate future research on anthropogenic and bedrock-related effects on the river longitudinal profile.

Studies covering relatively short monitoring periods (10-40 years) provide valuable insights on short-term or initial channel response to human intervention. Observations in the lower Rhine River, the Lower Mississippi River (*Harmar et al.*, 2005), as well as several Italian rivers (*Surian and Rinaldi*, 2003), indicate that the rates of channel response to human intervention are highest in the years following the intervention (regardless of its nature) and then strongly decrease. Channel adjustment continues for decades to centuries at reduced rates. During this time, however, additional river intervention may trigger different types of response, which are then superimposed to the (slowly) ongoing ones.

In the lower Rhine River, as well as in the above-mentioned river systems, human intervention has dominated channel response over the past century (*Billi and Rinaldi*, 1997; *Harmar et al.*, 2005; *Surian and Rinaldi*, 2003). In other words, there is no record of significant climate-related change of the river controls (i.e., flow duration curve, downstream base level, and sediment flux) which could have induced the observed behavior. This situation may, however, change in the future, given that accelerated rates of change of the river controls are foreseen in the coming century (*Chen et al.*, 2017; *Nerem et al.*, 2018; *Eisner et al.*, 2017; *Verhaar et al.*, 2010). In the case of the lower Rhine River, climate scenarios for the downstream base level (sea level) foresee rates of sea level rise of up to 3 cm/a by the end of the century, compared to the 2 mm/a observed currently (*Le Bars et al.*, 2017; *Haasnoot et al.*, 2018). Likewise, while no major changes in mean water discharge have been reported over the past century, water discharge scenarios foresee an increase of mean winter flow rates of up to 50% and a decrease of summer mean flow rates of up to 40% by the end of the century (*Sperna-Weiland et al.*, 2015). These changes in water discharge, as well as land use changes may, in turn, also considerably alter the upstream sediment flux. Given that the timescales of channel response are comparable to those of climate-related changes in the river controls (order of decades to centuries), future research will need to address the relative importance of climate forcing on channel response in rivers that are intervention-dominated today. Nevertheless we expect channel response to remain intervention-dominated over, at least, the next few decades.

2.6. Conclusions

Human intervention has governed channel response of the lower Rhine River over the past century. Strikingly, the main channel slope has increased in an incising reach. This response is counter-intuitive in that domain-wide channel narrowing is expected to decrease the equilibrium channel slope. We attribute the observed slope increase to the presence of bedrock in the upstream part of the domain. While the alluvial reach incises due to channel narrowing, bedrock prevents the bed from incising at engineering time scales, and an M2-backwater curve forms over the bedrock reach. The resulting flow expansion (and thus deceleration) at the downstream end of the bedrock reach leads to a net decrease of the sediment mobility. This is because low and mean flow rates lead to a larger mobility reduction than peak flows. The channel slope increases over the upstream part of the alluvial reach to compensate for this sediment mobility reduction. The situation can be considered as two competing effects: (1) a channel slope increase associated with a spatial reduction of the net annual sediment mobility due to the presence of bedrock, and (2) a channel slope decrease associated with large-scale channel narrowing in the past.

A second remarkable finding is that the Rhine River's gravel-sand transition (GST) has migrated and flattened. The explanation of GST flattening seems similar to the case of, for instance, the Fraser River (*Blom et al.*, 2017b), and relates to an increasingly decreased slope difference between the gravel reach and sand reach. The latter makes gravel particles overtake the gravel front, which further reduces the slope difference. We conclude that the Rhine River's gravel-sand transition is slowly fading.

This study constitutes an important step in understanding channel response in engineered river systems. The presented conceptual model of channel adjustment can help explain channel response in other bedrock-alluvium engineered river systems, and identify river systems governed by similar behavior.

Acknowledgements

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And then there was the pandemic. It was bad, there is no sugar-coating it. But lockdown also meant that, all of a sudden, there was free time popping up out of nowhere. And that is how my parallel life as an illustrator started. My friends at Tazz encouraged me to make postcards, and let me sell them at their lovely café. A dream come true. The postcards started spreading around, I designed posters for a bookshop, multiple celebration cards, and made fancy giclée prints that have found their homes in the Netherlands and Canada. It still feels surreal that someone uses your drawings to celebrate something dear to them. It is hard to express how grateful I am for all of this.

During that period, we could also experience heavy snow and frozen canals, which does not happen so often. People took days off to go ice-skate, play hockey, or beer-crate curling. It was a sparkle of joy amidst those difficult times, and some serious eye candy.

3

Response of the Lower Rhine River to 21st-Century Climate Change

Key Points

- Human intervention will continue to govern channel response in the lower Rhine River by 2100, mainly through channel bed incision.
- Climate change leads to sea level rise and hydrograph adjustment, the latter being dominant and causing enhanced incision.
- Channel response to human intervention slows down as the river approaches its equilibrium state, but response to climate change accelerates.

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In the previous chapter, we examined how the lower Rhine River has responded to human intervention since the 18th century. We found that channelization measures have caused meters of river bed incision over hundreds of kilometers. While the river continues to adjust to these past engineering measures, climate change increasingly alters the river controls through changes in water discharge and sea level rise. In this chapter, we investigate how the river controls may change according to different climate scenarios. We then assess how the lower Rhine River may adjust to these changes over the 21st century, in terms of bed level change and bed surface grain size change. To this end, we set up a highly schematized one-dimensional numerical model and test it for different scenarios of water discharge, sea level rise, and sediment flux.

Abstract

Human intervention makes river channels adjust their slope and bed surface grain size as they transition to a new equilibrium state in response to engineering measures. Climate change alters the river controls through hydrograph changes and sea level rise. We assess how channel response to climate change compares to channel response to human intervention over this century (2000–2100), focusing on a 300-km reach of the Rhine River. We set up a schematized numerical model representative of the current (1990–2020), non-graded state of the river, and subject it to scenarios for the hydrograph, sediment flux, and sea level rise. We conclude that the lower Rhine River will continue to adjust to past channelization measures in 2100 through channel bed incision. This response slows down as the river approaches its new equilibrium state. Channel response to climate change is dominated by hydrograph changes, which increasingly enhance incision, rather than sea level rise.

3.1. Introduction

River engineering measures such as channelization, diversion, and dam construction, alter the equilibrium state of rivers, triggering an adjustment towards the new equilibrium state (*Blom et al.*, 2016; *De Vriend*, 2015; *Mackin*, 1948). In engineered rivers with a fixed planform, this response is limited to (1) channel slope adjustment through channel incision or aggradation, and (2) changes in the bed surface grain size distribution. The magnitude, extent, and timescale of channel response to engineering measures can add up to meters of bed level change, extend over hundreds of kilometers, and take decades to centuries (*De Vriend*, 2015).

Climate change alters the river controls through changes in precipitation, ice- and snowmelt, and sea level rise, which modifies the hydrograph (*Blöschl et al.*, 2019; *Milliman et al.*, 2008), sediment supply (*Liu et al.*, 2013; *Verhaar et al.*, 2011), and base level (*IPCC*, 2022; *Chen et al.*, 2017). Changes in the river controls modify the equilibrium state of the river, prompting channel adjustment. With increasing rates of climate change, the relative influence of climatic controls on channel response becomes ever more important.

Field and modeling studies on channel response to interventions are abundant (e.g., *Czapiga et al.*, 2022a; *Arkesteijn et al.*, 2021; *Gao et al.*, 2020; *Verhaar et al.*, 2011; *Zaprowski et al.*, 2005; *Surian and Rinaldi*, 2003). Large-scale studies of channel response to overall climate change are scarce, and do not typically address the relative magnitude of climate-related and intervention-related changes. Yet climate change affects all of the river controls simultaneously, and many engineered rivers still feature an ongoing response to past human intervention over hundreds of kilometers (*Ylla Arbós et al.*, 2021b; *Harmar et al.*, 2005; *Surian and Rinaldi*, 2003; *Emerson*, 1971).

We focus on the lower Rhine River, a 300-km transboundary reach of the Rhine River between Bonn (Germany) and Gorinchem (the Netherlands), including a bifurcation near the German-Dutch border (Figure 3.1). The lower Rhine River is a paradigmatic engineered river with a long history of human intervention (*Ylla Arbós et al.*, 2021b). The mean water discharge and annual peak flow at Köln are, respectively, 2155 and 6450 m^3/s. Decades of field data on bed level and bed surface grain size show that the river channel is still adjusting to domain-wide narrowing and shortening measures carried out over the past century (about 30% width reduction and 10% length reduction), as well as to more recent measures (*Czapiga et al.*, 2022a; *Ylla Arbós et al.*, 2021b; *Quick et al.*, 2019).

Our objective is to assess how climate forcing adds to the ongoing channel response, in terms of bed level and bed surface grain size change, over the period 2000-2100. To this end, we set up a highly schematized numerical model, and subject it to multiple scenarios for climate-related hydrograph changes, sediment flux, and sea level rise.

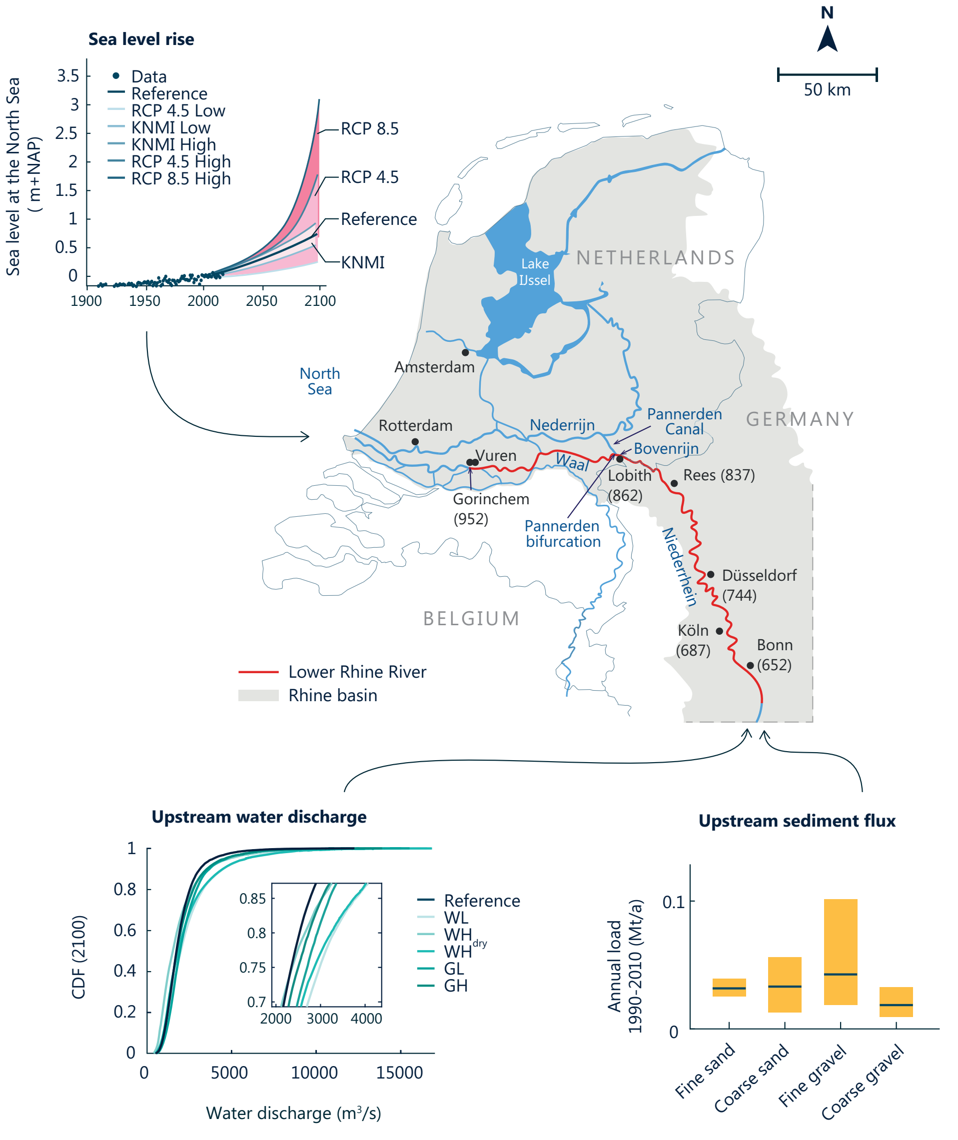

Figure 3.1: The lower Rhine River between Bonn (Germany) and Gorinchem (the Netherlands), with scenarios for change of the river controls over the 21st century. Numbers between parentheses indicate river km with origin at Konstanz (Bodensee). Water discharge scenarios follow *Sperna-Weiland et al.* (2015); sea level rise scenarios follow *IPCC* (2013) and *KNMI* (2015); sediment flux follows the *Frings et al.* (2014a) uncertainty estimates (mean values in blue, yellow boxes for the 95% confidence interval).

3.2. A Schematized Model of Centennial Channel Response

Given the spatio-temporal scale of our study, as well as the uncertainty associated with climate predictions and field data, we aim to identify the type and order of magnitude of channel response to scenarios of climate-related control change. We do not address short-term natural variability of the system, nor local width variations and local effects of structures. We use a one-dimensional model, as we focus on large-scale, order-of-magnitude changes over a century.

The schematization of a complex system to a one-dimensional problem is a balancing act between simplification and representativeness (*Paola*, 2011): the model needs to capture the main components of channel response, which is best done with a highly schematized model, and at the same time be representative of the lower Rhine River.

We set up a one-dimensional (i.e., cross-section-averaged) morphodynamic model, suitable for mixed-size sediment. The numerical solver is SOBEK-RE (*Deltares*, 2012a,b). Flow is computed using the steady solution of the shallow water equations (*De Saint-Venant*, 1871); bed level change is solved through mass conservation of bed sediment (*Exner*, 1925, 1931), and changes in bed surface grain size are computed through conservation of each grain size class for a surface layer (*Hirano*, 1971). Sediment transport is calculated with a relation which includes a threshold of motion and accounts for hiding and exposure effects. Further details on the sediment transport relation and model assumptions are provided in Appendix B.2.

Non-erodible reaches (fixed layers) are modeled as sediment that is sufficiently coarse to be immobile under the prevailing flow conditions. In the field, “summer levees” (relatively low-elevation levees between main channel and floodplain) reduce the occurrence of floodplain flow for, for instance, agricultural reasons. The model does not account for these summer levees, for simplicity reasons and because their effects are mostly relevant in cases with abrupt width changes (e.g., *Van Vuren et al.*, 2015), which do not occur in our model.

Given our focus on bed material load, and following data availability, we consider five grain size classes: fine sand, coarse sand, fine gravel, and two coarse gravel fractions, with characteristic diameters in the order of 0.5, 1.25, 5, 15, and 40 mm, respectively. The bed surface is coarser than the substrate (*Frings et al.*, 2014a).

The model initial state is based on the period 1990-2020, and follows smoothed bathymetric and bed surface grain size data (Figure 3.2a-c). The initial state covers a relatively long period due to the large natural variability of the data and data availability. This is not problematic as most system properties do not change significantly over this time frame on the large scale. Full details on the model schematization are provided in Appendix B.3.

As we focus on channel response to changes in the boundary conditions, model boundaries constitute an essential part of our domain of interest. We define three external boundary conditions (water discharge and grain size-specific sediment fluxes upstream, and base level downstream), and an internal nodal condition (sediment partitioning at the bifurcation).

We adopt a cycled hydrograph of daily discharge with a 20-year period, which allows us to account for the natural variability of water discharge while adding a climate signal to it. The hydrograph must capture the flow duration curve, as it governs the mean channel response, while the sequence of flow events determines the fluctuations around it (*Arkesteijn et al.*, 2021, 2019). We select a 20-year period from the historical record (1967-1986) such

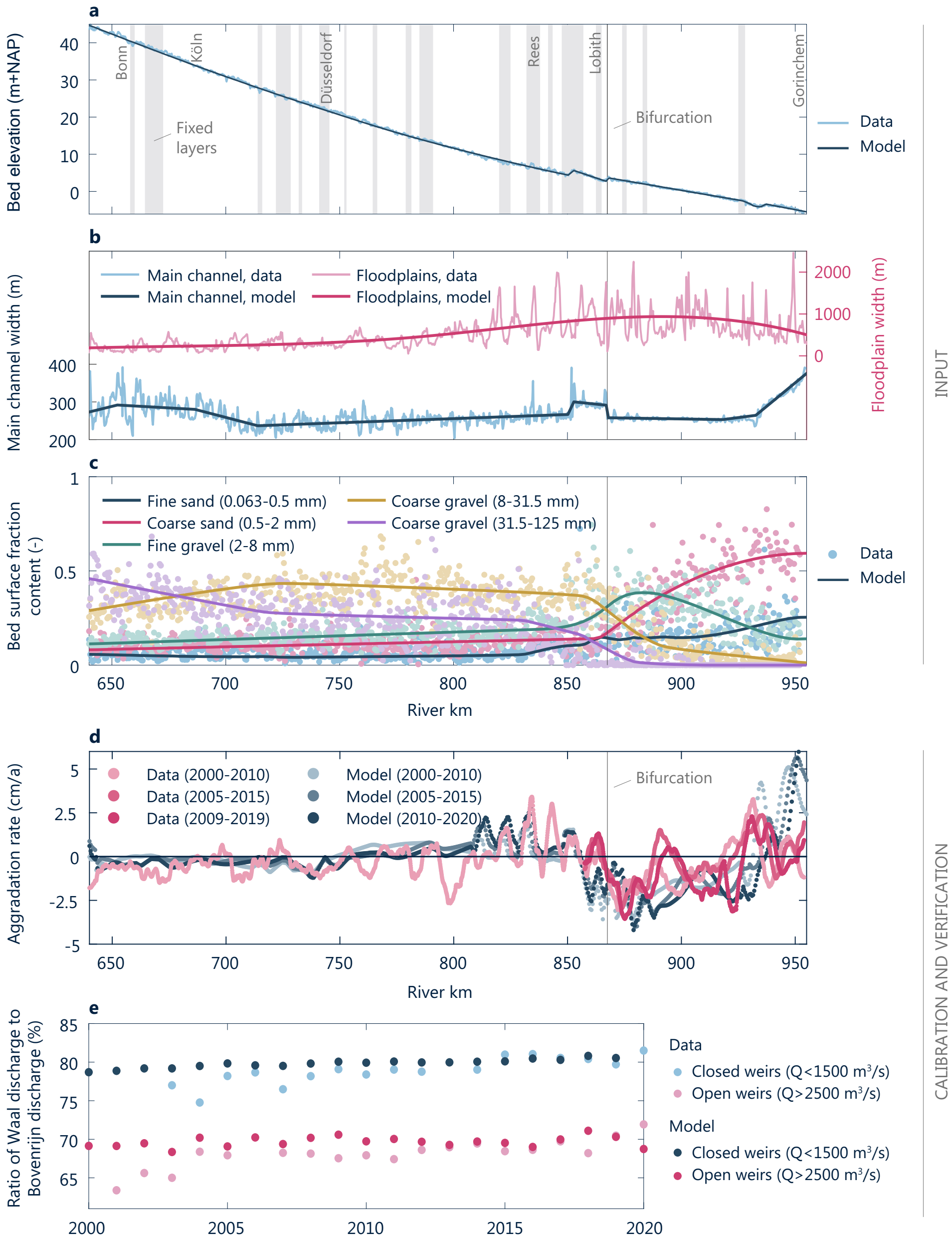

Figure 3.2: Initial state of the model based on the period 1990-2020 (a-c) and model calibration and verification (d-e): (a) mean main channel bed elevation; (b) main channel and floodplain width; (c) bed surface fraction content of each grain size class; (d) channel bed aggradation rates (5-km moving average); and (e) temporal variation of flow partitioning at the Pannerden bifurcation, represented by the ratio of Waal discharge to Bovenrijn discharge.

that its statistics (10th, 50th, and 90th percentiles, mean and standard deviation) best match those of the long-term time series (1951-2006, which is equal to the reference period used in the *Sperna-Weiland et al.* (2015) climate scenario studies).

The upstream sediment flux is set as a function of discharge using the sediment transport relation, scaled such that the annual mean sediment flux per grain size fraction at the upstream boundary resembles the normal-flow load distribution (*Blom et al.*, 2017a), and falls within the 95% confidence interval of the *Frings et al.* (2014a) sediment flux estimates (Figure 3.1). With a discharge-dependent sediment load resembling the normal-flow load distribution, we avoid the presence of an upstream boundary segment over the upstream part of our domain (*Blom et al.*, 2017a). We split the flux of the *Frings et al.* (2014a) coarsest fraction in two, proportionally to their substrate content (*Parker et al.*, 1982; *Parker and Klingeman*, 1982) following field data (Appendix B.3), as the hiding-exposure relation requires a limited difference between characteristic diameters of the grain size classes.

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The downstream boundary (Gorinchem, river km 955) is located upstream of the estuarine zone, at about 100 km upstream of the North Sea (Figure 3.1), as our model does not include estuary dynamics such as tides and salt intrusion. Water level at the downstream boundary (measured at the Vuren gauging station) depends on river discharge and sea level (Figure 3.3a). We approximate water level at the downstream boundary using the *De Vries* (1994) empirical fit to the *Bresse* (1860) analytical solution to the backwater equation. As the normal flow depth d_e is a function of $Q^{2/3}$ (with Q the water discharge), the *De Vries* (1994) empirical fit equals (see Appendix B.4 for its derivation)

$$d_v = \Lambda Q^{2/3} + \left(d_s - \Lambda Q^{2/3}\right) 2^{KQ^{2/9}/d_s^{4/3}} \tag{3.1}$$

where d_v denotes flow depth at the Vuren gauging station, d_s denotes flow depth at the North Sea, and Λ and K are assumed to be constants. We find the highest correlation between field data and Equation 3.1 for Λ=0.054 $s^{2/3}/m$ and K=-0.71 $m^{2/3}s^{2/9}$ (Figure 3.3b,c).

We include sea level rise at a rate corresponding to the centerline of the *KNMI* (2015) projections (Figure 3.1). We assume that water level increase at Vuren due to coastal storm surges and tidal constituents (Figure 3.3a) is a proxy for water level increase due to sea level rise.

As we use a one-dimensional numerical model, an internal nodal condition sets the sediment partitioning over the two bifurcates. Sediment partitioning at a bifurcation located on a river bend is governed by three-dimensional processes (e.g., *Frings and Kleinhans*, 2008; *Sloff and Mosselman*, 2012), which cannot be represented in a one-dimensional model. For each grain size class, the sediment partitioning is prescribed by a nodal point relation (*Wang et al.*, 1995; *Bolla Pittaluga et al.*, 2003; *Schielen and Blom*, 2018), which relates the ratio of sediment supply to the bifurcates to known model parameters.

We adopt a highly simplified nodal point relation, as the uncertainty related to nodal point relations is large, and available field data to calibrate them are scarce and uncertain. Our nodal point relation relates the ratio of the sediment supply of grain size class k, S_k, of bifurcates W (Waal) and P (Pannerden Canal), to the the ratio of their water discharge, Q, multiplied by the prefactor a_k:

$$\frac{S_{k,W}}{S_{k,P}} = a_k \frac{Q_W}{Q_P} \tag{3.2}$$

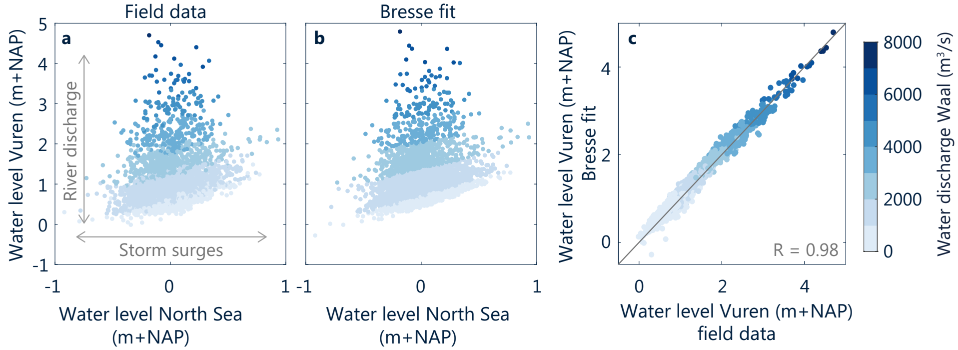

Figure 3.3: Water level at the downstream boundary of our model (gauging station Vuren, river km 952) as a function of water level at the North Sea: (a) field data averaged over two days, for the period 1990-2020; (b) *De Vries* (1994) empirical fit to the *Bresse* (1860) solution to the backwater equation; and (c) goodness of fit, with R the correlation coefficient.

where a_k equals 2.73 for both sand fractions, 0.4 for fine gravel, and 0.5 for both coarse gravel fractions. The resulting sediment flux ratios fall within the range of the *Frings et al.* (2015) estimates of annual sediment flux, and are comparable to the limited amount of field measurements and laboratory experiments (*Frings and Kleinhans*, 2008).

Sediment management practices are extensive in the lower Rhine River. We include fixed layers (Figure 3.2a); fine gravel nourishments at rates of 0.1 Mt/a over four 5-km reaches equally distributed between river km 810-855 (*Frings et al.*, 2014a) until 2020, beyond which they would cause unwanted aggradation; and dredging over the lowermost 25 km of the river, at an estimated rate of 5’000 m^3/a until 2025, when net-removal dredging contracts are set to terminate.

We calibrate the model over the period 2000-2010 against (1) measured channel bed aggradation rates (Figure 3.2d) and (2) the measured temporal change of flow partitioning at the Pannerden bifurcation (Figure 3.2e). For the latter, we consider two ranges of water discharge ($<$1500 and $>$2500 m^3/s), corresponding to closure and opening of the weirs downstream of the Pannerden Canal, which is dependent on water discharge at Lobith. Calibration parameters include a spatially variable, piece-wise linear Chézy friction coefficient, the prefactor and critical shear stress in the sediment transport relation, the grain size distribution of the sediment flux at the upstream boundary, and the coefficients a_k of the nodal point relation (Appendix B.5). The direction of change (aggradation versus degradation) is generally well captured. The mean absolute difference in aggradation rates is 0.25 cm/a in the German Rhine, and 0.6 cm/a in the Dutch Rhine. The relative error in the ratio of Waal to Bovenrijn discharge is 10%. Sediment fluxes are within the *Frings et al.* (2019) uncertainty range, albeit on the lower end.

We verify the model against the same variables, over the period 2010-2020 (Figure 3.2d,e). Aggradation rates are only verified for the Dutch Rhine, as bed level data for the German Rhine (river km 640-857) over 2010-2020 is not available to the authors. Verification results are of the same order of accuracy as calibration results.

3.3. Ongoing Channel Response to Past Human Intervention

We first address expected bed level change in 2050 and 2100, relative to the initial state (2000) and without climate scenarios (i.e., the reference case, Figure 3.4a).

Incision rates increase in the downstream direction between river km 640-750, slightly increasing channel slope. Between river km 870-925, incision rates decrease in the downstream direction. The latter slightly decreases channel slope, with a tilting point around river km 925, downstream of which the river aggrades, suggesting an overall increase in concavity, and a continuation of river bed incision trends (*Ylla Arbós et al.*, 2021b). This behavior is consistent with historical observations of bed level change, related to an ongoing slope adjustment due to domain-wide channel narrowing in the presence of an upstream bedrock reach (*Ylla Arbós et al.*, 2021b). The largest incision rates are observed immediately downstream of fixed layers.

Incision rates range between 0 and 2.5 cm/a up to 2050, and between 0 and 1 cm/a between 2050 and 2100 (Figure 3.4a). This means that while the channel is expected to continue to incise in the future, incision rates decrease with time as the channel approaches its equilibrium state.

Channel bed incision is less pronounced in the German Rhine (river km 640-857) than in the Dutch Rhine (river km 857-955). The relatively large incision rates in the Dutch Rhine seem to be associated with instability of the Pannerden bifurcation. The steady temporal increase of the fraction of water discharge flowing into the Waal branch (Figure 3.2e) likely enhances incision downstream from the bifurcation, which further increases the flow rate into the Waal branch. Additionally, the fixed beds have limited river bed incision in the German Rhine and over river km 850-885 (*Frings et al.*, 2014a; *Czapiga et al.*, 2022a).

The channel slightly aggrades between river km 770-860. This reach is characterized by a relatively low sediment transport rate in the initial state (Appendix B, Figure B.7e). The sediment transport rates upstream of this reach are larger, which creates an aggradational wave migrating in the downstream direction.

The bed surface continues to coarsen (Figure 3.4f, reference case): the past coarsening trend continues and the abruptness of the gravel-sand transition has ceased to exist (*Ylla Arbós et al.*, 2021b; *Frings et al.*, 2014a). Possible explanations of the continued bed surface coarsening include (1) downstream migration of the Rhine gravel-sand transition (*Ylla Arbós et al.*, 2021b); (2) temporal reduction of the sediment flux as the channel adjusts to the channelization measures of the past (Appendix B, Figure B.7e); (3) continued channel response to past sediment nourishments (carried out primarily before the model initial state in 2000). Channel narrowing has led to a temporary increase of the sediment transport rate. Narrowing does not affect the sediment flux from the upstream part of the basin, but leads to a decreased equilibrium channel slope (and so bed incision) until the sediment transport rate has decreased and equals the upstream sediment flux again.

Despite our simplified treatment of the bifurcation, we observe that (1) sand fractions are preferentially transported into the Waal independently of river discharge, while gravel fractions partition more evenly, and the relative amount of gravel transported into the Pannerden Canal increases with discharge; (2) overall, as discharge increases, relatively more sediment is being transported into the Pannerden Canal; and (3) the relative amount of sediment transported into the Pannerden Canal decreases with time (Appendix B.6). These observations suggest instability of the Pannerden bifurcation.

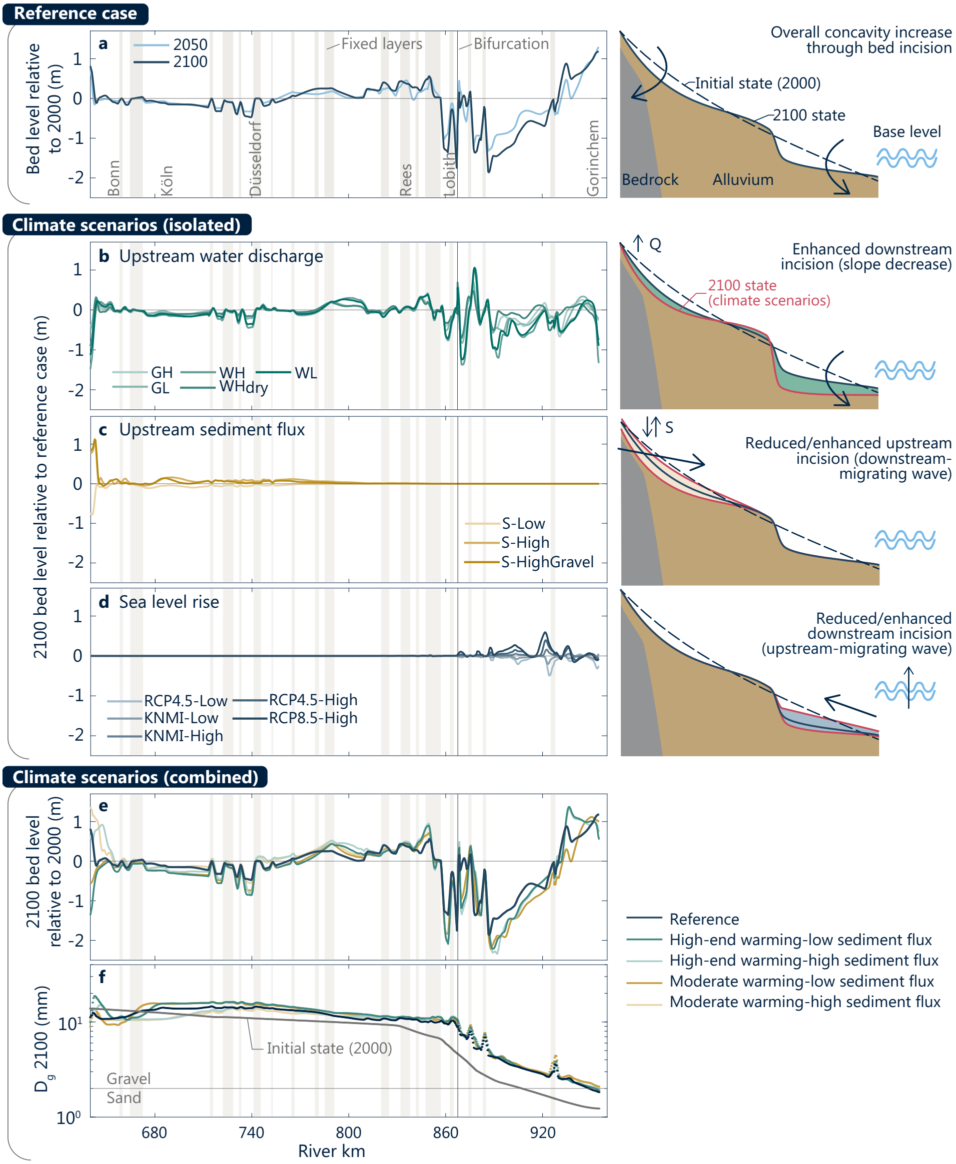

Figure 3.4: Expected channel response to human intervention and climate change scenarios: (a) bed level relative to 2000 for the reference case; (b-d) bed level in 2100 relative to the reference case for (isolated) scenarios for the (b) hydrograph, (c) sediment flux, and (d) sea level rise; (e) 2100 bed level relative to 2000 for combined climate scenarios (hydrograph, sediment flux, and sea level rise), and (f) geometric mean bed surface grain size for combined climate scenarios. Schematics to the right-hand side of subplots a-d illustrate the response schematically, where arrows indicate main direction of change, and shaded areas in b-d indicate the range of change relative to the reference case.

3.4. Channel Response to Climate Change: Isolated Climate Scenarios

To assess how climate change adds up to the ongoing response, we adopt scenarios of control change and translate them into model boundary conditions. Here we test different scenarios of a single control at a time. We focus on results for 2100, and mention intermediate changes by 2050. Additional results for 2050 are included in Appendix B.7. We consider channel response to, subsequently, climate-related hydrograph changes, sediment supply variations, and sea level rise.

Sperna-Weiland et al. (2015) use a hydrological model (*Hegnauer et al.*, 2014) to translate precipitation scenarios (*KNMI*, 2015) into five 50-year synthetic time series of daily river discharge at different stations of the Rhine River, representative of the predicted climate conditions in 2050 and 2085. We consider the discharge station at Köln (river km 687, Figure 3.1). The *Sperna-Weiland et al.* (2015) scenarios (WH, WHdry, WL, GH, GL, following *KNMI* (2015) nomenclature) consist of 15 to 50% higher peak flows in winter and 0 to 40% lower base flows in summer by 2085. Appendix B.8 describes how the *KNMI* (2015) scenarios account for uncertainty in climate predictions.

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We use information on the statistics of the flow duration curves (*Sperna-Weiland et al.*, 2015) to modify our reference cycled hydrograph. To this end, we estimate the pth-percentile of the discharge for the *Sperna-Weiland et al.* (2015) 2050 and 2085 data, Q_p^{itN}, where the superscript i denotes the scenario, t the time horizon (2050 or 2085), and N is the *Sperna-Weiland et al.* (2015) data. We repeat this for the *Sperna-Weiland et al.* (2015) reference case, Q_p^{refN}. We determine the relative change of the pth-percentile discharge according to *Sperna-Weiland et al.* (2015), F_p^{itN}:

$$F_p^{itN} = \frac{Q_p^{itN}}{Q_p^{refN}} \tag{3.3}$$

We then multiply each pth-percentile discharge in the hydrograph of our reference case, Q_p^{ref}, by the factor F_p^{itN} to account for climate change effects:

$$Q_p^{it} = F_p^{itN} Q_p^{ref} \tag{3.4}$$

For intermediate times, we linearly interpolate between values of Q_p^{it}, and linearly extrapolate for values up to 2100.

Our method provides a new hydrograph for each scenario with a new flow duration curve based on climate-related changes in flow statistics. The sequence of flow events is the same as in the reference case. Appendix B.8 the method with a workflow chart.

Figure 3.4b shows how the hydrograph scenarios add to the ongoing channel response in the reference case, in terms of bed level difference in 2100. Water discharge scenarios enhance the ongoing incision by 0 to 0.35 m (0 to 0.10 m by 2050) in the German Rhine and 0 to 1 m (0 to 0.35 m by 2050) in the Dutch Rhine. This enhanced incision is because all scenarios predict increased moderate to high discharges, which are the most relevant to channel response (*Blom et al.*, 2017a), and lead to a smaller equilibrium channel slope. More frequent high flows also increase the relative amount of sediment going into the Pannerden Canal enhancing bifurcation instability (Section 3.3).

In defining sediment flux scenarios, we assume that the large uncertainty of the *Frings et al.* (2014a) field data (40 to 150%, Figure 3.1) is larger than potential climate-related flux changes. We translate the lower and upper bounds of the uncertainty range into scenarios for the upstream sediment flux. We define three scenarios: low sediment flux (low end of uncertainty range), high sediment flux (high end of uncertainty range), and high gravel flux (high end of uncertainty range for the gravel fractions, and mean values for the sand fractions).

Figure 3.4c shows the difference in bed level change between the sediment flux scenarios and the reference case, in 2100. The response to changes in the sediment flux starts at the upstream boundary and migrates downstream. By 2100, the adjustment wave has advanced about 200 km (100 km by 2050). Over the upstream end of the domain, higher sediment fluxes reduce river bed incision by 0 to 0.15 m (0 to 0.10 m by 2050), and lower fluxes increase it by 0 to 0.10 m (0 to 0.05 m by 2050).

We consider five scenarios of sea level rise (Figure 3.1): the upper and lower end of the *KNMI* (2015) sea level rise scenarios, the upper and lower end of the RCP 4.5 scenarios, and the upper end of the RCP 8.5 scenarios (*IPCC*, 2013). Note that future sea level rise largely depends on whether Antarctic ice or Greenland ice melts (*Larour et al.*, 2017). We translate the scenarios into water level at the downstream boundary of our model at Vuren with Equation 3.1, adjusting d_s based on the scenarios.

Figure 3.4d shows that for rates of sea level rise larger or smaller than that of the reference case, the 2100 response consists, respectively, of reduced incision by 0 to 0.30 m (0 to 0.05 m by 2050), or enhanced incision by 0 to 0.25 m (0 to 0.10 m by 2050). Sea level rise leads to an upstream-migrating wave, covering about 90 km by 2100 (50 km by 2050), up to the Pannerden bifurcation (river km 867.5).

The limited influence of sea level rise on channel response can be explained by the fact that the rate of sea level rise is an order of magnitude smaller than that of the bed level change in the reference case. Bifurcation partitioning trends remain unaffected by sea level rise in 2100. Nonetheless, as sea level has risen since before 2000 (*IPCC*, 2022), the initial state of the river system is already affected by past sea level rise.

3.5. Channel Response to Climate Change: Combined Climate Scenarios

To assess the effects of combined scenarios, we perform model runs for several scenario combinations, associated with the smallest and largest predicted temperature and precipitation increase by 2100 (*IPCC*, 2013). This results in two hydrograph-sea-level-rise scenario combinations, hereafter referred to as moderate and high-end warming scenarios (respectively, scenarios GL-RCP4.5-Low and WH-RCP8.5-High). As sediment flux scenarios are assumed to be independent of climate scenarios, we test the climate scenario combinations for both the lower and upper bound of the sediment flux scenarios (S-Low and S-High), resulting in four scenario combinations.

Figure 3.4e shows the bed level difference between 2100 and the initial state (2000) for the reference case and the combined scenarios. Overall, the ongoing response to past channelization measures is dominant, and climate scenarios further enhance incision by 0.15 to 0.70 m (0 to 0.30 m by 2050). Furthermore, these results suggest an overall dominance of water discharge scenarios over sea level rise in channel response to climate change. The bed surface coarsening and the downstream-migrating coarsening wave are not significantly affected by climate scenarios (Figure 3.4f).

Our results agree with field observations and modeling efforts regarding climate change effects in engineered rivers (e.g., *Verhaar et al.*, 2010; *Muñoz et al.*, 2018), and confirm the key role of engineering measures in channel response, even in the presence of notable climate forcing. The relative importance of extreme flow events may, however, be significant in bifurcating river systems. In particular, peak flows may lead to substantial sediment deposition in one bifurcate, which may alter flow and sediment partitioning at the bifurcation, affecting future channel response (*Chowdhury et al.*, 2023a).

3.6. Conclusions

We have developed a strategy to assess climate-related impact on river channels. Our model aims to identify large-scale and multi-decadal trends of channel response, and therefore only provides order-of-magnitude expected change. Our conceptual analysis of channel response to isolated and combined climate scenarios provides clues to how engineered rivers worldwide respond to climate change.

Our results suggest that (past) human intervention is the main driver of channel response in the lower Rhine River over the 21th century, leading to channel bed incision.

Climate forcing enhances this incision, mostly due to increased moderate discharges, which decreases the equilibrium channel slope. Sea level rise mildly reduces river bed incision in the downstream part of the domain.

While channel response to human intervention slows down as the river approaches its equilibrium state, channel response to climate change accelerates, as changes in controls accelerate. The relative importance of climate forcing on channel response therefore increases with time. Bifurcation dynamics are expected to play a key role in future channel adjustment.

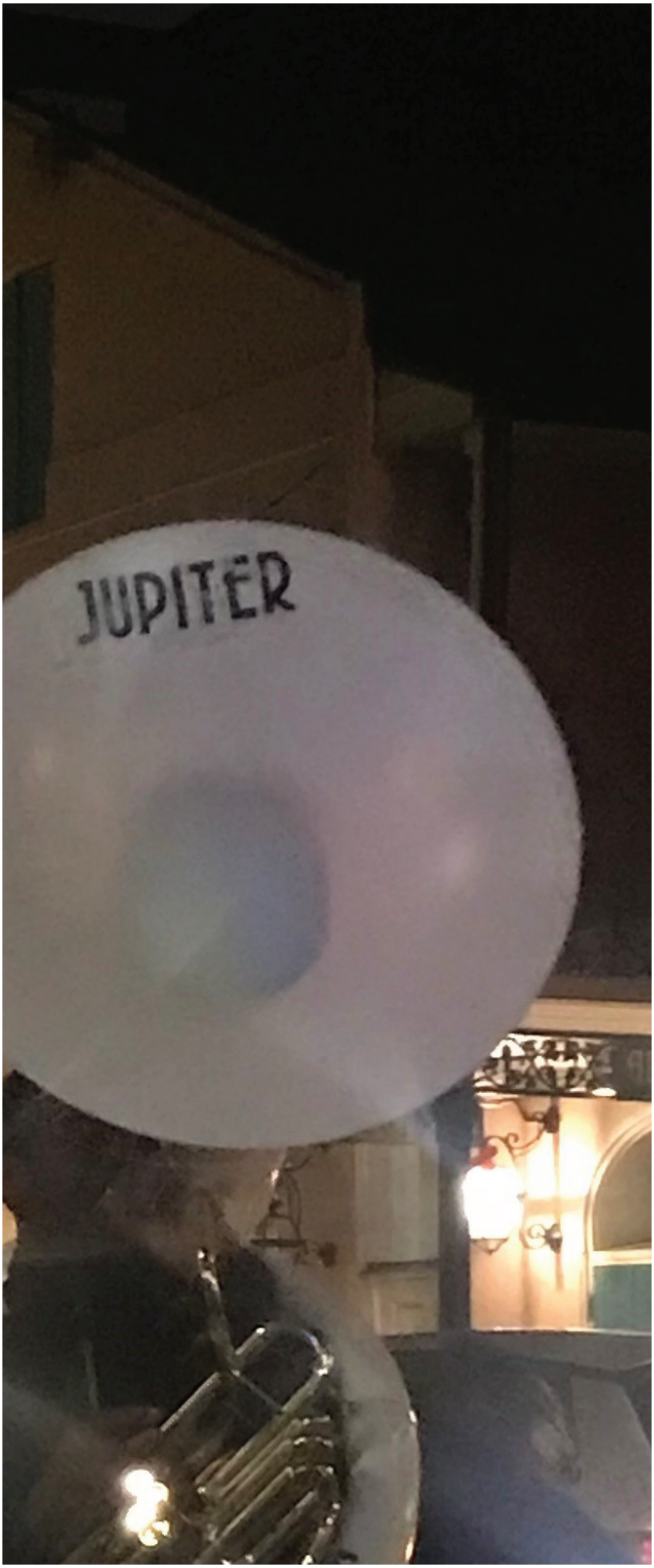
The uncertainty related to climate projections and measured data being high, our highly schematized one-dimensional model proves to be a useful, and computationally cheap tool to assess channel response at large spatio-temporal scales, for a wide range of scenarios.

Acknowledgments

This study is part of the research program Rivers2Morrow, financed by the Dutch Ministry of Infrastructure and Water Management. We thank Regina Patzwahl and Víctor Chavarrías for their help in understanding and modeling the system.

Data Availability

The input of our model is based on field data. Bed level data is accessible at *Quick et al.* (2019, German Rhine) and *Ylla Arbós et al.* (2021a, Dutch Rhine). Main channel width data is obtained from Google Earth (`https://earth.google.com/web/`). Floodplain width data is available from *BfG* (2020a). Grain size data is available on the SedDB database for Germany (*BfG*, 2020b), and at *Ylla Arbós et al.* (2023). Historical discharge data is available via *BfG* (2020c) and *Chowdhury et al.* (2023b). Water level data is available at `https://waterinfo.rws.nl`. Model input files and results are available at *Ylla Arbós et al.* (2023).



After almost two years of online meetings, it was finally possible to go to conferences again. I made it to AGU 2021 in New Orleans, which was another great experience. I was a bit worried about going alone to a conference with more than 10'000 people on-site, but Matt and Shelby put me in touch with their American friends and colleagues, and I also got to meet other people. Going alone to conferences is not so bad after all, you are more open to new things and connections. I was impressed at the amount of work that AGU puts into communicating science, and into making science more open and inclusive. We have some things to learn from our American colleagues in this regard. And New Orelans is such an eclectic city! Full of contrasts, but also full of light, music, and beautiful architecture. A truly inspiring place.

4

Large-Scale Channel Response to Erosion Control Measures

Key Points

- Erosion control measures locally reduce erosion or create wider navigation channels, but their large-scale effects are often not considered.
- These large-scale effects are upstream and downstream migrating waves of, respectively, reduced and enhanced incision.
- The response to multiple erosion control measures may interfere and amplify, depending on the spacing between them.

This chapter has been submitted for publication as:

Ylla Arbós, C., A. Blom, S.R. White, R. Patzwahl, & R.M.J. Schielen (submitted for publication). Large-scale channel response to erosion control measures.

In the previous chapters we investigated how climate change and human intervention affect channel response in the lower Rhine River. The most important feature of this response is domain-wide river bed incision. River managers have attempted to deal with river bed incision using different strategies. In this chapter, we consider erosion control measures, which prevent the bed from incising with the goal to mitigate channel bed incision, or increase the navigable width. First, we describe the different types of erosion control measures in the lower Rhine River. We then analyze field data on bed elevation, and set up a one-dimensional schematized numerical model to gain insight on the large-scale physics of erosion control measures. Finally, we assess how measures with different length and spacing affect the large-scale channel response.

Abstract

Erosion control measures in rivers aim to provide sufficient navigation width, reduce local erosion, or to protect neighboring communities from flooding. These measures are typically devised to solve a local problem. However, local channel modifications trigger a large-scale channel response in the form of migrating bed level and sediment sorting waves. Our objective is to investigate the large-scale channel response to such measures. We consider the lower Rhine River from Bonn (Germany) to Gorinchem (the Netherlands), where numerous erosion control measures have been implemented since the 1980s. We analyze measured bed level data (1999-2020) around four erosion control measures, comprising scour filling, bendway weirs, and two fixed beds. To get further insight on the physics behind the observed behavior, we set up an idealized one-dimensional numerical model. Finally, we study how the geometry and spacing of the measures affect channel response. We show that erosion control measures reduce the sediment flux due to (1) lack of erosion over the measure and (2) sediment trapping upstream of the measure, resulting in downstream-migrating incision waves that travel tens of kilometers at decadal timescales. When the measures are in close proximity, their downstream effects may be amplified. We conclude that, despite fulfilling erosion control goals at the local scale, erosion control measures may worsen large-scale channel bed incision.

4.1. Introduction

Rivers erode and aggrade in response to natural and anthropogenic change (*Blom et al.*, 2016; *De Vriend*, 2015; *Mackin*, 1948). Such erosion and deposition may hinder navigation and increase flood risk (*Ylla Arbós et al.*, 2021b; *Hiemstra et al.*, 2020; *Habersack et al.*, 2016; *Buijse et al.*, 2002). For example, erosion pits may cause locally high flow velocities, which hampers navigation (*Guan et al.*, 2014), and spatial variation in erosion rates may lead to locally reduced flow depths, which limits the amount of cargo that ships can transport, especially at low flows (*Ylla Arbós et al.*, 2021b; *Hiemstra et al.*, 2020). Excessive deposition may decrease the conveyance capacity of river channels and increase flood risk (e.g., *Ahrendt et al.*, 2022), or reduce the navigable width at channel bends, as eroded sediment from the outer bend deposits in inner bends (*Havinga*, 2020).

Various measures have been implemented to control channel erosion around the world. Grade-control structures, ground sills or weirs made of different materials and setups are commonly installed to mitigate incision in high-gradient rivers. A non-exhaustive list includes examples in the United States (*Simon and Darby*, 2002), Japan (*Yasuda*, 2021), Taiwan (*Lin et al.*, 2008), Poland (*Korpak et al.*, 2021), Austria (*Stephan et al.*, 2018; *Habersack and Piégay*, 2007), Italy (*Lenzi et al.*, 2003), Serbia (*Kostadinov et al.*, 2018), and the Czech Republic (*Galia et al.*, 2016). Other measures include bottom groynes (*Xu et al.*, 2023; *Alexy*, 1995; *Sanyal*, 1991); the artificial supply of sediment to increase the sediment supply or fill erosion pits (*Czapiga et al.*, 2022a; *Frings et al.*, 2014b; *Gaeuman*, 2012); and the installation of rip-rap layers or fixed beds (*Havinga*, 2020; *Sloff et al.*, 2006) and bendway weirs (*Havinga*, 2020; *Jia et al.*, 2009; *Abad et al.*, 2008) to increase the navigable width.

Erosion control measures are generally aimed at solving a problem locally (i.e., at scales of tens of meters to few kilometers). In the case of large-scale incision, multiple measures are carried out along the basin (e.g., *Frings et al.*, 2014b; *Simon and Darby*, 2002). Detailed feasibility studies and tests of different variants are conducted, often limited to numerical simulations and scale models, with the aim to find the solution that most effectively meets the specific erosion control goal (e.g., *Xu et al.*, 2023; *Jia et al.*, 2009; *Sloff et al.*, 2006; *Bormann and Julien*, 1991). However, the potential large-scale effects of such measures (i.e., considering scales of tens of kilometers or more) are often disregarded.

Erosion control measures constitute a change to the channel characteristics, for instance, a change in channel geometry, grain size, roughness, or sediment supply. Channels respond to such changes through upstream- and downstream-migrating aggradation and incision waves (*Lin et al.*, 2023; *Chowdhury et al.*, 2023a; *Martín-Vide et al.*, 2020; *An et al.*, 2019; *De Vriend*, 2015; *Madej and Ozaki*, 1996). Depending on the magnitude and spatial extent of the change, channel response may develop over centuries and extend over hundreds of kilometers (e.g., *Ylla Arbós et al.*, 2021b; *Yang et al.*, 2018; *Simon and Rinaldi*, 2006; *Surian and Rinaldi*, 2003). Consequently, the side effects of interventions may negatively affect areas elsewhere in the basin. Examples range from sediment starvation in deltas due to upstream dams (e.g., *Bussi et al.*, 2021; *Rao et al.*, 2010; *Hu et al.*, 2009; *Syvitski et al.*, 2005), to local erosion pits of different depths downstream of erosion control measures (*Czapiga et al.*, 2022b; *Korpak et al.*, 2021; *Kostadinov et al.*, 2018; *Lenzi et al.*, 2003).

Here we consider the lower Rhine River, the 300-km reach of the Rhine River between Bonn (Germany) and Gorinchem (the Netherlands), where numerous erosion control measures have been undertaken since the 1980s (Figure 4.1). The lower Rhine River is the most important inland waterway in Europe, as it connects the continent with major shipping routes overseas via the port of Rotterdam (*Christodoulou et al.*, 2020). The Rhine has been heavily engineered and intensely monitored to ensure reliable navigation and protect populations from floods (*Ylla Arbós et al.*, 2021b; *Quick et al.*, 2019; *Frings et al.*, 2014b). Past channelization measures in the lower Rhine River have led to meters of river bed incision over hundreds of kilometers over the past century (*Ylla Arbós et al.*, 2021b; *Quick et al.*, 2019; *Frings et al.*, 2014b). Current incision rates range between 0-2 cm/a (*Ylla Arbós et al.*, 2021b). To mitigate this incision and to maintain the navigation channel, numerous interventions have been carried out, ranging from sediment nourishments, to scour filling measures, bendway weirs, longitudinal training walls, and fixed beds (*Czapiga et al.*, 2022b,a; *Ylla Arbós et al.*, 2021b; *Havinga*, 2020; *Quick et al.*, 2019; *Frings et al.*, 2014b).

In this study, we focus on three types of erosion control measures: scour filling, bendway weirs, and fixed beds (Figure 4.1). All these measures fix (a part of) the river bed, resulting in zones of locally reduced sediment mobility. Our objective is to assess the large-scale channel response to such measures in terms of bed level change. To this end, we first characterize the different types of measures (Section 4.2). We then analyze the local effects measures at four field sites, based on detailed bathymetric data over the period 1999-2020 (Section 4.3). Subsequently, we investigate the large-scale channel response to the measures by analyzing the propagation of bed level waves that appear after their construction (Section 4.4). To conceptualize the physics of the large-scale response, we set up an idealized one-dimensional numerical model that simulates channel response to an erosion control measure (Section 4.5). Finally, we assess the effects of the length and spacing of erosion control measures on channel response (Section 4.6).

4.2. Erosion Control Measures in the Lower Rhine River.

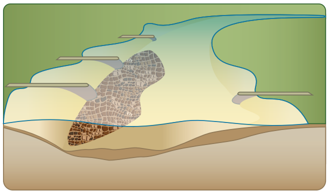
Despite having different configurations and goals, erosion control measures share a number of characteristics. The most important ones are the reduction of sediment mobility (which limits or prevents incision at the measure itself), and the increase of hydraulic roughness given the larger size of the material of the measures, or their protrusion onto the river bed. In this section we describe the three types of measures deployed in the lower Rhine River (Figure 4.1): (1) scour filling (*Frings et al.*, 2014b); (2) bendway weirs (*Havinga*, 2020); and (3) fixed beds (*Havinga*, 2020).

Scour filling measures aim to mitigate local scour. These measures have been carried out since the 1980s and are widespread in the Niederrhein (*Frings et al.*, 2014b, Figure 4.1). Specifically, coarse sediment with a diameter of 4-150 mm is dumped in scour holes to fill them, and then covered with a top layer of finer material, to avoid large variations in roughness (*Decker*, 2014). This top layer is only slightly coarser than the surrounding bed surface sediment, which has a geometric mean grain size of 15-20 mm (*Frings et al.*, 2014b; *Ylla Arbós et al.*, 2021b).

Fixed beds and bendway weirs have been used in the Waal since the 1980s. They are installed in the outer parts of river bends to increase the navigable width in relatively sharp bends (*Havinga*, 2020). Fixed beds consist of a layer of boulders of 10-400 kg (rip-rap), which is placed on top of a finer filter layer (Figure 4.1). Bendway weirs are partial dams constructed on the river bed, made of boulders of 60-300 kg, placed on top of a filter layer.

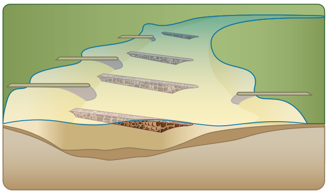
Bendway weirs are not to be confused with bottom groynes (Figure 4.1). Despite having

Scour filling



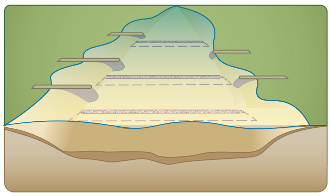
Material: sediment of 4-150 mm

Bendway weirs



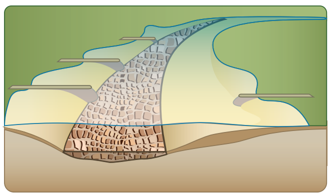
Material: boulders of 60-300 kg

Bottom groynes

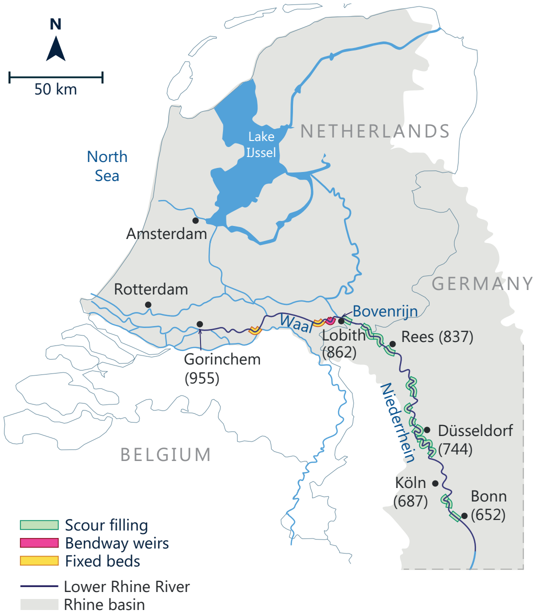


Material: boulders of 60-300 kg

Fixed beds



Material: boulders of 10-200 kg



Installation	River km	Type	Purpose
1970	658.0-660.0	Scour filling	Erosion control
1998-1999	664.7-665.8	Scour filling	Erosion control
2001	666.5-668.2	Scour filling	Erosion control
1995-1996	670.0-672.4	Scour filling	Erosion control
1994-1996	714.0-716.1	Scour filling	Erosion control
1985-1987	721.8-725.1	Scour filling	Erosion control
1992-1993	732.0-733.4	Scour filling	Erosion control
1990-1991	741.1-742.8	Scour filling	Erosion control
1990-1991	743.2-745.6	Scour filling	Erosion control
2002-2003	752.0-753.0	Scour filling	Erosion control
1987-1990	764.4-766.7	Scour filling	Erosion control
1993-2002	778.9-781.5	Scour filling	Erosion control
1987-1992	784.9-788.0	Scour filling	Erosion control
1989-1990	789.2-790.8	Scour filling	Erosion control
1993-2010	820.0-824.9	Scour filling	Erosion control
1998-2003	832.0-837.7	Scour filling	Erosion control
1994-1996	841.7-843.7	Scour filling	Erosion control
1995-1998	847.3-849.0	Scour filling	Erosion control
2002-2007	850.5-857.2	Scour filling	Erosion control
2014	858.1-861.8	Scour filling	Erosion control
1994-1996	873.2-876.0	Bendway weirs	Increase navigable width
1985-1988	883.1-885.1	Fixed bed	Increase navigable width
1997-1999	925.0-928.1	Fixed bed	Increase navigable width

Figure 4.1: Erosion control measures in the lower Rhine River, with details on their installation period, location, type, and main purpose.

similar structural characteristics, bottom groynes aim to limit channel bed incision (e.g., *Xu et al.*, 2023; *Alexy*, 1995), by preventing the water level to drop below a certain threshold. Bottom groynes can be found, for instance, in the Elbe River, both at a river bend and in an incising straight reach downstream from a bedrock reach (*Alexy*, 1995).

There are two fixed beds in the lower Rhine River: one at the river bend in Nijmegen (river km 883.1-885.1, Figure 4.1) and one at the bend in Sint Andries (river km 925-928.1, Figure 4.1). The fixed bed in Nijmegen was installed in 1985-1988. It extends over two kilometers along the gravel-sand transition zone of the lower Rhine River, where the geometric mean grain size of the channel bed ranges between 3-5 mm. The measure is placed in the outer bend of the river and is 160-180 m wide. It consists of a 50 to 75 cm thick layer of 10-60 kg boulders lying on top of a 40 cm thick filter layer made of gravel sized 20-180 mm (*Franssen*, 1995).

The fixed bed at Sint Andries extends over three kilometers, and is located at the sandy reach of the lower Rhine River (geometric mean grain size around 1 mm). In this area, the channel has aggraded (around 2 cm/a) over the past 20 years (*Ylla Arbós et al.*, 2021b). The measure was constructed in the period 1997-1999, ten years after the one in Nijmegen, which allowed for modification based on the experiences with the latter (*Leeuwestein*, 1996). To prevent instability of individual stones, a 80 cm thick layer of heavier boulders (40-200 kg) was installed on top of a 40 cm thick filter layer made of coarse gravel (40-100 mm, *Leeuwestein*, 1996). The measure was placed in the outer bend of the river, and has a width of 140 m.

Bendway weirs were constructed at the river bend in Erlecom in 1994-1996 (river km 873.2-876, Figure 4.1). Despite pursuing the same goal as fixed beds (i.e., increasing the navigable width in relatively sharp bends), a different design was chosen under concerns that a fixed-bed type of measure would create undesirable backwater effects at the Pannerden bifurcation (Figure 4.1). The bendway weirs at Erlecom consist of 54 partial dams installed on the river bed, spaced by 50 m, at an angle of 67.5 degrees relative to the thalweg (*Van Amerongen*, 1997). The dams are between 1.80 and 2.80 m high.

Fixed beds and bendway weirs have the same working principle related to flow dynamics in bends. Specifically, bend curvature is associated with a centrifugal force that directs fluid toward the outer bend, leading to a superelevation of the water surface at the outer bend (*Rozovskii*, 1957; *Azpiroz-Zabala et al.*, 2017). The resulting flow depth difference between the outer and inner bends leads to a transverse gradient in water pressure. The imbalance between these two forces (i.e., the centrifugal force directed to the outer bend, and the pressure gradient directed towards the inner bend) results in a transverse flow circulation characterized by the near-surface fluid flowing toward the outer bend, and the near-bed fluid flowing toward the inner bend (e.g., *Thorne et al.*, 1985; *Azpiroz-Zabala et al.*, 2017). This transverse flow pattern is superimposed to the streamwise flow, resulting in a helical flow pattern (*Rozovskii*, 1957; *Thorne et al.*, 1985).

Helical flow circulation affects the direction of sediment transport. In rivers where sediment transport is bedload-dominated, the direction of sediment transport is mostly determined by the near-bed flow, and therefore predominantly directed from the outer bend to the inner bend (*Van der Mark and Mosselman*, 2013; *Sloff and Mosselman*, 2012). As a result, outer bends tend to be deeper than inner bends (*Edwards and Smith*, 2002). A shallow inner bend may reduce the available channel width for navigation (*Havinga*, 2020; *Sloff* *et al.*, 2006).

Fixed beds and bendway weirs change the helical motion of the flow. By increasing and fixing the bed level at the outer bend, they direct a larger fraction of the flow towards the inner bend. As a result, the inner bend becomes deeper and the navigation channel widens (*Havinga*, 2020).

4.3. Local Channel Response to Erosion Control Measures

Here we analyze the local channel response to four erosion control measures belonging to the three categories described in Section 4.2, namely the scour filling measure at Spijk (river km 858.1-861.8), the fixed beds at Nijmegen (river km 883-1-885.1) and Sint Andries (river km 925.1-928), and the bendway weirs at Erlecom (river km 873.2-876). We select these case studies given the availability of detailed bathymetric data in the area. These data consist of multibeam echo-soundings with a resolution of 1x1 m^2 over the period 1999-2020 (Figure 4.2).

The scour filling measure at Spijk is 4 km long and has a variable width ranging from 30 to 100 m (Figure 4.2a). Its main purpose is erosion mitigation, though a secondary aim to increase navigable width has been reported. The measure is installed at the outer side of a mild bend, which is somewhat deeper than the inner bend. The measure itself is not clearly visible on the bathymetry map (Figure 4.2a), which is likely due to (a) the use of a relatively similar material as the surrounding river bed, and (b) the fact that the measure does not protrude, which may be related to its recent installation (2014) and to the non-erosional character of the surrounding river bed.

Figure 4.3a shows the temporal change in bed level at a cross-section located at river km 861.1, where the width of the stabilization measure is maximal. The cross-sectional profiles show that the measure has so far been successful in achieving its primary and secondary goals. On the one hand, the scour hole has been filled, and bed level has remained stable since its construction in 2014. On the other hand, the inner bend has incised, increasing the navigable width. Figure 4.3e shows a series of longitudinal bed level profiles taken 85 meters from the centerline of the river, over the fixed bed. The profiles show a sudden increase in bed level in 2014, when the scour hole was filled. The river bed has remained stable over the fixed bed since then. Downstream of the measure, a 1.5 m deep and 500 m long scour hole has developed, and seems to slightly migrate downstream with time.

For the bendway weirs at Erlecom, the two-dimensional bathymetry clearly shows the extent of the measure and the disposition of the weirs (Figure 4.2b). The measure extends over three kilometers in an outer bend, and covers slightly more than half of the cross-section. Directly upstream of the weirs the bed is relatively shallow. Downstream, the left bank is substantially deeper than the right bank.

Based on the temporal change of bed level at a cross-section approximately in the middle of the whole measure (river km 874.6, Figure 4.3b), we can affirm that the bendway weirs are successful in achieving their goal of increasing the navigable width through deepening the inner bend. In particular, the inner bend has systematically degraded at a rate of about 7 cm/a over the past 20 years, which is larger than the 20-year reach-averaged degradation rate of about 1.7 cm/a. The transverse profiles also show aggradation on the outer bend, indicating that sediment is deposited in-between weirs (Figure 4.3b). In the longitudinal direction, a profile measured 65 meters from the centerline (Figure 4.3f) reveals a double 2

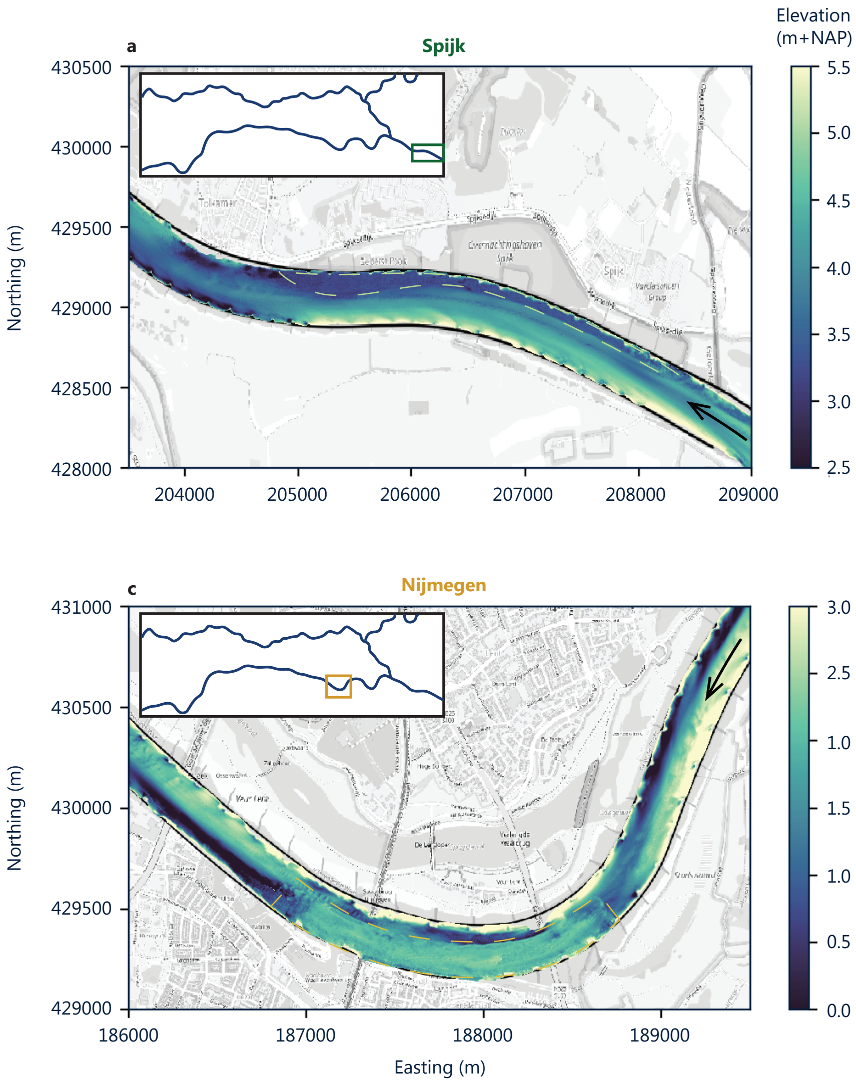
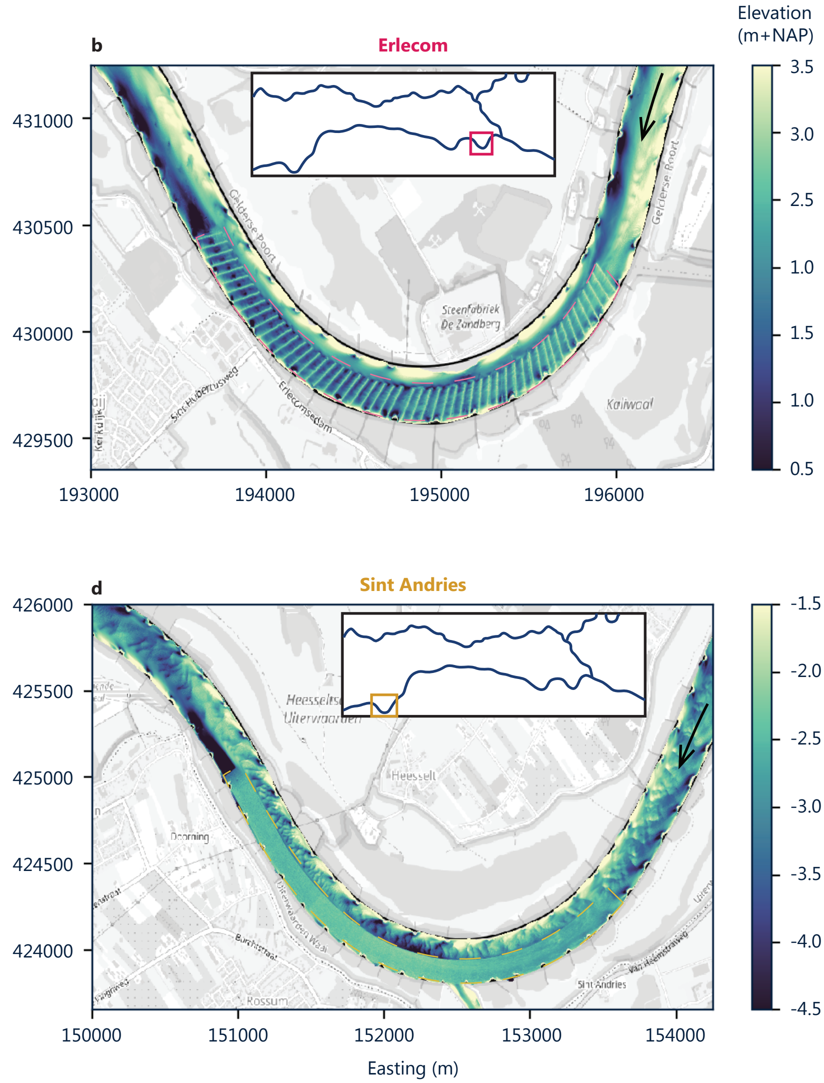


Figure 4.2: Two-dimensional bathymetry maps of the erosion control measures at (a) Spijk (river km 858.1-861.8, scour filling), (b) Erlecom (river km 873.2-876, bendway weirs), (c) Nijmegen (river km 883-1-885.1, fixed bed), and (d) Sint Andries (river km 925.1-928, fixed bed). Dashed lines on each map show the extent of the measures. All the maps show data from 2020.


b
Erlecom
Elevation
(m+NAP)
3.5
3.0
2.5
1.0
1.5
1.0
0.5
431000
430500
430000
429500
193000
194000
195000
196000
Gelderse Poort
Steenfabriek
De Zandberg
Kaiwaal
Erlecomsedam
d
Sint Andries
426000
425500
425000
424500
424000
-1.5
-2.0
-2.5
-3.0
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Heesselt
Rossum
Sint Andries
150000
151000
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153000
154000
Easting (m)

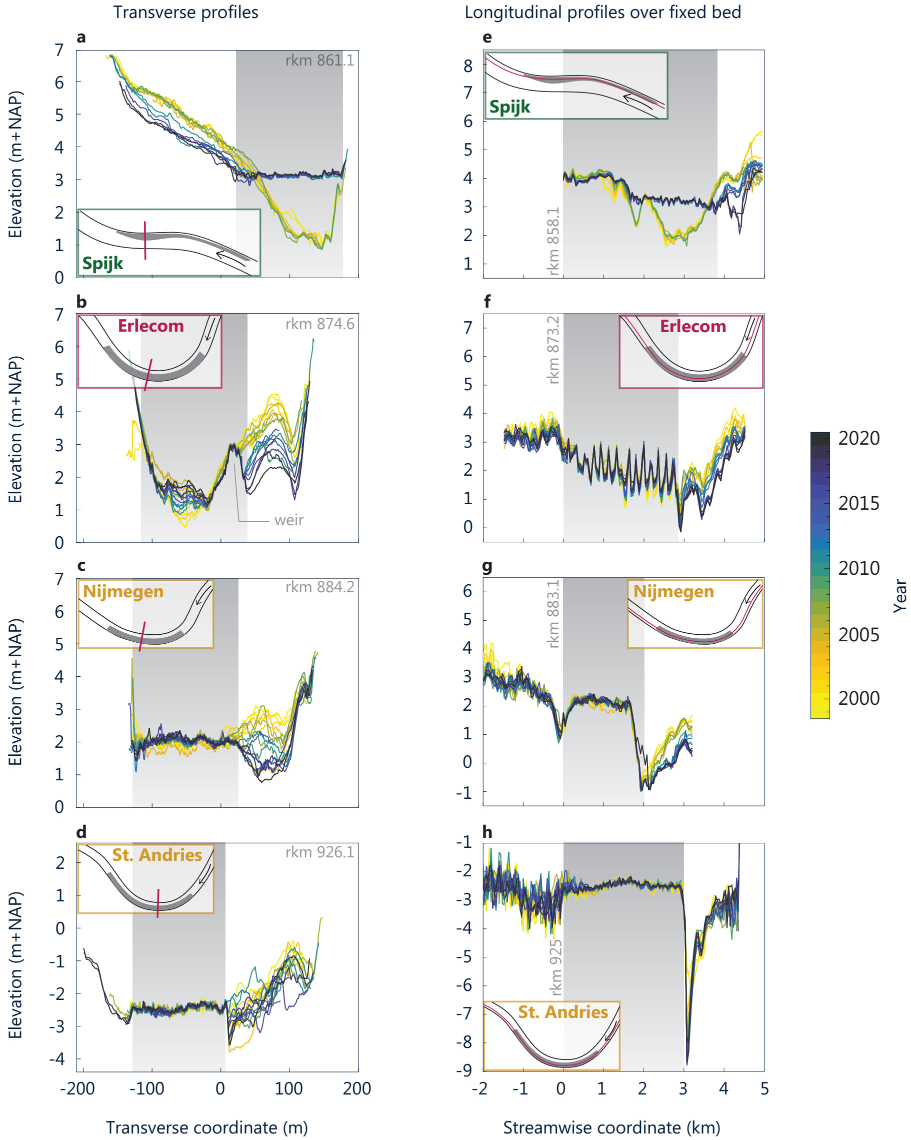

Figure 4.3: Temporal change in bed level around the erosion control measures over the period 1999-2020: respectively, transverse and longitudinal profiles at Spijk (a,e), Erlecom (b,f), Nijmegen (c,g), and Sint Andries (d,h). The 0 coordinate in the transverse and longitudinal profiles refers to, respectively, the centerline of the river and to the upstream end of the fixed bed. Negative transverse coordinates correspond to the left (south) bank. Longitudinal profiles are measured at 85 m from the centerline for Spijk, and 65 m from the centerline for the remaining measures. The river km on the transverse and longitudinal profiles corresponds to, respectively, the measured cross section and to the upstream end of the fixed bed. Shaded gray areas highlight the extent of the fixed bed. All the transverse profile plots have the same aspect ratio but different absolute bed levels. The same holds for the longitudinal profiles.

m deep erosion pit downstream of the fixed bed that extends over 1 km. The pit migrates downstream with time.

Figure 4.2c shows the two-dimensional bathymetry around the fixed bed at Nijmegen. The fixed bed is shallower than the surrounding channel bed, indicating protrusion of the fixed bed. This protrusion is due to large-scale channel bed incision, at an average rate of about 1.5 cm/a in Nijmegen over the past 20 years. Despite the intended non-erodability of the fixed bed, Figure 4.2c reveals lower bed levels at the upstream and downstream ends of the measure. This could be due to boulder displacement (especially at the downstream end, where boulders may fall into the erosion pit) or due to mechanical removal of the most protruding boulders in 2020 (*Rijkswaterstaat*, 2020). *Franssen* (1995) reports instabilities at the lateral edges of the fixed bed, which are potentially due to locally smaller thickness of the top layer and heavy loading from ship manoeuvres.

The surface of the fixed bed does not appear to be smooth, which could indicate some alluvial cover on the measure (Figure 4.2c). Cross-sectional profiles measured halfway along the fixed bed (river km 884.2, Figure 4.3c) seem to confirm this alluviation. These profiles also show significant bed erosion in the inner bend over time. Bed incision rates at the inner bend were about about 5 cm/a until 2010, and 3.5 cm/a since then. These rates are larger than the 20-year 5 km reach-averaged degradation rate of 1.5 cm/a and indicate success in achieving the intended goal of increasing the navigable width.

Figure 4.2c shows a long erosion pit downstream of the fixed bed at Nijmegen. Figure 4.3g shows that the pit is about 3 m deep, and has migrated downstream with time. The protrusion of the fixed bed from the surrounding channel bed (Figure 4.3g) has caused numerous problems to navigation (*Havinga*, 2020). In addition, Figure 4.3g shows some slight aggradation over the fixed bed during the early 2000s, which may be associated to a temporary aggradation wave.

The fixed bed at Sint Andries shows a smoother surface than the one at Nijmegen (compare Figures 4.2d and 4.2c). Near the Sint Andries fixed bed, we observe relatively large bedforms (about 20-80 m long and 1 m high). This may be due to the sandy nature of the river bed at Sint Andries. The inner bend appears deeper than the outer bend, especially halfway along the fixed bed (Figure 4.3d). We also observe a deep pit downstream of the fixed bed (Figure 4.3h).

The transverse profiles (Figure 4.3d) show a stable and smooth surface of the fixed bed in the outer bend, which is shallower than the inner bend. Gradual bed erosion in the inner bend is less obvious than in other measures, which may be due to the presence of migrating bedforms. This bedform-induced noise is also observed in Figure 4.3h, upstream from the fixed bed.

At the upstream end of the fixed bed, some alluvial cover is visible, indicating that some sediment may be transported onto the upstream end of the fixed bed, and then directed toward the inner bend due to the helical flow. A deep erosion pit (over 6 m deep) is present downstream of the fixed bed (Figure 4.3h). The pit is shorter, advances more slowly in the downstream direction, and shows a faster incision rate than the pit downstream of the fixed bed at Nijmegen (Figure 4.3g). A reason for these differences seems to be the finer bed surface sediment at Sint Andries (*Ylla Arbós et al.*, 2021b).

The continued incision of the pit can likely be attributed to two-dimensional effects (i.e., the flow in the inner bend being increasingly attracted toward the erosion pit, deepening it with time). This may be analogous to the two-dimensional effects observed downstream of the storm surge barrier in the Eastern Scheldt estuary in the Netherlands (*Broekema et al.*, 2018).

4.4. Large-Scale Channel Response to Erosion Control Measures: Insights from Measured Data

In Section 4.3 we have shown that the different erosion control measures have succeeded in achieving their intended goals (i.e., erosion mitigation or widening of the navigation channel). Yet we have also observed some unintended side effects, namely erosion pits of variable depths and lengths downstream of the measures. These pits seem to migrate downstream in the form of an incision wave. In this section we focus on the large-scale dynamics of these waves.

Even though many of the erosion control measures are installed on river bends and their dynamics are influenced by two-dimensional flow features, a one-dimensional analysis provides order-of-magnitude insight on the large-scale effects. Specifically, we focus on the (conceptual) large-scale stream-wise propagation of incision waves associated with erosion control measures, which is expensive to compute in two dimensions. To this end we analyze a space-time plot of the cross-sectionally averaged measured bed level relative to 1980 (before any of the measures were installed) until 2020, averaged over 2 km in the longitudinal direction (Figure 4.4a). Bed level in 1980 is defined as the average of a three-year period (1979-1981) to avoid too strong a dependency on the specific initial state associated with bedforms or temporary sediment waves. Data prior to 1999 are obtained with single beam echo-soundings (see *Ylla Arbós et al.* (2021b) for further details on data collection and pre-processing).

As the Spijk bed stabilization measure is too recent to recognize any large scale trends (given the multi-decadal timescales of channel response), we focus on the bendway weirs at Erlecom and the fixed beds in Nijmegen and Sint Andries. Figure 4.4a reveals downstream-migrating incision waves after construction of the different erosion control measures, especially the fixed beds at Nijmegen and Sint Andries. Downstream of Erlecom, no clear incision wave is visible.

At the upstream end of the study reach (down to river km 885), we notice an area of more intense incision (Figure 4.4a). This incision area and the associated wave are related to the Pannerden bifurcation (river km 867.5), where larger incision rates have been reported, possibly reflecting instability of the bifurcation (*Chowdhury et al.*, 2023a).

The 5-year aggradation rates over the period 1980-2020 (Figure 4.4b) give additional information on the shorter-term dynamics of the bed level waves. Interestingly, the aggradation rates show that the incision wave is followed by an aggradation wave of the same celerity. These aggradation waves indicate deposition of sediment in the erosion pits, which implies that (part of the) response is a temporary effect. This is particularly visible for the fixed beds in Nijmegen and Sint Andries, and less so for Erlecom.

After establishing that bed level waves appear upon construction of the fixed beds, we take a closer look at Figure 4.4a by zooming in on space-time windows of 50 km by 25 years (Figures 4.4c-e). Here we set the initial state to (the average of) two years prior to the construction of each measure to focus on the response to the measure itself.

The downstream effects of the bendway weirs at Erlecom (Figure 4.4c) are mild. There is a sign of a mild wave that travels some 18 km in 10 years (celerity of 1.8 km/a), although this wave may also be related to the bifurcation. Some slight aggradation can be observed at the location of the weirs, which seems to be due to trapping of sediment between the weirs. Mild aggradation is noticeable upstream of the measure after its construction. The 5-year aggradation rates may suggest an upstream-migrating aggradation wave (Figure 4.4b).

Figure 4.4d shows a downstream-migrating incision wave downstream of the fixed bed at Nijmegen. Over a period of 10 years, the wave has migrated about 15 km in the downstream direction, which implies a celerity of 1.5 km/a. The migrating pit seems to be partially filled with time. Here we also see deposition on the fixed bed, especially in the first five years after its construction. We notice a zone of reduced incision upstream of the fixed bed, especially over the period 1985-1995. There is no data in 1994 between river km 857-885.

A downstream-migrating incision wave also appears downstream of the fixed bed at Sint Andries (Figure 4.4e). This wave has advanced about 12 km in 10 years (celerity of 1.2 km/a) and has been followed by a deposition wave. The area around Sint Andries shows very mild incision rates and even some aggradation, already prior to the construction of the fixed bed. Aggradation on top of the fixed bed as well as upstream of it is identified on Figures 4.4b and 4.4e.

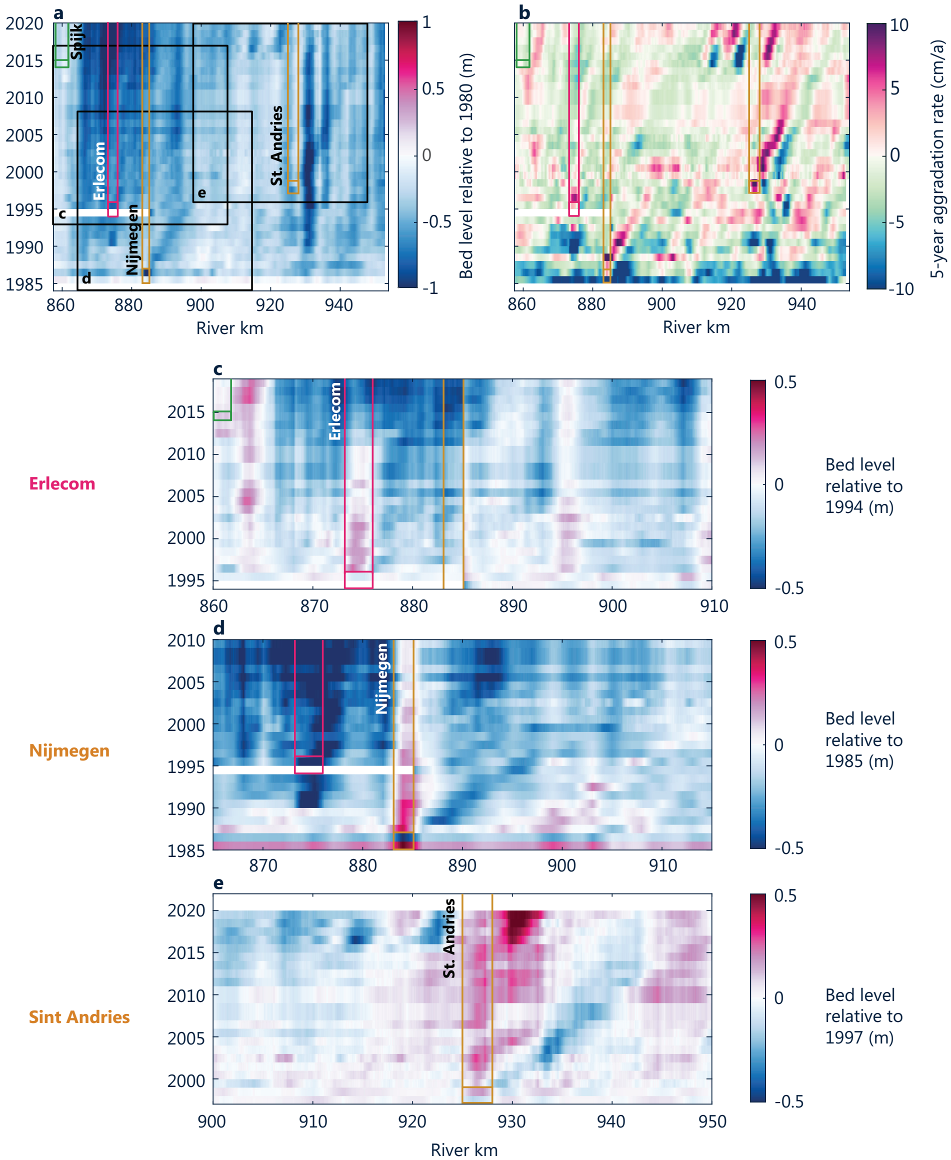

Figure 4.4: Space-time plots of bed level change and aggradation rates in the study area. (a) Bed level relative to 1980; (b) 5-year aggradation rates; (c) bed level relative to 1994 at the vicinity of Erlecom; (d) bed level relative to 1985 at the vicinity of Nijmegen; (e) bed level relative to 1997 at the vicinity of Sint Andries. Vertical lines on all plots represent the location of the erosion control measures, with the box at the bottom of the lines indicating the construction period. Bed levels are averaged over 2 km. The initial bed level on each plot is averaged over 3 years. The large boxes on plot (a) indicate the extent of plots (c-e). Note the different scaling of the color bar between plot a and plots (c-e).

4.5. Large-Scale Channel Response to Erosion Control Measures: Insights From Numerical Simulations

Measured data on bed level around the erosion control measures suggest that such measures are associated with a large-scale channel response. Specifically, we notice a downstream-migrating incision wave propagating from the downstream end of the measure, and a zone of slightly reduced incision upstream of the measure. Yet the measured data does not allow for identifying channel response to solely the erosion control measures. This is because these data reflect channel response to the combination of numerous interventions, climate change, and natural variability of the system.

To better understand the physics of this large-scale response, we set up an idealized one-dimensional numerical model. Numerical simulations allow for comparison with a base case without erosion control measures, which is more difficult in the field. In addition, an idealized model allows us to limit the variability of channel characteristics, such that we can better isolate the effects of an erosion control measure.

We use the numerical code Elv (*Blom et al.*, 2017b; *Chavarrías et al.*, 2019), which is suitable for mixed-size sediment morphodynamics. Flow is computed by solving the backwater equation, changes in bed elevation are computed using the *Exner* (1920) equation, and changes in the bed surface grain size distribution are computed with the *Hirano* (1971) active layer model, regularized to avoid ill-posedness following *Chavarrías et al.* (2019). We model erosion control measures as non-erodible reaches, in particular by using a sediment size that is sufficiently large to be immobile under all flow conditions. We use the approach of *Chavarrías et al.* (2022, specifically the ILSE model), as the *Hirano* (1971) model does not provide realistic results with immobile sediment under aggradational conditions.

We consider an active layer of 1 m (e.g., *Arkesteijn et al.*, 2021), and a constant Chézy friction coefficient of 32 $m^{1/2}/s$ (e.g., *Arkesteijn et al.*, 2019). As a closure relation we use the *Meyer-Peter and Müller* (1948) sediment transport relation, and we include hiding effects following *Egiazaroff* (1965). All model assumptions are detailed in *Chavarrías et al.* (2019).

We consider a 200 km long rectangular channel in equilibrium, which we subject to narrowing to half its width (from 500 m to 250 m) to create domain-wide incision. When the maximum incision rates are below 2 cm/a, which is comparable to conditions in the Rhine River (*Ylla Arbós et al.*, 2021b; *Quick et al.*, 2019), we install a 4 km long erosion control measure made of immobile sediment with a grain size of 85 mm. The model initial state corresponds to the moment where the measure is installed. We run the model for 50 years. The length of the modeled erosion control measure is of the same order as the measures in the lower Rhine River. Note that by using a one-dimensional model, the erosion control measure is assumed to occupy the full width of the channel.

We consider four cases in order to understand the effects of grain size and variable flow: (1) constant discharge - unisize sediment; (2) constant discharge - mixed-size sediment; (3) variable discharge - unisize sediment; and (4) variable discharge - mixed-size sediment. The constant discharge cases have a formative discharge of 3000 m^3/s, which corresponds to the dominant discharge of the hydrograph used in the variable discharge - unisize sediment case. By dominant discharge we refer to the constant discharge that, for a given sediment supply rate, leads to the same equilibrium channel slope as the natural hydrograph (*Blom et al.*, 2017a). For simplicity, we use the same discharge in the constant discharge - mixed-size sediment case, as the definition of the dominant discharge for a mixed-size sediment case is less straightforward (*Blom et al.*, 2017a). In the variable discharge cases, we use a 20-year cycled hydrograph which is equal to measured data at Köln (river km 640) over the period 1967–1986, and is statistically representative of the long-term discharge conditions of the lower Rhine River (*Ylla Arbós et al.*, 2023a).

For the unisize case, we adopt a sediment size of 11 mm, which corresponds to the geometric mean grain size of the mixed-size case. The latter consists of a gravel mixture of 6 and 15 mm in proportions of 30 and 70% in the substrate, respectively. This composition is loosely based on the characteristics of the gravel reach of the lower Rhine River (*Ylla Arbós et al.*, 2023a). The model bed surface composition has adjusted due to the narrowing (i.e., it has become slightly finer), though it remains coarser than the substrate sediment. Slight bed surface fining under conditions of narrowing-induced incision is explained by the fact that channel narrowing increases the flow velocity and bed shear stress, thereby reducing the mobility difference between the fine and coarse grains (*Blom et al.*, 2017a). Under these conditions, the bed surface does not need to coarsen as much to be able to transport the same sediment flux downstream.

The total annual sediment flux equals to 0.126 Mt/a following *Frings et al.* (2019). The composition of the flux is the same as the composition of the substrate (*Parker et al.*, 1982; *Parker and Klingeman*, 1982).

We analyze channel response relative to a base case without the erosion control measure, which responds to narrowing through channel bed incision. Figure 4.5a shows the spatio-temporal changes in bed level relative to the base case for the constant discharge-unisize case. Relative to the base case, the measure leads to a downstream-migrating wave of additional incision. Upstream of the measure, the bed elevation is higher than in the base case, which for our narrowing channel means reduced incision rather than net aggradation.

The reduced incision upstream of the erosion control measure can be partially explained by the presence of an M1 backwater curve, which leads to deceleration of the flow and a reduction of the sediment transport rate (*Czapiga et al.*, 2022a). This backwater curve is due to progressive protrusion of the measure as the surrounding channel bed incises. In addition, as the erosion control measure is immobile, the sediment flux over the measure is smaller than in the reference case, further reducing the flux downstream of the measure, relative to the reference case. The reduced sediment flux downstream of the measure, leads to the downstream-migrating incision wave (see also Appendix C, Figure C.1).

The incision wave has a celerity of about 2 km/a, which is in the same order of magnitude as the field data. In the field, the M1 backwater effects would be enhanced by the fact that the measure is coarser (i.e., rougher), which leads to a larger flow depth over the measure. The roughness effect is, however, not captured by our simulations given the constant friction coefficient.

In the presence of mixed-size sediment, we observe similar behavior (Figure 4.5b), with the exception of a downstream-migrating pit that is subsequently (partially) filled. This relatively deep part of the erosion wave is related to entrainment of fines from the substrate, as illustrated by the fining wave visible in Figure 4.5c. It is, however, difficult to assess whether the characteristics of the downstream-migrating pit are representative of field conditions or rather a consequence of the limitations of the *Hirano* (1971) model.

The fining wave is followed by a mild (almost negligible) coarsening wave (Figure 4.5c). This net coarsening is likely due to sediment trapping upstream of the erosion control mea-

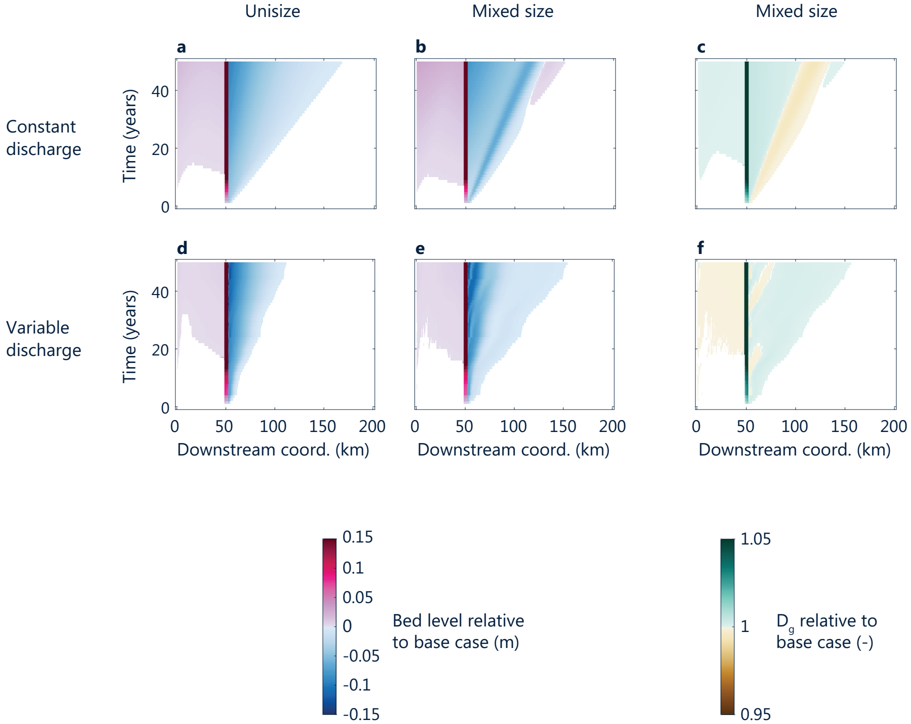

Figure 4.5: Space-time plots of simulated bed level change and bed surface grain size change due to an erosion control measure, relative to a base case without the measure: (a) constant discharge - unisize sediment; (b,c) constant discharge - mixed-size sediment; (d) variable discharge - unisize sediment; (e,f) variable discharge - mixed-size sediment.

sure, and non mobility of the measure, which limits the supply to the downstream reach. The resulting incision seems to preferentially entrain fine material from the surface, which consequently becomes coarser.

Upstream of the measure, the bed surface becomes slightly coarser with time. This seems to be related to the larger share of coarse material in the sediment flux, combined with the sediment trapping due to the M1 backwater curve.

In general terms, the behavior for the case with variable discharge and unisize sediment (Figure 4.5d) is similar to the constant discharge case. However, while the zone of decreased incision is smaller, the erosion pit is deeper, and the downstream-migrating incision wave is slower (about 1.2 km/a, compared to the 2 km/a of the other cases). The slower wave celerity is due to the variability of the water discharge, as this celerity depends on the water discharge (*Sloff and Mosselman*, 2012). Even though both the constant and variable discharge cases have the same forming discharge, larger discharges are more relevant to channel response and associated with a smaller propagation celerity.

A reason for the slightly reduced upstream sediment trapping in the variable discharge case (compare Figures 4.5d and 4.5a) may be the fact that the backwater effects are relatively less pronounced in the case of moderate and high flows than in the case of base flows. This is because the ratio of the protrusion-related bed level step height (which causes the M1 backwater curve) to flow depth is larger for base flows than for peak flows, making the latter relatively less effective at trapping sediment.

In the case of variable discharge and mixed-size sediment, we notice two types of incision waves: one that is faster and shallower, and one that is slower and deeper (Figure 4.5e). The faster and shallower wave may be associated with the presence of finer material, which moves faster in the downstream direction. Figure 4.5f shows slight general coarsening of the bed surface, which we attribute to the same reasons as that explain coarsening in the constant discharge - mixed-size case. We also notice two fining waves at about 10 and 30 years. These fining waves are associated with peak flows (see Figure C.2 in Appendix C), which lead to entrainment of fines from the substrate.

In contrast to the constant discharge case, in the variable discharge case the bed surface upstream of the measure becomes slightly finer. This may be due to the fact that upstream backwater effects are relatively more pronounced for base flows than for peak flows, making the first relatively more efficient at trapping sediment. The sediment transported by base flows is finer than the sediment transported by peak flows, resulting in slight net bed surface fining.

4.6. Length and Spacing of Erosion Control Measures

In this section we analyze the effects of length and spacing of erosion control measures on channel response. To this end, we consider a case with variable discharge and mixed-size sediment.

Figures 4.6a-4.6c show space-time plots of bed level relative to the base case for one erosion control measure with a length of 2, 4 and 8 km respectively, centered at the same location. We note that the longer the measure, the more pronounced the additional incision downstream. This can be explained, on the one hand, by the fact that a longer measure leads to stronger backwater effects. Upstream of the measure, the stronger backwater traps more sediment, further reducing the sediment supply to the downstream reach. On the other

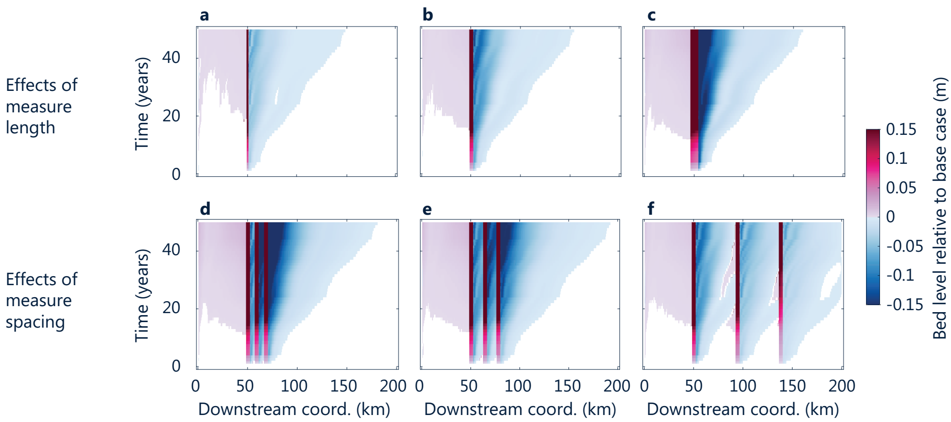

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Figure 4.6: Space-time plots of simulated bed level change relative to a base case without an erosion control measure, in variable discharge and mixed-size sediment conditions. The top row considers the effects of length, where the length of the erosion control measure is (a) 2 km, (b) 4 km, and (c) 8 km. The bottom row considers the effects of spacing, where three 4 km long erosion control measures are spaced (d) 5 km, (e) 10 km, and (f) 40 km.

hand, a longer measure reduces the sediment mobility over a longer reach, leading to a larger net reduction of the sediment flux at the downstream end of the measure relative to the reference case. This results in enhanced incision downstream of the erosion control measure (see also Figure C.3 in Appendix C).

To assess the effects of spacing, we model three erosion control measures of 4 km length, spaced 5, 10, and 40 km apart (Figures 4.6d-4.6f). The differences in upstream effects are negligible across configurations. However, the downstream incision is more pronounced when the measures are closer together. This is because the incision waves interfere and amplify. The case with the smallest fixed bed spacing (Figure 4.6d) largely resembles the case of one long measure (Figure 4.6c), as it creates an upstream backwater zone, and a zone of reduced sediment mobility similar to what a long erosion control measure would create (see also Figure C.4 in Appendix C).

4.7. Discussion

Our study shows that large-scale channel response to erosion control measures consists of enhanced and reduced incision downstream and upstream of the measures. The deep erosion pits downstream of fixed beds are particularly problematic, and illustrate the need for monitoring as well as opportunities for optimized installation and maintenance of the measures.

Problems are most pronounced for the fixed beds at Nijmegen and Sint Andries due to the continued large-scale incision of the surrounding bed. The increasing protrusion of these fixed beds repeatedly disrupts navigation during low flows. Water management authorities have considered reducing the surface elevation of these fixed layers by removing or scraping off their top layer. This would aid navigation thanks to the decreased protrusion of the fixed beds, and would lead to smaller backwater effects, hence reducing the additional downstream incision. This is because smaller backwater effects lead to less sediment trapping upstream of the erosion control measure and thus a smaller reduction of the sediment flux to the downstream reach. The latter results in less additional downstream incision.

However, a lower elevation of the fixed bed surface may be detrimental to the upstream reach. This is because fixed beds mitigate upstream erosion through backwater-related flow deceleration. This effect is generally overlooked. The reduction of the upstream backwater effects given by a lower elevation of the fixed bed surface results in less sediment trapping upstream of the fixed bed, which implies less erosion mitigation over the upstream reach or, depending on the specific conditions, even channel bed incision. Operations to reduce the fixed bed surface elevation may need to be repeated over time, if the large-scale channel bed incision that leads to fixed bed protrusion is expected to continue over the next decades (e.g., *Ylla Arbós et al.*, 2023a).

The erosion control measures in the Niederrhein have less unwanted effects than those in the Waal. On the one hand, the former are less prone to protrusion than the latter. A reason for this is the fact that water management authorities have succeeded in mitigating large-scale channel bed incision in the Niederrhein through a combination of scour filling measures and sediment nourishments (*Ylla Arbós et al.*, 2021b; *Frings et al.*, 2014b). Bed level change in the Niederrhein, however, has been milder than in the Waal since, at least, the 1960s, which is prior to scour filling and nourishment measures since the late 1980s (*Ylla Arbós et al.*, 2021b). This may be due to the coarser bed surface grain size and sediment flux in the Niederrhein, which may limit incision. On the other hand, erosion control measures in the Niederrhein consist of more numerous scour filling measures of smaller magnitude, whose characteristics more closely resemble those of the surrounding channel bed. The coarser sediment of the scour filling measures is covered with finer sediment similar to the surrounding bed surface sediment. Despite the erosion control measures in the Waal having different goals than those in the Niederrhein, it may be interesting to consider optimized geometries and materials for the fixed beds in the Waal, as this may help in mitigating their unwanted effects.

In our numerical simulations, erosion control measures cover the full cross section of the main channel (i.e., their effects are schematized in a one-dimensional manner). While some erosion control measures certainly cover the full cross section of the main channel, the measures in the lower Rhine River are installed in river bends and cover approximately half of the main channel width. Our one-dimensional modeling approach (i.e., accounting for variations in the streamwise dimension only) does not allow for considering the effects of helical flow, which plays an important role in river bends. Besides, it cannot capture two-dimensional erosion pit dynamics, such as potential localized deepening due to helical flow (*Broekema et al.*, 2018). Future research should focus on how these two-dimensional effects affect the large-scale channel response to erosion control measures.

4.8. Conclusions

Erosion control measures in the lower Rhine River aim to mitigate channel bed erosion or to increase the navigable width. While they have succeeded in achieving these goals, they show signs of unintended large-scale downstream effects, specifically in the form of downstream-migrating incision waves, which enhance the ongoing channel bed incision. These waves of additional incision have a celerity of about 1.5 km/a, and are more pronounced for the fixed-bed type of measures, such as the ones in Nijmegen and Sint Andries.

Erosion control measures trap sediment upstream due to backwater effects, related to protrusion of the measure and their increased roughness. This sediment trapping, combined with the non-erodability of the erosion control measure, reduces the flux of sediment to the downstream reach, resulting in a downstream-migrating incision wave. The reduction of sediment flux downstream of the measure and the magnitude of the associated downstream incision both scale with the length of the measure. When erosion control measures are placed close together, their downstream incision waves interfere and amplify.

These results shed light on the often-ignored large-scale effects of erosion control measures, which are traditionally planned with a local scope. Our findings suggest that while such measures may solve river management issues at local scale, they may worsen incision-related issues tens of kilometers away.

Acknowledgments

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Data Availability

Two-dimensional bathymetry data from the period 1999-2020 is available at *Ylla Arbós et al.* (2023b). We have used the transect extraction functions in `https://github.com/shelbyahrendt/transect-functions/tree/main` to extract longitudinal and transverse profiles from the two-dimensional bathymetry data. One-dimensional bed elevation data over the period 1980-2020 are accessible at *Ylla Arbós et al.* (2021a). Model simulations are performed with the code Elv (*Chavarrías et al.*, 2019), accessible at `https://oss.deltares.nl/web/riverlab-models/elv`.

In 2022 I got to go to Colorado for a short visit to CSDMS in Boulder, and a hiking week in the Rawah Wilderness and Rocky Mountain National Park. It was, once again, an incredible experience. CSDMS is such an open and curious community, and they are all so outdoorsy. We were only there for a short period, but we ended up camping together and sharing some deep moments. Thanks Astrid and Shelby for making that happen, Colorado has a special place in my heart.

5

Synthesis

We do not inherit the Earth from our ancestors;
we borrow it from our children.

American Indian proverb

In this chapter we reflect on the objective and research questions of this dissertation. To this end, we first answer the research questions that we initially posed (Section 5.1). We then discuss the possibilities for application of our findings (Section 5.2), as well as the implications of this research for river management (Section 5.3). Finally, we highlight opportunities for further research (Section 5.4), and conclude with a general reflection on river research and management (Section 5.5).

5.1. Project Conclusions

This dissertation aims to understand how human intervention and climate change affect channel response in the lower Rhine River at centennial timescales. We have articulated this objective with three research questions, which we answer below.

1. How has the lower Rhine River adjusted to past human intervention over the 20th century, in terms of change in bed level and bed surface grain size?

Through analysis of measured bed level data over the period 1898-2018, we show that the lower Rhine River has incised over its entire domain (from Bonn in Germany to Gorinchem in the Netherlands), with up to 5 m of incision over a century in some locations. The incision is mostly associated with channelization (narrowing) measures carried out during the 19th and 20th centuries, although we have not tried to unravel the relative effect of each of the potential causes of channel incision, as numerous interventions have been carried out over time and space, and the observed response is associated to the combination of these multiple interventions. The main channel slope has increased in the upstream part of the domain and decreased in the downstream part, resulting in an overall increase of profile concavity. A narrower channel has an increased flow velocity, which requires a smaller equilibrium channel slope to transport the same amount of sediment arriving from the upstream part of the basin. The upstream slope increase is an unexpected component of the channel response. We attribute this slope increase to the presence of bedrock at the upstream end of the domain.

Regarding the change of bed surface grain size, field data over the period 1966-2020 show that the lower Rhine River has become coarser and, importantly, that the gravel-sand transition of the Rhine River has migrated about 40 km downstream and flattened. The flattening is shown by an increase in length of the gravel-sand transition zone, from about 50 km in 1997 to about 90 km in 2020. We argue that this flattening is due to an increasingly reduced slope difference between the gravel and the sand reaches, which makes it easier for gravel particles to overtake the gravel front. The migration of the gravel-sand transition is a natural process, though it is potentially enhanced by the nourishment of coarse sediment at the downstream end of the Niederrhein.

2. How does the lower Rhine River adjust to climate change over the 21st century, in terms of change in bed level and bed surface grain size?

Climate change affects the controls of the lower Rhine River, namely the river hydrograph, sediment flux from the upstream part of the basin, and base (sea) level. Climate scenarios predict higher peak flows and lower base flows, as well as increased rates of sea level rise. Sediment fluxes are highly uncertain (40-150%), and we have hypothesized that this uncertainty is larger than potential climate-related changes to the flux.

With a highly schematized numerical model, we have assessed how these projected changes in the river controls affect channel response over the 21th century. We have shown that climate forcing enhances the ongoing channel bed incision associated with past channelization measures by up to 50% in 2100. This is mostly due to increased moderate-to-high discharges, which decrease the equilibrium channel slope. For larger discharges, a smaller channel slope suffices to transport the same amount of sediment coming from the upstream part of the basin, which is achieved through channel bed incision. Sea level rise mildly reduces incision in the downstream part of the domain by up to 15% in 2100, by means of an upstream-migrating aggradational wave.

Future channel adjustment will be influenced by bifurcation dynamics. This is because extreme flow events can lead to sudden large differences in incision and deposition rates across bifurcates, which alters the flow and sediment partitioning at bifurcation points (*Chowdhury et al.*, 2023a). The resulting variations in water discharge and sediment supply to the bifurcates affects future channel adjustment.

Overall, we find that channel response in the lower Rhine River continues to be dominated by past channelization measures rather than climate change. Yet while channel response to past human intervention slows down as the river approaches a new equilibrium state, the response to climate change accelerates, as the rate of change of river controls accelerates. Therefore, the relative influence of climate change on channel response increases with time.

3. How do erosion control measures affect large-scale channel adjustment in terms of change in bed level and bed surface grain size?

Different erosion control measures have been installed in the lower Rhine River to mitigate incision-related issues and to increase the navigable width. Through analysis of measured data on bed level over the period 1980-2020, we show that, while they succeed in achieving their design objectives, they can lead to unintended large-scale downstream effects. Specifically, downstream-migrating incision waves originate at the downstream end of the erosion-control measures and propagate with a celerity of about 1.5 km/y.

With an idealized numerical model, we have shown that the observed channel response is related to sediment trapping upstream of the erosion control measures. This trapping is due to backwater effects resulting from protrusion and increased roughness of the erosion control structures, and reduces the flux of sediment to the downstream reach, leading to a downstream-migrating incision wave. Such wave is more pronounced with increased length of the erosion control measure, or with decreased spacing between them.

We conclude that despite their success in locally mitigating channel bed incision, or increasing the navigable width, erosion control measures enhance large-scale channel bed incision downstream from them.

5.2. Possibilities for Application

Our findings, as well as the tools we have developed, are readily available for a series of applications.

The schematized model we set up in Chapter 3 can be used for preliminary assessment of planned interventions in rivers (e.g., nourishments, erosion-control structures, cross-sectional changes, etc.). Similarly, updated climate scenarios, or scenarios different to the ones we have adopted, can be incorporated following the transformation methods between climate scenarios and boundary conditions that we have developed. The power of our model is in its speed and simplicity, and thus in its ability to provide rapid order-of-magnitude estimates of large-scale channel response.

Besides insight on the physics of channel response, the model can also be used in order-of-magnitude economic analysis, or variant studies. Considering a sediment nourishment project, for instance, the model can be used to roughly estimate the potential benefits of the measure, and inform comparative cost analyses.

Our model can help pinpoint locations and processes that require better understanding. For example, we notice that the gravel-sand transition zone, which includes the Pannerden bifurcation, is a sensitive area affected by many processes that are poorly understood, for which modeling in one dimension is not trivial. Another example is fixed beds in river bends, whose dynamics cannot be captured by one-dimensional models. This information can inform the development of, for instance, two-dimensional models, which can provide additional insight on these processes.

The model we have set up is part of a framework that we have developed to assess large-scale channel response to climate change (Chapter 3). This framework can readily be translated to other river basins. Our method fills an existing gap in predictive morphodynamic modeling, which generally focuses on either (a) two-dimensional analyses at relatively small spatio-temporal scales (order of meters to tens of kilometers, over hours to days), or (b) highly idealized cases at very large spatio-temporal scales (order of hundreds of kilometers over thousands of years). None of the two approaches can be easily used for river management at basin scales. Our approach fills this gap, and is meant to inspire similar studies in other rivers. In addition, our conceptualization of the physics behind channel response to climate change can provide insight on future channel response in basins where data and resources are scarce.

5.3. Implications for River Management

This research raises a series of questions to be considered in short to mid term river management.

A common assumption in Dutch river management is that the lower Rhine River, and specifically the Waal river, is constantly incising at a rate of 2 cm/a. This incision rate is widely used as a boundary condition for river modeling studies that provide input to river management policy making. In Chapter 2, we show that current incision rates are neither constant in time and space, nor equal to 2 cm/a. More importantly, we elucidate that this spatial variability follows large-scale trends of channel slope adjustment. We believe that policy decisions should consider the spatial variability of large-scale channel response in future intervention planning.

Our analysis reveals that the bed surface of the lower Rhine River has become coarser, and that the Rhine River's gravel-sand transition has migrated downstream and flattened (Chapter 2). These trends are expected to continue in the next decades (Chapter 3). Changes in bed surface grain size feed back into bed level adjustment, and may contribute, for instance, to slowing down channel bed incision in the Waal branch and to altering bifurcation dynamics. Despite concerns on the accuracy of measured bed surface grain size, it is important that predictive tools are updated with the latest measured data. Similarly, as climate scenarios are updated, models should be rerun to remain representative.

In Chapter 3 we have shown that past channelization measures are the main driver of channel response in the 21th century, more so than climate change. This realization does not, in any way, undermine the importance of climate change and river response to climate change. Yet it emphasizes the need to consider the long-term effects of human intervention in rivers, as these effects may be even stronger than those related to natural forcing. Interestingly, while some studies address river response to climate change, long-term studies of channel response to interventions are not typically carried out. Reasons for this may include lack of resources and prioritization, or the idea that future uncertainty is too large to provide trustworthy insights. While accurate predictions of future channel response are not possible, we have shown that highly-schematized models are a powerful tool to assess long-term channel response over large scales, given their high speed and cheap computational cost. Such models provide valuable insight on the general trends of channel response to natural and anthropogenic change. We therefore recommend that schematized long-term studies complement shorter-term, more detailed analysis of channel response, especially when such studies are used for intervention planning.

Our findings on the large-scale channel response to erosion control structures (Chapter 4) are an example of the potential implications of overlooking the large-scale response to interventions in rivers. Specifically, we have seen that erosion control structures may increase large-scale channel incision, despite mitigating it locally. An idealized model can readily provide insight on such behavior. Additionally, analysis of measured data on the Dutch fixed beds raised questions on whether their construction exactly followed their design, given certain mismatches between construction plans and measured data. Besides the implications of such doubts for interpretation of channel response around structures, it emphasizes the need to evaluate measures after their implementation.

In Chapters 2 and 3 we have conceptualized the physics of large-scale, centennial channel adjustment in the lower Rhine River. Here we advocate ensuring that large-scale physics are systematically considered in policy decisions. An example is in the debate on whether to nourish sediment in the Dutch Rhine based on reported success of similar strategies in Germany, and if so, how, how much, where, and how frequently. When considering such an endeavor, the current slope-change trends of the system need to be understood. Options such as "simply" restoring the river bed to a bed level profile of a certain year, without further consideration of how the channel slope and bed surface grain size are affected by the river controls may have enormous costs but only a temporary effect or even adverse effects.

The actual implications of river bed incision for Dutch river management are another source of debate. Some argue that sea level rise may lead to channel bed aggradation and therefore counteract river bed incision. We have shown that aggradation due to sea level rise is too limited to compensate for river bed incision, and even less so when climate-related changes to the hydrograph are considered (Chapter 3). Another recurrent claim is that channel bed incision may partially reduce flood risk due to decreased water levels. Although this has not been the focus of our research, our model suggests that the increase in water levels due to higher discharges is larger than the decrease of water levels due to channel bed incision.

Despite our recommendations to consider large-scale channel adjustment in intervention planning, we emphasize that our schematized model (Chapter 3) has limited accuracy at small spatio-temporal scales. Despite its potential for quick assessment of large-scale channel response, this model should *not* be used to draw conclusions on channel behavior at specific locations or times. When more detailed tools to predict future channel response are unavailable, it may be tempting to "use what is at hand". We argue that using our model with a small spatio-temporal scope - in lack of a better option - is a risky choice that can provide a false sense of security. Nevertheless, our model can give important clues to where further detail is necessary for better system understanding (e.g., bifurcation processes, or dynamics of non-erodible reaches).

Finally, our research reminds us of the multiple sources of uncertainty in predicting future channel response. This ranges from our knowledge of the physics underlying the system, to our capacity to simulate it with numerical models, and the data we use to calibrate and validate such models. In addition, the boundary conditions and climate scenarios that we use are typically output of predictive models, with the same chain of uncertainties (i.e., knowledge, modeling approximations, data). Policy making looks for certainty, as ultimately, very practical decisions need to be made and resources need to be allocated in a certain way. Yet we advocate a more systematic use of scenario-based and probabilistic methods (or more plainly, in discussing bandwidths rather than lines) in policy making. This requires the readiness and open-mindedness from policy makers to deal with future uncertainty. A way to take this future uncertainty into account is to consider multiple possibilities for future change, and multiple ways to adapt to change (e.g., adaptive policy pathways *Haasnoot*, 2013).

5.4. Opportunities for Further Research

Our results provide several avenues for further research.

In the first place, we have identified areas in the lower Rhine River whose behavior is particularly complex. One of these areas is the gravel-sand transition zone, which also includes the Pannerden bifurcation. From both our data analysis (Chapter 2) and modeling exercise (Chapter 3), we have realized that processes in these areas need better understanding. This includes the dynamics and implications of a migrating and flattening gravel-sand transition and bed surface coarsening, as well as the two- and three-dimensional dynamics of bifurcations, which determine their flow and sediment partitioning.

Similar considerations apply to the dynamics of fixed beds in relatively sharp river bends. While channel response to fixed beds in sharp bends has strong two-, and even three-dimensional components, field data suggests that this response can substantially extend in the longitudinal direction, and therefore also have a relevant one-dimensional component (Chapter 4). It will be useful to better understand how the longitudinal response is influenced by two-dimensional dynamics.

Research by *Chowdhury et al.* (2023a) shows that peak flows may have altered the sediment partitioning at the Pannerden bifurcation, due to differential erosion and deposition rates in the bifurcates. Eventually, such dynamics may trigger tipping of the system towards new equilibrium states. The effects of peak flows on future large-scale channel response should therefore be further explored.

We have excluded the estuary zone from our domain of interest, and used data correlations to set our downstream boundary conditions upstream of the estuary zone, based on conditions at the North Sea. This is because our model does not include estuarine processes such as tides or salt intrusion. River and estuarine processes are often studied separately. This implies that measured data or modeling output from the downstream part of the river becomes input to the upstream boundary of estuary models and vice-versa. Integration of the two subsystems may reveal interdependencies that are currently unexplored, including the influence of morphodynamic change in the estuary on downstream water levels of the river domain, the effects of increased tidal ranges due to climate change on upstream river morphodynamics, or a clearer perspective on how sediment fluxes change between the river and the estuary.

In a similar manner, hydrodynamic and morphodynamic problems are often addressed separately. While this can be justified by limitations in modeling tools, the two types of processes are largely interdependent. For simplicity, studies of flood risk, freshwater availability, ecology, or navigation regarding the Rhine River tend to ignore morphodynamic change. Given the direct influence of channel adjustment on flood risk, freshwater availability, navigation and ecology, there is a lot of room to explore the effects of channel adjustment in these fields.

Our results also raise the question on how to adapt to the predicted channel response. Further research is needed to explore efficient ways of managing rivers in a context of increasing climatic pressure in an ever more populated world. This requires investigating sustainable and green river management policies and interventions. Nature-based solutions are emerging as a concept with strong potential for climate adaptation with added socioeconomic and environmental benefits. These solutions are defined as “actions to protect, sustainably manage, and restore natural and modified ecosystems, which address societal challenges effectively and adaptively, while simultaneously benefiting people and nature” (*Cohen-Shacham et al.*, 2016). Nature-based solutions prioritize natural (green) over concrete-intense (gray) infrastructure, and are estimated to have the potential to contribute 30% of the global climate mitigation required to limit the global temperature increase to 1.5-2°C by 2030-2050, as per the Paris Agreement (*Girardin et al.*, 2021; *Griscom et al.*, 2017; *Roe et al.*, 2019). Yet such solutions remain scattered pilot projects, and their upscaling and mainstreaming is challenged by limited knowledge, as well as political and financial aspects. Pathways to overcome these challenges include the combination of (technical) research on system understanding (which needs to rely on consistent monitoring), as well as socioeconomic approaches tackling mindset shifts, cooperation strategies, and innovative financial schemes.

5.5. A Vision on the Future of Science, Policy, and Society

With this research we have aimed to contribute a grain of sand to the future of river management. Yet, ultimately, we work towards a more sustainable, equitable and peaceful world. Here we take a step back and reflect on the role that science, policy, and society can play in this pursuit.

From the experience of this project, it is clear that (systems to ensure) cooperation in transboundary rivers are essential. On the one hand, river management policies in one country can have dramatic effects on a neighboring country. On the other hand, jointly addressing river challenges needs open data collection and sharing practices, and general cooperation, which can be hindered by a myriad of geopolitical reasons. Beyond river management, it is important that countries develop a sense of shared responsibility towards the future of their ecosystems, and the planet.

In order to efficiently work together, we need to find ways to reliably centralize knowledge and assure its accessibility. Nowadays research studies, as well as data, information, capacity and resources are largely scattered. Easier ways to find information and resources will help accelerate progress.

In science, reductionist approaches are needed to gain understanding of natural and anthropogenic systems. Yet such approaches need to be combined with integrated system approaches. The challenges that the world is currently facing are too pressing to solely focus on sub-process understanding. This means that small-scale approaches need to be combined with large-scale approaches, short-term studies with long-term studies, and isolated mechanisms with system dynamics. It is not one or the other. Science-based policy initiatives, and in general, a larger share of scientists and technical profiles in government circles will be beneficial in this regard. Knowledge exchange should be promoted at the international level, as successful science-based policy experiences in certain administrations can inspire initiatives elsewhere.

Finally, while we are concerned with adapting to climate change and mitigating its impacts, we should not forget that (current) climate change is not an environmental or socioeconomic problem that needs technological solutions or more progressive policies. Climate change is a human problem that is deeply rooted in our human (read: animal) nature. Technical solutions are only patches. The pursuit of climate adaptation cannot be separated from that of a more peaceful and equitable world.

What I thought would be the last conference of my PhD took me to Chile. The occasion was the Gravel Bed Rivers 2023 meeting, the most niche conference I have ever been to. It used to be an invitation-only conference, but they decided to open it, and I am so glad they did. Not only for the quality of the conference and the speakers, but also to have the chance to discover a part of Chile and its people. It was refreshing to talk rivers

with indigenous people and activist groups, and to make inspiring and full-of-life new friendships that have lasted beyond the conference. I also got to meet the professors I would have had, had I stayed in Barcelona. I cannot imagine how different my life would have been if I had not moved to Lausanne and Delft. Despite the challenges, my world is now immensely richer, and all these travels have contributed a great deal to that.

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Acknowledgements

One day back in 2017, when I was doing my MSc thesis in Lausanne, I emailed a certain Víctor Chavarrías from TU Delft. A friend from my exchange at EPFL, who had later moved to Delft, told me I should definitely contact this Víctor if I wanted more information about doing a PhD at the TU. "He's really nice", he said (¡gracias Nacho!). If I ended up starting a PhD, it is partly thanks to Víctor - and if I finished it, it is also partly thanks to him. Gràcies, Víctor.

A few months after my email exchange with Víctor, I got another email from him - there were two open PhD positions in coastal engineering. By then, I was working as a project engineer at the Laboratory of Hydraulic Constructions at EPFL, and while I was working on tsunami waves, my coastal background was limited-to-non-existent. I decided to apply, thinking "worst case, I will have updated my CV". In the midst of the application process, Bram emailed me telling me that I would not make it to the interview round, as there were people with a more fitting background, but that another position in the Rivers group would open soon. He said that he had taken the liberty to show my CV to another professor, who was interested in contacting me, and asked me permission to share my contact. A couple of hours later, I had an email from Astrid telling me about the project. I was sold when I read "climate change" and "sea level rise" on the title, and just one week later, I said yes to moving to the Netherlands. I didn't know what I was doing, and I certainly didn't think it through. The instinct was strong, though, and that's something worth trusting. And I am glad I did - this experience has changed my life. So thank you Bram, now I have a fun story to tell. And, may I add, thank you for not hiring me - Jill and Ana filling those vacancies has been one of the greatest joys of my PhD.

In December 2018, I arrived to Delft one dark and rainy evening. Anne-Catherine, with whom I had worked in Lausanne and was now in Delft, picked me up, took me to dinner, and helped me find "landing housing". Thank you, and Cristina, for your hospitality - you made it a soft landing for me. On my first day of work, Matt and Otti were ready for me. I did drive Otti a bit crazy by arriving some 20 minutes early, sorry about that. And thank you, Otti, for always helping out. I will always remember that first day. Matt took me around (instant good vibe) and introduced me to everybody. Thank you

Matti for all the good times, good laughs and good food, it always feels very homey. A highlight of that day was when we got to the large office, and there he was, Stuart with his big smile and inexhaustible energy, giving me a welcome mug that I could paint on. I felt so welcome. Thank you, Stuart, your friendship and patience are invaluable. Then there were Yorick and Erik, who were like Dupont et Dupond to me. And so tall! And of course, Ana, Jill, Xin, Lodewijk, and Bram and Wim (thank you for all the inspiring talks and for putting up with my high energy), and Kees (thank you for being the "model doctor" so many times, and for all the exciting talks), and Erik Mosselman (I'm never not impressed by your wisdom, thank you for sharing it with us). And Merel (thank you for all the lovely times, your support, and for honoring me with being your paranymph), Maria, Gonzalo, Irene, and Zeinab, though we did not have a long time together. For the first time in my life, I felt like I was more like everybody around than different from most people around. I cannot express how precious this has been to me.

One week later, Astrid arrived from Myanmar. Victor and I were chatting in the lab kitchen, and there she came down the stairs, with this memorable opening sentence: "Oh! I thought you were taller!". Although I have not become taller after all these years, I have certainly grown, and Astrid, you have played a large role in this. Working with you has been like going to brain-gym, and I am happy to report that I can now keep up with the light speed of your mind a bit more often. But we all know that a PhD is so much more than its content. I thought I was a good communicator before coming here, but I learned so much from you. One can now see your influence on my writing and presenting, and I am quite happy it is that way. I am proud of what I have achieved (yes, it happened!) and this would have not been possible without you pushing me towards my limits (which I think we have, at least, visualized). Although maybe most of all, I am incredibly grateful for the opportunities you have given me. You have encouraged me to travel the world (quite literally) with this project, and I will never be able to thank you enough for that. It has certainly made me a better professional, and given meaning and a platform to our work. But more importantly, it has enriched me as a person, and this is priceless. Thank you so much.

A few weeks later I met Ralph. Always with colorful shirts and daring shoes, I thought he was the Rijkswaterstaat sheriff. In all seriousness, thank you for always being available and ready to help. You have always made sure that external conditions (data, information, tools, you name it) were not an impediment to my work, and I am really grateful for that. I am inspired by your drive and energy to keep things moving forward. Your constant reminders that my work matters (which was my main concern about starting a PhD), your high-level questions on the implications of the results, your will to transfer the knowledge from my computer to the outside world, and your overall

motivation have been an important source of encouragement. I have also really enjoyed our digressions on how the world works (or doesn't) and on what a better future looks like. Let's update these conversations in the future.
Ralph is also one of the masterminds behind Rivers2Morrow, the larger project my PhD is part of. Being a part of Rivers2Morrow has given more context and meaning to our work, so thank you Ralph, Matthijs and Evelien for all your efforts in this regard, and to Rijkswaterstaat for the funding. I would also like to thank the members of my user committee for the perspective they have provided (Regina, thanks for all the chats and for welcoming me in Karlsruhe; Kees, Hermjan, Saskia, Wilfried, Michiel, Maarten), and all the PhD students of this project. I have really enjoyed all our exchanges and encounters. A special mention to Kifayath, my little PhD brother. I'm glad you came, research has been more fun and less lonely with you.
An important part of the PhD journey is writing and publishing papers. What an anxiety-inducing process, especially for us newbies! Truth be told, it can be pretty wild out there. I have seen anything from nice, constructive, and encouraging reviews, to rather disrespectful ones; reviewers that only browse through manuscripts, and reviewers that want to explain you how the world works. I have been very lucky in the reviewer lottery, and I am very thankful to Andy Wickert (a couple times), Shawn Chartrand, Chenge An, and an anonymous reviewer for their constructive criticism and encouraging words. It does not take much more to move forward in science (and in life, probably), and it made a whole difference for me. Here I would also like to acknowledge committee members Caroline Katsman, Bart van den Hurk, Silke Wieprecht, Andy Wickert and Matthijs Kok. I really appreciate your time and interest in reviewing this thesis.
During my time at the TU, I had the chance to help kickstart and chair, for a while, the young professionals board of the Netherlands Centre for River Studies. I am incredibly grateful for this experience. Thanks Koen for the initiative and trust. But also thank you to all my fellow YNCR-ians (Anna, Iris, Jana, Patricia, Niek, Henry, Matthijs, Emma, Fateme) for the fun, for your enthusiasm, work, and patience with my chairing/leadership experiments. I grew a lot from this, and I think we did pretty well, if I may say so myself. I am excited for what the new faces will bring.
With YNCR I get to the friend-colleague (or frolleague) arena. When one has to work so many hours on a project, one can only hope that they will find a supporting group of frolleagues like the ones I have found in the Waterlab. I said it before, but I insist: I am so grateful for you all. You are a really kind and special group. Jill, I am so happy that I can call you a friend, office mate, and mountain-and-fun partner. You really are amazing. Ana, me alucina tu combinación de trabajo duro-diversión-bondad, sé presidenta de todo, por favor. Alejandra, me inspiras cada día con tu capacidad de luchar por

lo que eres, quieres, y mereces, y con la perspectiva que le das a todo. Gracias por tan buenas charlas y tanta paciencia. Stuart, again, it is awesome to be your friend, thanks for everything. Patricia, you are so strong and caring, you inspire me to be (a bit of) a better person. Jianwei, you are the best of us, your kindness will never cease to amaze me. Jelle, Jellybeans, you are so much fun, thank you for letting me be the kid that I am, this is priceless. Chit, your integrity and determination are commendable, I am impressed by you every day. Kshitiz, you are the cool kid, I hope I can hear your laugh for many years to come. Laura, I am inspired every day by your inner freedom and creativity, I have learnt valuable things from you. Eki, Amber, Kieran, you just got here, but you are cool and in good hands. Shelby, you are part of the Waterlab. I had so much fun with you while you were here (and in Colorado!), it was like having a sister from a different continent. It is hard to laugh harder than with you.

And I have to go back to Victor. And Elisa, Silke, and Ilse. Gràcies per fer-me sentir com a casa, per tants bons moments, i per tant suport (moral i literal). Sou la meva família de Delft (Silke e Ilse, gracias por dejarme ser vuestra tía adoptiva) i per això estaré sempre agraïda.

During this roller coaster of a journey, there have been some people whose support and friendship have been invaluable. From my Julianlaaan family (Dor, Ilaria, Viktoria, Sanjana, Caio, it has been great to live and share the everyday with you), and Delft friends (Katerina, Carolina, Eva, Robert, Jessica), to those who are a bit further - I miss you, but you have periodically refilled my batteries during all these years. Je pense surtout à vous, mes petits EPFLiens (Joël, tu es un vrai ami; Melchior, Abdo, Morgan, Titi, Matthieu, Claire, merci de m'acqueillir à chaque fois, c'est tojours si marrant d'être avec vous; Joseph, gran contribuidor a mi biblioteca de influencias e intereses, esto es priceless). Elena, Tere, estar amb tu és estar a casa. Gerard i Martí, gràcies per l'alegria i pels ànims. I als de sempre, Ian i Marina, quina sort tenir-vos tan a prop en la distància després de tants anys.

None of this would have been possible without my family. The large one (molts petons a tots), and the small one, my parents. Gràcies per recolzar-me sempre, quan calgui, i tot el que calgui, per la paciència infinita, per donar-m'ho tot, per creure sempre en mi, i per animar-me cada dia a seguir definint el meu camí i a no deixar-me anar. Gràcies pel vostre exemple, per tenir tanta vida i per aprofitar-la tant, per ser tan bons amb mi i amb tothom. Però, sobretot, gràcies per haver-me fet créixer en un entorn tan saludable i estimulant. Tinc molta sort, i estic molt contenta del que he pogut viure gràcies a vosaltres. I no puc deixar de pensar en els avis i la tia, que a la seva manera també hi han estat. Crec que estarien molt orgullosos, així que jo també.

And just when I thought conferences were over, I still got to go to RCEM one more time in Urbana, Illinois. We had the chance to spend some time in Chicago, which was a wonderful surprise of a city. But most importantly, I got to see some previous colleagues that had left Delft, meet new faces, and spend very good quality time with the Delft colleagues. RCEM was the first and the last international conference of my PhD - talk about coming full circle! The whole conference had a nostalgic undertone for me, as it really felt like "the last one". But probably because of that, it will have a special place in my memory. So long, PhD.

A

Supporting Information for "Response of the Lower Rhine River to Human Intervention since the 18th Century"

This appendix has been published as supporting information for the following article in *Geophysical Research Letters* (Chapter 2):

Ylla Arbós, C., A. Blom, E. Viparelli, M. Reneerkens, R.M. Frings, & R.M.J. Schielen. (2021). River response to anthropogenic modication: channel steepening and gravel front fading in an incising river. *Geophysical Research Letters*, 48 (4), e2020GL091338, doi: 10.1029/2020GL091338.

A.1. Introduction

This supporting information includes specifications about bed elevation and bed surface grain size data collection and treatment, in relation to Chapter 2. These specifications concern the following aspects:

- Measurement techniques
- Spatio-temporal density of measurements
- Systematic and calibration errors
- Data treatment

A.2. Bed Elevation Data

In the Niederrhein, bed elevation field data have been obtained with single beam echo sounders since 1934. Measurements were taken at cross sections spaced 100 m (*Frings et al.*, 2014b). The total estimated error of single beam data, accounting for calibration and systematic errors, is 5 cm (*Frings et al.*, 2014b). An earlier data record from 1898 was digitized from historic charts (*Quick et al.*, 2019), likely with a considerably higher error, though exact error estimates are not available. In the Bovenrijn and Waal, bed elevation has been measured annually since 1926. Single beam echo sounders were used until 1999, and multibeam echo sounders have been used since 1999. Single beam measurements were taken at cross sections spaced 25 m, and were averaged over 1 km. Multibeam measurements covered the entire length of the river, and were averaged over 100 m. The total estimated error in bed elevation data (defined as two times the standard deviation) is 0.2-0.5 m until 1990; 0.2-0.3 m, between 1990-1999, and 0.05-0.1 m since 1999 (*Wiegmann*, 2002). All bed elevation data were averaged over the cross-sectional profile between the groyne tips.

When multibeam systems were introduced (1999), both single beam and multibeam soundings were carried out. Differences in bed level between the two techniques reached 0.25 m, the values varying in space. This is due to (1) differences in accuracy and footprints of both systems, (2) the presence of bedforms, and (3) spatial and temporal differences in the water level, which affect the beam footprint. We solve this discontinuity by correcting the single beam data with a local correction factor. We define this factor, at every river km, as the difference between the average bed level during the last three years of single beam data, and the average bed level during the first three years of multibeam data. This avoids errors related to the state of the river bed at the time of the measurement. A disadvantage of this choice is that we implicitly assume bed level change over a three year period (1.5 years before the transition until 1.5 years after) to be zero.

Bed elevation profiles have been smoothened using a moving average of window size 2 km. The results are not particularly sensitive to the averaging window, other than the fact that the natural variability of bed elevation data decreases with larger averaging windows. A 2 km averaging window is enough to clearly visualize the results without losing too much detail on local features.

For channel bed slope, on the other hand, a large averaging window is required, as the slope trends have spatial scales of tens of kilometres and cannot be appreciated otherwise. Window sizes of 30-50 km provide similar results, the natural variability of the data obviously decreasing with increasing window size. As we are interested in large scale slope trends and not so much in local variations, we have chosen a window size of 40 km for visualisation purposes. Larger window sizes alter the transition zone between the slope-increase zone and the slope-decrease zone.

A.3. Bed Surface Grain Size Data

Grain size sampling campaigns have varied in space and time, and we have grouped together (and averaged) data from a limited number of years following *Frings et al.* (2014b). Measurement techniques, sampling depths, and measurement density are summarized in Table A.1. We have used D_{50} as a representative diameter to enable comparison with the early data, as grain size data until 1984 of the Bovenrijn and Waal only include characteristic diameters D_{10}, D_{50}, and D_{90}.

We consider cross-sectional average values of bed surface grain size. In the Niederrhein, five samples (spaced 50 m) were taken per cross section. In the Bovenrijn and Waal, three samples (spaced 65 m) were taken per cross section.

Bed surface grain size data have been smoothened using a moving average of window size 10 km. A window size of at least 5 km is required, as the spatiotemporal density of bed surface grain size data is otherwise not enough to distinguish any trends. For visualisation purposes, we choose a window size of 10 km. Larger window sizes affect the shape and extension of the gravel-sand transition zone.

The uncertainty of grain size data is high due to the high natural spatio-temporal variability and limited spatial and temporal sampling density. Measurement techniques themselves and changes to the measurement techniques over time contribute to this uncertainty. For instance, an unknown amount of fines is lost when using grab samplers, biasing the results towards coarser fractions. On the other hand, larger sampling depths (as in 2016-2020) bias the results towards finer fractions. This is because by sampling over larger depths, the sample includes a larger fraction of substrate sediment, which is typically finer than surface sediment.

Table A.1: Specifications of the bed sampling campaigns in the Lower Rhine River since 1951.

Reach	Year	Distance between sampled cross-sections (km)	Sampled depth (cm)	Method
NRH	1981-1983	1	10	Diving shaft
	1992-2010	0.5	10	Diving bell
	2011	10	1-10	Diving bell
	2015-2016	0.2-0.5	50	Grab sampler
BR-WL	1966	500, 1000 or 2000	5-10	Digging bucket
	1976	0.5	5-10	Digging bucket
	1984	1	5-10	Digging bucket
	2008	1	3-4	Van Veen grab sampler
	2016	1	20-30	Hamon grab sampler
	2017	1	20-30	Hamon grab sampler
	2020	0.5	20-30	Hamon grab sampler

B

Supporting Information for "Response of the Lower Rhine River to 21st-Century Climate Change"

This appendix has been published as supporting information for the following article in *Geophysical Research Letters* (Chapter 3):

Ylla Arbós, C., A. Blom, C.J. Sloff, & R.M.J. Schielen (2023). Centennial channel response to climate change in an engineered river, *Geophysical Research Letters*, 50 (8), e2023GL103000, doi: 10.1029/2023GL103000.

B.1. Introduction

This supplementary information discusses the details of the model used in Chapter 3, including schematization and calibration procedure, nodal point relation, model boundary conditions, and additional results.

B.2. Model Assumptions

Our model relies on a series of assumptions and simplifications, which are listed below:

- The model is one-dimensional, and all the variables are cross-sectionally averaged
- Water is an incompressible fluid
- Pressure in the water column is hydrostatic and vertical accelerations are negligible
- The radius of curvature of the channel is large relative to the channel width
- The flow is subcritical
- The active layer has a constant thickness
- Sediment is non-cohesive
- Changes in sediment porosity are neglected
- Only bed-material load is considered (i.e., bed load and suspended bed-material load)
- Abrasion is neglected
- All grain size classes follow the same type of sediment transport relation
- Sediment is transported at capacity
- Sediment is only transported over the main channel (i.e., floodplain deposition is neglected)
- Channel banks are non-erodible (i.e., the river planform is fixed)
- Subsidence, uplift, and delta outbuilding are neglected

Given that the channel bed is predominantly composed of gravel, we use a sediment transport relation that includes a threshold of motion. Its shape is based on *Meyer-Peter and Müller* (1948), which is devised for bed load transport. We consider both gravel and sand to be part of the bed material load. As gravel is the dominating sediment in setting channel characteristics (*Blom et al.*, 2017a), we consider this approach to be adequate for the purpose of our study. Our sediment transport relation accounts for hiding and exposure following *Egiazaroff* (1965):

$$\phi_k = \Gamma \left(\mu\theta_{sk} - \xi_k\theta_c\right)^b \tag{B.1}$$

where, for each grain size fraction k, ϕ is the dimensionless sediment transport (without pores), θ_{sk} is the Shields stress of size fraction k, θ_c is the critical Shields stress, μ is the ripple factor, which represents the ratio between total friction and skin friction and is set to $\mu = 0.7$ (*RiverLab*, 2020), ξ is the hiding and exposure correction function given by *Egiazaroff* (1965), Γ is a calibration parameter, and b is a constant, set to $b = 3/2$, following *Meyer-Peter and Müller* (1948).

The hiding and exposure correction function is the one of *Egiazaroff* (1965):

$$\xi_i = \begin{cases} \beta \cdot \frac{D_m}{D_k}, & \text{if } \frac{D_k}{D_m} < \alpha_{max} \\ \left[\frac{\log_{10}(19)}{\log_{10}(19 \cdot D_k / D_m)}\right]^2, & \text{if } \frac{D_k}{D_m} \geq \alpha_{max} \end{cases} \tag{B.2}$$

where D_k is the characteristic diameter of sediment fraction k, D_m is the mean bed material grain size, $\alpha_{max} = max(\alpha, 0.1)$, and $\beta = \alpha_{max}\left(\frac{\log_{10}(19)}{\log_{10}(19 \cdot \alpha_{max})}\right)^{\gamma}$. Following *RiverLab* (2020), α and γ are set, respectively, to $\alpha = 0.4$, and $\gamma = 2$.

Details on the calibration of the transport relation (i.e., the prefactor Γ and the critical Shields stress θ_c) are provided in Section B.5.

B.3. Model Schematization: Reference Case

This section provides details on the schematization of our one-dimensional numerical model, and more extensively discusses the choices behind the model schematization (Figure 3.2).

Our schematization is based on field data, from which we filter out small-scale features, as we are interested in the main components of large-scale channel response. We approximate the field data using (piecewise-)linear fits and when the data is insufficiently linear, we use shape-preserving interpolation (*D'Errico*, 2009). We detail below how the different input variables are approximated.

Regarding mean channel bed elevation (*Ylla Arbós et al.*, 2021b; *Quick et al.*, 2019), we identify five main reaches based on the 2000 longitudinal profile: a concave reach (river km 640-852), a steeper linear reach between two bed level steps (river km 852-867.5), a milder-sloped linear reach between river km 867.5-928, a concave reach between river km 928-937, and a linear reach between river km 937-955.

The main channel width (width between the bottom of the groyne heads) is extracted from Google Earth. To this end, we consider the width between the top of the groyne heads, and subtract to it 30 m (i.e., 15 m on each side, roughly assuming a groyne height of 5 m and a groyne slope of 1:3). We approximate it using a piecewise-linear fit (Figure 3.2b). Floodplain width data is available through the IKSR Rheinatlas 2020 Geoportal (*BfG*, 2020a). We approximate it by means of shape-preserving interpolation (Figure 3.2b).

Following the schematization of mean bed elevation, main channel width, and floodplain width, we define 20 locations where cross sections are specified in order to capture spatial changes in the variables (Figure B.1). The schematized cross sections are obtained by means of a piecewise-linear fit of more detailed cross-sections, which are defined as width-elevation profiles (*Becker*, 2017; *RiverLab*, 2020). In particular, the width-elevation profiles are first zeroed with respect to the mean bed elevation, and discretized to a common grid (i.e., the same grid for all profiles). We then fit a piecewise-linear function at each level of this common grid. The limits of each piecewise-linear reach correspond to those identified in the spatial variation of main channel and floodplain width.

The width-elevation profiles (Figure B.2a) are used to create a cross-sectional profile (Figure B.2b). This cross-sectional profile is used to calculate the cross-sectional area and

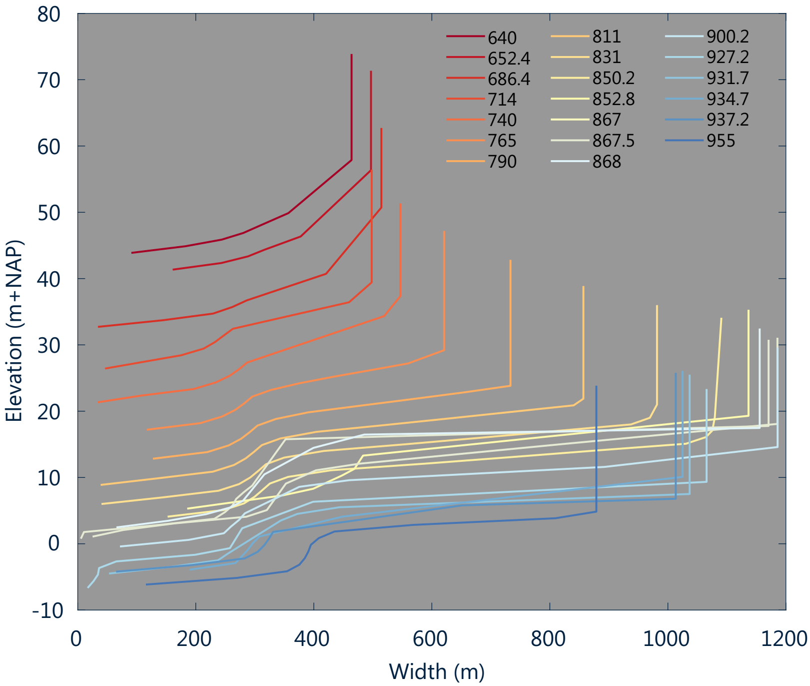

Figure B.1: Model cross sections as width-elevation profiles. The legend indicates cross section location (river km).

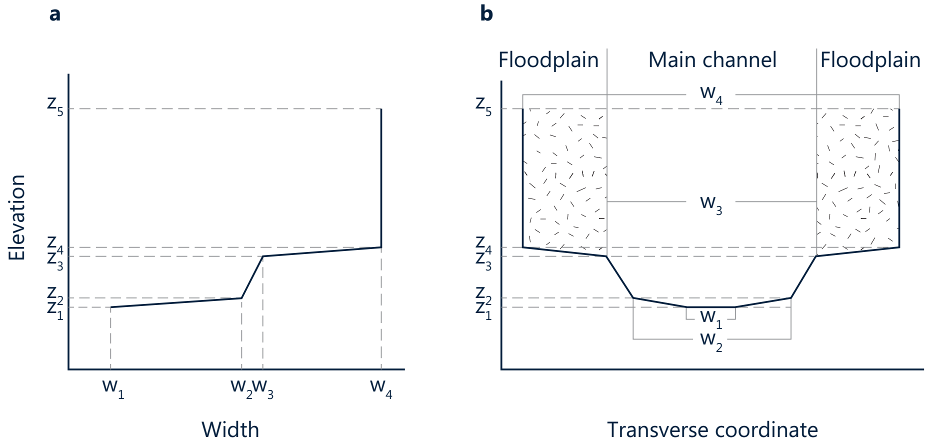

Figure B.2: Schematic of the transformation of a width-elevation profile (a) into a two-dimensional cross section (b). The patterned area in (b) indicates the floodplain area.

B

hydraulic radius. In so doing, the model accounts for variations in channel width with water level, and can account for the presence of floodplains.

Grain size data for the period 1990-2020 is available via *BfG* (2020b), in *Ylla Arbós et al.* (2021b), and this paper. In the model, each grain size class is represented by a characteristic diameter, defined by Equation B.3:

$$D_{char,k} = \sqrt{D_{upper,k} D_{lower,k}} \tag{B.3}$$

where $D_{char,k}$ is the characteristic diameter of grain size class k, $D_{upper,k}$ and $D_{lower,k}$ are respectively the upper and lower bounds of the model grain size bin k. Note that the model grain size bins are different than the grain size bins related to field data, which follow sieve sizes.

We consider five model grain size bins, with bounds of 0.49, 0.51, 3, 8, 30, and 50 mm. These bounds are purely numerical, and are set to obtain characteristic grain sizes in the order of 0.5, 1.25, 5, 15, and 40 mm following Equation B.3. We assume that these grain sizes are sufficiently representative of field conditions (Figure 3.2c). This leads to model characteristic grain sizes equal to 0.5, 1.24, 4.9, 15.49, and 38.73 mm. Due to the large variability of the bed surface grain size, we process the data by means of a 10-km moving average, and subsequently approximate it using shape-preserving interpolation (Figure 3.2c).

Substrate data for the period 1990-2010 (*BfG*, 2020b) are smoothed using a piecewise-linear function per fraction (Figure B.3). In the Dutch Rhine, due to a lack of data, we assume that surface and substrate fraction contents are equal, as the ratio of substrate to surface fraction content of the different fractions approaches 1 at the Dutch-German border (river km 857.5, Figure B.4).

The active layer thickness (*Hirano*, 1971) is set to 0.8 m, in the same order as *River-Lab* (2020). The substrate is schematized as a series of 20 book-keeping layers, each with a

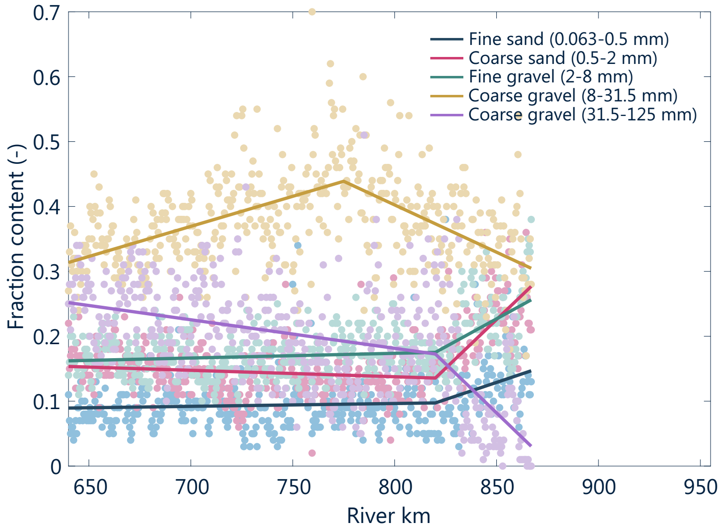

Figure B.3: Substrate fraction content. Dots represent field data, lines are approximated values as introduced in the model.

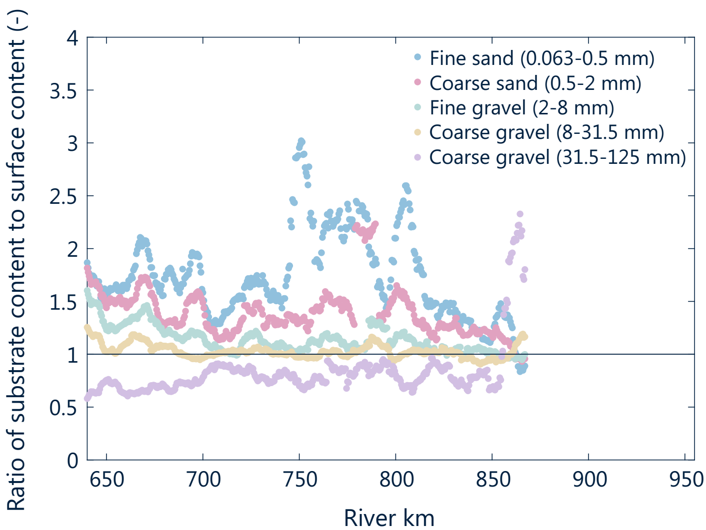

Figure B.4: Ratio of substrate fraction content to bed surface fraction content, per grain size fraction. The data have been approximated by means of a 10-km moving average.

thickness of 0.5 m.

At locations where fixed beds are present, the substrate composition is altered to make it non-erodible. To do so, we set the substrate composition such that 99% is made of the coarsest grain size fraction, and 1% is the one but coarsest grain size fraction (setting the coarsest fraction to 100% would activate an unwanted parameterization in the solver).

The porosity and relative density of the sediment are set respectively to 0.3 and 2.65, which is within the range of *Frings et al.* (2014a) and *Arkesteijn et al.* (2021).

The model spatial step is set to 500 m, which suffices for the level of detail that we are pursuing. The computation time step is set to one day, which coincides with the temporal resolution of our upstream hydrodynamic boundary condition (Section 3.2).

B.4. Water Levels at the Downstream Boundaries

Our model has two downstream boundaries: one at the downstream end of the Waal (river km 955), and one in the Pannerden Canal, 1.5 km downstream of the Pannerden bifurcation (i.e., river km 869). Water level data at the downstream boundaries over the period 1990-2020 is obtained from *Rijkswaterstaat* (2023).

The Waal downstream boundary condition includes sea level rise, also in the reference case. How water level at the North Sea affects the water level at Vuren is expressed by the *De Vries* (1994) empirical fit to the *Bresse* (1860) analytical solution of the backwater equation (Eqs. B.4 and B.5):

$$d_v = d_e + (d_s - d_e)\, 2^{\frac{s_v - s_s}{L_{1/2}}} \tag{B.4}$$

where the backwater half length equals

$$L_{1/2} = 0.24 \frac{d_e}{i_b} \left(\frac{d_s}{d_e} \right)^{4/3} \tag{B.5}$$

and d denotes flow depth, d_e is the normal flow depth, s indicates the streamwise coordinate, i_b the channel bed slope, the subscript s the North Sea, and the subscript v indicates the downstream end of our domain at Vuren.

For simplicity, we now take an expression for the normal flow depth that is associated with a main channel without floodplains. The normal flow depth d_e is then defined as:

$$d_e = \left(\frac{c_f}{i_b} \frac{Q^2}{gB^2} \right)^{1/3} \tag{B.6}$$

with Q the water discharge, g the gravitational acceleration, and B the channel width.

We approximate Eq. B.6 as follows:

$$d_e \approx \Lambda Q^{2/3} \tag{B.7}$$

where we assume Λ to be a constant. Substituting Eqs. B.7 and B.5 into Eq. B.4, we obtain Eq. B.8 (which corresponds to Eq. 3.1):

$$d_v \approx \Lambda Q^{2/3} + \left(d_s - \Lambda Q^{2/3} \right) 2^{K Q^{2/9} / d_s^{4/3}} \tag{B.8}$$

where we assume K to be a constant.

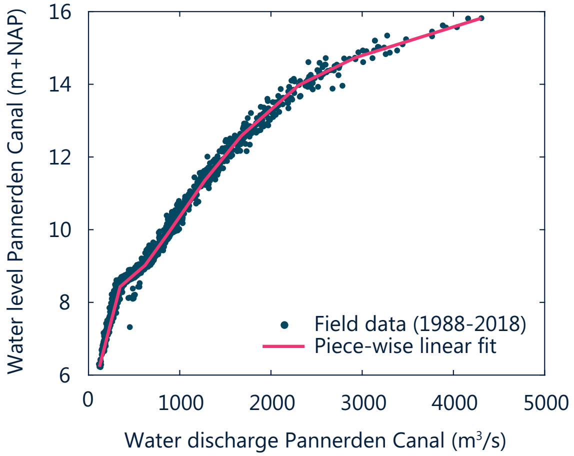

Figure B.5: Stage-discharge relation at the Pannerden Canal, downstream from the Pannerden bifurcation (river km 869).

We find the highest correlation between the field data and Eq. B.8 for values of Λ=0.054 $s^{2/3}$/m and K=-0.71 $m^{2/3}s^{2/9}$.

A stage-discharge relation seems to suffice as a downstream boundary condition at river km 869 of the Pannerden Canal (Figure B.5), which is set as a piece-wise linear fit to the data. In doing so, we capture the backwater effects resulting from the weirs in the Nederrijn-Lek branch, downstream from the Pannerden Canal, in particular the Driel weir at river km 891 of the Nederrijn-Lek. It controls the water levels at the two bifurcation points and so the flow partitioning among the Dutch Rhine branches. The Driel weir is fully closed when the water discharge at Lobith is below 1500 m^3/s (corresponding to a Pannerden Canal discharge of about 500 m^3/s), and fully open for a Lobith discharge larger than 2600 m^3/s (about 870 m^3/s for the Pannerden Canal).

B.5. Model Calibration

We use the prefactor Γ and critical Shields stress θ_c of the sediment transport relation, a (spatially-variable) bed roughness, the grain size distribution of the sediment flux at the upstream boundary, and the coefficients a_k of the nodal point relation as calibration parameters.

We first calibrate the parameters of the transport relation against the order of magnitude of aggradation rates. Our transport relation is based on the *Meyer-Peter and Müller* (1948) transport relation and adopts the hiding and exposure function of *Egiazaroff* (1965), following earlier models of the lower Rhine River (*RiverLab*, 2020).

As the bed surface grain size largely varies between the upstream and downstream part of the domain, with a transition zone in between (Figure B.7c), we define three calibration reaches for the sediment transport parameters (i.e., the reach upstream from the bifurcation between river km 640-867.5, the reach downstream from the bifurcation between river

Table B.1: Calibration parameters for the transport formula

Reach	Γ	θ_c
Reach upstream of the bifurcation (river km 640-867.5)	8	0.041
Reach downstream of the bifurcation(river km 867.5 - 930)	5.6	0.048
Reach downstream of the bifurcation (river km 930 - 955)	6.8	0.041

km 867.5-930, and the reach downstream from the bifurcation between river km 930-955). We account for the differences in grain size in these reaches through different calibration coefficients along each reach. The calibration coefficients are the same for all the grain size classes in each reach. The calibrated transport parameters are provided in Table B.1.

We subsequently calibrate bed friction to capture the spatial variability of aggradation rates, as well as the temporal change of discharge distribution at the Pannerden bifurcation.

We follow a series of steps to calibrate bed friction. Bed friction is imposed by means of a spatially-variable Chézy coefficient, C, which relates to the dimensionless friction coefficient c_f following $c_f = g/C^2$. The friction coefficient has two components, namely skin friction, c_{sk}, and form drag, c_{form} (i.e., $c_f = c_{skin} + c_{form}$). A number of analytical, semi-analytical and empirical approaches have been developed to approximate these two components (see *Warmink et al.* (2013) for an overview), which are associated with a large degree of uncertainty.

First, we identify roughness reaches following the spatial distribution of hydraulic radius R_h and grain size (i.e., D_{50}), as these are the two main variables affecting skin friction. We then compute skin friction. Form drag is computed following several approaches (*Van Rijn*, 1993; *Yalin*, 1964; *Haque and Mahmood*, 1983; *Karim*, 1999; *Vanoui and Hwang*, 1967; *Engelund*, 1966, 1977). The form drag estimates are dependent on bedform (i.e., dune) dimensions, for which we use field data at limited locations from *Carling et al.* (2000), *Julien et al.* (2002), *Wilbers and Ten Brinke* (2003), and *Lokin et al.* (2022). Finally, we calibrate the bed friction values at the limit of each roughness reach based on two criteria: (1) calibrated roughness values are within the range of data-derived values; (2) the spatial variation of bed roughness is, in a rough manner, coherent with data-derived values. Figure B.6 shows the identified roughness reaches, the calibrated friction values, and their comparison with field data-derived values, following the different approaches. Due to data availability, floodplain friction is set equal to main channel friction.

We then calibrate the upstream sediment flux using field data from *Frings et al.* (2019). We consider the estimated total annual mean sediment flux, and adjust the relative contribution of each fraction to the total flux so as to approach the normal flow load distribution (*Blom et al.*, 2017a). In so doing, we minimize the combined variation of bed level change and grain size change at the upstream boundary. The calibrated upstream flux per grain size class is provided in Table B.2.

Finally, we calibrate the parameters a_k of the nodal point relation against aggradation rates at the bifurcation (Section 3.2). We start from annual mean sediment flux values per fraction at the bifurcates (*Frings et al.*, 2015), and adjust them to better capture aggradation rates at the bifurcation, ensuring that the resulting sediment flux ratios fall within the range of the *Frings et al.* (2015) estimates on annual sediment fluxes. The calibrated values of a_k equal 2.73 for both sand fractions, 0.4 for fine gravel, and 0.5 for both coarse gravel fractions.

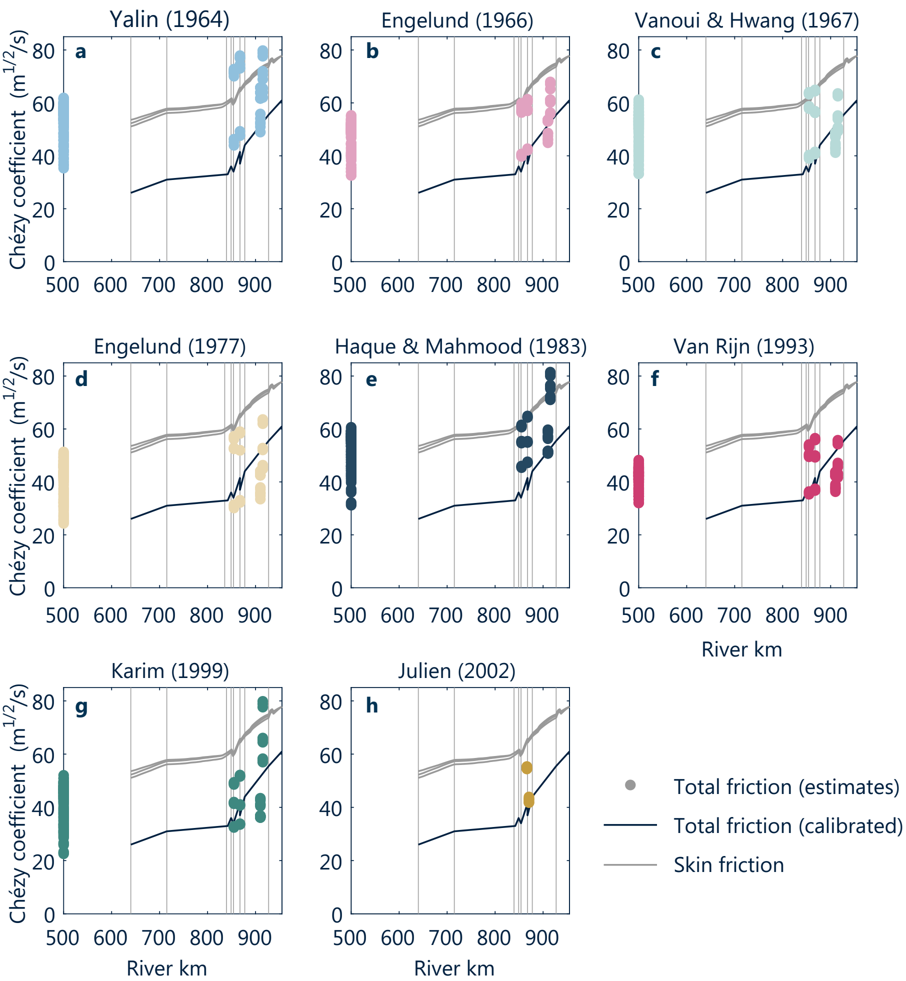

Figure B.6: Channel roughness estimates (colored dots) and calibrated values (dark blue line). Panels a-h correspond to different analytical, semi-analytical, and empirical estimates of channel roughness from literature. As an indication, we also include skin friction values derived following Darcy-Weissbach, for values of the Chézy coefficient of 35, 40, and 45 $m^{1/2}/s$ (gray lines). Vertical lines indicate the limits of roughness reaches.

Table B.2: Upstream sediment flux

Fraction	Mean annual sediment flux (Mt/a)
Fine sand (0.063-0.5 mm)	0.0188
Coarse sand (0.5–2 mm)	0.0336
Fine gravel (2-8 mm)	0.0286
Coarse gravel (8-31.5 mm)	0.025
Coarse gravel (31.5-125 mm)	0.02

B.6. Additional Results for the Reference Case

Figure B.7 shows additional results on the reference case. These results consist of channel bed slope, sediment flux, and bed surface and sediment flux grain size, and provide additional support to our hypotheses on the physics of channel response in the reference case (Section 3.3).

Additionally, Figures B.8 and B.9 show results on the sediment partitioning at the Pannerden bifurcation, in particular the ratio of Pannerden Canal to Waal total sediment flux (Figure B.8), and the ratio of Pannerden Canal to Waal sediment flux per grain size class (Figure B.9).

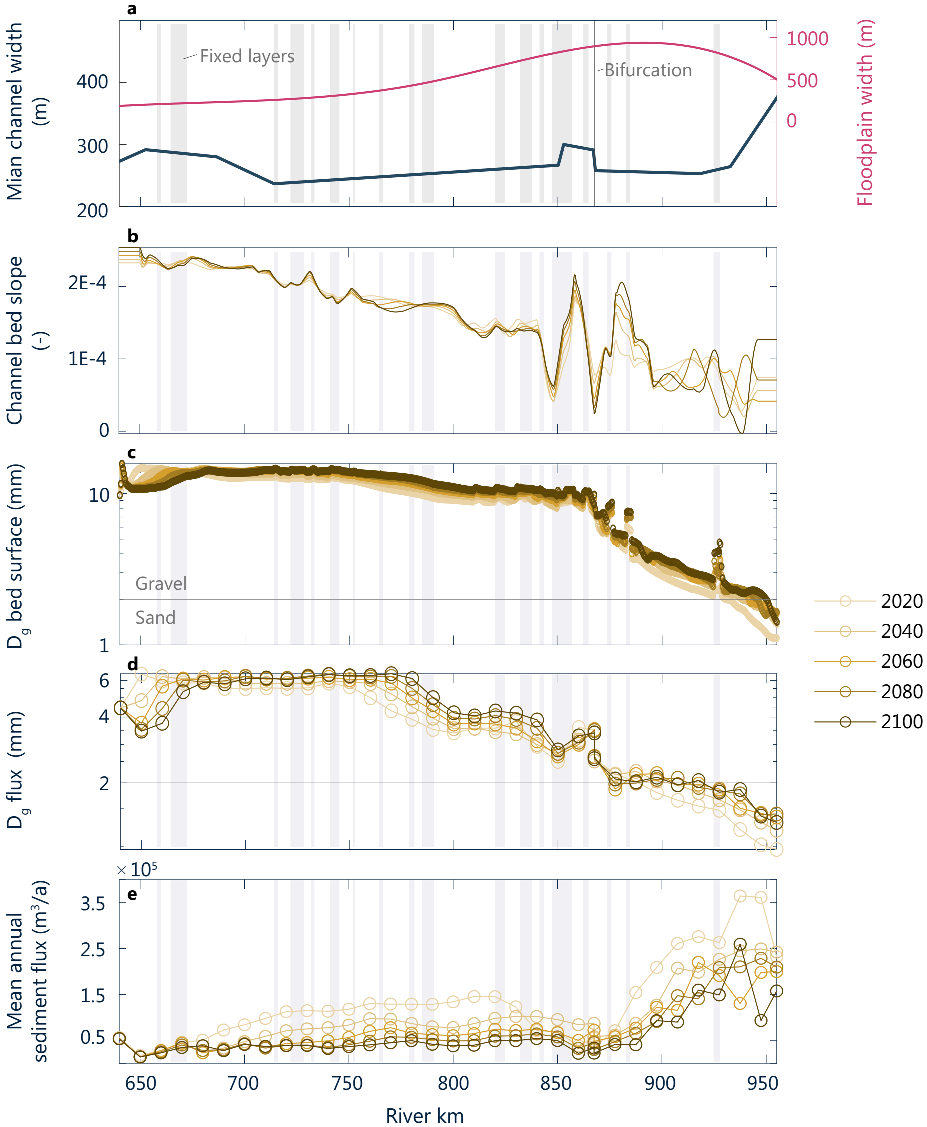

Figure B.7: Additional results for the reference case. (a) Main channel and floodplain width; (b) channel bed slope; (c) geometric mean bed surface grain size; (d) geometric mean sediment flux grain size; (e) mean annual sediment flux.

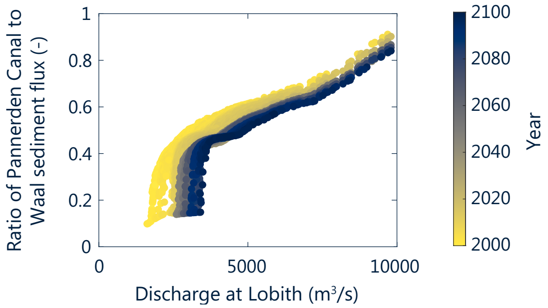

Figure B.8: Ratio of Pannerden Canal to Waal total sediment flux as a function of Lobith discharge and time.

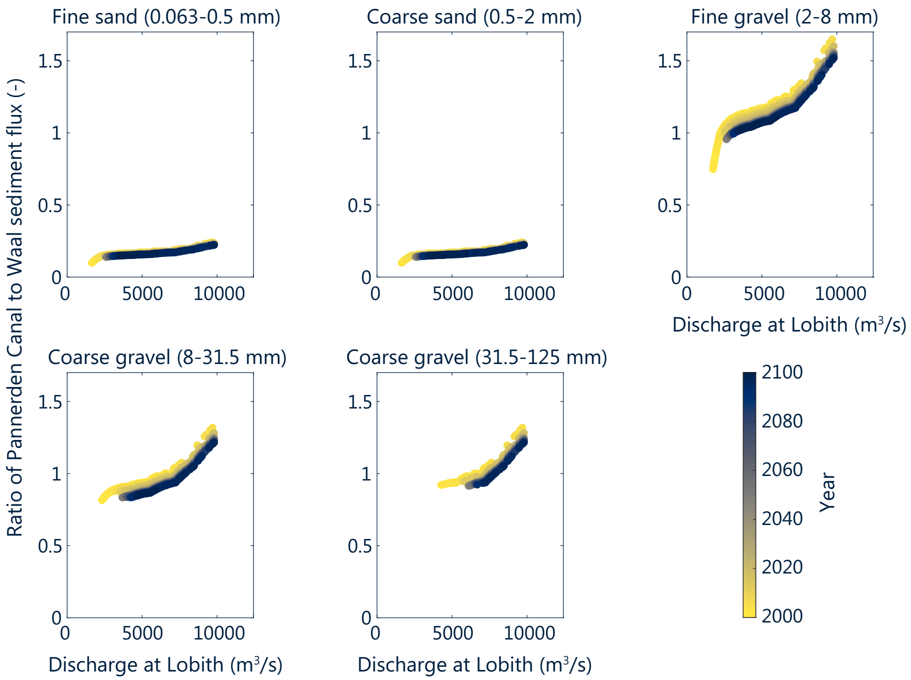

Figure B.9: Ratio of Pannerden Canal to Waal sediment flux per grain size class as a function of Lobith discharge and time.

B.7. Additional Results for 2050

We include additional results for 2050 for isolated and combined control changes in Figure B.10. These results consist of change in bed level and bed surface grain size by 2050 (Sections 3.4 and 3.5). The results provide additional support to our claim that channel response to climate change accelerates with time, as opposed to channel response to past human intervention, which slows down with time.

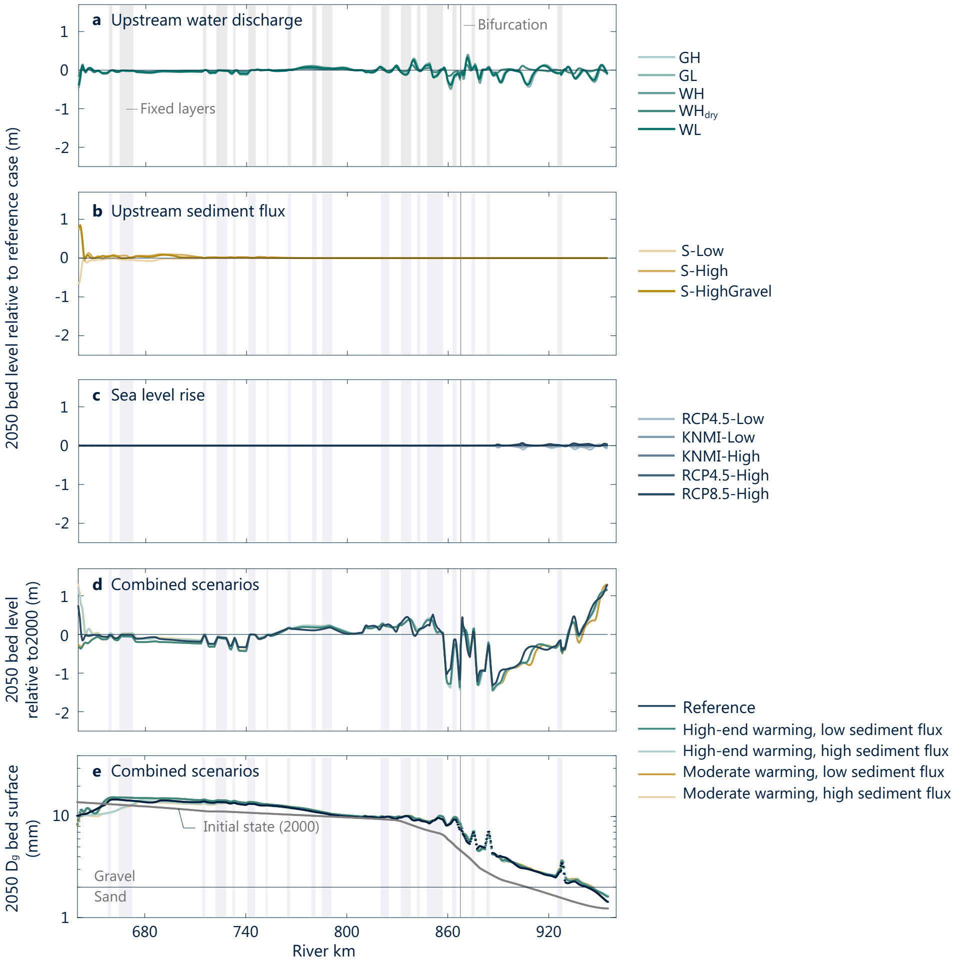

Figure B.10: Expected 2050 channel response to human intervention and climate change scenarios. Bed level in 2050 relative to the reference case for (isolated) scenarios of (a) water discharge, (b) sediment flux, and (c) sea level rise; (d) 2050 bed level relative to 2000 for combined climate scenarios (water discharge, sediment flux, and sea level rise), and (e) geometric mean bed surface grain size change for combined climate scenarios.

B.8. Obtaining Hydrographs from Climate Projections

Numerous global climate models have been set up to predict future climate. The Coupled Model Intercomparison Project (CMIP5, *IIASA*, 2009) provides a set of simulations carried out with 29 different global climate models, which inform the climate projections of the 5th Assessment Report, AR5 (*IPCC*, 2013).

The KNMI'14 scenarios for the Netherlands (*KNMI*, 2015) were created to capture, with four scenarios, 65-80% of the spread of the CMIP5 ensemble. The creation of the KNMI'14 scenarios is explained in detail by *Lenderink et al.* (2014).

The main steering variable for the comparison is the increase of mean global temperature. Specifically, the KNMI'14 scenarios are divided in two groups: the high-end warming scenarios (W-scenarios, from *warm* in Dutch) and the moderate warming scenarios (G-scenarios, from *gematigd*, in Dutch). The G and W scenarios are created to capture, respectively, the 10th and 90th percentile of mean global temperature increase predicted by the CMIP5 ensemble (Figure B.11, box 1).

The KNMI'14 scenarios stem from an ensemble of 8 model simulations made with the EC-EARTH global climate model (*Hazeleger et al.*, 2012). The comparison between the EC-EARTH results with the CMIP5 runs shows that the EC-EARTH ensemble covers 65-80% of the spread of the CMIP5 ensemble (Figure B.11, box 2). Since the entire CMIP5 spread cannot be covered by one single member of the EC-EARTH ensemble, *Lenderink et al.* (2014) resample the EC-EARTH results to obtain 4 single scenarios that capture 65-80% of the CMIP5 ensemble spread (Figure B.11, boxes 3 and 4).

The EC-EARTH simulations are subsequently downscaled with the regional climate model RACMO2 (latest version at *Wessem and Laffin*, 2020), and the results are resampled in the exact same way as was done with the global climate model (Figure B.11, box 5). Finally the EC-EARTH runs are bias-corrected and used to create transformation coefficients between future and present climate. These transformation coefficients are used to modify historic precipitation and temperature time series (Figure B.11, box 6), following *Hegnauer et al.* (2014). The transformed time series are fed into a rainfall-runoff HBV hydrological model (*Lindström et al.*, 1997) which provides the *Sperna-Weiland et al.* (2015) hydrographs (figure B.11, box 7).

Figure B.12 illustrates the transformation of our reference hydrograph based on climate scenarios. Note that the *Sperna-Weiland et al.* (2015) reference hydrograph is not strictly equal to our reference hydrograph. The statistics of our cycled reference hydrograph resemble the statistics of the measured discharge record more closely. To include the climate change effects on the hydrograph, we have applied the relative change between the *Sperna-Weiland et al.* (2015) reference case and climate change scenarios to our reference hydrograph.

Figure B.13 shows how representative values of discharge change across scenarios and over time.

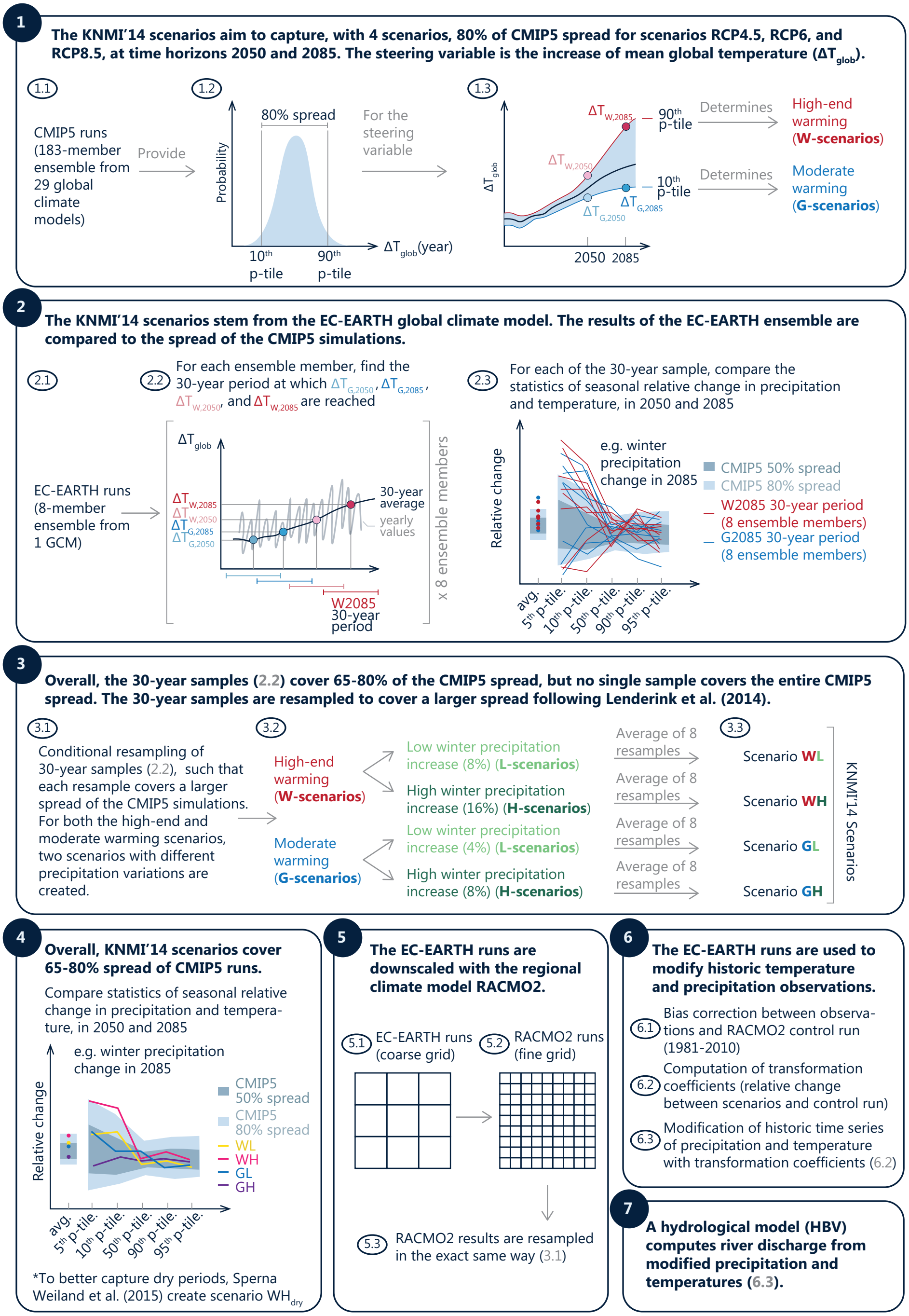

Figure B.11: Workflow chart indicating how the CMIP5 (*IIASA*, 2009) ensemble informs the KNMI'14 scenarios (*KNMI*, 2015), and subsequent *Sperna-Weiland et al.* (2015) hydrographs. The process follows *Lenderink et al.* (2014).

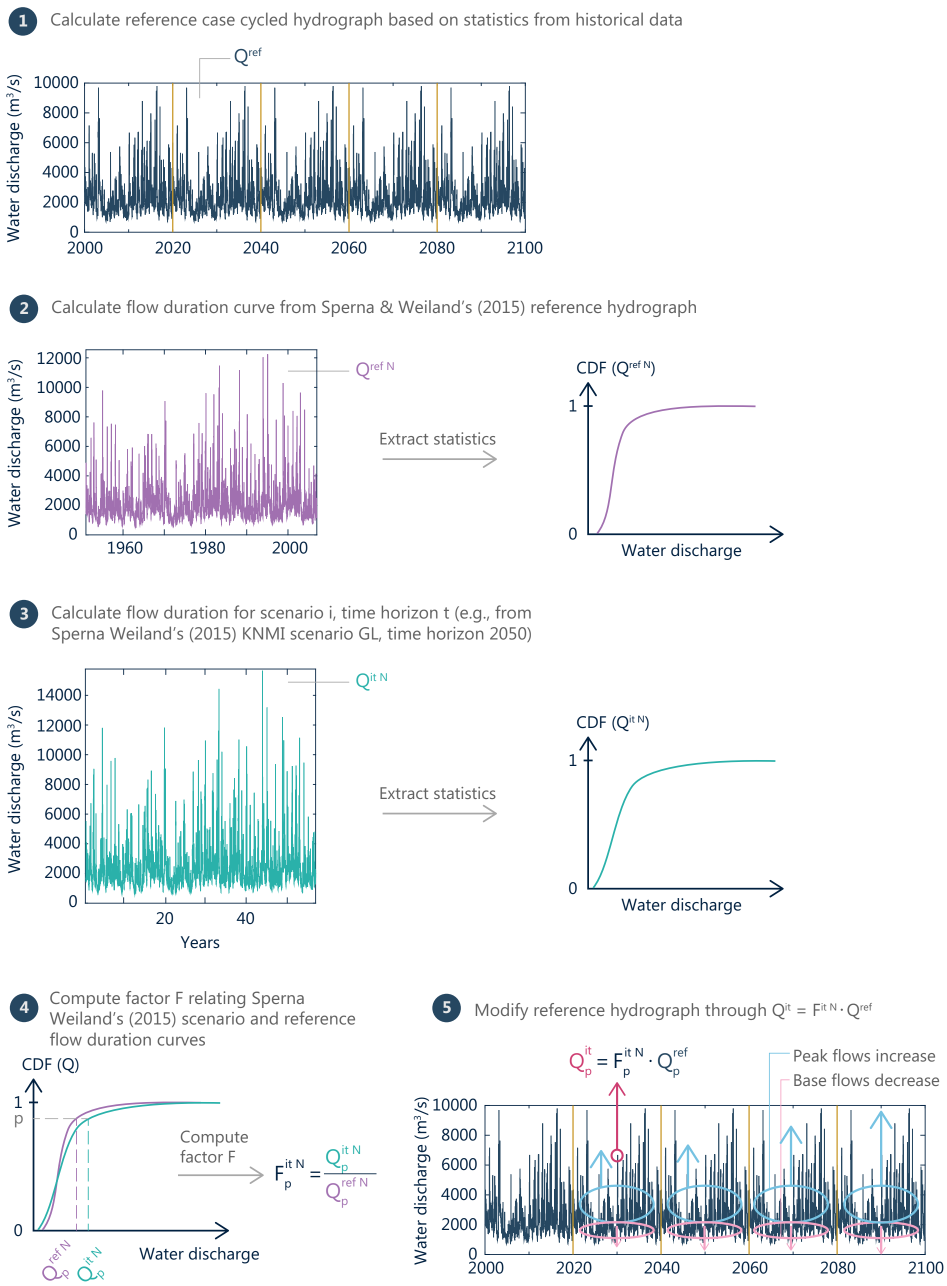

Figure B.12: Procedure to transform a reference cycled hydrograph into a scenario cycled hydrograph using the statistics of the *Sperna-Weiland et al.* (2015) water discharge scenarios.

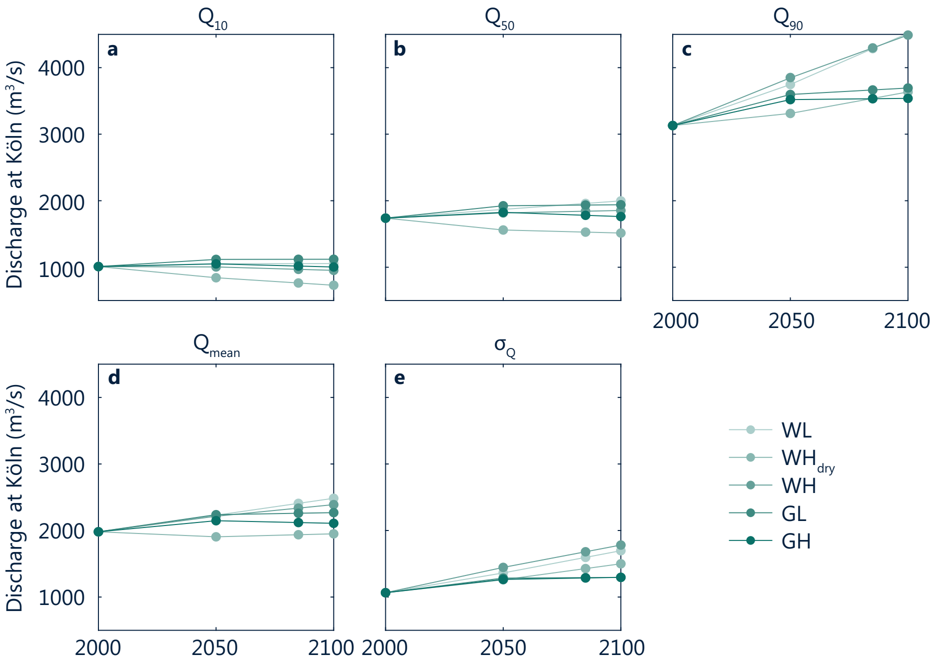

Figure B.13: Selected statistics of water discharge for KNMI scenarios (following *Sperna-Weiland et al.* (2015)'s transformation into water discharge) at 2000, 2050, 2085, and 2100 (extrapolated, as *Sperna-Weiland et al.* (2015)'s projections end at 2085). (a) 10th percentile, Q_{10}; (b) 50th percentile (median), Q_{50}; (c) 90th percentile, Q_{90}; (d) Mean daily discharge, Q_{mean}; (e) standard deviation, σ_Q.

C

Supporting Information for “Large-scale Channel Response to Erosion Control Measures”

This appendix has been submitted as supporting information for the following article (Chapter 4):

Ylla Arbós, C., A. Blom, S.R. White, R. Patzwahl, & R.M.J. Schielen (submitted for publication). Large-scale channel response to erosion control measures.

C.1. Introduction

This Supporting Information includes additional model results of Chapter 4.

C.2. Spatio-Temporal Channel Response to One Erosion Control Measure

Figure C.1 shows additional results for simulations of one erosion control measure. For illustration purposes, we show a case with constant discharge and unisize sediment, and consider a 16 km long measure. The results show a temporal decrease in flow depth over the erosion control measure (Figure C.1a), and a temporal increase in flow velocity (Figure C.1b). Figure C.1c shows the spatial reduction of sediment flux over the erosion control measure, and Figure C.1d shows the pronounced incision downstream of the erosion control measure.

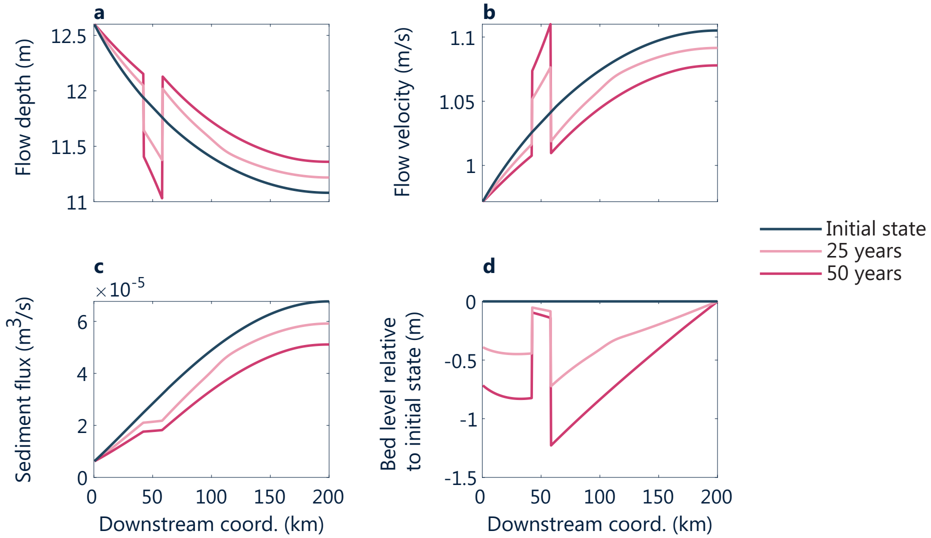

Figure C.1: Additional model results at initial state, and after 25 and 50 years for one erosion control measure of 16 kilometers, in a case with constant discharge and unisize sediment. (a) Flow depth, (b) flow velocity, (c) sediment flux, and (d) bed level relative to initial state.

C.3. Effects of Peak Flows on Fine Entrainment Downstream of Erosion Control Measures

Figure C.2 shows the effect of peak flows on fine entrainment downstream of erosion control measures (case with variable discharge and mixed size sediment). We consider a 4 km long measure. The largest peak flows lead to sediment fining waves, related to fine entrainment from the substrate.

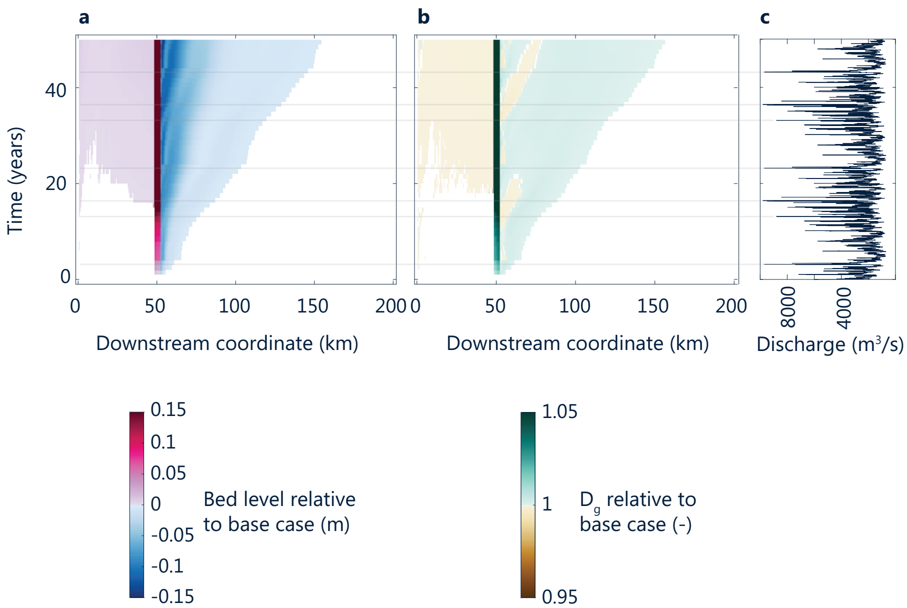

Figure C.2: Relationship between peak flows and fining waves for a variable discharge-mixed-size case with one erosion-control measure of 4 km. (a) Bed level relative to the base case without an erosion-control measure; (b) geometric mean grain size (D_g) relative to the base case; model hydrograph.

C.4. Effects of the Length of Erosion Control Measures on Large-Scale Channel Response

Figure C.3 shows the effect of length of erosion control measures on large-scale channel response, 50 years after its installation. For illustration purposes, we consider a case with constant discharge and unisize sediment. The longer the measure, the stronger the upstream backwater effects (Figure C.3a,b), and the longer the reach over which the sediment flux is reduced (Figure C.3c), resulting in the most pronounced erosion downstream of the measure (Figure C.3d).

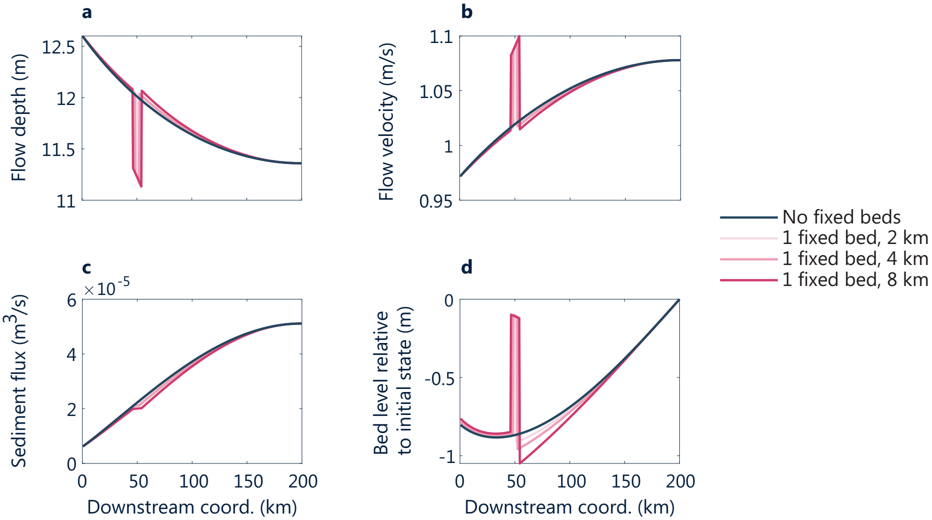

Figure C.3: Effects of the length of erosion control measures, based on model results for a case with constant discharge and unisize sediment after 50 years. (a) Flow depth, (b) flow velocity, (c) sediment flux, and (d) bed level relative to initial state.

C.5. Effects of the Spacing Between Erosion Control Measures on Large-Scale Channel Response

Figure C.4 shows the effect of the spacing between erosion control measures on large-scale channel response, 50 years after its installation. For illustration purposes, we consider a case with constant discharge and unisize sediment, and 4 km long measures. When the measures are closer together the sediment flux reduction effects of the different measures enhance each other (Figure C.4c), resulting in more pronounced erosion downstream of the measure (Figure C.4d).

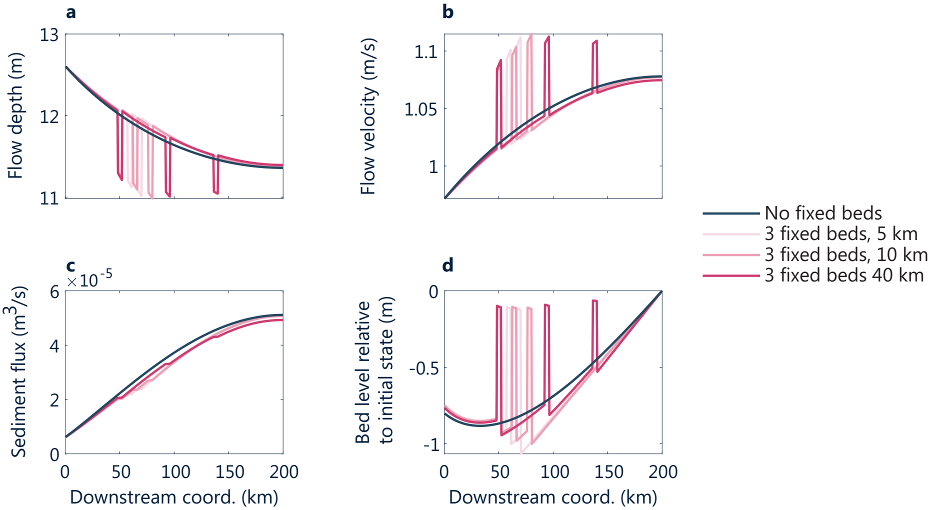

Figure C.4: Effects of the spacing between erosion control measures, based on model results for a case with constant discharge and unisize sediment after 50 years. (a) Flow depth, (b) flow velocity, (c) sediment flux, and (d) bed level relative to initial state. All the measures are 4 km long.

Curriculum Vitæ

Clàudia YLLA ARBÓS

05-09-1993	Born in Barcelona, Spain

Professional Experience

Sept. 2023 - Dec. 2023	Advisor - River management
Aug. 2023 -	Source-to-Sea working group on climate action coord. by Stockholm International Water Institute, Stockholm, Sweden
Dec. 2018 - Oct. 2023	Doctoral researcher - River morphodynamics and climate change Delft University of Technology, Delft, the Netherlands
Dec. 2020 - Jan. 2023	Chair and founding member Young NCR Netherlands Centre for River Studies, the Netherlands
Mar. 2020 -	Illustrator, Freelance
Mar. 2018 - Nov. 2018	Project engineer and research assistant - Hydraulic structures Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
Mar. 2017 - Jul. 2017	Intern project engineer - Numerical modeling and R&D GeoMod ingénieurs conseils, Lausanne, Switzerland
Sept. 2016 - Mar. 2017	Teaching assistant - Hydrology Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
Jul. 2016 - Sept. 2016	Intern project engineer - Numerical modeling, dams Stucky SA, Renens, Switzerland
Jul. 2015 - Aug. 2015	Field staff - Water distribution networks Camaay, Bamenda, Cameroon
Jun. 2014 - Aug. 2014	Supply chain intern Galenicum, Barcelona, Spain

Education

Dec. 2018 - Feb. 2024	PhD - River morphodynamics and climate change Delft University of Technology, Delft, the Netherlands
Sept. 2015 - Feb. 2018	MSc Civil Engineering - Water & Energy Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland MSc thesis awarded prize IM Maggia
Sept. 2011 - Jul. 2015	BSc Civil Engineering Universitat Politècnica de Catalunya, Barcelona, Spain Valedictorian

List of Publications

Peer-Reviewed Journal Articles

First Author

3. **C. Ylla Arbós**, A. Blom, S.R. White, R. Patzwahl, and R.M.J. Schielen, Large-scale channel response to erosion control measures (submitted for publication).

2. **C. Ylla Arbós**, A. Blom, A., C.J. Sloff, and R.M.J. Schielen (2023). Centennial channel response to climate change in an engineered river. *Geophysical Research Letters*, 50, e2023GL103000. doi:10.1029/2023GL103000.

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Co-Author

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1. **C. Ylla Arbós**, A. Blom, S. van Vuren, F. Acevedo Goldaracena, and R.M.J. Schielen (2020). Bed level change in the Upper Rhine Delta and Niederrhein, in *River Flow 2020: Proceedings of the 10th Conference on Fluvial Hydraulics, 7-10 July, Delft, the Netherlands [online]*, edited by W.S.J. Uijttewaal, M.J. Franca, D. Valero, V. Chavarrías, C. Ylla Arbós, R.M.J. Schielen, and A. Crosato, pp. 680-684, CRC Press / Balkema - Taylor & Francis Group, doi:10.1201/b22619.

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9. **C. Ylla Arbós**, A. Blom, C.J. Sloff, and R.M.J. Schielen (2023). 21st-century channel response of the lower Rhine River to climate change and human intervention, in *Proceedings of Gravel Bed Rivers 9, 10-13 January, Villarrica, Chile*.

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5. **C. Ylla Arbós**, A. Blom, and R.M.J. Schielen (2021). Scenarios for controls of river response to climate change in the lower Rhine River, in *NCR Days 2021: Rivers in an uncertain future, 11-12 February, Enschede, the Netherlands [online]*, edited by J. Warmink, A. Bomers, V. Kitsikoudis, R.P. van Denderen, and F. Huthoff, 46-2021, pp. 70-71, Netherlands Centre for River Studies.

4. **C. Ylla Arbós**, A. Blom, and R.M.J. Schielen (2020). Bed level change in the Upper Rhine Delta between 1926-2018, in *NCR Days 2020: Managing changing rivers, 13-14 February, Nijmegen, the Netherlands*, edited by M. Boersma, R.M.J. Schielen, and E. van Eijsbergen, 40-2020, pp. 91-92, Netherlands Centre for River Studies.

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CHANNEL RESPONSE OF AN ENGINEERED RIVER TO CLIMATE CHANGE AND HUMAN INTERVENTION

CLÀUDIA YLLA ARBÓS