Looking back, looking forward:

Human impacts on fluvial morphodynamics since the Industrial Revolution and the return to a natural morphological river state

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vorgelegt von

Anna-Lisa Maaß

Berichter: Univ.-Prof. Dr.-Ing. Holger Schüttrumpf

Univ.-Prof. Dr. rer. nat. Frank Lehmkuhl

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Kurzzusammenfassung

Die Mobilisierung, der Transport und die Ablagerung von Sediment sind dynamische Prozesse, welche Umweltbedingungen sowie ökologische Prozesse und Lebewesen im und am Fluss beeinflussen. Anthropogene Einflüsse in Form von Landnutzungsänderungen, Hochwasserschutzmaßnahmen, Wasserkraftanlagen, Bergbauaktivitäten, Schifffahrt und Trinkwasserversorgung haben nicht nur die Abflussdynamik, sondern auch die Morphodynamik der Fließgewässersysteme verändert.

Es besteht nur selten ein umfangreiches Prozessverständnis über den dynamischen Transport von Sedimentströmen in Bezug zur gesamten Einzugsgebietsebene der meisten Fließgewässersysteme. Dennoch ist es entscheidend, die hydrodynamischen und morphodynamischen Prozesse unserer heutigen Fließgewässersysteme zu verstehen und dabei sowohl den historischen, annähernd natürlichen, als auch den heutigen, menschlich beeinflussten, Zustand zu untersuchen sowie zukünftige Entwicklungen zu analysieren. Bereits in der EG-Wasserrahmenrichtlinie (aus dem Jahr 2000) ist festgeschrieben, dass es nicht möglich ist, zu einem „natürlichen“ morphologischen Zustand zurückzukehren, sodass bei Renaturierungsmaßnahmen Kompromisse eingegangen werden müssen.

Heutzutage werden vor allem kleine Fließgewässersysteme renaturiert, da diese direkt abhängig von natürlichen und menschlichen Veränderungen im Einzugsgebiet sind und menschliche Aktivitäten die ursprünglichen Bedingungen überlagern. Folglich ist insbesondere für kleine Fließgewässer ein umfangreiches Verständnis von historischen und aktuellen hydro- und morphodynamischen Prozessen notwendig, um Renaturierungsmaßnahmen erfolgreich zu planen und umzusetzen. In kleinen Einzugsgebieten existieren diverse, kleinskalige Einflussfaktoren, deren Auswirkungen sowohl unabhängig voneinander als auch in der Überlagerung untersucht werden müssen.

Das Ziel dieser Arbeit ist es, dass Verständnis von Sedimenttransportprozessen und morphodynamischen Veränderungen auf der Einzugsgebietsebene von kleinen Fließgewässern zu verbessern und dieses Wissen bei der Planung, Umsetzung und Kontrolle von Renaturierungsmaßnahmen zu nutzen. Im Fokus stehen dabei unterschiedliche technischen Einflussfaktoren seit der Industriellen Revolution. Es werden Querbauwerke in Form von Wassermühlen, bergbaulich bedingte Senkungen der Geländeoberfläche und Renaturierungsmaßnahmen als drei Beispiele für menschliche Einflussfaktoren in kleinen Flusseinzugsgebieten ausgewählt und hinsichtlich ihrer Einflüsse auf die fluviale Morphodynamik untersucht. Es wird mittels unterschiedlicher Methodik (theoretische Analysen, numerische Modellierungen, Feldmessungen) jeder Einflussfaktor einzeln untersucht und hinsichtlich der Auswirkungen auf das Gewässersystem miteinander verglichen. Es werden historische Zustände rekonstruiert, um die Ausprägungen heutiger Gewässersysteme zu verstehen. Vor allem die numerische 2D-Modellierung über Zeitskalen von 10 bis 200 Jahren stellt eine Besonderheit dieser Arbeit dar. Solche langzeitlichen Untersuchungen können genutzt werden, um zukünftige morphodynamische Gewässerentwicklungen besser abschätzen und zielgerichtete Maßnahmen zur Verbesserung des gesamten Gewässersystems entwickeln zu können.

In dieser Arbeit werden zunächst die menschlichen Einflüsse auf die fluviale Morphodynamik in Mitteleuropa anhand einer Literaturrecherche zusammengefasst und die Möglichkeiten der Rückkehr zu einem „morphologisch natürlichen“ Zustand dargestellt. Anschließend werden die Einflüsse des Baus und Rückbaus von Querbauwerken in Form von Wassermühlen auf die fluviale Morphodynamik untersucht.

Es werden physikalische Gleichungen zur Beschreibung des Längsprofils angewandt sowie Feldmessungen zur Bestimmung der Vorlandsedimentation im Staubereich von Mühlenwehren ausgewertet. Zusätzlich werden die Auswirkungen von bergbaulich bedingten Senkungen auf die *trapping efficiency* von Vorländern untersucht. Mittels numerischer 2D-Modellierung werden unterschiedliche Szenarien verglichen und hinsichtlich der mittleren Vorlandsedimentation analysiert. In den Szenarien werden Tiefe, Ort und Ausdehnung der Bergsenkungen variiert. Anschließend werden die Auswirkungen einer Gewässerverlegung und Renaturierung auf die fluviale Morphodynamik anhand von umfangreichen Feldmessungen, die über mehr als 10 Jahre durchgeführt wurden, untersucht und ausgewertet. Das konkrete Beispiel dieser bereits umgesetzten Renaturierung soll aufzeigen, ob es möglich ist, einen „morphologisch natürlichen" Zustand wiederherzustellen und ob dieser auch im Kontext der EG-Wasserrahmenrichtlinie ausdrücklich erwünscht ist. Abschließend erfolgt eine numerische Szenarien-Studie, in der unterschiedliche Varianten zum Wiederanschluss von Vorländern bei Renaturierungsmaßnahmen an die Gewässerdynamik analysiert werden. Der Fokus liegt dabei auf den langzeitlichen Auswirkungen dieser Maßnahmen auf die Mobilität der Feinsedimentdepots von Vorländern.

Die Ergebnisse dieser Arbeit zeigen, dass

- es diverse natürliche und anthropogene Einflüsse gibt, die den Feinsedimenttransport in Gewässersystemen beeinflussen,
- der Bau von Querbauwerken wie beispielsweise Mühlenwehren zu einer Erhöhung der (Fein-)Sedimentdepots führt,
- die Entfernung von Querbauwerken zu einer Einschneidung des Gewässerbettes und damit zu einer Entkopplung von Fluss und Vorland führt,
- es Sedimentfallen wie bergbaulich bedingte Senkungen gibt, die lokal zu einer Erhöhung der Vorlandsedimentation führen,
- Bergsenkungen mit Größenordnungen von lediglich einigen wenigen Metern an kleinen Fließgewässern mit einer tief eingeschnittenen Sohle eher eine untergeordnete Rolle spielen,
- im Rahmen von Renaturierungsmaßnahmen Vorländer wieder an die Überflutungsdynamik von Fließgewässern angeschlossen werden, dies jedoch nicht zwangsläufig eine Remobilisierung von Vorlandsedimenten, sondern eine erneute Deposition von Sediment zur Folge hat und dass
- Feinsedimenttransport ein intrinsischer, natürlicher Bestandteil von (kleinen) Gewässersystemen ist.

Die beiden menschlichen Einflussfaktoren in Form von Wassermühlen und Bergsenkungen sind Beispiele für diverse menschliche Faktoren in kleinen Flusseinzugsgebieten, dessen morphodynamische Konsequenz – eines tief eingeschnittenen Flusses mit hohen, steilen Ufern und entkoppelten Vorländern, die große Feinsedimentdepots beinhalten – charakteristisch ist für viele dieser Gewässersysteme in Mittel- bis Westeuropa und unabdingbar bei Gewässerrenaturierungen berücksichtigt werden muss, um die Auswirkungen von Feinsedimenten auch für die zukünftige Entwicklung zu berücksichtigen und zu beurteilen.

Abstract

Mobilization, transport and deposition of sediment are dynamic processes, which affect environmental conditions as well as ecological processes and living organisms in and at river systems. Anthropogenic impacts in terms of land-use changes, flood protection, hydropower plants, mining activities, shipping and drinking water supply have not only changed the hydrodynamics but also the morphodynamics of river-floodplain systems.

Information and process knowledge about sediment budgets and dynamics of (fine) sediment fluxes on the river basin scale of most river-floodplain systems are rarely present. Information is missing for the historical or rather “natural” as well as for the present-day situation. Changes of the “natural” fine sediment fluxes in the last centuries result in changes of the fluvial morphology, so that the fluvial morphodynamics of both states might be completely different. It is already embedded in the EU Water Framework Directive (from 2000) that it is not possible to achieve a “natural” morphological state and that it is therefore necessary to make compromises during restoration interventions.

Today, especially small river-floodplain systems are restored due to their direct dependence on natural and anthropogenic changes in the catchment. Here, human activities overwhelm pristine conditions. Therefore, it is essential to understand the historical as well as the present-day morphological processes in small river-floodplain systems to successfully plan and realize restoration interventions. In small catchments, diverse small-scale impact factor exists, whose consequences need to be analyzed individually as well as in superposition.

The aim of this thesis is to improve the understanding of sediment transport processes and morphological changes on a river basin scale of small river-floodplain systems and to use this knowledge during the planning, realization and monitoring of restoration interventions. The thesis focusses on different technical impact factors since the Industrial Revolution. Transverse structures in terms of water mills, subsidence induced by underground coal mining and river restoration interventions are selected as three examples of human impact factors in small river-floodplain systems and are analyzed focusing on their impacts on fluvial morphodynamics. Using different methodology (theoretical analyses, numerical modelling, field measurements), each factor is individually analyzed and compared regarding its consequences on the river-floodplain system. Historical conditions are reconstructed to understand today’s river characteristics. In particular, the morphodynamic numerical 2D modelling over time scales of 10 to 200 years is a special characteristic of this thesis. Such long-term investigations can be used, to assess future morphodynamic river developments and to develop restoration interventions to improve the entire river-floodplain system.

In this thesis, at first all human impact factors on fluvial morphodynamics in Central Europe are summarized within a literature review and the possibilities to return to a near-natural morphological river state are presented. Subsequent, the consequences of the construction and the removal of transverse structures in terms of water mills on the fluvial morphodynamics are analyzed. Physical equations are applied to describe the longitudinal river profile and field measurements are used to determine the deposition of sediment on floodplains inside the backwater area of mill weirs. Additionally, the consequences of mining-induced subsidence on the trapping efficiency of floodplains are analyzed with a 2D-numerical modelling study. Subsidence scenarios with different subsidence depths, locations and extensions are compared and analyzed focusing on the average floodplain deposition of sediment. After that, the consequences of a river relocation and restoration on the fluvial morphodynamics are investigated and evaluated with extensive field measurements over a time period of more than 10 years. This specific example of an already realized river restoration shows, if it is possible to restore a near-natural morphological state and if such a state is explicitly wanted in context of the EU Water Framework Directive. Finally, a numerical scenario study is performed, in which different possibilities to reactivate floodplains in course of river restoration interventions to natural river dynamics are analyzed. The study focuses on the long-term consequences of these interventions on the mobility of floodplain deposits of small rivers.

The results of this thesis show that

- diverse natural and anthropogenic impact factors exist, which influence the fine sediment transport in river-floodplain systems,
- the construction of transverse structures such as mill weirs leads to an increase of (fine) sediment deposits,
- the removal of transverse structures leads to incision of the river bed and therefore to decoupling of the river and the floodplains,
- sediment traps like mining-induced subsidence exist, which locally increase floodplain deposition,
- mining-induced subsidence on a scale of only a few meters plays a minor role in small river basins with a deeply incised river bed,
- floodplains are reconnected in river restorations to the inundation dynamics of a river system, but that this does not inevitable lead to a remobilization of floodplain sediment deposits but again to deposition of sediments on the floodplains and that
- fine sediment transport is an intrinsic, natural component of (small) river-floodplain systems.

Water mills and mining-induced subsidence are two examples of all the diverse anthropogenic impact factors in small river basins, whose morphodynamic consequence – of a deeply incised river with high, steep banks and decoupled floodplains containing large fine sediment deposits – is characteristic for many river-floodplain systems in Central to Western Europe and must be taken into account during river restorations to consider and evaluate the consequences of fine sediment on future river development.

Contents

1 Introduction

1.1 Motivation

River-floodplain systems all over the world are strongly impacted by natural and anthropogenic activities (Dotterweich 2008; Hoffmann et al. 2010). A superposition of short- and especially long-lasting impact factors characterizes and drives today's river-floodplain systems, whereas it is difficult to distinguish between natural and anthropogenic causes (Bebermeier et al. 2018). Human impact continuously increased since the beginning of the Holocene (Zolitschka et al. 2003; Hoffmann et al. 2009; Ibisate et al. 2011; Birks et al. 2015) and can therefore be seen as an essential factor for changes of fluvial systems (Erkens et al. 2011; Broothaerts et al. 2013; Heyvaert and Walstra 2016). Floodplains store historical sediment (Dotterweich 2008; Protze 2014) and therefore information about river response to external impacts. Colluvial deposits are mainly related to periods of intensified human activities, whereas alluvial deposits are mainly related to climatic changes (Zolitschka et al. 2003).

In Central Europe, anthropogenic factors include indirect factors like land-use change including agriculture, deforestation, reforestation, and urbanization, which affect runoff and sediment yield, as well as direct factors like river regulations, dams, reservoirs, water abstraction, gravel mining, canalization, dredging, embankment or riprap, which directly modify the channel and the floodplains (Surian and Rinaldi 2003; Syvitski et al. 2005; Syvitski and Milliman 2007; Notebaert and Verstraeten 2010; Ibisate et al. 2011; Yamani 2011; Petts 2016). Figure 1-1 shows a schematic diagram of different human impact factors in Central Europe on river-floodplain systems since the beginning of the Holocene.

Since the Neolithic (in Central Europe mainly 5,300 years ago), humans settled down, established agriculture and forest clearance began locally. River-floodplain systems were no longer not only impacted by climate and geology, but also by social, political, economic and technical impact factors. Anthropogenic activity affected soils and resulted in different erosion and deposition processes. Taking a temporal offset under consideration, anthropogenically induced soil erosion led to increased sediment inputs in river systems (Lewin et al. 2005; Hoffmann et al. 2009; Reiß et al. 2009; Larsen et al. 2013; Macklin et al. 2014; Hoffmann 2015) and consequently to an increased formation of colluvial deposits (Bork et al. 1998; Dreibrodt et al. 2010). Therefore, river-floodplain systems were affected for the first time by indirect human impact factors in terms of land-use changes (Dotterweich 2008; Dreibrodt et al. 2010).

Further technological development and growth of population led to greater river modifications and geometrical changes of river-floodplain systems. Already in the Iron Age (in Central Europe approximately 800 BC to 50 BC), direct human impact factors such as water mills and dams were constructed or rivers were straightened, which directly affected fluvial morphodynamics (Vandenberghe et al. 2012).

In the Medieval Times (5th to 15th century), the use of forests, mining activities and an increase in settlement led to increased and widespread soil erosion and therefore to an increased sediment input and morphological changes (Vandenberghe et al. 2012) as well as another period of increased colluvial deposits (Bork et al. 1998; Lehmkuhl et al. 2012).

Figure 1-1: Schematic diagram of human impact factors on river-floodplain systems in Central Europe since the beginning of the Holocene (modified after Gibling 2018).

Since the Industrial Revolution (~ 200 years ago), rivers were embanked, narrowed and extensively straightened, which extensively changed firstly the hydrodynamic and secondly the morphodynamic behavior of a river. Additionally, humans settled down closer to the resource water. Urbanization required greater flood protection measures and led to an increased input of contaminants into river-floodplain systems (Schneider 1982). The Industrial Revolution and the accompanying increasing urbanization result also in a greater input of new and different contaminants in river systems.

Fine sediments play a major role in the distribution of contaminants during flood events. Contaminants absorbed on fine sediment can be deposited on the river bed or on the floodplains and might be remobilized by subsequent flood events. Floodplains act as a trap for fluvial fine, cohesive, potentially contaminated sediment. Therefore, changes in fine sediment fluxes are of importance especially in (old) industrial regions (Germershausen 2013). Figure 1-2 shows the development of land-use changes and soil erosion in Central Europe since the occurrence of widespread deforestations. Phases of stabilization and destabilization in soil erosion alternated in the last centuries due to different land-use changes (Bork 2006).

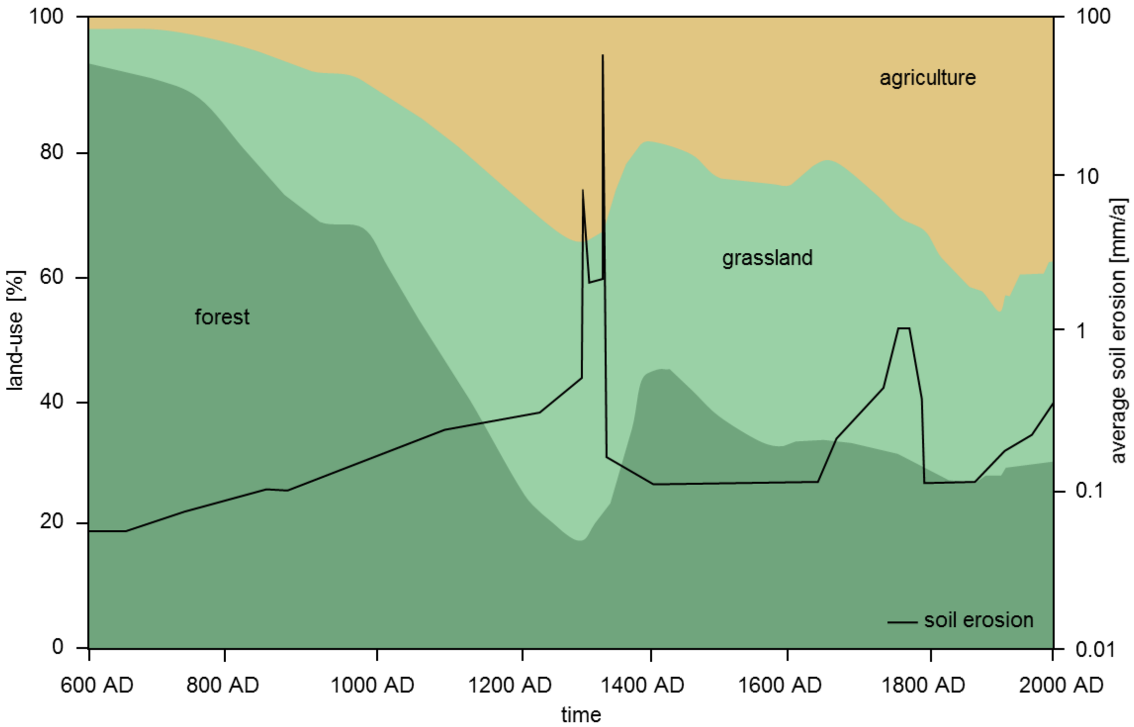

Figure 1-2: Development of land-use and soil erosion in Central Europe (modified after Bork 2006).

In the 21st century, national (e.g., German Water Resources Law) and international (e.g., EU Water Framework Directive) laws and guidelines define that previous anthropogenic impacts should be undone and emphasize a natural hydrological and morphological development. The “natural” characteristics of a river-floodplain system are abstracted and formulated in a pre-defined guiding principle, which also considers irreversible anthropogenic impacts (Patt 2016). The pre-defined development goals should be realized within river restorations and are evaluated comparing the current state of a river and its guiding principle with each other. During river restorations, flooding areas are generated, flow lengths are increased, anthropogenic barriers are reduced and a “natural” river development is initiated (Gerken et al. 1988).

The motivation behind river restoration projects vary with land ownership, funding agency and cultural setting (James and Marcus 2006) and there is often the problem of presenting the public a “good and healthy” river-floodplain system (Wohl et al. 2015). For the public, a river is healthy if the water is clear and the stream banks are not rapidly eroding (Wohl 2005). Following Frings and Maaß (2018), ten misinterpretations of fluvial morphodynamics can be concluded:

1. Natural river systems are in a morphological equilibrium and have continuous sediment fluxes.
2. Erosion and deposition of sediment always have anthropogenic causes.
3. Sediment transport is a spatial-continuous process.
4. Natural rivers transport only less sand, clay and silt, so that increasing fine sediment continuity should be prevented at any price.
5. Clogging is not present in natural rivers.
6. Returning to an initial morphological river state is possible.
7. Restoring the sediment continuity leads to natural fluvial morphodynamics.
8. Measures at transverse structures are sufficient for restoring sediment continuity.

9. Measures at a river-floodplain system are restricted locally.
10. Indicators are sufficient to describe fluvial morphodynamics.

Realizing a natural development means again an anthropogenic impact in river-floodplain systems. Even though it is sometimes possible to restore an initial, “natural” hydrodynamic situation, it is (often) not possible to achieve initial, “natural” morphodynamic conditions. Human impacts of the last decades to centuries have irreversibly changed the fluvial morphodynamics. But, ending up some human impact factors, it might be possible to restrict further unintended and negative morphological changes and to transform river-floodplain systems in a state, which is of equal value as the “natural” morphological state (Koenzen 2005; Frings and Maaß 2018). It must be clear that a return to “natural” morphological conditions accompanies with a return to “natural” morphodynamic processes. River management that accounts for often-conflicting interests requires awareness and understanding of “natural” morphodynamic processes (Vandenberghe et al. 2012). Therefore, understanding historical hydrodynamic and morphodynamic river conditions, monitoring present-day processes and assessing future development are essential for today’s proper river management.

1.2 Problem definition

Information and process knowledge about sediment budgets and dynamics of (fine) sediment fluxes on a river basin scale of most river-floodplain systems are rarely present. Information is missing for the historical or rather “natural” as well as for the present-day situation. Therefore, this thesis contributes to improve the understanding of sediment transport processes and morphological changes on a river basin scale of small river-floodplain systems towards a better understanding of river-specific sedimentological and morphological characteristics taking the natural and anthropogenic impact factors of the entire river catchment into account.

The thesis focuses on technical direct human impacts since the Industrial Revolution taking especially three impact factors under consideration: water mills, subsidence induced by underground coal mining and the realization of river restorations. Changes in land-use are only of secondary importance.

Water mills

In a river system without any human impact, the energy of the water is normally dissipated by friction. However, energy can also be removed in other ways. One of these ways is the transformation of water energy into electrical energy in a hydropower scheme (Janssen 1979). Water mills use flowing water as a power source to generate mechanical energy, e.g., to grind flour or to saw wood. In most cases, a water mill is located at a mill leat that can either be a channel or a pond. With the construction of a (mill) weir, a mill channel is artificially separated from the main river channel to enable a greater hydropower usage of the water mill. A mill channel might have a length of a few meters to a few kilometers. At a mill weir, water is impounded, and the impoundment can be regulated by managing the height of the weir. The location of the mill weir is limited by the surrounding landscape and by the fall that is needed to meet the mill owner’s power needs (Reynolds 1983; Müller and Trossbach 1999; Bishop and Muñoz-Salinas 2013). At water mill systems, there are four impact factors changing the hydraulic regime of a river and consequently its morphodynamics: (1) decrease in flow velocity upstream of the weir, (2) backwater effects upstream of the weir, (3) diversion of the discharge into two flow paths and (4) redirection of the main flow into a mill channel.

At the end of the 19th century, the time of active water mills approached its end as water power was replaced by other forms of energy (mainly coal). Consequently, most water mills (especially mill weirs and water wheels) were removed from river systems and the water level in the river channel was no longer impounded, which again changed the hydraulic regime and morphodynamics of a river.

Underground coal mining industry

Another field of human impacts on fluvial morphodynamics is related to the coal mining industry and the extraction of coal from the underground, which results in surface movement in terms of subsidence or uplift of the landscape as one type of active tectonics. Subsidence occurs during the persistent coal mining industry because of the extraction of mineral resources. In contrast, sinkholes provided by a sudden collapse of the ground or uplift effects provided by raising groundwater levels occur after mine closure.

Subsidence can alter and create preferential flow paths, thus causing dewatering and rerouting of surface water and groundwater. Subsidence changes channel and drainage morphology, which could affect channel erosion, sediment delivery and routing in stream (Ouchi 1985; Schumm 1986; Sidle et al. 2000). The effects of subsidence underneath the river bed can be divided into primary, secondary and tertiary ones. At first, the channel and valley gradient changes. Second, the river responds to modified gradient with aggradation or degradation and third, there will be increased or decreased sediment loads (Schumm 1986). Subsidence and uplift effects caused by underground coal mining depend, e.g., on the type of mining and the size of extraction. The whole coal mining industry influenced the landscape by elevation changes according to the deposition of mining materials on the surface or by draining mine water into river systems. Water quality was deteriorated, while contaminants absorbed on cohesive sediment and were transported into the river system. The former coal mining industry had and still has a great impact on the environment.

River restoration

Since the last 50 years, the perspective regarding the use of and handling with river-floodplain systems has completely changed. In many national (e.g., German Water Resources Law) or international (e.g., EU Water Framework Directive) laws and guidelines, a “natural” development of river-floodplain systems is required. It is stated that heavily modified water bodies need to be returned into their natural or near-natural state. The “natural” characteristics of a river-floodplain system are abstracted and formulated in a pre-defined guiding principle, which also considers irreversible anthropogenic impacts (Patt 2016). The pre-defined development goals should be realized within river restorations and are evaluated comparing the current state of a river and its guiding principle with each other.

Analyzing fluvial morphodynamics is still a challenge because the dynamics of a river-floodplain system encompass long-term effects and large-scale developments, which can only be monitored over longer time-scales or within schematized numerical models with overlapping natural and anthropogenic impact factors on different temporal and spatial scales (James and Marcus 2006; Schüttrumpf 2017). Even though, if several human impact factors are already removed from the system, their consequences affect the morphodynamics of a river, decades to centuries after the impact. Changes of the “natural” sediment fluxes in the last centuries result in changes of the fluvial morphodynamics. Therefore, in context of the

EU Water Framework Directive, “natural” river-floodplain conditions and the return to a “natural” morphological state are required. However, what is natural? How can this “natural” state be defined and does this state include river dynamics?

Figure 1-3 summarizes the human impact factors of water mills, the underground coal mining industry and river restoration on river-floodplain systems. The colors of Figure 1-3 are repeated in Figure 1-4 and Figure 1-5 to emphasize the relation between the research areas and the human impact factors. Since the Industrial Revolution, the human impacts of water mills and mining activities on especially fine sediment continuity cannot be determined detached from urbanization and land-use changes. River-floodplain systems with a long-lasting anthropogenic history predominantly occur in urban areas. Consequently, rivers were relocated or embanked and therefore heavily modified to avoid damages of the infrastructure or dangers to humans. However, land-use changes are of secondary importance in this thesis.

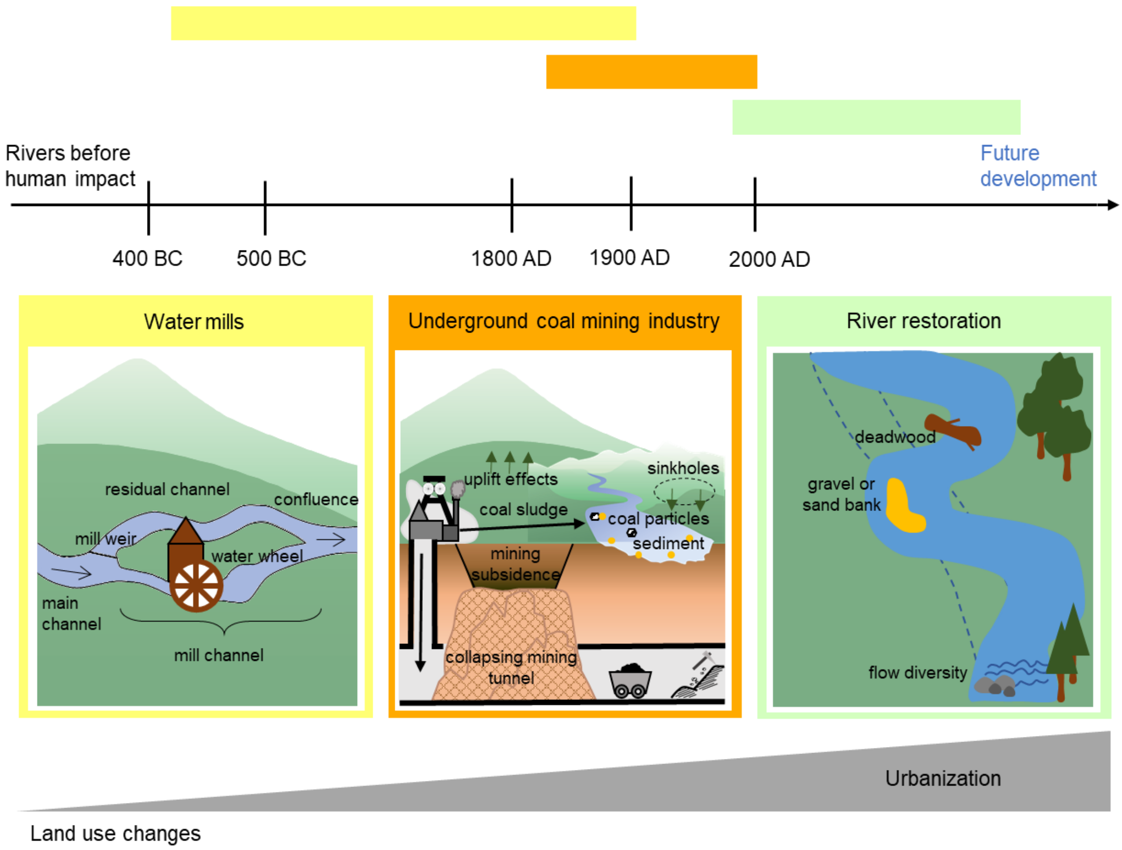

Figure 1-3: Time line of human impact on river-floodplain systems in terms of water mills, underground coal mining industry and river restoration in Central Europe.

1.3 Objectives

The general objective of the research presented in this thesis is to improve the understanding of sediment transport processes and morphological changes on a river basin scale of small river-floodplain systems and to use this knowledge during the planning, realization and monitoring of river restorations. The thesis focuses on different technical impact factors since the Industrial Revolution and their future implications. Transverse structures in terms of water mills, subsidence induced by underground coal mining and river restorations are selected as three examples of human impact factors in small river-floodplain systems and are analyzed focusing on their impacts on fluvial morphodynamics. Fluvial morphodynamics cannot be observed without any consideration of historical sediment characteristics. The current morphological state of river-floodplain systems is influenced by many historical and present-day natural and anthropogenic impacts. The fundamental effects of each impact factor need to be analyzed directly after its beginning with theoretical and numerical models. Input data for the numerical models is determined with field measurements. Historical data for discharge, water level, grain size distribution and cross sections are reconstructed by analyzing historical maps and using theoretical hydraulic relations.

With respect to water mills, the following research questions are formulated:

- Does the decreased flow velocity upstream of a mill weir according to backwater effects of the weir result in higher sedimentation rates on the river bed, so that also the floodplains are more often inundated, and more sediment is trapped on the floodplains as well?
- How do slope and discharge influence backwater in upstream direction and which modifications develop if backwater reaches the next upstream located water mill? According to the river gradient, the channel might be effectively stepped.
- How long does it take for a river to adapt its longitudinal profile to the construction or the removal of a water mill in a river system? Is there an equilibrium status where the river accepts the human impact? The removal of a water mill including mill weir and mill channel removal can lead to extensive channel instability and the channel tries to establish new equilibrium conditions with changing river gradient.
- Does the removal of a water mill result in a greater incision of the river into the valley floor compared to the initial conditions without water mills? According to the removal of mill weirs, flow velocity may increase and might be more concentrated on the river bed, because of former elevated floodplains. Sediment might be eroded, which leads to river bed incision into the ground.

With respect to mining-induced subsidence, the following research questions are formulated:

- How does mining subsidence influence the beginning, the duration and the frequency of floodplain inundation?
- Does mining subsidence result in a local increase of sediment trapping efficiency of floodplains, because flow velocities on the floodplains decrease and more sediment is accumulated on the floodplains during overbank floods?
- Does local mining subsidence lead to contrasting results depending on the magnitude, size, location and rate of subsidence area?
- Does mining subsidence accumulate fine sediment and act as a trap for contaminants, so that the terrestrial and the aquatic environment is negatively affected?

With respect to river restorations the following research questions are formulated:

- Which historical anthropogenic impacts can be undone? There will be anthropogenic impacts that cannot or do not want to be undone due to reasons like widespread canalization and embankments of rivers in urban areas as well as the construction of reservoirs due to drinking water supply.
- What is defined as a “natural river-floodplain system before human impact”? How can a system achieve such a state? And is such an achievement always the best? The history of a river-floodplain system should be evaluated and understood extensively to determine its historical status and to avoid

negative and unwanted consequences like for example extensive fine sediment input in downstream reaches.

- How long does it take for a river to reach a morphodynamic equilibrium after river relocation and restoration?
- Which long-term implications of reactivated floodplains in river restorations can be derived for the mobility of floodplain sediment deposits of small rivers?

To answer these questions, a variety of research methods are used, ranging from literature research, analysis of historical maps, morpho- and hydrodynamic field measurements, theoretical analyses based on physically-derived equations and numerical model simulations.

1.4 Research areas

The consequences of water mills, mining-induced subsidence and river restorations on fluvial morphodynamics are analyzed exemplary at three small, meandering rivers typical for Central to Western Europe. The Geul River, the Wurm River and the Inde River are located in a transitional landscape between the low mountain range of the Eifel-Ardennes-massif and the lowland of the Lower-Rhine Embayment. Figure 1-4 shows the catchment areas of the three rivers.

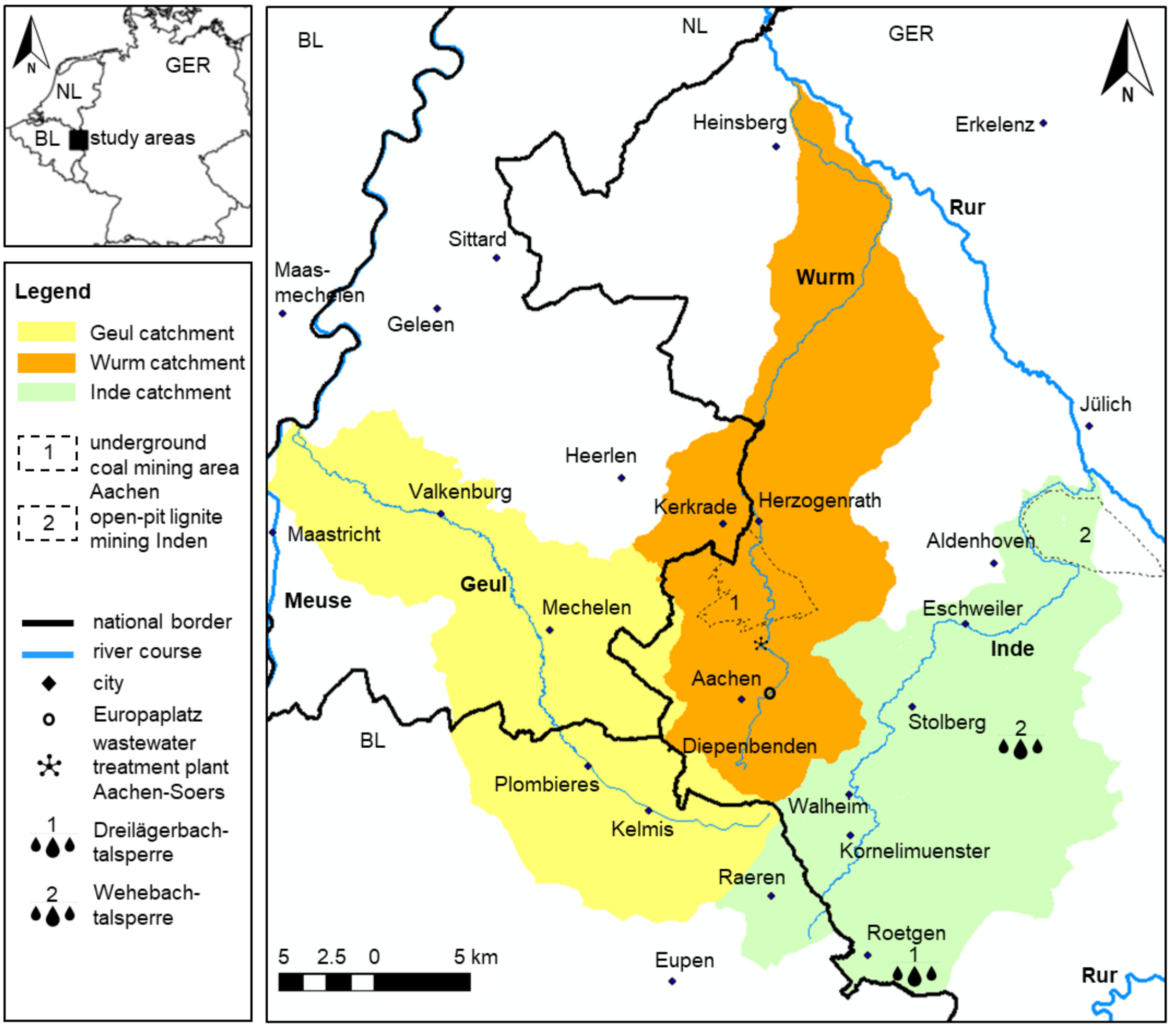

Figure 1-4: Catchment areas of the Geul River, the Wurm River and the Inde River.

The upper courses of the Wurm, the Geul and the Inde River flow through the low mountain range that is characterized by a steep relief, where settlement is present since the Medieval Times. The lower courses of the three rivers flow through the lowland that is characterized by a shallower relief and the deposition of loess, which already shows indicators for an early Neolithic settlement (Lehmkuhl 2011).

The three rivers have similar catchment sizes as well as similar hydrological and sedimentological characteristics, but each river has its own anthropogenic history combining the effects of water mills, ore, coal or lignite mining and urbanization. The historical (underground coal mining at the Wurm River and lead mining at the Geul River) as well as the still present (lignite mining at the Inde River) mining industry is the key factor for the early economic development in all three catchments. Site specific natural conditions like relief and soil characteristics affected and still affect land-use changes of the three catchments in different ways (Borchardt 2006; Nilson and Lehmkuhl 2008; Lehmkuhl 2011).

Since the Neolithic, human impact increased in this area typical for Central to Western Europe firstly due to (local) deforestation and therefore increased colluvial sediment deposition. Since the Industrial Revolution, the region is predominantly affected by technological development and urbanization (Lehmkuhl 2011). In this thesis, the analyses focus on technical human impact factors on the fluvial morphodynamics of the three rivers since the Industrial Revolution. Changes in land-use of the three catchments are extensively described and discussed in (Nilson 2006) and are of secondary importance.

1.4.1 Wurm River

The Wurm River is a small stream with a catchment size of 356 km^2 and a length of 57.9 km in a low mountain area near the Dutch-German border. It is a tributary of the Rur River. The Wurm is characterized as a gravel-bed river, but the sediment that is carried along the river in the water phase and deposited on the floodplains is fine cohesive sediment (clay, silt, fine sand) (MULNV NRW 2008a). The sources of the Wurm are in the forest south of Aachen. After a few kilometers, the water leads to the reservoir Diepenbenden and flows down this reservoir through a 25 km long canal underneath the city of Aachen and resurfaces in the east of Aachen at the Europaplatz, where the Wurm River flows in a modified river bed to the wastewater treatment plant Aachen-Soers (see Figure 1-4). Cleaned wastewater of the city of Aachen is passed into the Wurm. From that point, the Wurm runs as a free meandering river to the Dutch-German border to the city of Herzogenrath. The Wurm flows through an 11 km long valley where the river meanders over floodplains that are several hundred meters wide. The hillsides are partly forested (Fischer 2000). Between Herzogenrath and the mouth of the Wurm River into the Rur River near Heinsberg nearly natural parts and highly modified parts are alternating.

Nilson (2006) investigated the most significant land-use changes in the Wurm catchment regarding transformation from heathland to cropland, reforestation of grassland, and a substantial growth of urban area since the 1960s AD. The canalization of the Wurm River due to sanitary problems in the middle of the 18th century included the whole part of the Wurm River underneath the city of Aachen. The city of Aachen with 250,000 habitants influences the discharge regime of the Wurm. During dry weather conditions, the discharge of the Wurm consists of about 90 % cleaned sewage from the wastewater treatment plant Aachen-Soers (LANUV NRW 2004). Downstream of the canalization of the city of Aachen, the mean annual discharge (MQ) is equal to 0.3 m^3/s and enlarges to approximately 4 m^3/s at the mouth (LANUV NRW 2004). Today's discharge is increased because of inflow from urban drainage systems (approximately 514 l/s) including drinking water from the reservoirs in the North-Eifel (MULNV NRW 2017).

For the Wurm River, it is supposed that sub-surface coal mining already started in the Roman period, whereas extensive extraction of hard coal in underground mines took place in the 20th century. The water quality of the Wurm River and some of its tributaries were sustainably impacted by the underground coal mining industry. A black discoloration because of coal sludge and coal particles carried into the Wurm River was visible until 1978 AD (Büttgenbach 1898; Fischer 2000). The Aachen coalfields were directly connected to the Südlimburger coalfields in the Netherlands. The last mine in the Südlimburger coalfields was closed in 1974 AD, but because of the ongoing coal mining industry in the adjacent area in Germany, groundwater was still pumped until 1994 AD (Rosner 2011; Heitfeld et al. 2017). The last mine (Emil Mayrisch) in the Wurm valley was closed in 1992 AD and the last mine (Sophia-Jacoba) of the Aachen coalfields was closed in 1997 AD (Schetelig et al. 2007).

Another extensive human impact on the discharge regime and the fluvial morphodynamics of the Wurm River was the presence of minimum 60 water mills that were used for different purposes like oil production, grain milling, textile manufacturing or mining (von Coels 1958; Lohrmann 1992; Kalinka 1993; Vogt 1998). Today, only remnants of the abandoned mills like mill houses or mill ponds are still present in the landscape.

1.4.2 Geul River

The Geul River (Southern Limburg, The Netherlands) has a catchment size of 380 km^2 and a length of 57 km. The catchment area of the Geul is located on the northern slope of the High Venn Mountains, within the triangle of Belgium, the Netherlands and Germany (see Figure 1-4). The Geul is a tributary of the Meuse River. The mean annual discharge (MQ) at the Dutch-Belgian border is equal to 1.6 m^3/s and close to the confluence 3.4 m^3/s. Its river bed consists of gravel, whereas suspended load transport is the dominant transport mechanism. The river gradient decreases in downstream direction from 0.005 m/m near the Belgian-Dutch border to 0.0015 m/m near the confluence of the Geul River with the Meuse River (De Moor 2007).

The Geul River is still influenced by four water mills, which are permanently, and three water mills, which are temporarily in use. Additional 12 water mills are not in use anymore, but still have functioning mill weirs (Anderer et al. 2016). Although the river is influenced by human activities, it can still be characterized as a natural system. The upper course is dominated by grassland, which changes in agricultural usage in the downstream reaches (Blümel et al. 2003; De Moor et al. 2008). The settlement density of the river Geul is low. Many households are not connected to a central wastewater sewage system and induce unpurified wastewater into the Geul River (Vigener and Blümel 2006). According to the reduced number of cities and villages around the Geul, the river has the potential to flood the floodplain nearly everywhere. Only in the downstream part of Valkenburg and Mechelen (see Figure 1-4) or near bridges, the cross section of the river is fixed (Borchardt 2004).

1.4.3 Inde River

The Inde River is a 54.1 km long river in North Rhine Westphalia in Western Germany with a catchment area of 344 km^2. After a flow length of 2.5 km from its source in Belgium, the Inde River reaches the Belgian-German border and flows in the south of the city Kirchberg into the Rur River. Parts of the Inde River and its tributaries are straightened and canalized (Blümel et al. 2003; MULNV NRW 2008b, 2015). Two reservoirs (Wehebachtalsperre and Dreilägerbachtalsperre) are in the Inde catchment to ensure drinking water supply (MULNV NRW 2008b, 2015) (see Figure 1-4). The mean annual discharge (MQ) of the Inde River is equal to 2.82 m^3/s and the highest annual discharge (HQ) is equal to 89.45 m^3/s.

The river bed of the Inde River is characterized as a gravel-bed dominated river bed with a water landscape dominated by loess fields.

In former times, the different geo-resources in the catchment area of the Inde River resulted in widespread mining of iron, lead and zinc ores close to the city of Stolberg. In addition, open-pit lignite mining occurred i.e. close to the city of Eschweiler (Forkel and Rinaldi 2008). The open-pit lignite mining area Inden is still located in the catchment area of the Inde River (see Figure 1-4). Until 2005 AD, the lower reaches of the Inde River flowed through the prospective extraction field of the open-pit lignite mining area Inden. A 5 km long reach of the Inde River was relocated as the consequence of progressing open-pit lignite mining towards a 12 km long river reach. The relocation includes different restoration interventions.

1.5 Thesis outline

This thesis consists of 7 chapters. Chapter 2 to 5 can be read as independent scientific studies, whereby chapter 2 to 4 have been published peer-reviewed international journals and chapter 5 has been submitted to a peer-reviewed international journal. Figure 1-5 visualizes the relations between the several chapters.

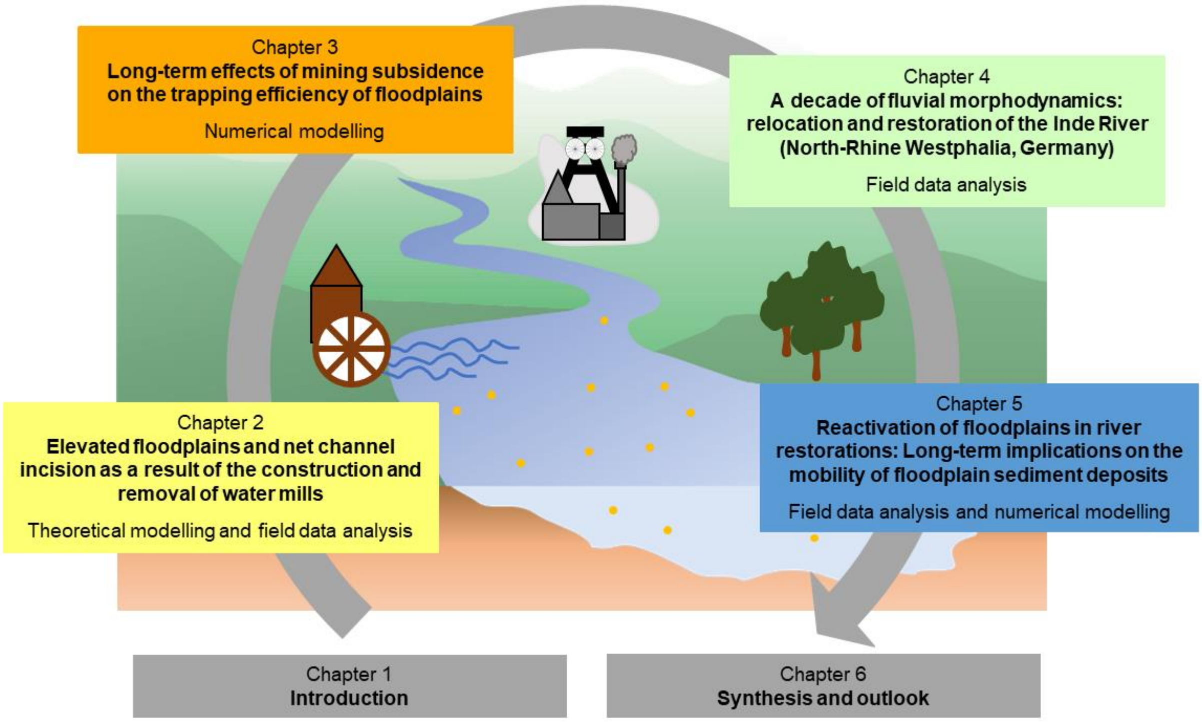

Figure 1-5: Visualization of the thesis outline.

Chapter 2 is a literature review combined with a theoretical analysis to describe the life cycle of water mills and its consequences on the longitudinal river profile and floodplain sedimentation. The construction and the removal of water mills are direct human impacts on hydrological and morphodynamic mechanisms in river-floodplain systems. The dynamics of river-mill systems are analyzed using an analytical model to describe the river's equilibrium channel slope at three different states: initial without water mills, then construction of water mills and later removal of water mills. Another analytical model is used to describe the floodplain development between these states. The results of the theoretical model are related to field measurements at the Wurm and the Geul River. At the Wurm River, all water mills are removed, whereas the Geul River is still influenced by four water mills that are permanently in use and three water mills that are occasionally in use. An additional 12 water mills are not in use anymore but still have functioning mill weirs.

Chapter 3 involves a literature review that describes the appearance and the consequences of mining subsidence in a river catchment and its consequences of the longitudinal river profile. A 2D-numerical modelling study based on the characteristics of a 1 km section of the Wurm River is used to investigate the effects of subsidence induced by underground coal mining on the sediment trapping efficiency of floodplains. Deposition of fine sediment on floodplains is analyzed over a period of 200 years.

Chapter 4 is based on field measurements at the relocation and restoration of the Inde River focusing on the development of the new river reach its pre-defined guiding principle. The fluvial morphodynamics of the new Inde River reach are analyzed over a period of almost 15 years taking sediment samples, analyzing echo soundings of the river's bathymetry and determining the heavy metal content of the sediment as a tracer material for the morphological development. The analysis of the heavy metal content is not the main focus of this thesis.

Chapter 5 is an outlook of long-term implications on floodplain sediment deposits in river restorations. River restorations include the reactivation of floodplains, e.g., by lowering the floodplain and raising the riverbed elevation. Such a reactivation has extensive consequences on the fluvial morphology as it potentially increases the mobility of fine sediments, which are located on the floodplains. The long-term effects of reactivated floodplains on the mobility of floodplain deposits of small rivers are analyzed with a 2D-numerical modelling approach. The numerical model is loosely based on the characteristics of the Wurm River (Lower Rhine Embayment, Germany), which can be seen as typical for small river systems in Central Europe. Input data for the numerical model is determined from turbidity and suspended sediment concentration measurements over two years at the Wurm River.

Chapter 6 is a synthesis of the chapters 2 to 5 and concludes the thesis.

1.6 Declaration of personal contribution

The authors of the different scientific research studies contributed in the following proportions to conception and design, data collection, data analysis, interpretation and conclusions, and manuscript preparation of the different chapters:

- Chapter 1: Anna-Lisa Maaß defined the objectives of the thesis, designed the structure of the chapter, created the figures, wrote and corrected the manuscript. Holger Schüttrumpf and Frank Lehmkuhl proof-read and commented on the chapter.
- Chapter 2: Anna-Lisa Maaß defined the objective of the manuscript, performed the theoretical analysis and discussed the results. Anna-Lisa Maaß also designed the structure of the manuscript, created the figures, wrote and corrected the manuscript. Holger Schüttrumpf discussed the objective as well as the results of the theoretical analysis with Anna-Lisa Maaß, proof-read and commented on the manuscript. Overall, the idea of the theoretical analysis described in this chapter was based on the research project 'Human impact on fluvial morphodynamics and contaminant dispersion in small

river catchments (case study: Wurm, Lower Rhine Embayment)' funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, Grant Number FR3509/3-1).

- Chapter 4: Anna-Lisa Maaß defined the objective of the manuscript, set up the numerical model and discussed the results. Anna-Lisa Maaß also designed the structure of the manuscript, created the figures, wrote and corrected the manuscript. Holger Schüttrumpf discussed the objective as well as the results of the numerical model with Anna-Lisa Maaß, proof-read and commented on the manuscript. Overall, the idea of the numerical modelling analysis described in this chapter was based on the research project 'Human impact on fluvial morphodynamics and contaminant dispersion in small river catchments (case study: Wurm, Lower Rhine Embayment)' funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, Grant Number FR3509/3-1).
- Chapter 4: Both, Anna-Lisa Maaß and Verena Esser had an equal contribution to this work. Roy M. Frings´s previous survey from past projects has been a valuable basis and input for this research. Anna-Lisa Maaß focused on the analysis of the sedimentological and morphological data of the former field measurement campaign. Verena Esser focused on the analysis of the heavy metals as tracer material for fluvial morphodynamics. Anna-Lisa Maaß and Verena Esser designed the structure of the manuscript, created the figures, wrote and corrected the manuscript. Holger Schüttrumpf and Frank Lehmkuhl discussed the objective as well as the results with Anna-Lisa Maaß and Verena Esser, proof-read and commented on the manuscript.
- Chapter 5: Anna-Lisa Maaß defined the objective of the manuscript, set up the numerical model and discussed the results. Anna-Lisa Maaß also designed the structure of the manuscript, created the figures, wrote and corrected the manuscript. Holger Schüttrumpf discussed the objective as well as the results of the numerical model with Anna-Lisa Maaß, proof-read and commented on the manuscript. Overall, the idea of the numerical modelling analysis described in this chapter was based on the research project 'Human impact on fluvial morphodynamics and contaminant dispersion in small river catchments (case study: Wurm, Lower Rhine Embayment)' funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, Grant Number FR3509/3-1).
- Chapter 6: Anna-Lisa Maaß defined the overall conclusions of the thesis, discussed the results, designed the structure of the chapter, wrote and corrected the manuscript. Holger Schüttrumpf and Frank Lehmkuhl discussed the results with Anna-Lisa Maaß, proof-read and commented on the manuscript.

2 Elevated floodplains and net channel incision as a result of the construction and removal of water mills

Anna-Lisa Maaß, Holger Schüttrumpf

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Abstract

An often underrated but historically long-lasting human impact on river-floodplain systems is that of the presence of water mills. The objective of this study is to determine how the construction and later removal of water mills influence the longitudinal bed profile of a river and its floodplain sedimentation. The effects of a river-mill system were analyzed using physically-based equations of backwater effects and sediment mobility in combination with field measurements of channel slope and floodplain development pre- and postdating water mills in the Wurm River (Germany) and the Geul River (Netherlands). The results show that the construction and removal of water mills likely resulted in a net incision of the river bed into the valley bottom to a level below the original bed, with reduced floodplain inundation rates and, consequently, reduced floodplain sedimentation.

Keywords: Water mills, Longitudinal profile, Sediment transport capacity

2.1 Introduction

Many river catchments in Europe have a long cultivation history. Human activities such as coal mining, deforestation associated with the development of agriculture and urbanization led to changes in discharge regimes and floodplain dynamics (e.g., Houben 1997, 2002; Klimek 2002; Starkel 2002; Lang et al. 2003; Mäckel et al. 2003; Zolitschka et al. 2003; Raab and Völkel 2005; Rommens et al. 2006; Lewin 2010; Gibling 2018). Floodplains in lowland rivers are often important sinks for suspended sediment transported through a river system, and vertical accretion of the floodplains results from the trapping of sediment on the floodplains by overbank deposition (Lambert and Walling 1987; Middelkoop and Asselman 1998; Hesselink et al. 2003; Walling and Owens 2003; Hobo et al. 2010; Walling and Owens 2011).

While many smaller streams are targeted by efforts to restore channels to past conditions, an often-underrated human impact on their morphology is the influence of water mills on past and present fluvial morphodynamics. In restoration, people often want to restore a system to its state at some previous time, but if the system is dramatically changed by water mills that is perhaps not possible (Bishop and Jansen 2005; Downward and Skinner 2005; Bishop and Muñoz-Salinas 2013; Kaiser et al. 2018). Water mills have been used extensively in river systems since the fifth century BC to generate water-powered energy (Reynolds 1983; Droste 2003). In most small streams in Central to Western Europe, a water mill is usually located in an artificial mill channel. The mill channel is separated from the main channel to enable greater hydropower usage of the water mill. The mill weir is often constructed as a movable weir, in which the gates can be opened for flow, while sediment can pass underneath the gates to further downstream. The gates are always open to guarantee a minimum amount of water in the former main channel. From the water wheel, water is then channeled into the tailrace and returned to the main channel.

In most European river systems, a chain of water mills was constructed to generate as much energy as possible. At each mill weir, the water discharge and, consequently, the sediment discharge was distributed by deliberate design between the mill channel and the original channel as follows. The amount of water that flows into the mill channel must guarantee that the water mill can operate as efficiently as possible. On the other hand, the amount of sediment transported into the mill channel must be as small as possible to avoid the need for removal and damage to the water wheel. During high-flow conditions, the original channel acts as a spillway to reduce floodplain inundation.

Water mill builders and operators aimed for stable bifurcation of the main channel and the mill channel, meaning that the division of flow and sediment between the two branches does not change systematically over time (Kleinhans et al. 2013). Factors influencing the fluvial morphodynamics of bifurcations are the gradient advantage of one branch, as well as the division of water and bed-material flux into the two branches, and on the dominant transport mechanism of suspended-load or bed-load transport (Kleinhans et al. 2013). The geometry of the bifurcation can be used to maximize the water flux into the mill channel and the sediment flux into the original channel.

At the end of the nineteenth century, water mills were decommissioned for water power and were replaced by other forms of energy, e.g., coal and wind. Consequently, most water mills, especially mill weirs and water wheels, were removed from river systems, and the water level in the river channel was no longer impounded. However, the morphological effects of mills are longer-lasting.

Generally, the effects of the construction and removal of mill weirs are similar to those of dams analyzed by, e.g., Juracek (1999), Stanley et al. (2002), Wong et al. (2004), Pöppl et al. (2005), Chang (2008), Downs et al. (2009), Csiki and Rhoads (2014), Pearson and Pizzuto (2015) and Słowik (2015). Downward and Skinner (2005), Walter and Merritts (2008), De Mars (2009) and Merritts et al. (2011) analyzed the geomorphological effects of water mill systems on the basis of field observations, core drillings and river maps. Based on landscape reconstructions, Walter and Merritts (2008) found that mill dam construction led to widespread floodplain inundation and converted river catchments into a series of linked slackwater ponds, which gradually changed the longitudinal river profile. Merritts et al. (2011) found that the important factors for sediment accumulation in rivers in the USA affected by water mills are dam height, mill pond trap efficiency, mill pond age and the frequency and severity of high flood events that might flush sediment out of the pond. This finding corresponds to field observations by Downward and Skinner (2005) at three English rivers, in which the stepped longitudinal river profile is due to the closely spaced water mills in the river.

These observations generally show that rivers with water mills exhibit changed channel dynamics and changed floodplain dynamics, but it remains unclear how these changes affect the response of the rivers after mill removal and whether the rivers tend to return to their original state or remain in an alternative stable state of channel and floodplain function. Here, the following hypotheses about the effects of the construction and subsequent removal of one water mill system on the longitudinal river profile and on floodplain sedimentation are tested:

(1) During the period of active water mills, sediment deposition upstream of a mill weir results in an increase of the main channel and floodplain elevation levels; and

(2) After water mill removal, the flow is concentrated on the river bed, which results in a reduction of the active flow width, erosion of the formerly deposited sediment and incision of the river bed to a level below the initial level.

These hypotheses are also enlarged to the case of a chain of water mills. The objective of this study is to determine how the construction and later removal of water mills influence the longitudinal bed profile of a river and its floodplain sedimentation. The effects of a river-mill system are analyzed using physically-based equations of backwater effects and sediment mobility in combination with field measurements of the channel slope and floodplain development pre- and postdating water mills in the Wurm River (Germany) and the Geul River (Netherlands).

First, the study sites of two rivers in Western Europe are presented. Then, the methods of analyzing the alterations of the longitudinal river profile and floodplain sedimentation caused by the construction and removal of water mills are described. Afterwards, the results are presented and discussed.

2.2 Study sites

The research focuses on two small river-floodplain systems in Western Europe: a river still impacted by water mills (Geul River, Southern-Limburg, Netherlands) and a post-water-mill river (Wurm River, Lower Rhine Embayment, Germany). Figure 2-1 shows the catchment areas and study sites of the Geul and the Wurm River in detail.

Field data from the Geul River are used to analyze the effects of the construction of water mills on fluvial morphodynamics. The Geul River has a catchment area of 380 km^2 and a length of 57 km. The catchment of the Geul is located on the northern slope of the High Venn Mountains within the triangle of Belgium, the Netherlands and Germany. The mean annual discharge at the Dutch-Belgian border is 1.6 m^3/s. Close to the confluence with the Meuse River, the mean annual discharge is 3.4 m^3/s (De Moor 2007). Field data from the Wurm River are used to analyze the effects of the removal of water mills on fluvial morphodynamics. The Wurm River is a small stream with a catchment area of 356 km^2 and a length of 57.9 km in a low mountain area near the Dutch-German border. It is a tributary of the Rur River. The upper part of the Wurm River is canalized underneath the city of Aachen. Downstream of the canalization, the mean annual discharge is 0.3 m^3/s and increases to approximately 4 m^3/s at the mouth (LANUV NRW 2004).

Based on turbidity and suspended sediment concentration measurements over two years, suspended sediment loads of 2 10^{-5} million tons per year were determined for the two river systems. Overall, both rivers have similar hydrological and morphological characteristics and are therefore comparable to each other (see Table 2-1).

Table 2-1: River characteristics of the Geul River and the Wurm River.

Parameter	**Unit**	**Geul River**	**Wurm River**
Source	-	Aachen (GER)	Aachen (GER)
Mouth	-	Meuse River, Maastricht (NL)	Rur River, Heinsberg (GER)
Catchment size	km^2	380.0	356.0
Flow length	km	57.0	57.9
Mean annual discharge	m^3/s	3.4	3.5
Sediment	-	gravel-bed channel, silty clay-dominated floodplain	gravel-bed channel, silty clay-dominated floodplain

The Geul River is still influenced by four water mills that are permanently in use and three water mills that are occasionally in use. An additional 12 water mills are not in use anymore but still have functioning mill weirs, so that their hydromorphological effects are maintained (Anderer et al. 2016). Figure 2-2 shows a schematic of the water mill system of the Volmolen (Epen, Netherlands) at the Geul River in plan view. Based on an analysis of water mill systems shown in historical maps of several small lowland river systems in Germany and field observations of the structure of the 19 water mills still present at the Geul River, the structure of the water mill system of the Volmolen is one typical system for water mills located in Western Europe.

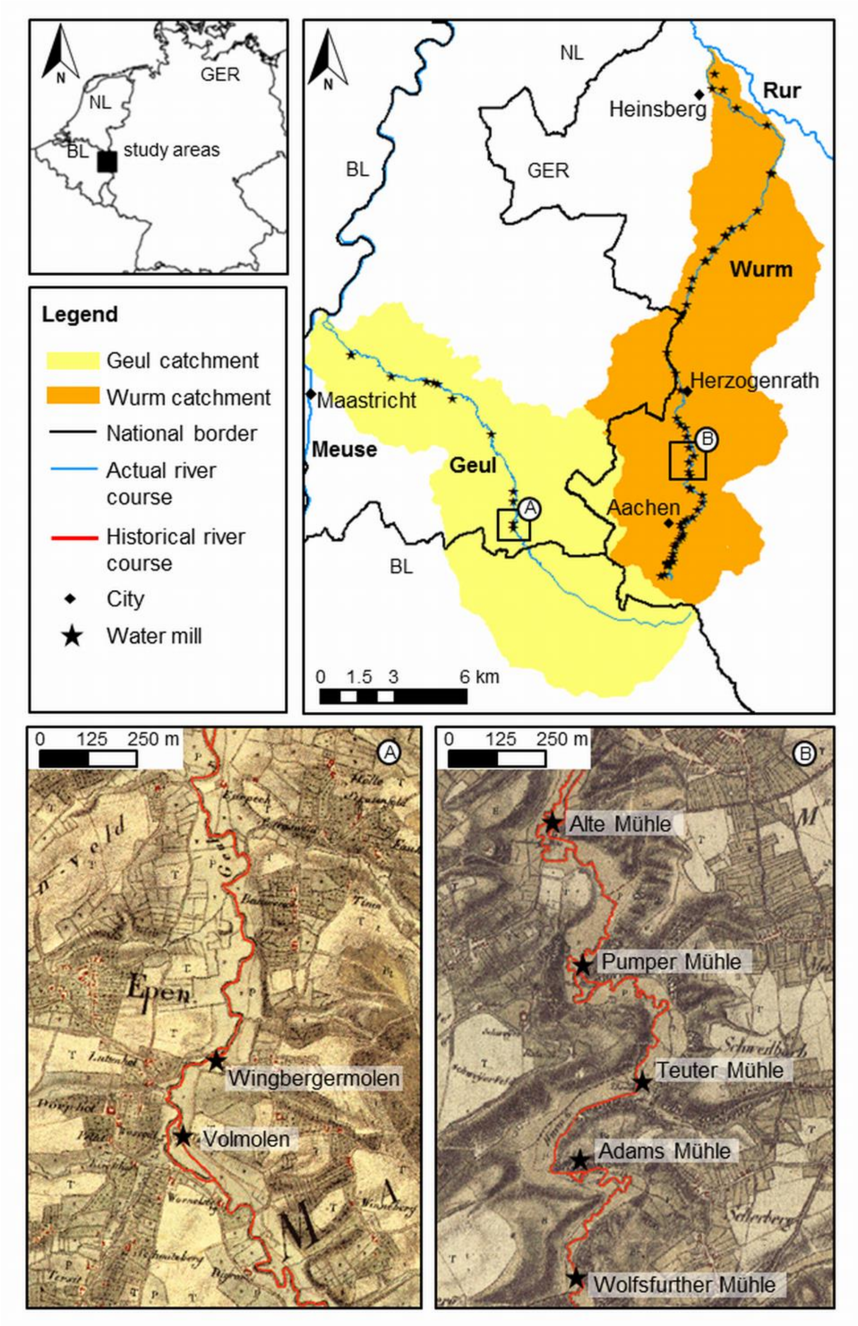

Figure 2-1: Map of the Geul River and the Wurm River showing catchment areas, and detailed maps of the water course around the Volmolen and the Wingbergermolen (A, Geul River) and between the Wolfsfurther Mühle and the Alte Mühle (B, Wurm River).

At the Volmolen, the impoundment of water is permanent (see Figure 2-2, photo A and B). The Volmolen is the first water mill downstream of the Belgian-Dutch Border with a breast-shot water wheel (see Figure 2-2, photo D). Water is impounded at a vertically movable mill weir (see Figure 2-2, photo B) and then separated into a 450 m long original channel and a 345 m long mill channel (see Figure 2-2, photo C). The distance between the confluence of the Volmolen and the next downstream water mill (Wingberger-molen, abandoned) is 395 m (see Figure 2-1). The floodplains on the right bank of the mill channel of the Volmolen are flat and covered with grass, whereas steep slopes are present on the left bank of the original channel.

The Wurm River was historically impacted by a chain of approximately 60 water mills. All water mills have been removed for different reasons (Vogt 1998). Mill weirs, water wheels or related flow diversions are no longer present. Only remnants such as the old mill houses can still be found. Field measurements and a detailed comparison of the historical (pre-mill) to the present-day (post-mill) gravel bed has been performed 696 m downstream of the Pumpermühle and 648 m upstream of the Alte Mühle (see Figure 2-1) in the near-natural part of the Wurm River.

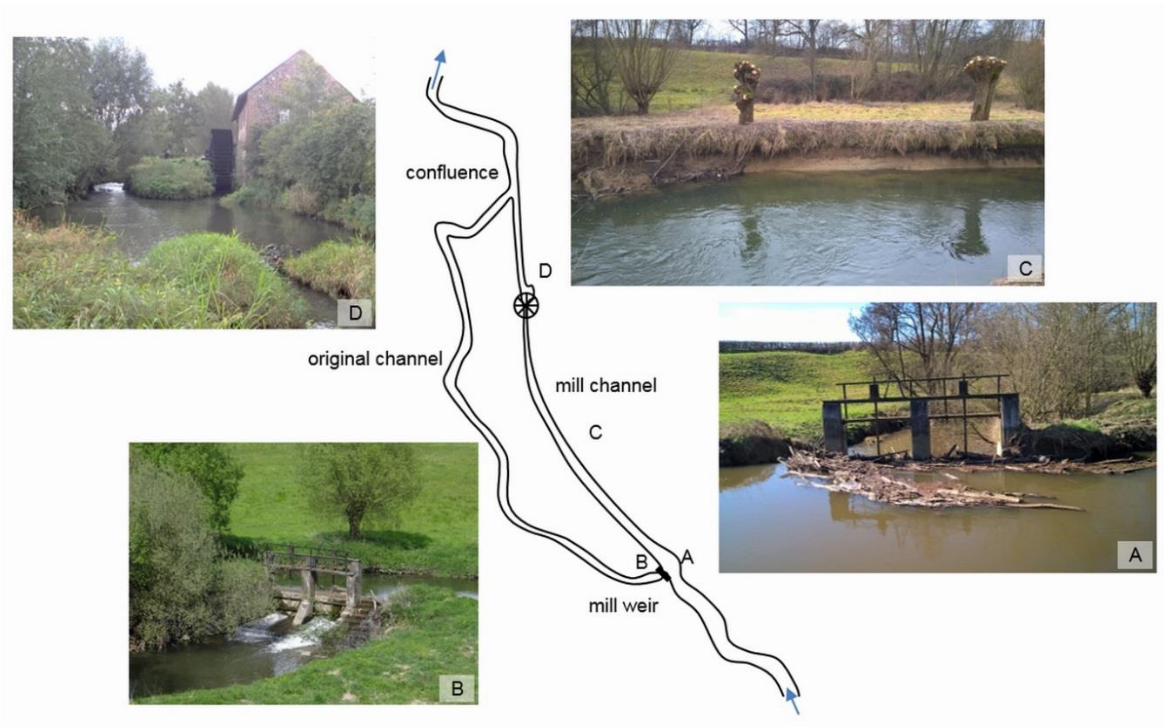

Figure 2-2: Schematic map of the water mill system of the Volmolen (plan view). Photographs show the mill weir of the Volmolen (A, view of the entrance from the original channel into the mill channel and B, view of the entrance from the original channel). Floodplain deposits of the left river bank of the mill channel (C). Water wheel and mill house (D, upstream view from downstream of the water wheel).

2.3 Materials and methods

The effects of a river-mill system are analyzed using physically-based equations of backwater effects and sediment mobility in combination with field measurements of the channel slope and floodplain development pre- and postdating water mills in two very similar river-floodplain systems. The morphology before water mill construction is reconstructed analyzing a gravel bed layer visible at the river bank of the Wurm River (Germany, see Figure 2-1), which represents the historical pre-mill river bed (Buchty-Lemke and Lehmkuhl 2018). Floodplain accretion is determined in the Geul River (Netherlands, see

Figure 2-1) using artificial lawn mats as sediment traps (see Figure 2-4). The similarity of two meandering gravel-bed streams with silty floodplains is used to study the effect of mills in operation and of their removal, allowing a degree of control that is usually only the case in experiments or numerical models. However, this interpretation requires certain assumptions outlined, as below.

2.3.1 Assumptions

In the analysis of water mill systems, it is assumed that the major portion of discharge (90%) is flowing into the mill channel and that only a small amount of water passes the original channel (10%). The effects of this partitioning of water and sediment on the model results are discussed later focusing on differences in the types of water mills and (geo-) morphological settings. Tributaries and other additional water inflows are not present. The cross-sectional area of the river channel is idealized as rectangular for width-averaged flow calculations. The channel width - here, 15 m - and sediment composition of the river bed are assumed to remain constant in space and time. Morphodynamic time scales are of interest, meaning that the flow can be treated as quasi-steady at a characteristic flow condition (Parker 2004).

A characteristic water mill system is analyzed, and the generic results are applied to a chain of water mills along the river-floodplain system. This entails the assumption that the distance between two water mills is greater than the length of the weir-related backwater effect, so that neither the mill channel nor the original channel of an upstream located water mill is affected by the depositional effects of a downstream mill.

During the time of active water mills, water and sediment is divided into the original channel and the mill channel at the mill weir. Here, it is assumed that not only the suspended and wash load but also maximum water flows into the mill channel due to the most efficient use of the water mill. Water-driven mills use either the force of flowing water or the weight of water to turn water wheels (e.g., Reynolds 1983; Lewin 2010). Therefore, a constant flow of water to the wheel is required for a constant and an efficient use of the water wheel.

Sediment deposited inside the mill channel was periodically dredged or flushed by the millers. Flushing or dredging the mill channel has different consequences for the sediment budget. If the mill channel is dredged, sediment is removed from the system. If the mill channel is flushed, sediment is transported further downstream but remains in the system. In this analysis, it is assumed that the mill channel is periodically flushed and that no sediment is externally removed from the system to guarantee a constant sediment flux.

The removal of water mills means that water flows only into the former original channel after removing the water wheel. It is assumed that mill channels were closed off and disconnected from the flow.

Additionally, it is assumed that the river channel was initially in equilibrium preceding mill construction. Reaching new stable conditions may take decades to centuries, because of the volume of sediment that needs to be transported into the system for significant morphological change with a low sediment supply rate (De Vries 1975). Water mills were present in river-floodplain systems for long time scales. The main assumptions are tested in the discussion section of this paper.

2.3.2 Analysis of the longitudinal river profile

A river channel is in equilibrium when the amount of sediment carried into a reach is equivalent to the amount of sediment transported out of it and neither deposition nor erosion occurs in the reach (Gilbert 1877; Lacey 1930; Mackin 1948; Knighton 1998). In the equilibrium theory, changes in the longitudinal river profile refer to the reach-averaged river characteristics, without taking local morphological changes, such as scour holes or bar formations, into account (Janssen 1979).

The changes of the longitudinal river profile due to the construction and removal of water mills are characterized by the following steps and calculations:

(1) Determination of the median grain size diameter, D_{50}, and the D_{90} of the gravel bed by taking sediment samples from the present-day river bed.

(2) Determination of the critical Shields number, θc (Brownlie 1981)

$$\theta_c = 0.22\, Re_p^{-0.6} + 0.06\, 10^{\left(-7.7 Re_p^{-0.6}\right)} \qquad \text{2-1}$$

where Re_p is Reynolds particle number [-] calculated with

$$Re_p = \frac{\sqrt{\left(\rho_s/\rho_w - 1\right) g\, D_{50}}\, D_{50}}{\vartheta} \qquad \text{2-2}$$

where ϑ is the kinematic viscosity, which is equal to 1.81 10^{-6} m^2/s, g is the acceleration due to gravity [m/s^2], ρ_w is the water density [kg/m^3], ρ_s is the sediment density [kg/m^3] and D_{50} is the median grain diameter [m].

(3) Determination of the equilibrium channel slope of the longitudinal river profile at representative historical mean annual flood conditions predating water mills, in which the grain-related Shields number, θ, given below is equal to the critical Shields number, θc (following Parker et al. (2007)):

Transforming:

$$\theta = \frac{\rho_w\, g\, H\, S}{(\rho_s - \rho_w)\, g\, D_{50}} \qquad \text{2-3}$$

and

$$\mathrm{Q} = C\, \sqrt{R\, S}\, \mathrm{B}\, \mathrm{H} \qquad \text{2-4}$$

and

$$C = 18 \log\left(\frac{12\, R}{k_s}\right) \qquad \text{2-5}$$

to

$$S = \frac{\theta_c\, (\rho_s - \rho_w)\, g\, D_{50}}{\rho_w\, g\, H} \qquad \text{2-6}$$

where H is the water depth [m], S is the channel slope [-], B is the width of the river [m] R is the hydraulic radius [m], k_s is the equivalent sand roughness equal to D_{90} following Garbrecht (1961) and C is the Chezy friction coefficient [$m^{1/2}/s$] following the Colebrook-White logarithmic relation.

(4) Determination of the grain-related Shields number of the flow relative to the critical Shields number as an indicator of sediment transport capacity (Parker et al. 2007)
(5) Determination of the equilibrium channel slope following equation 2-6 of the longitudinal river profile at representative present-day mean annual flood conditions postdating water mills, in which the grain-related Shields number, θ, is equal to the critical Shields number θc.

For the calculations, a representative discharge and critical transport conditions are assumed. The historical (8.0 m^3/s) and present-day (24.2 m^3/s) mean annual flood conditions are based on a precipitation-discharge model (kindly provided by the Wasserverband Eifel Rur).

Additionally, the longitudinal river profiles of the Geul River and the Wurm River are measured from the national Digital Elevation Models, which are a LIDAR DEM with a spatial resolution of 1 m and a height resolution of +/- 0.2 m (Actueel Hoogtebestand Nederland 2015; Land NRW 2017). It is assumed that the differences between the water surface elevation displayed by the DEM and the river bed elevation are negligible because of the water depths smaller than 50 cm in the original channel of the Volmolen.

2.3.3 Analysis of floodplain sedimentation

Floodplain sedimentation is evaluated by comparison of the water levels in the main channel and the floodplain elevation. To gain insight into present floodplain accumulation rates for comparison with the historical accumulation since mill construction, sedimentation close to the Volmolen was measured over one season using artificial lawn mats, which is a commonly used event-based sampling method (Middelkoop and Asselman 1998). Preliminary investigations were conducted to analyze the practicability of the method for sampling floodplain sedimentation with different types of lawn mats, during different flood events and at different locations of the Rhine River. Additionally, Middelkoop and Asselman (1998) showed that the sedimentation rates measured with artificial lawn mats are comparable with the results of raster-based sedimentation models, so that this method is an adequate method for measuring floodplain sedimentation rates. Overall, the method includes several uncertainties (Walling and Owens 2003), which all result in an underestimation of the amount of sediment deposited onto the floodplains. In total, 27 sediment traps, which were Astroturf mats with a rectangular size of 40 x 60 cm, were distributed on the right floodplain in the backwater area of the water mill Volmolen at the Geul River within 7 cross sectional profiles to quantify the amount of sediment deposited on the floodplains during flood events (see Figure 2-4). The inundation frequency of the floodplains in the backwater area of the Volmolen is increased because of the permanent impoundment of water at the mill weir to a bankfull water level. After one flood event, the sediment traps were taken to the laboratory for further analyses and redistributed on the field afterwards to evaluate further flood events. During this flood event, 9 of the 27 sediment traps could not be analyzed because they were either damaged, relocated by animals or not inundated. Sediment was collected, dried and weighted according to methods described by Middelkoop and Asselman (1998). The amount of sediment trapped on each mat was not separated into coarse and fine proportions because it was visually obvious that the amount of coarse material was insignificantly small.

Floodplain accretion due to sediment deposited on the sedimentation mats is determined by dividing the sediment mass trapped on a sediment mat by the size of the mat and the dry bulk density of the sediment. Here, a dry bulk density of 1,320 kg/m^3 is used, which represents the clayey silt deposited on the traps. Geostatistical analysis tools enable interpolation of the point data determined from the sediment traps to the entire inundation area. Empirical Bayesian Kriging (Burrough et al. 2015) is used in ArcGIS in automatic mode as a geospatial interpolation method to interpolate the point data determined from the sediment traps to the entire inundation area.

2.4 Results

A comparison of the results of the Wurm River as a river-floodplain system after water mill removal and the Geul River as a river-floodplain system in which water mills are still present (see Figure 2-1) suggests that the floodplains of the Volmolen at the Geul River are prone to overbank flooding and that sedimentation rates close to the river banks are approximately 7 times higher than sedimentation rates at the incised Wurm River. Due to suspended sediment loads of 20 tons per year of the two rivers determined from continuous field measurements, it can be concluded that floodplain sediment rates after mill removal are lower than floodplain sedimentation rates after mill construction.

2.4.1 Construction of water mills

a) Longitudinal river profile

The median grain size diameter (D_{50}) of the river bed of the Wurm River is 33 mm. With this diameter, a critical Shields number θc (see equation 2-1) of 0.057 is calculated. To determine the equilibrium channel slope predating water mills, the Shields value θ is set equal to the θc of 0.057 following Parker et al. (2007) that in gravel-bed rivers the bankfull Shields number is typically the critical one. Combining equations 2-3, 2-4 and 2-5, an equilibrium water depth of 0.36 m and following equation 2-6 an equilibrium channel slope of 8 ‰ for the time before water mills are determined. The real regional channel slope measured on the DEMs is only 3 ‰. The difference results from the fact that a representative discharge and critical conditions were assumed in the calculations and that other natural and human impact factors superimpose the development of the longitudinal river profile.

The longitudinal river profile of the Volmolen at the Geul River (see Figure 2-1) is determined via a DEM analysis to confirm the modelling results. The slope upstream of the backwater area is equal to 2.72 ‰. The slope decreases inside the backwater area to 1.43 ‰ and decreases even more in the original channel to 0.49 ‰. The slope downstream of the confluence is equal to 2.66 ‰, and the initial slope of 2.72 ‰ is nearly re-attained (see Figure 2-3).

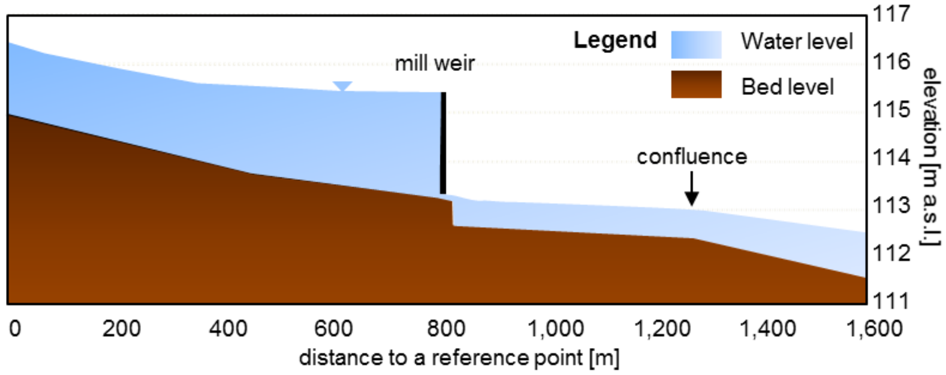

Figure 2-3: Generalized longitudinal river profile of the Geul River around the Volmolen. The confluence is where the mill channel flows back into the original channel.

During the time of active water mills, water is impounded at the mill weir, which leads to backwater effects. Flow velocities are reduced, and sediment is deposited onto the river bed, which leads to a decreased equilibrium river bed slope. With a movable weir, the deposition will have been controlled within certain limits to guarantee a constant impoundment of water at the mill weir and hydropower production of the water wheel. Mill weirs are adjustable so that the backwater effect and the amount of water and sediment entering the mill and the original channel can be controlled. The longitudinal profile will fluctuate around a mean level but will definitively be much higher than the original bed level (Janssen 1979).

Assuming that 90 % of the discharge (0.9 of 8.0 m^3/s) enters the mill channel, a grain-related Shields value θ = 0.011 results for the original channel downstream of the mill weir following equation 2-3 with a slope of 8 ‰. The Shields value in the mill channel is nearly zero due to the impoundment of water. The nearly-zero slope of the channel supplies as much potential energy as possible to the water wheel. The grain-related Shields value of 0.011 in the original channel is smaller than the critical Shields value of 0.057, so that deposition of sediment occurs in the original channel and the equilibrium channel slope of 8 ‰ is decreased. In reality, the decrease might be less due to other natural and anthropogenic effects such as flushing of the original channel during flood events or dredging of deposited sediment (Lewin 2010). It is assumed that a different discharge partitioning ratio between the original and mill channel would not affect this conclusion because the difference between the actual and critical Shields values is so large. The construction of a water mill always leads to a reduction of water discharge in the original channel to guarantee an efficient use of the water wheel due to a constant flow of water to the wheel. Therefore, a reduction of water discharge in the original channel always leads to deposition of sediment in the original channel and a decreased equilibrium slope. At one water mill system, most of the sediment is deposited upstream of the mill weir or in the original channel (see Figure 2-3 and Figure 2-6). In the case of a chain of water mills, the sediment budget is reduced after each water mill system, and maximum sedimentation only occurs in the upstream channel segment.

b) Floodplain sedimentation

Floodplain inundation took place at the Geul River at the end of April 2018 AD. The maximum discharge at the upstream gauging station Cottessen close to the Dutch-Belgian border was 19.11 m^3/s. The flood discharge was below the mean annual flood discharge (23.14 m^3/s, personal communication Waterschap Limburg) measured at the gauging station Cottessen. Statistically, such a discharge occurs less than once a year and will inundate the floodplains of the Volmolen. Therefore, the sedimentation rates determined from this flood event are representative of annual sedimentation rates. To critically evaluate the results presented in this paper, the grass mats were redistributed on the field to collect data from more than one flood event. Table 2-2 shows the amount of sediment deposited on the sediment traps during the flood event in April 2018 AD. Trap numbers and cross sections refer to Figure 2-4. The results of the sediment traps show that most of the sediment is deposited directly at the river bank, and the amount decreases with increasing distance away from the river bank, which is consistent with the principle of settling from suspension away from the channel (see Table 2-2). Cross section II (see Table 2-2 and Figure 2-4) forms an exception because, here, the maximum sediment deposition occurred on the second sediment trap, which is 5 m away from the river bank of the Geul River (see Table 2-2 and Figure 2-4). Figure 2-4 shows the result of geostatistical interpolation (RMSE = 0.17) after the Empirical Bayesian Kriging method. Overall, sedimentation rates between 0.2 cm and 0.7 cm per year were determined close to the river banks of the backwater area of the Volmolen.

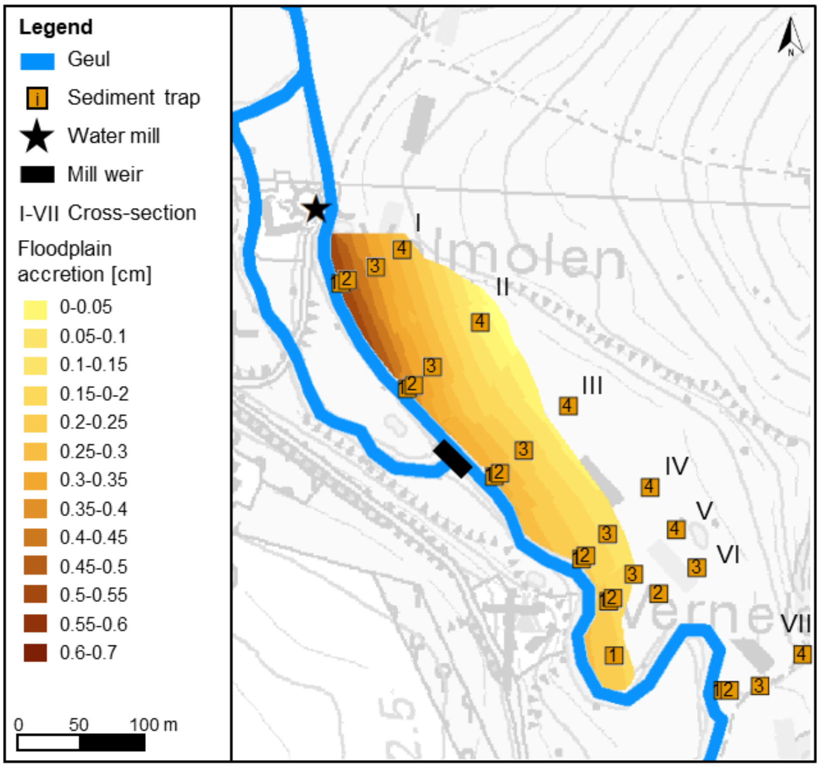

Figure 2-4: Floodplain accretion of the right floodplain of the Volmolen at the Geul River, interpolated from the measured sediment deposition in traps during one flood event with a peak discharge of 19.11 m^3/s.

Table 2-2: Amount of sediment [g] deposited on the sediment traps during the flood event in April 2018. In the case of 0 g, the amount of sediment is not significant.

Distance to the river bank [m]	Trap number	Cross section I	Cross section II	Cross section III	Cross section IV	Cross section V	Cross section VI	Cross section VII
0	1	1977.58	934.62	1441.49	1877.56	1123.07	1.42*	0
5	2	1908.73	1090.54	62.69	178.54	135.46	0**	0
25	3	794.54	523.83	23.18	25.32	6.95	0***	0
50	4	375.87	51.28	0	0	0	0	0

*distance to the river bank of 25 m, **distance to the river bank of 50 m, ***distance to the river bank of 75 m

2.4.2 Removal of water mills

Postdating water mills, today's mean annual flood discharge of the Wurm River is equal to 24.2 m^3/s. To determine the equilibrium channel slope postdating water mills, the Shields value, θ, is set equal to the θ_c of 0.057. By again combining equations 2-3, 2-4 and 2-5, an equilibrium water depth of 0.87 m is obtained and following equation 2-6 an equilibrium channel slope of 4 ‰ is derived for the time after water mills. The equilibrium channel slope after water mill removal is lower than the initial equilibrium channel slope of 8 ‰.

At the Wurm River, steep banks and armoring of the river bed were observed along the near-natural reach from downstream of the wastewater treatment plant, Aachen-Soers, to the city of Herzogenrath. Parts of a gravel bed layer are visible in many locations, forming only one layer in all cases. One clearly visible horizontal gravel layer on the left river bank at one location between the Pumpermühle and the Alte Mühle (see Figure 2-1) is seen as the historical pre-mill river bed of the Wurm River following Nanson and Croke (1992) and the results of Buchty-Lemke and Lehmkuhl (2018). Buchty-Lemke and Lehmkuhl (2018) analyzed different cross-sectional profiles of the Wurm River between 1965 AD and

2012 AD and concluded that incision of the river bed of the Wurm River into the ground had occurred. Comparison of the elevation of this gravel layer to that of the actual river bed shows a difference in height of approximately 70 cm (Figure 2-5). These observations are evidence for spatially large-scale incision of the river bed in this near-natural part in which a chain of water mills was present but has now been removed.

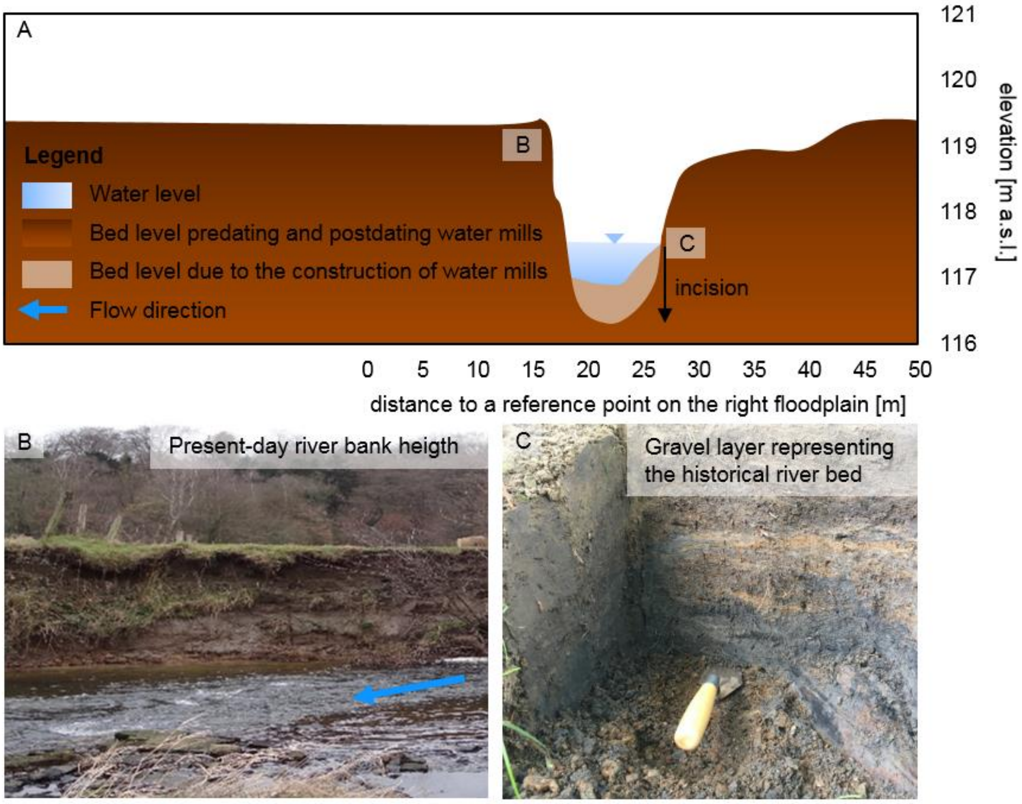

Figure 2-5: River bed incision of the Wurm River between the Pumpermühle and the Alte Mühle.

At the Wurm River, analysis of geochemical marker beds in cores collected at the Wurm River by Hagemann et al. (2018) resulted in mean sedimentation rates of approximately 2 m for the last 200 years, which indicates sedimentation rates of approximately 0.1 cm per year.

Figure 2-6 summarizes the effects of the construction and removal of a water mill system on the longitudinal river profile and floodplain sedimentation. The figure shows the general model results. The results of the DEM analysis and the field measurements at the Wurm River and the Geul River are shown in Figure 2-3, Figure 2-4 and Figure 2-5. An extensive analysis of the cross-sectional profiles and changes of the longitudinal river profile around the Adamsmühle (see Figure 2-1) based on the LIDAR DEM (1 m, Land NRW 2017) of the Wurm River has been given by Buchty-Lemke and Lehmkuhl (2018). Their results underline the conclusion that the removal of water mills at the Wurm River led to river bed incision and changes of the river bed slope. Buchty-Lemke and Lehmkuhl (2018) superimposed their results with other anthropogenic impact factors like urbanization that control the availability of sediment and the discharge conditions. These factors also led to an incision of the river bed of the Wurm River.

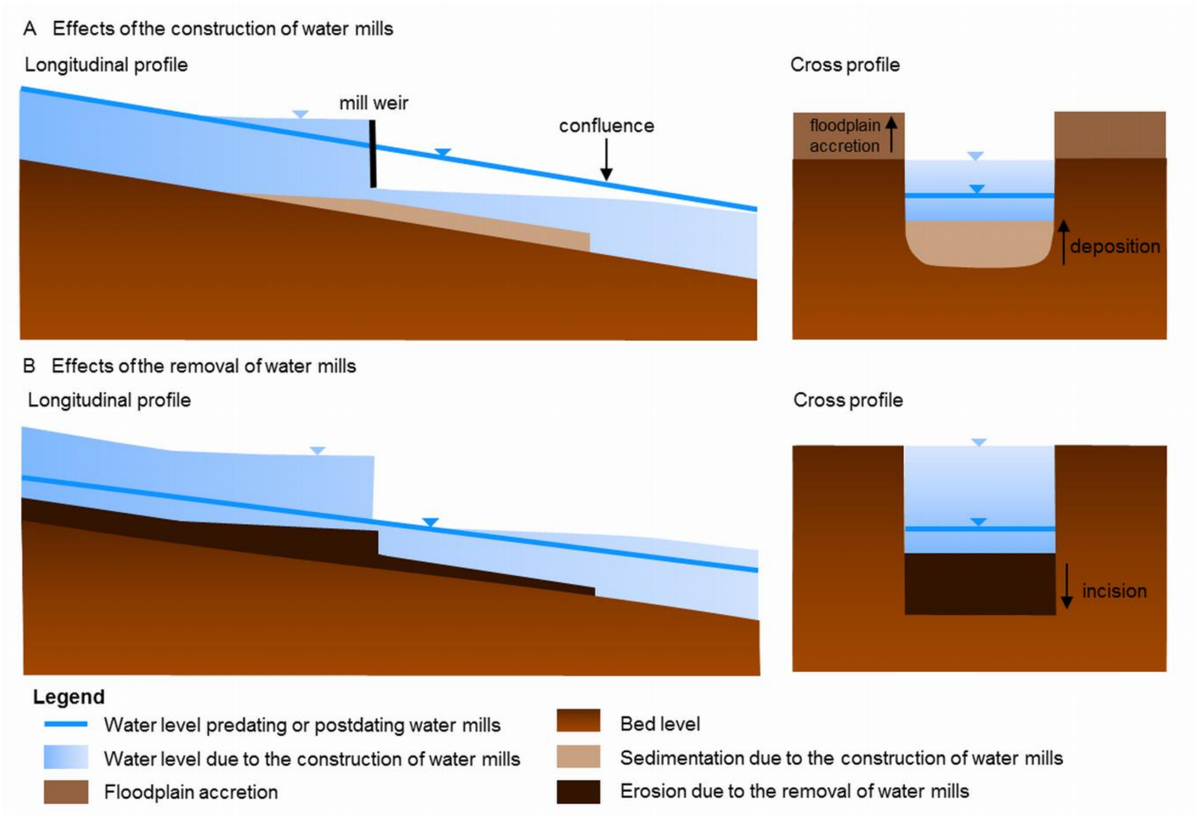

Figure 2-6: Development of the longitudinal river profile and the floodplain sedimentation as a result of the construction (A) and removal (B) of water mills.

2.5 Discussion

2.5.1 Environmental implications

After water mill removal, bank heights are increased in comparison to the initial state without water mills. The impacts of increased bank heights on the fluvial morphology are similar to those of embankments (Hesselink et al. 2003; Frings et al. 2009; Zhang et al. 2017). Due to the higher floodplains, bankfull water levels are increased in the main channel in comparison to the water levels predating mills. The increased water levels cause an increase in the shear stresses. An increase of the bed shear stress typically leads to the erosion of fine grains and coarsening of the river bed grain sizes (Frings et al. 2009). Here, incision is also associated with problems that continue today such as in the excavation of pipelines and the construction of foundations for engineering works and in navigability issues during low flow, as well as the drying of natural vegetation on the embanked floodplains.

Increased bank heights are the result of the deposition of fine sediment during the period of active water mills and the incision of the river bed after water mill removal. The physical model results of van Dijk et al. (2012) show that cohesive floodplains decrease bank erosion and chute incision compared to experiments without the addition of fine cohesive sediment. This relation leads to the conclusion that the pre-mill meander migration may have been more dynamic than the present-day meander migration, because the floodplains consist of a high amount of fine cohesive sediment after mill removal.

Another impact factor in the meander morphodynamics is vegetation on the floodplains. van Oorschot et al. (2018) modelled meander morphodynamics with riparian vegetation following dam installation and removal. The modelling results show that flow stabilization by dams leads to an instantaneous reduction of seedling recruitment, the development of a narrower vegetation band, and aging, which increases succession towards terrestrial species (van Oorschot et al. 2018). In contrast, restoring natural flow regimes by dam removal and gradual flow alteration increases riparian vegetation cover (van Oorschot et al. 2018). Today, many river-floodplain systems in Western Europe and worldwide are impacted by either the construction or the removal of transverse structures such as mill weirs. The interaction between construction and removal of transverse structures results in decoupling the processes of the river bed from those of the floodplains, an effect which needs to be considered during river restoration measures. Many smaller meandering rivers are currently being restored without understanding the differences between small meandering rivers with bends tight enough for flow separation and larger rivers with more open bends (Blanckaert et al. 2013). The major objective of river restorations is to counteract human impacts and to restore river-floodplain systems “naturally”. Countermeasures against incision might be the input of sediments into the river systems or the dredging of floodplains. Such processes are planned, e.g., for the Waal River (The Netherlands) or for the Lippe River (Germany), two larger rivers in comparison to the Geul River and the Wurm River, with higher mean flow discharges and incised beds. Even Walter and Merritts (2008) found that the conditions of single gravel-bedded channels with high, fine-grained banks and relatively dry valley-flat surfaces disconnected from groundwater differ from pre-settlement conditions. The re-connection of floodplains as natural parts of the environment might only be possible by lowering the floodplains to a more natural level or by increasing the river bed elevation.

Many river restoration interventions are accompanied by the removal of transverse structures such as dams or mill weirs to ensure better passability for fish and/or continuous transport of sediment. The advantages and disadvantages of an increased sediment continuity were recently assessed by Frings and Maaß (2018). Concerning water mills, Bishop and Jansen (2005) and Bishop and Muñoz-Salinas (2013) showed that the consequences of mill weir removal strongly depend on the (geo-) morphological setting of the river. Rivers in Southern England have lower slopes, are affected by less rainfall and have higher mill weirs in comparison to rivers in North-East Scotland (Bishop and Muñoz-Salinas 2013). Downward and Skinner (2005) focused their research on water mills in Southern England and concluded (as did Walter and Merritts (2008) and Pizzuto and O'Neal (2009)) that the failure of mill dams generates river management issues because great amounts of sediment will be flushed along the downstream direction after dam removal. But Bishop and Jansen (2005) and Bishop and Muñoz-Salinas (2013) concluded that this process critically depends on the geomorphological setting and history of the dammed river. However, dam failure and the subsequent mobilization of trapped sediment will increase sediment loads downstream (Bishop and Jansen 2005). For example, Scottish mill dam characteristics (in contrast to those of English dams) reflect the region’s higher bedrock channel gradients and higher rainfall, leading to generally smaller mill dam heights with lower sediment trapping efficiencies (Bishop and Muñoz-Salinas 2013). Most sediment passes over the dam wall (Bishop et al. 2011). Additionally, Lewin (2010) concluded that if channels are dammed or flow is restricted by in-channel structures, more sediment is deposited under lower-energy conditions.

Overall, the results of this study show the small-scale effects of water mills on fluvial morphology in terms of the impoundment of water upstream of a mill weir and the water and sediment diversion into two channels. But large-scale effects of widespread (mill) damming on the riverine environment also exist (Kaiser et al. 2018). Kaiser et al. (2018) analyzed the sedimentary sequences of the Havel River (Germany) focusing on the water level dynamics during the last two millennia. The Havel River was and still is influenced by mill dams, which change the flow regime, water levels, and groundwater over large areas. Kaiser et al. (2018) concluded that the rise in the water level due to impoundment widened the river and increased the size of existing lakes or initiated secondary lakes that previously aggraded, thus causing flooding of large parts of land, and this flooding resulted in the abandonment of several medieval rural settlements.

Generally, comparison of these different studies shows that the results presented here are applicable to other areas in Europe and not only to the Wurm River and the Geul River. Many small and large river-floodplain systems in Europe were or are still impacted by a chain of water mills or by other types of damming, in which the synergy of construction and removal of these transverse structures will result in incision of the river bed.

2.5.2 Assessment of assumptions

First, a constant channel width is assumed over the entire time. Pöppl et al. (2005) noted that dams decrease the flux of water and sediments, leading to channel changes such as upstream aggradation (Stanley et al. 2002; Csiki and Rhoads 2014) and downstream degradation and channel widening (Juracek 1999; Csiki and Rhoads 2014; Pearson and Pizzuto 2015). After dam removal, the opposite effects of degradation were found upstream of dams. Wong et al. (2004) investigated incision into the deposit and erosional narrowing of a channel after sudden dam removal, which both propagate upstream in a relatively short time. But in the long term, the depositional contribution from the side slopes eventually balances and then surpasses erosional narrowing, and the channel widens towards some new equilibrium state with a lower streamwise slope (Wong et al. 2004). However, it can be concluded that the application of equations 2-4 and 2-6 shows that a decreased river width, B, leads to an increased water depth, H, and, therefore, to a decreased river bed slope, S, (and vice versa) under the assumption that all other parameters remain constant. River narrowing might support the development of a decreased river bed slope, whereas river widening might counteract this development.

Second, it is assumed that minimum water, but maximum sediment enters the original channel during the time of active water mills. Kleinhans et al. (2013) concluded that the bed-load transport capacity varies nonlinearly with the local shear stress of the flow and that the bed-material load entering a bifurcation is divided more unequally than is the water independent of the dominant transport process. But below some threshold shear stress, the bed sediment transport capacity is negligible, so that it is possible for the smaller branch of a bifurcation to receive some flow but transport no bed material (Egozi and Ashmore 2009; Kleinhans et al. 2013). At water mills, the mill builders will have constructed their inlet structures to minimize sediment input and dredging work and to maximize water input into the mill channel. This suggests that the most extreme scenario is that all sediment, but very little flow, enters the original channel during operation. During the period of mill operation, all bed sediment will have deposited on the river bed in the original channel. In case of a chain of water mills, this amount of sediment deposition differs from the sediment budget of the natural channel, because sediment is deposited at each mill system. Fencl et al. (2015) analyzed the effects of a series of low-head dams (dam height < 7.6 m). Their results show a negative correlation between the number of dams upstream and the downstream spatial extent of low-head dam impacts, which corresponds to the results noted by Csiki and Rhoads (2014), who showed that sediment delivery to downstream dams is limited by sediment storage upstream of dams.

Focusing on water mills and following Bishop and Muñoz-Salinas (2013), water mills can be constructed in different ways. The water wheel can be set immediately downstream of a reservoir or can even be built into the wall of the reservoir. The water can also be brought to the wheel along a mill channel from the dam or by a channel located a little downstream of a knickpoint, which is a step in the longitudinal river profile or even simply a steeper reach in the profile (Tann 1965; Reynolds 1983).

These results show that the partitioning of water and sediment varies and depends on the type of water wheel and the (geo-) morphological setting between, e.g., alluvial and bedrock channels. In case of a water mill that does not abstract the major part of the water and sediment, less sediment is trapped upstream of the weir and more sediment is transported in the downstream direction through the original channel. This will lead to a decreased deposition of sediments on the river bed during the time of active water mills and, consequently, to decreased river bed incision after water mill removal in comparison to the water mill construction analyzed above, in which the major part of the water is abstracted into the mill channel. However, generally, the morphological consequences of the construction and removal of water mills are the same and result in an incised river bed with high river banks.

Third, it is assumed that the backwater effects of a chain of water mills are independent. In reality, the streamwise distance between two water mills might have been larger than the estimated backwater adaption length. The streamwise distance between two water mills is divided by the estimated backwater adaption length to evaluate the assumption mentioned above. Figure 2-7 shows a probability plot of the streamwise distance between two water mills divided by the estimated backwater adaption length for the Wurm River and the Geul River to test the assumption of independent backwater effects.

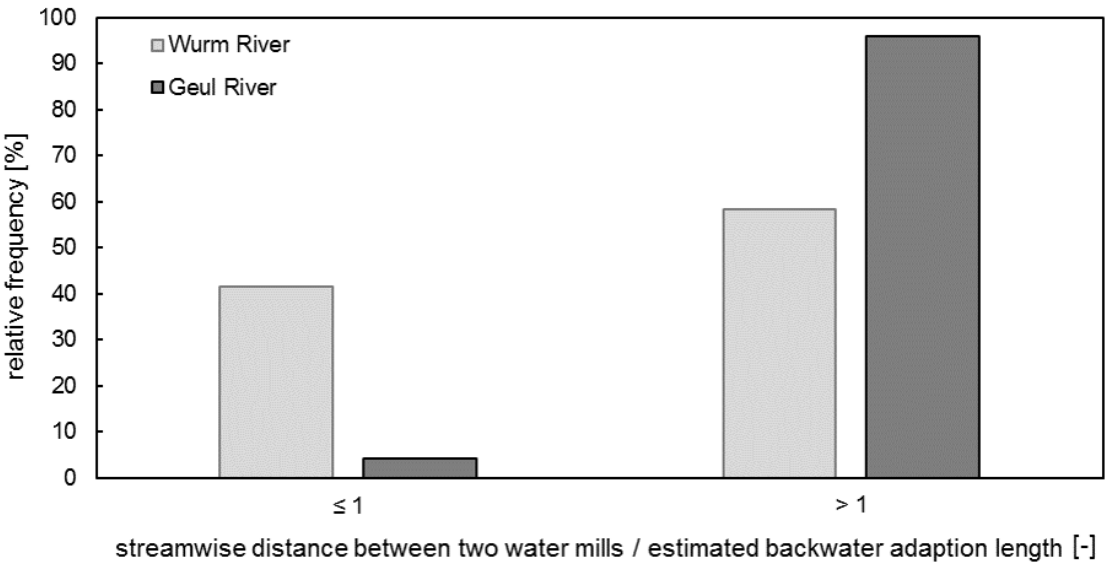

Figure 2-7: Probability plot of the streamwise distance between two subsequent water mills divided by the estimated backwater adaption length in the Wurm River and in the Geul River.

The impoundment height is assumed to be 2 m. A value larger than one shows that the water mills are independent, which is mostly present in the Geul River (see Figure 2-7). More than 90 % of all water mills of the Geul River have a longer streamwise distance between two water mills than the estimated backwater adaption length (see Figure 2-7). In the Wurm River, water mills were closely constructed, and approximately 40 % of all water mills influenced each other, while 60% of the mills were independent (see Figure 2-7). It can be concluded that the assumption of independent backwater effects for a chain of water mills is valid for many cases. Otherwise, in the case of overlapping backwater effects, the impoundment of water at a downstream located mill weir will raise the water level in the tail race downstream of an upstream located water mill, which will lead to a decreased efficiency of the wheel and a decreased river bed slope downstream of the wheel.

Additionally, it is assumed that the river channel always reaches equilibrium conditions after the construction of a water mill and before the removal of this water mill. The final state may be reached after decades to centuries (De Vries 1975). It must be noted that the internal and external controlling factors of a river-floodplain system might not be constant over such a long time. Different natural and human impact factors such as changes in land use, sealing of the ground or canalization might occur and might change the overall system. Such impact factors cannot be considered and investigated in this theoretical analysis.

2.6 Conclusions

The effects of the construction and subsequent removal of water mills on the channel and floodplain morphology of two small streams were analyzed, which showed the following:

- Floodplains around the backwater zones are more often inundated because of the higher water levels during the period of active water mills than that preceding their construction due to the impoundment of water at the mill weir, which results in relatively high floodplain sedimentation. After the removal of water mills, water levels are no longer impounded.
- In the channels, the decelerated flow upstream of mill weirs results in the deposition of sediment in the backwater zone.
- The period between mill construction and removal was so long that floodplain inundation rates and, therefore, floodplain sedimentation decreased due to increased bank heights.
- Following mill removal, the flow no longer entered the mill channel, leading to channel incision into the valley bottom deeper than the deposit formed during the period of active water mills.
- The morphological response was so hysteretic that the effects of mills are still present in today’s river systems.

Comparison to other studies showed that the results of the two streams analyzed here are applicable to many other river-floodplain systems in Europe with gravel beds and silty floodplains, which were or are still impacted by either a chain of water mills or by other types of damming, because the overall morphological consequences of channel incision are independent from specific study site conditions.

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3 Long-term effects of mining subsidence on the trapping efficiency of floodplains

Anna-Lisa Maaß, Holger Schüttrumpf

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Abstract

Effects of human activities such as land-use changes, flood protection measures, coal-mining activities, and urbanization on river-floodplain systems are widespread and have been well known to extensively change the hydro- and morphodynamics of rivers. Land subsidence, e.g., that caused by the extraction of coal in subsurface mining tunnels in riverine environments, results in local or large-scale ground-surface irregularities where sediment is eroded or deposited during flooding. This study determined the long-term effects of mining-induced subsidence on the trapping efficiency of floodplains. The Wurm River (Lower Rhine Embayment, Germany) provided a test case owing to its central location in a previous underground coal-mining region. To analyze the effects of mining subsidence on the trapping efficiency of floodplains, we developed a numerical model based on the Delft3D software that applied the embedded space-varying subsidence module. The time series for the space-varying changes of the surface elevation were defined on a computational grid. Results of nine scenarios showed that subsidence led to a local increase in the silt trapping efficiency on floodplains when subsidence generally increased the frequency and magnitude of floodplain inundation and acted as a local trap for sediment. The model developed in this study is applicable to rivers with similar characteristics, such as small meandering rivers with large floodplains, where suspended sediment accounts predominantly for the deposition on floodplains.

Keywords: Mining subsidence, Floodplain deposition, Silt trapping efficiency of floodplains, Numerical modelling

3.1 Introduction

River-floodplain systems all over the world are greatly affected by human activities (Dotterweich 2008; Hoffmann et al. 2010). Underground coal-mining industry is one type of human activities that affected the river-floodplain systems since the High-Middle Ages; its effects peaked in the 20th century. For example, the effects of the coal-mining industry are related to neotectonical movements of the ground that produce subsidence, sinkholes, or uplift regions, which may damage infrastructures (Booth 1986; Bell et al. 2000; Sidle et al. 2000; Harnischmacher 2012; Can et al. 2013). Coal particles and coal sludge may be carried into river channels from different sources (e.g., water for washing the coal), which colors the water black (Renes 1998) and may cause environment contamination (Figure 3-1).

The extraction of coal in underground mining tunnels, in combination with pumping of groundwater, may cause a collapse of these tunnels. The collapse can result in subsidence or sinkholes at the ground surface. Subsidence indicates a relatively continuous surface deformation, which is measured as vertical and horizontal displacements of surface points (Bräuner 1973). The pumping of groundwater is of secondary importance in the subsidence processes (Oberste-Brink 1940). Subsidence may occur several weeks or decades after the start of mining activities. The depth and areal size (spatial extension) of subsidence depend on several factors such as depth of extraction, geometry of the seam, and mining method as well as the type and nature of the overlying strata and rock type. Heitfeld et al. (2005) analyzed the areas of land collapses due to underground mining and indicated a slope angle of 45° in the subsidence depression relative to the ground surface (Figure 3-1). The maximum surface displacement of subsidence (subsidence depth) was equal to 90 % - 95 % of the removed seam thickness (Szelag and Weber 1993; Harnischmacher and Zepp 2010; Harnischmacher and Zepp 2016). Field studies in coal mines in England and France showed that residual subsidence, which is characterized as subsidence that occurs after mine closure, accounted for only 6 % of the total (maximum) subsidence (Bräuner 1973). In the Ruhr area, surface displacements with total depths of up to 24 m have been measured (Harnischmacher 2012).

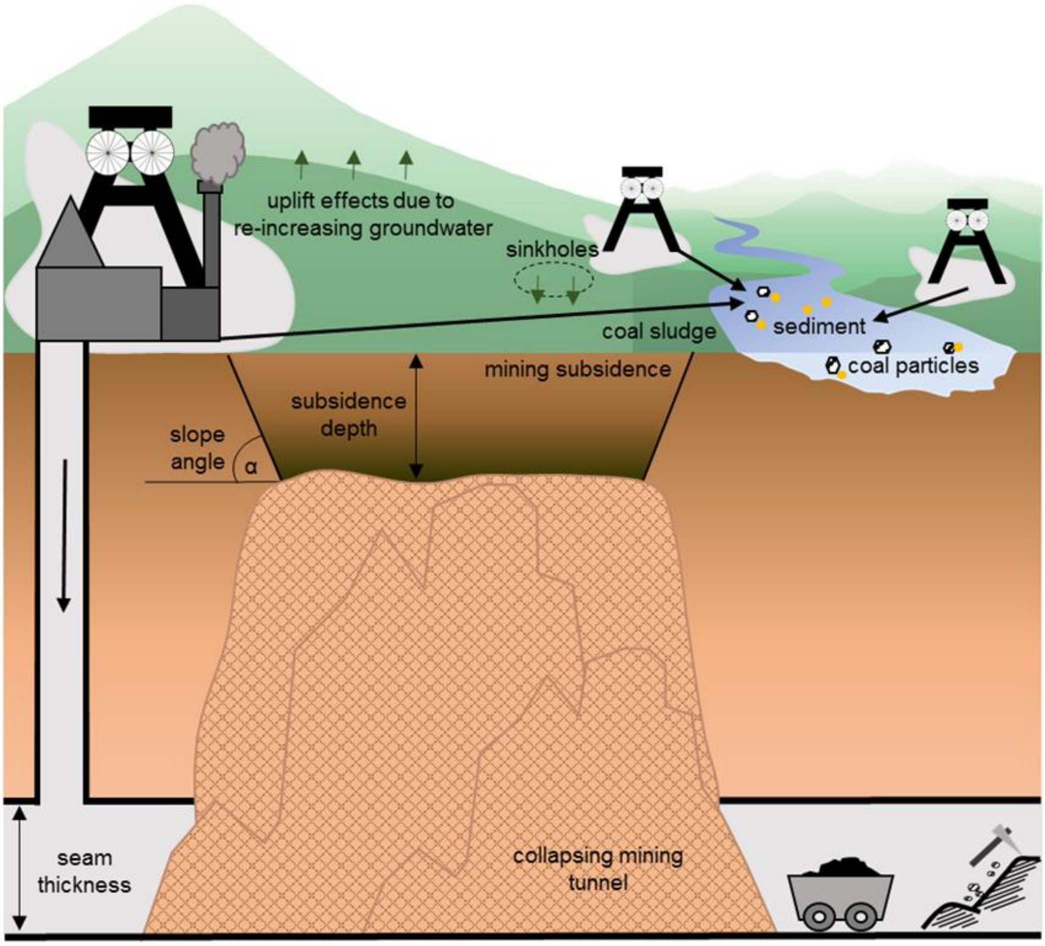

Figure 3-1: Effects of the underground coal-mining industry on river-floodplain systems.

The extraction of underground coal also results in the occurrence of sinkholes. Sinkholes locally and suddenly occur and are uncontrollable, in contrast to the continuous process of mining subsidence. Another effect of coal-mining activities is uplift. After the mines are closed, stoppage of dewatering and increase in the groundwater level may result in uplift of the area. Uplift occurs in previous areas with subsidence and may account from 2 % - 5 % of the subsidence depths (Fenk 1997).

The subsidence or uplift effects in the surroundings of a river can cause morphological changes. Previous studies (Volkov et al. 1967; Ouchi 1985; Benito et al. 1998; Holbrook and Schumm 1999) focused on the effects of subsidence on sediment characteristics, channel-pattern type, and development of the longitudinal river profile. Holbrook and Schumm (1999) stated that the changes in the longitudinal river profile can be divided into three zones (see Appendix, Figure A.1). (1) At the beginning of subsidence, the river bed slope increases, which leads to increased flow velocities and erosion of sediment (Benito et al. 1998; Holbrook and Schumm 1999; Schumm et al. 2006); (2) Inside the subsided area, the river bed slope decreases, which leads to reduced flow velocities and deposition of sediment (Volkov et al. 1967); (3) At the end of subsidence, the slope decreases to reach the original bed level, which leads to further reduction in the flow velocities (Volkov et al. 1967; Schumm 1986; Holbrook and Schumm 1999). Holbrook and Schumm (1999) stated that deposition inside the subsided area results in reduced bank heights and leads to increased water levels and higher inundation frequencies in the surrounding floodplains (see Appendix, Figure A.2). The deposition of sediment is caused by the decreased flow velocities inside the subsidence area.

We hypothesize that mining subsidence will result in increased deposition in river floodplains. The deposition is controlled by the trapping efficiency, which depends on the available accommodation space (Lewin and Ashworth 2014) and efficiency of the sediment distribution into this accommodation space (Erkens 2009). It is an internal characteristic of the fluvial sedimentary system and can be used in addition to the upstream sediment delivery to define the amount of sediment storage in a certain fluvial range (Erkens 2009). However, research concerning the effects of mining-induced subsidence on the coupled river-floodplain system is lacking. In the present study, we address the poorly studied issue on the effects of floodplain subsidence on sediment deposition and storage. We numerically model the effects of subsidence from mine collapse on the net sedimentation, flooding, and silt trapping on river floodplains over a period of 200 years. Over time scales of centuries, multiple natural and anthropogenic disturbances that affect channel morphology and floodplain sedimentation have occurred. Separating these influences on the floodplain sedimentation by analyzing the alluvial stratigraphic deposits is difficult. Thus, the strength of a numerical modelling approach is that it can examine the influence of only one impact factor on the floodplain sedimentation given the specific initial and boundary conditions.

In the current study, our model uses the Delft3D software to consider the effects on a sample river system, the Wurm River (Lower Rhine Embayment, Germany), using the perimeters of this system as boundary conditions. Our investigations are based on the numerical analysis of nine scenarios. This study does not attempt to characterize specific subsidence events at the Wurm River. The scenarios differ from one another in terms of subsidence location, size, vertical depth, and vertical rate.

3.2 Case study area

3.2.1 Current environment

The Wurm River (Lower Rhine Embayment, Germany) is a small stream with a catchment size of 356 km² and a length of 57.9 km in a low mountain area near the Dutch-German border (MULNV NRW 2008a) (left part in Figure 3-2).

The headwater tributaries as well as the main river channel of the Wurm River run entirely through tunnels underneath the city of Aachen. Sediment is captured in sand traps (approximately 2,500 m^3 per year, personal note in 2016 Wasserverband Eifel Rur), which significantly reduces the sediment load, before the river returns to the surface downslope of Aachen. The mean annual discharge is approximately 3 m^3/s, and the mean flood discharge is approximately 25 m^3/s (LANUV NRW 2004) in which up to 90 % (Weber 1991; Hoppmann 2006) consists of treated sewage (the mean sewage-treatment discharge in 2015 AD was 0.85 m³/s) from the main wastewater treatment plant in Aachen-Soers (upper part in Figure 3-2). The Wurm River is characterized as a gravel-bed river; coarse sediment fractions (coarse sand and gravel) are generally immobile. Fine sediment (clay, silt, and fine sand) is predominantly transported as suspended load.

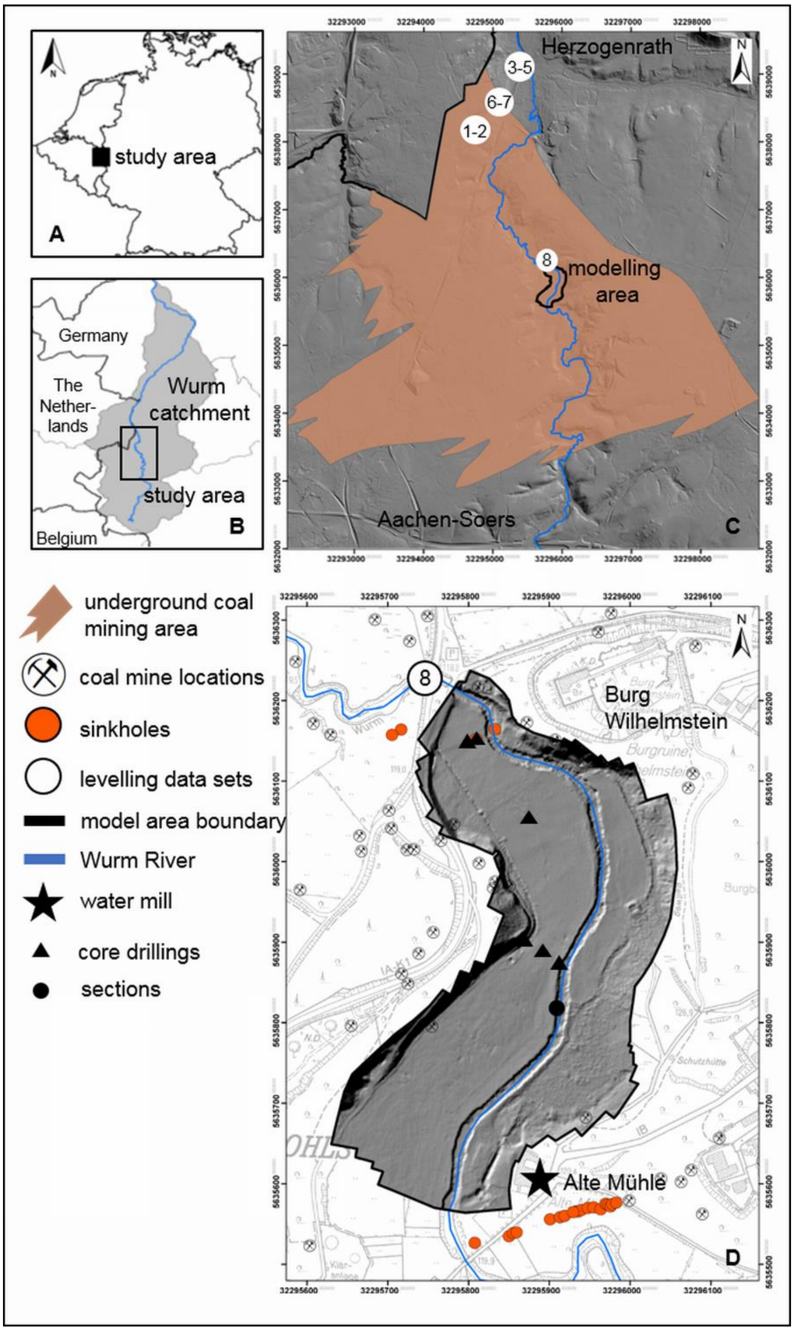

Figure 3-2: A: Map of Germany and surrounding states. B: Catchment of the Wurm River. C: Near-natural part of the Wurm River inside a previous underground coal-mining area of Aachen. D: Modelling area.

Our analysis focusses on a 1 km section of the Wurm River between historical water mill *Alte Mühle* and castle *Burg Wilhelmstein* (lower part in Figure 3-2). The study area is approximately 10 km downstream of Aachen. It is directly located in a previous underground coal-mining area. It is considered as a representative river section of the near-natural part of the Wurm River between the cities of Aachen and Herzogenrath and is characterized by variable fluvial morphodynamics.

3.2.2 Underground coal mining industry

Underground coal mining took place in the Wurm valley between the Roman period and 20th century. The last mine (Emil Mayrisch) in the Wurm valley was closed in 1992 AD (Schetelig et al. 2007). Quantification and localization of mining subsidence adjacent to the Wurm River are difficult, but Schetelig et al. (2007) stated that mining subsidence was definitively recognized in the Aachen underground coal-mining areas. The current river-floodplain system is influenced by collapses of mining tunnels, which result in sinkholes, or by increasing groundwater levels, which results in uplift (Wrede and Zeller 1988; Heitfeld et al. 2017). A study by Rosner (2011) showed that the mining subsidence in the study area varied between 1.2 m and 10 m in depth, but because of the different seam thicknesses, larger subsidence areas were possible. Pöttgens (1985), Pöttgens (1998) and Miseré and Wings (2004) stated that the uplift effects in the Aachen and adjacent Südlimburger coal-mining area (Dutch-German border) only accounted for 2 % to 5 % of the subsidence depths (from 2.4 cm to 50 cm).

Because of the different overlapping erosional and depositional processes, definition of specific subsidence locations close to a river is difficult. Furthermore, in contrast to the Ruhr area, underground coal mining in Aachen took place at shallower depths, which led to shallower subsidence depths. These shallower depths fell within the uncertainty range of determining subsidence by comparing the time-sequential topographic maps (method used by Harnischmacher and Zepp (2010) and Harnischmacher (2012)). We believe that mining subsidence occurred in the modelling area because the mine locations and mining tunnels were close to the Wurm River or even passed beneath the river (Figure 3-2 C and D; Büttgenbach 1898). Furthermore, our expectation was based on the analysis of the surveying data (determination of the geodetic height) of different benchmarks in the Aachen underground coal-mining region close to the Wurm River (Figure 3-2, distance of the leveling points varied between 0 m and 650 m). Surveying datasets are available for different points in time between 1951 AD and 2015 AD. Most of the surveying activities were done after the end of the underground coal mining and covered only the residual mining subsidence or even uplift effects. Point 8 is directly located at the end of the modelling area. This point is located in the previous area of coal mine Gouley, which was closed in 1969 AD. The topographic survey data show that uplift occurred between 1998 AD and 2015 AD (last dataset) with an average uplift rate of 3 mm per annum. Under the assumption that this uplift is an indicator of previous subsidence, we determined a total uplift of 51 mm (3 mm per annum over 17 years; 1998 AD – 2015 AD). In underground coal mining regions, uplift occurs in former subsidence areas and may account for 2 % - 5 % of the subsidence depths (Fenk 1997). These uplift values lead to subsidence estimates of from 1.02 m (2 %) to 2.55 m (5 %) in the study area. Points 1 to 7 are located farther away from the Wurm River upstream to the city of Herzogenrath. The average residual subsidence is 52 mm and ranges between 21 mm and 248 mm. Residual subsidence is characterized as subsidence that takes place after mine closure. Using the estimate of Bräuner (1973) that residual subsidence accounted for 5 % to 10 % of the maximum subsidence, we determine subsidence depths between 0.21 m (10 % from 21 mm) and 4.96 m (5 % from 248 mm) with an average of approximately 2 m.

3.2.3 Morphological development

The Wurm River has experienced diverse anthropogenic changes in its morphology and landscape since Medieval Times. The historical state 200 years ago (approximately 1800 AD) was different compared with the present river characteristics. Field measurements provided insights about its morphological evolution. Mean sedimentation rates of approximately 2 m for the last 200 years were determined using geochemical marker beds in cores collected in the modelling area (Hagemann et al. 2018; measurement locations in Figure 3-2). The cores were analyzed for grain size composition, total organic carbon, trace element inventory, and organic compounds (Hagemann et al. 2018) to derive the sedimentation rates. Upstream of the modelling area, incision of the river bed of approximately 70 cm was determined from field measurements. The incision was caused by the construction and subsequent removal of a chain of water mills (Buchty-Lemke and Lehmkuhl 2018). Figure A.3 in the Appendix shows the difference in height between the old river bed in terms of a visible gravel layer in the bank of the Wurm River and the contemporary river bed.

3.3 Methods

3.3.1 General concept of Delft3D

We numerically analyze the effects of mining subsidence on floodplain inundation and floodplain deposition using the Delft3D software in 2D (depth-averaged) mode (Deltares 2016). Delft3D-Flow solves the Navier-Stokes equations of an incompressible fluid under shallow water and the Boussinesq assumptions using the finite-difference method on a structured grid (for further explanation, see Lesser 2009 and Lesser et al. 2004). In Delft3D, considering the turbulence in a 2D simulation is also possible using a constant eddy viscosity and diffusivity and/or using the horizontal large eddy simulation approach. Generally, both concepts can improve the simulation results (Pasche et al. 2006; Awad et al. 2008).

The simplification of the inflow hydrograph to a stepwise discharge (quasi-steady) hydrograph accelerates the computational time of long-term simulations using Delft3D. Each discharge represents one simulation, and these simulations are coupled to one another. The hydrodynamic conditions are transferred from one simulation under the same discharge condition using separate databases. To avoid instabilities between the sharp transitions of different discharges, any sub-simulation provide sufficient spin-up time to adapt to the new hydrodynamic conditions (for detailed description of this simulation management tool of Delft3D, see Yossef et al. 2008).

The transport of cohesive sediment can be modelled using the Partheniades-Krone equation (Partheniades 1965). On the basis of hydrodynamic flows, morphological development takes place in a time scale that is several times longer than the typical flow changes (Deltares 2016). The application of morphological scaling factor F additionally accelerates the computational time. Bed level changes are multiplied by this factor after each hydrodynamic time step (for further explanations, see Lesser 2009 and Ranasinghe et al. 2011). The morphological scaling factor is inversely proportional to the discharge because of the increasing morphological changes with increasing scaling factor.

The application of the space- and time-varying subsidence tool in Delft3D requires the definition of the changes in the surface elevation on the computational grid. Figure A.4 in the Appendix shows an example of subsidence that occurs on a computational grid between two points in time with a total depth of 1 m and collapsing side walls with a slope angle of 45°. The net changes in the surface elevation are defined in the cell center of each grid cell. The bed and the water levels can freely adjust because of the subsidence process.

3.3.2 Model setup

Our model represents a 1 km section of the Wurm River. The total number of cells is equal to 18,383 grid cells, including 1,513 grid cells in the main channel. The average cell size of the entire grid is equal to 8.33 m^2. The current topography of the floodplains (around 2000 AD) of the Wurm River is based on a digital elevation model (LIDAR DEM with a spatial resolution of 1 m, height resolution +/- 0.2 m, Land NRW 2017). The current bathymetry is based on the cross-sectional profiles. The model is laterally restricted to the hillsides of the valley. Historical characteristics of the Wurm River at around 1800 AD are transferred to the model by decreasing the floodplain elevation by 2 m and increasing the river bed elevation by 0.7 m to achieve historical bank heights of approximately 1.3 m. All other parameters remain constant for both states. Figure A.5 in the Appendix shows a summary of all model parameters in the model setup. The parameters are based on hydrodynamic and morphodynamic calibrations of the model (see Section 3.3.4, Calibration).

We define a time-dependent inflow for the upstream boundary condition. For the downstream boundary condition, we define a relation between the discharge (Q) and water depth (H). Simulations using time scales from decades to centuries can only be performed by simplifying the boundary conditions and using some additional numerical tools to achieve an acceptable computational time. In this study, we use a quasi-steady hydrograph and a discharge-dependent morphological scaling factor. Using these tools, we manage to simulate 200 years of a single scenario with a computational time of approximately two weeks. Discharges measured at the gauging station in Herzogenrath between 1969 AD and 2016 AD are used to determine the representative discharges of the quasi-steady hydrograph. The measured discharges are in the range between 0.13 m^3/s and 44.30 m^3/s. We define nine discharge steps (2.5 m^3/s and in steps of 10 m^3/s from 10 m^3/s to 80 m^3/s), which capture the characteristic flow situations such as the average flow and bankfull conditions as well as overbank flows. For discharges between 2.5 m^3/s and 40 m^3/s, we determine the relative frequency of each discharge step based on all measurements of the gauging station and multiply it with the total duration of 200 years to calculate the total duration of each discharge in this period. We extrapolated our results for discharges between 50 m^3/s and 80 m^3/s (see Appendix, Figure A.6). We need to mention that floodplain sedimentation is highly dependent on the frequency and duration of flow events used in a simulation. In this study, we always refer to the same reference scenario and qualitatively compare the results of all scenarios with one another. We do not change the overall boundary conditions.

When morphological scaling factor F is used during the morphological simulations, we need to distinguish the differences between the hydrodynamic and morphodynamic times. Hydrodynamic time is defined in the inflow boundary condition of a numerical model. Morphodynamic time is defined as the total time of morphological development. In Delft3D, the morphodynamic time is calculated by multiplying the hydrodynamic time with morphological scaling factor F. For example, if we want to investigate the morphological development over 200 years, by setting morphological scaling factor F = 200, a constant inflow of 10 m^3/s over 1 year must be defined as the inflow boundary condition. In our model, we achieve an acceptable computational time and reasonable results with a scaling factor of 800 for discharges of the quasi-steady hydrograph between 2.5 m^3/s and 20 m^3/s and a scaling factor of 200 for discharges greater than 20 m^3/s. Turbulence is considered using a constant eddy viscosity and diffusivity term.

On the basis of the grain size analyses of the floodplain sediment and the sediment transported in suspension, we determine that silt primarily contributed to the floodplain sedimentation in the modelling area. The grain size analyses show that the floodplain sediment consisted of approximately 51 % silt, 39 % sand (26 % fine sand, 11 % medium sand and 2 % coarse sand), and 10 % clay. Sand might have possibly volumetrically composed more of the floodplain deposits than silt, but in our model, the mechanisms of floodplain deposition such as levee building and splays are not considered. Therefore, the model is predominantly applicable at rivers where suspended overbank deposition is the dominant mechanism of floodplain deposition. In this work, the modelling scenarios are performed using only one grain size fraction with a grain diameter of 24.5 µm (silt), which is equal to the median diameter (D_{50}) of all sediment cores taken from the floodplains. Flocculation is not considered. One major assumption in our modelling approach is to keep the sediment input constant over the entire simulation time. The effects of this assumption on the modelling results are discussed later (see Section 3.5.1, Assessment of model quality).

3.3.3 Scenarios

Table 3-1 lists an overview of the subsidence scenarios performed in this work. We analyze the effects of mining subsidence on the trapping efficiency of floodplains by varying the subsidence parameters: location, size, final depth, and vertical subsidence rate. Because the specific subsidence conditions are not known, the scenarios represent only potential subsidence scenarios. The characteristics of the scenarios are based on the literature and previously presented calculations (see Section 3.2.2, Underground coal-mining industry). According to the leveling datasets, we know that mining subsidence is present along the Wurm River. Therefore, we decide to use this study area as a representative reach directly located in the previous underground coal-mining area of Aachen to predict the morphodynamic responses of a river for realistic mining-subsidence scenarios.

Table 3-1: Characteristics of the different subsidence scenarios applied in the numerical Delft3D model.

Scenario	**Location**	**Size [m²]**	**Subsidence depth [m]**	**Subsidence rate [m/a]**
1	Without subsidence	-	-	-
2	Underneath the river bed	50 x 50	2	0.4
3	Left floodplain	43 x 50	2	0.4
4	Right river bank	50 x 48	2	0.4
5	Left river bank (middle of the model)	48 x 47	2	0.4
6	Left river bank (middle of the model)	23 x 26	2	0.4
7	Left river bank (close to the downstream boundary)	49 x 63	2	0.4
8	Left river bank (close to the downstream boundary)	49 x 63	4	0.8
9	Left river bank (close to the downstream boundary)	49 x 63	1	0.2

Scenario 1 represents the reference scenario, i.e., no subsidence occurs. Scenario 2 is used to analyze the effects of subsidence that occurs downstream of a river bed. In scenario 3, subsidence occurs in the left floodplain with a distance of approximately 80 m from the main channel. In scenarios 4 and 5, subsidence occurs immediately next to the river banks. Each scenario consists of a total morphological duration of 200 years, including an initial period of 5 years where no subsidence occurs and a subsequent period of 5 years where the land is subsiding.

The total amount of sediment deposited on the floodplains over 200 years is separately calculated for each scenario and is used to determine the trapping efficiency of the floodplains considering the floodplain inundation frequencies, durations, and magnitudes. We further investigate the deposition of sediment in the subsidence sinkholes and compare the amount with the deposition in the reference area without any subsidence.

3.3.4 Calibration

A hydrodynamic calibration was performed by adopting the Chézy roughness coefficient to achieve a minimum deviation between the modelled and measured water levels of a 20-year flood event in 2014. During the flood event in 2014 AD, water levels in the main channel were measured at the end of the modelling area up to a discharge of 45 m^3/s. Using a Chézy coefficient of 31 $m^{1/2}/s$, we were able to reproduce these water levels with a relative maximum deviation of 0.05 %, a correlation coefficient of 0.995 and a Nash-Sutcliffe index of 0.98 (Nash and Sutcliffe 1970).

In the study area, on the average, sediment with D_{50} of 24.5 µm were transported in suspension and deposited on the floodplains. Therefore, we adopted the settling velocity and critical shear stress for erosion and sedimentation of the floodplains during our morphodynamic calibration according to sediment with D_{50} of 24.5 µm. The roughness of the main channel as well as the critical shear stress for erosion and sedimentation of the river bed was adopted as the characteristics of the gravel that characterized the river bed (D_{50} of 33 mm).

The calibration of the sediment input was based on the historical model setup of the Wurm River that represented its condition approximately 200 years ago. We used the mean sedimentation rate of 2 m for the last 200 years, which was derived from the trace element gradients and organic geochemistry analysis, as an indirect calibration parameter to determine the sediment input of the modelling area. Using a sediment input of 5 kg/m^3 for all discharges of the quasi-steady hydrograph, we were able to reproduce these sedimentation rates, which were determined by dividing the total amount of sediment deposited on the floodplains in the modelling time. The average sedimentation on the right floodplain was equal to 0.5 m, and on the left floodplain was 0.95 m. The maximum sedimentation on the right floodplain was equal to 7.3 m, and it was 2.8 m on the left floodplain. Figure A.7 in the Appendix shows the cumulative sedimentation based on the calibration model results between 1800 AD and 2000 AD.

3.4 Results

3.4.1 Average floodplain sedimentation

Figure 3-3 shows the average floodplain sedimentation on the left and right floodplains for all scenarios.

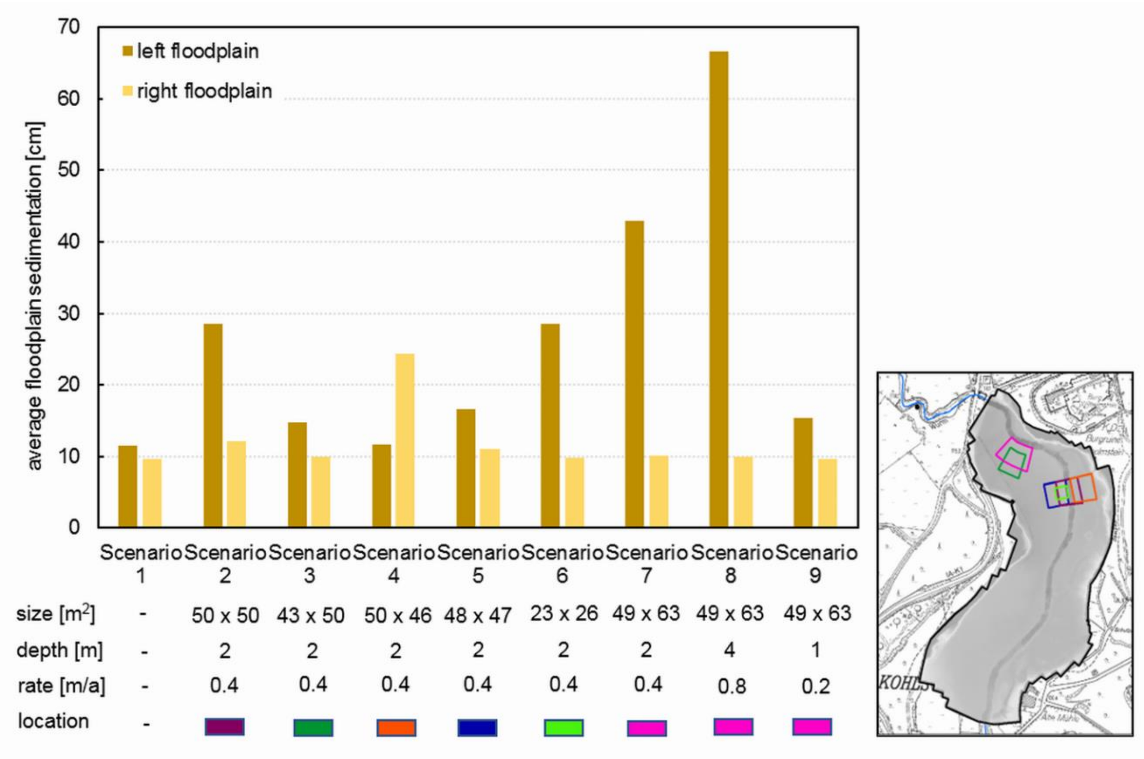

Figure 3-3: Comparison of the average floodplain sedimentation on the left and right floodplains of the system.

For the reference scenario (scenario 1), the left floodplain is first inundated, which results in greater deposition of sediment on the left floodplain (11.6 cm) than that on the right floodplain (9.6 cm). For scenario 2, the average sedimentation increases on both floodplains (28.5 cm on the left and 12.1 cm on the right) compared with the reference case because subsidence influences both sides of the valley. When subsidence occurs on the left floodplain of the Wurm River (see scenarios 3 and 5-9), the average floodplain sedimentation on the left floodplain increases. For scenario 4, mining-induced subsidence occurs in the right floodplains, and the average floodplain sedimentation on the right floodplain increases (11.6 cm on the left and 24.4 cm on the right). Overall, Figure 3-3 shows that mining-induced subsidence leads to an increase in the average floodplain sedimentation.

3.4.2 Subsidence size

The detailed comparison between scenarios 5 and 6 (Figure 3-4) shows that the smaller the spatial expansion of subsidence is, the greater is the average sedimentation in the subsidence area (18 cm in scenario 5 and 75 cm in scenario 6).

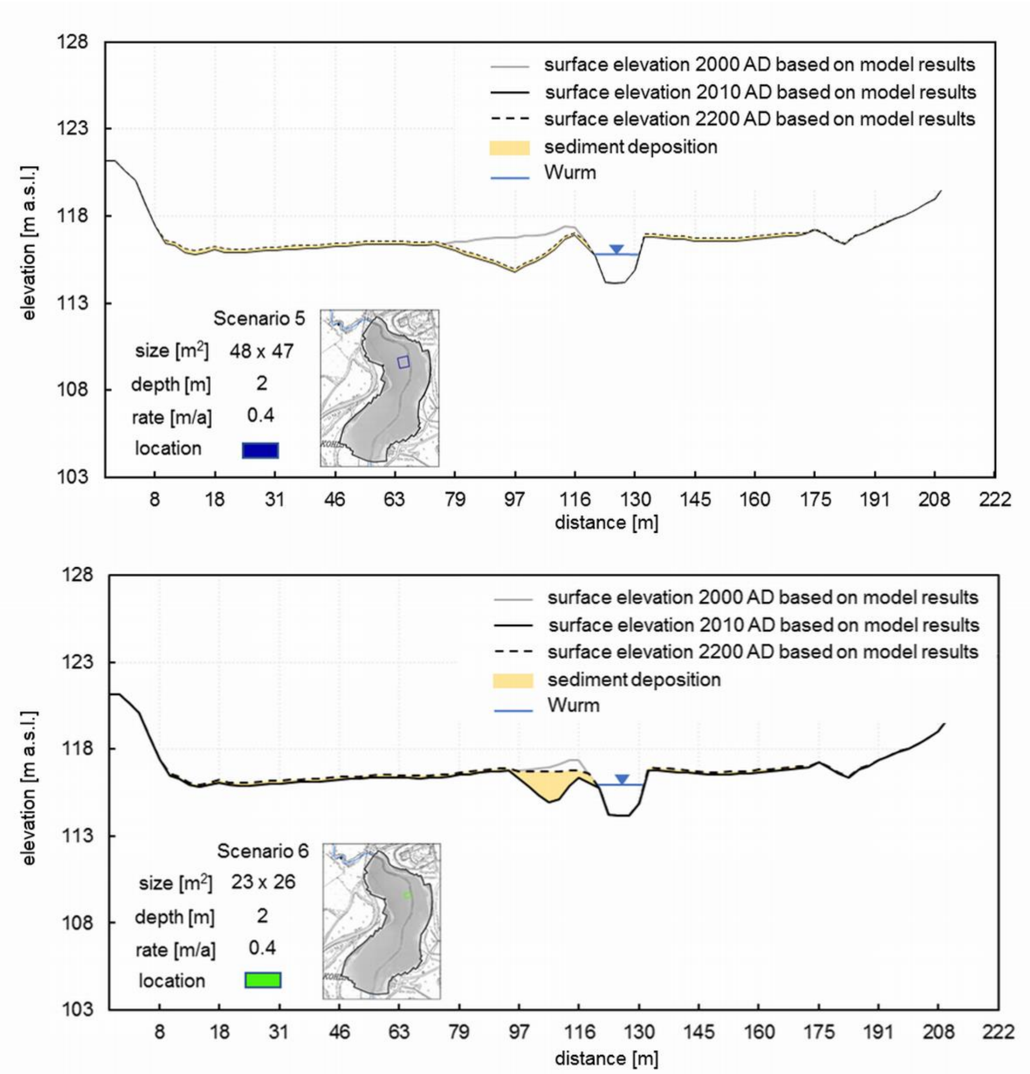

Figure 3-4: Sediment deposition of scenarios 5 and 6. The smaller the spatial expansion of a subsidence is, the greater is the average sedimentation in the subsidence area.

The vertical subsidence rate remains constant at 0.4 m per annum. The subsidence area in scenario 5 (dimension of approximately 25 m x 25 m) is almost filled up with sediment after a period of 200 years. In comparison, only a small layer covers the subsidence area in scenario 6 (dimensions of approximately 50 m x 50 m). Ponding increases in smaller subsidence areas.

3.4.3 Subsidence depth

Figure 3-5 shows the average sedimentation in the subsidence area compared with the sedimentation in the reference area without subsidence. Relative to the mining subsidence depth of 2 m, the results of doubling the mining subsidence depth from 2 m (scenario 7) to 4 m (scenario 8) and in halving the subsidence depth from 2 m (scenario 7) to 1 m (scenario 9) do not show a causal relationship between subsidence depth and average sedimentation in the subsidence area. Generally, we can see that the average sedimentation in the subsidence area increases with increasing subsidence depth. In scenario 9, the average sedimentation is equal to 17 cm in a subsidence area with a depth of 1 m. In scenario 7, the average sedimentation is equal to 92 cm in a subsidence area with a depth of 2 m, and in scenario 8, the average sedimentation is equal to 185 cm in a subsidence area with a depth of 4 m. The difference in these results might be related to the differences in local topography such as levee building, human impacts from agricultural use, relief characteristics of the area where the subsidence occurs, and hydrodynamic characteristics where deposition of sediment occurs in the numerical model.

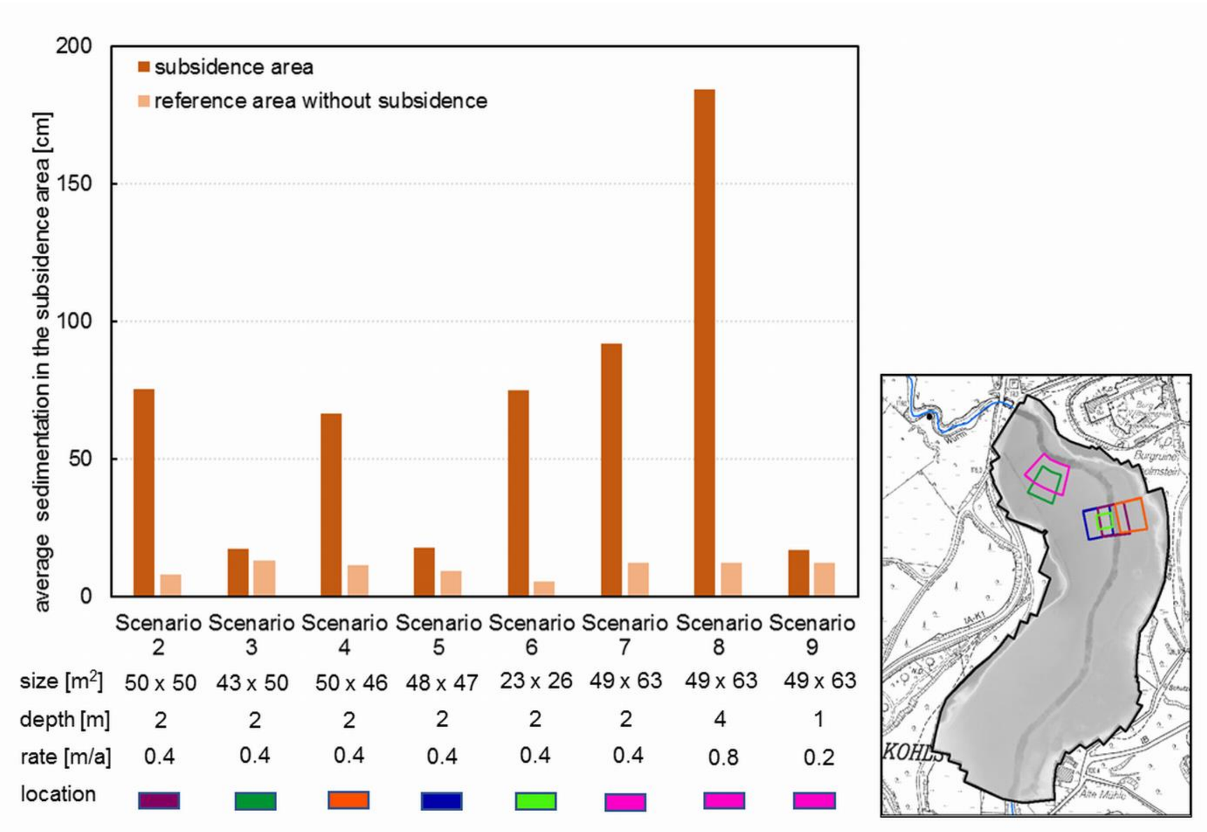

Figure 3-5 Average sedimentation in the subsidence area compared with the sedimentation in the reference area without subsidence.

3.4.4 Subsidence location

A comparison of the water depths of the reference scenario and scenario 7 shows that subsidence at the river bank of the Wurm River already leads to floodplain inundation at a discharge of 10 m^3/s. For the reference scenario, floodplains are not inundated at 10 m³/s (Figure 3-6, top). A comparison of the water depths of the reference scenario and scenario 3 shows that subsidence on the left floodplain of the Wurm River does not change the beginning of the floodplain inundation but enlarges the inundated area (Figure 3-6, bottom).

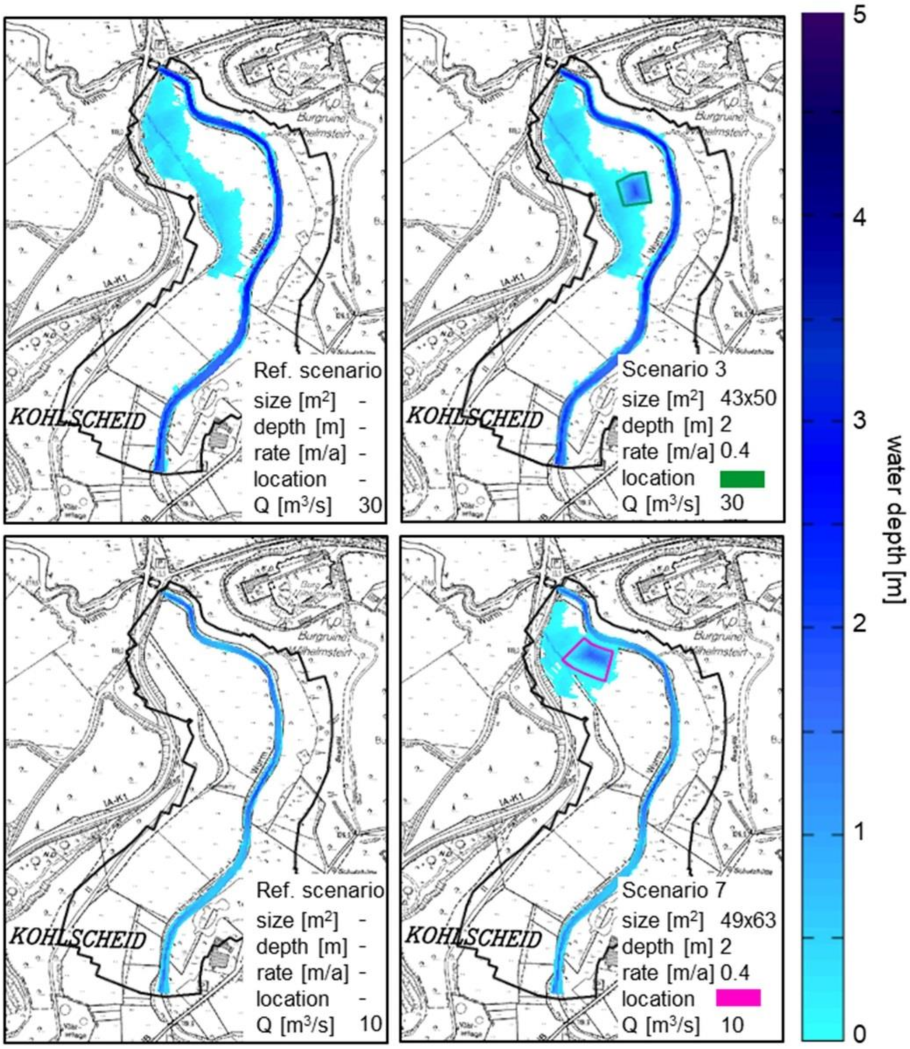

Figure 3-6: (Top) Comparison of the water depths of the reference scenario without any subsidence and scenario 3 at a discharge of 30 m³/s. (Bottom) Comparison of the water depths of the reference scenario without any subsidence and scenario 7 at a discharge of 10 m³/s.

3.4.5 Backfilling of subsidence

The results show that the subsidence areas are not filled to the original ground-surface level over a period of 200 years after reaching its final subsidence depth (2010 AD). Scenario 2 presents an exception of the backfilling process. The subsidence partially exceeds the original surface elevation after 200 years, whereas other parts remain subsided and are not filled with sediment (Figure 3-7).

The subsidence in scenario 2 directly occurs underneath the river bed and leads to a significant increase in sedimentation (approximately 950 %) on the river bed in the subsidence area compared with the reference case. Inside the subsided area, flow velocities are reduced, and sediment is deposited. The accommodation space is backfilled with sediment.

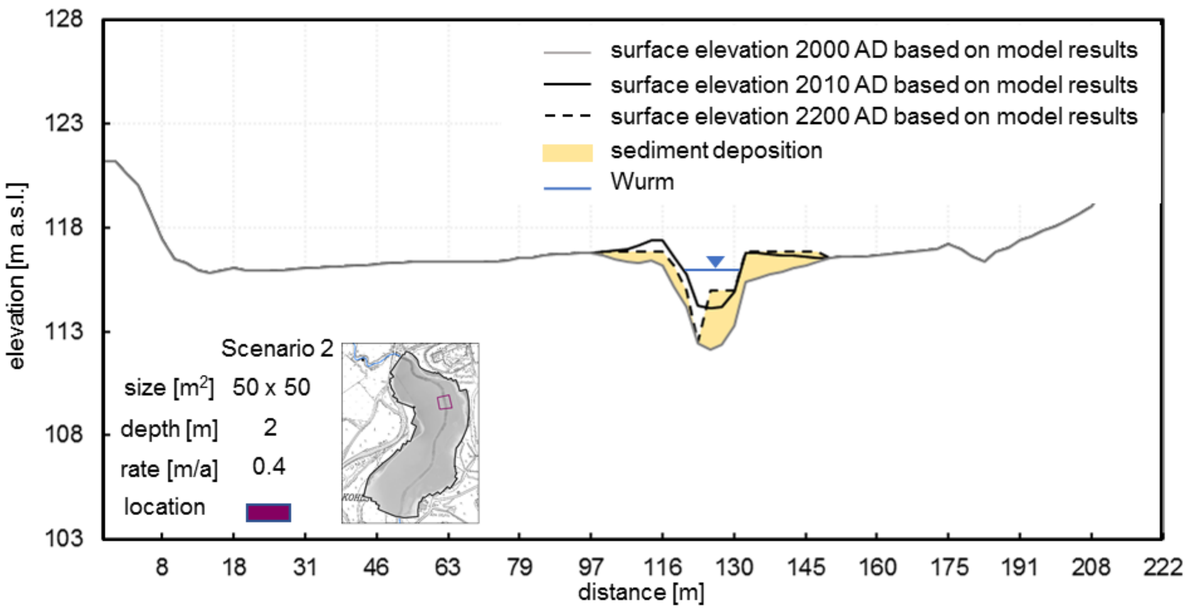

Figure 3-7: Subsidence underneath the river bed partially filled up with sediment over a period of 200 years.

3.5 Discussion

We analyzed the long-term effects of mining-induced subsidence on the silt trapping efficiency based on the characteristics of the Wurm River. The aim of this analysis was to assess the model quality. The applicability of the model to other river-floodplain systems that were affected by the influences of the underground coal-mining industry and (typical for old-industrial areas) by many different natural and anthropogenic superimposing impact factors that affected the morphological development of these systems was examined.

3.5.1 Assessment of model quality

First, we analyzed the effects of the quasi-steady hydrograph on the simulation results. We defined a symmetrical quasi-steady hydrograph with discharges between 2.5 m^3/s and 80 m^3/s based on measurements at the gauging station in Herzogenrath (see Section 3.3.2, Model setup, and Figure A.6). The hydrograph consisted of linked steady discharge events and represented (in combination with the discharge-dependent morphological scaling factor F) a simulation period of 200 years. In the rising limb, the steady discharges increased from 2.5 m^3/s to 80 m^3/s and symmetrically decreased in the falling limb from 80 m^3/s to 2.5 m^3/s. We summarized the duration of the two steps with the same discharge to one duration and defined only one increasing limb from 2.5 m^3/s to 80 m^3/s over a total duration of 200 years. Summarizing the representative discharges to one series compared with dividing the discharges into a series of consistently linked events for a period of 200 years resulted in a greater deposition of sediment of approximately 3.78 % in the left floodplain and 0.24 % in the right floodplain. Therefore, the sensitivity of the modelling results to the structure of the quasi-stationary hydrograph was negligible.

Second, we investigated the effects of the morphological scaling factor on the simulation results. On the basis of the hydrodynamic flows, morphological development took place on a time scale that was several times longer than the typical flow changes. In Delft3D, the speed of the changes in the morphology was scaled up to a rate that it began to exert a significant effect on the hydrodynamic flows using a so-called morphological scaling factor. Erosion and deposition fluxes from the bed to the flow and vice-versa were multiplied by this factor (Deltares 2016). The sensitivity of the model outcomes to morphological scaling factor F was negligible. The error deviation from the comparison of the average amount of sedimentation on the floodplains was less than 2 % for F values equal to 200, 400, and 800 for discharges smaller than 20 m^3/s and was less than 2 % for F values equal to 50, 100, and 200 for discharges greater than 20 m^3/s.

Third, we qualitatively investigated the sensitivity of the model to sediment transport rates and sediment size distribution. The sediment transport rates between 1800 AD and 2000 AD were definitively affected by the construction of water mills including mill ponds and impoundment of water at mill weirs, as well as by the removal of water mills and subsequent channel incision. The other impact factors were related to the underground coal-mining activity and land-use practices that significantly differed from the present processes. In addition to these effects, the characteristics of the surrounding landscape of the modelling area were constant within a small range over the entire observation period between 1800 AD and 2200 AD. The modelling area is located in the near-natural part of the Wurm River. Because of the ongoing urbanization and the economic growth in Aachen, the canalization of the Wurm River underneath the city was realized in the middle of the 18th century. Therefore, the sediment input has been influenced by the trapping of sediment underneath the city of Aachen since the middle of the 18th century.

In this work, we needed to distinguish between the sediment input as a model boundary condition in kg/m^3 and the sediment transport rates. We assumed a constant sediment input for all different discharges. Generally, higher discharges transport larger quantities of sediment and likely result in higher sedimentation rates. This relationship was captured in the model. Multiplying the sediment input (in kg/m^3) with the discharge (in m^3/s) resulted in different sediment transport quantities that depended on the discharge. Therefore, the model revealed that higher discharges carried more sediment and resulted in more deposition than lower discharges.

In this study, we focused on the transport of silt, and the effects of flocculation were not considered. Flocculation is the process in which destabilized suspended particles are aggregated. Clay, silt, fine sand, and organic materials have cohesive properties due to electrochemical or biochemical attraction (Son and Hsu 2011). Winterwerp (2001) stated that flocculation is a factor that explains why properly simulating the observed features in suspended sediment concentrations is not possible using constant settling velocity. At the flocculation stage, the settling velocity increases as far as the concentration increases. Additionally, the flocculation processes control the bed erodibility, which is parameterized in a numerical model using the critical shear stress and the bottom supply of cohesive sediment (Son and Hsu 2011). If clay were considered in our model, the consideration of flocculation would become more important because, in general, flocculation would result in an increased deposition of sediment on the floodplains and inside the subsidence areas because of the increased settling velocities.

Finally, we qualitatively analyzed the relationship of an occurrence of subsidence and the prevalent discharge. The timing of the discharge and the sequence of the following discharges in which subsidence occurs remained constant in all scenarios. Because of the backfilling process in a subsidence sinkhole, we concluded that the occurrence of subsidence in relation to the prevalent discharge did not change the overall results.

3.5.2 General implication of mining-induced subsidence on the environment

The results of the mining subsidence scenarios show that the effects of subsidence can be divided into two categories: (1) subsidence that directly influences the beginning of floodplain inundation (floodplain inundation begins at lower discharges compared with that in the reference scenario) and (2) subsidence that does not influence the beginning of floodplain inundation but affects the duration and magnitude of the floodplain inundation (floodplain inundation lasts longer and is more widespread compared with that in the reference scenario).

Overall, by comparing the amount of deposited sediment in the subsidence areas with the amount of sediment deposited in the same area in the reference scenario, we can determine that subsidence always leads to an increase in sedimentation and, therefore, to an increase in the silt trapping efficiency of floodplains. Under the assumption of a constant sediment input, if the deposition of fine sediment on the floodplains increases, the silt trapping efficiency also increases.

The sensitivity of a river-floodplain system to the depth of mining subsidence cannot be fully determined in this analysis and requires further research. However, generally, we determine that the silt trapping efficiency increases with increasing subsidence depth. Compensating the subsidence process will last longer than two centuries, but the subsidence locations can be definitively characterized as hotspots in the sedimentation. Naturally, if subsidence areas occur close to a river channel, the subsidence slopes might become unstable and might break into and very quickly fill the subsidence depression. From our model results, we do not investigate such a process inside the subsidence area. The observed deposition of the sediment only results from the increased suspended sedimentation of a thicker water column inside the subsided area, which slowly fills the subsidence. Therefore, the model is predominantly applicable at rivers where suspended overbank deposition is the dominant mechanism of floodplain deposition.

Most rivers in Western Europe and all over the world are strongly affected by human activities and are subjected to subsidence. In Germany, tectonic movement due to underground coal-mining is especially present at rivers in the Ruhr area such as the Emscher and the Ruhr River. For example, in the Ruhr area, subsidence of up to a depth of 9 m directly occurred at the river bank of the Rhine River close to Duisburg. At the Rhine River, subsidence resulted in floodplain inundation even during periods of mean discharge. Discharge dynamics and sediment transport capacities locally changed. The subsidence led to a risk of sedimentation in the navigation channel with potentially negative effects on the safety of navigation. Sounding datasets in this area showed that the sediment had a tendency to accumulate in this section (BAW 2015). Additionally, Bell et al. (2000) stated that areas in the Lippe and the Emscher Rivers in the Ruhr area have to be drained now by a large number of pumping stations to protect them from flooding induced by mining subsidence. Even before the underground coal-mining began, flooding was characteristic in the Ruhr area, which was later increased by mining subsidence. Most of the river banks in these two rivers are now embanked to protect the adjacent areas from flooding, which is especially important here because urbanization is dominant in the Ruhr area (Bell et al. 2000; Harnischmacher and Zepp 2010; Harnischmacher 2012).

The consequences of subsidence due to not only to underground coal-mining but also to mining of plumb (e.g., Geul River, the Netherlands) or other types of soil extraction from the ground (e.g., salt) are the same as those mentioned in our analysis. For example, Gomez and Marron (1991) analyzed the effects of subsidence due to seismic and neotectonic activities on the sinuosity at the Belle Fourche

River in Western South Dakota. Benito et al. (1998) analyzed the river response of the Gállego River in Ebro Basin in Spain to quaternary subsidence due to synsedimentary karstic subsidence. Bell et al. (2000) also analyzed the effects of mining of salt in Chesire in England. The mining of salt between 1870 AD and 1920 AD resulted in a series of subsidence at the Weaver River that caused damages to banks, locks, and bridges. They also affected the Trent-Mersey-Canal, which passes over several flooded salt mines (Bell et al. 2000).

Our model estimates the effects of subsidence on the floodplain sedimentation at the Wurm River and is applicable to rivers with similar characteristics such as small meandering rivers with large floodplains where predominantly suspended overbank deposition accounts for floodplain deposition (such as the Wurm River). Our model can likely represent the suspended-load transport processes in river-floodplain systems with these characteristics.

3.5.3 Long-term development of the silt trapping efficiency in old-industrial regions

Over time scales of centuries, multiple natural and anthropogenic disturbances that affect channel morphology and floodplain sedimentation occur. Separating these influences on the floodplain sedimentation by analyzing alluvial stratigraphy deposits is difficult. Thus, the strong point of a numerical model is to examine the influence of only one impact factor on the floodplain sedimentation given specific initial and boundary conditions. In this work, we analyzed the changes in the silt trapping efficiency of the Wurm River due to mining subsidence for two periods: 1800 AD-2000 AD and 2000 AD-2200 AD.

For modelling purposes, we decided to keep the sediment input constant for both periods. However, several factors were definitely present that affected sediment transport rates. The sediment transport rates between 1800 AD and 2000 AD were affected by the construction of water mills, including mill ponds and the impoundment of water at mill weirs, as well as by the removal of water mills. The impoundment led to deposition of fine sediment on the river bed, whereas the removal of the mills led to incision of the river bed and erosion of the previously deposited fine sediment. Other impact factors were related to the underground coal-mining activity and land-use practices that significantly differed from the present condition. The canalization of the Wurm River underneath the city of Aachen in the middle of the 18th century decreased the sediment transport rates. Today, the increased discharge due to the inflow of the wastewater treatment plant Aachen-Soers in the Wurm River could result in the increased sediment transport rates. Research is currently underway, which aims to the present-day sediment transport rates of the Wurm River using turbidity sensors. Using our model assumption of constant sediment transports rates, we only determine how different bank heights affect the silt trapping efficiency of floodplains.

Figure A.7 in the Appendix shows the cumulative sedimentation based on the model results between 1800 AD and 2000 AD. The average sedimentation on both floodplains is equal to 2 m. Figure A.8 in the Appendix shows the cumulative sedimentation based on the model results between 2000 AD and 2200 AD. The average sedimentation on both floodplains is equal to 0.1 m. Figure 3-8 shows the deposition of the sediment in both periods (1800 AD-2000 AD and 2000 AD-2200 AD) on the left floodplain of the cross section marked in Figure A.5 in the Appendix.

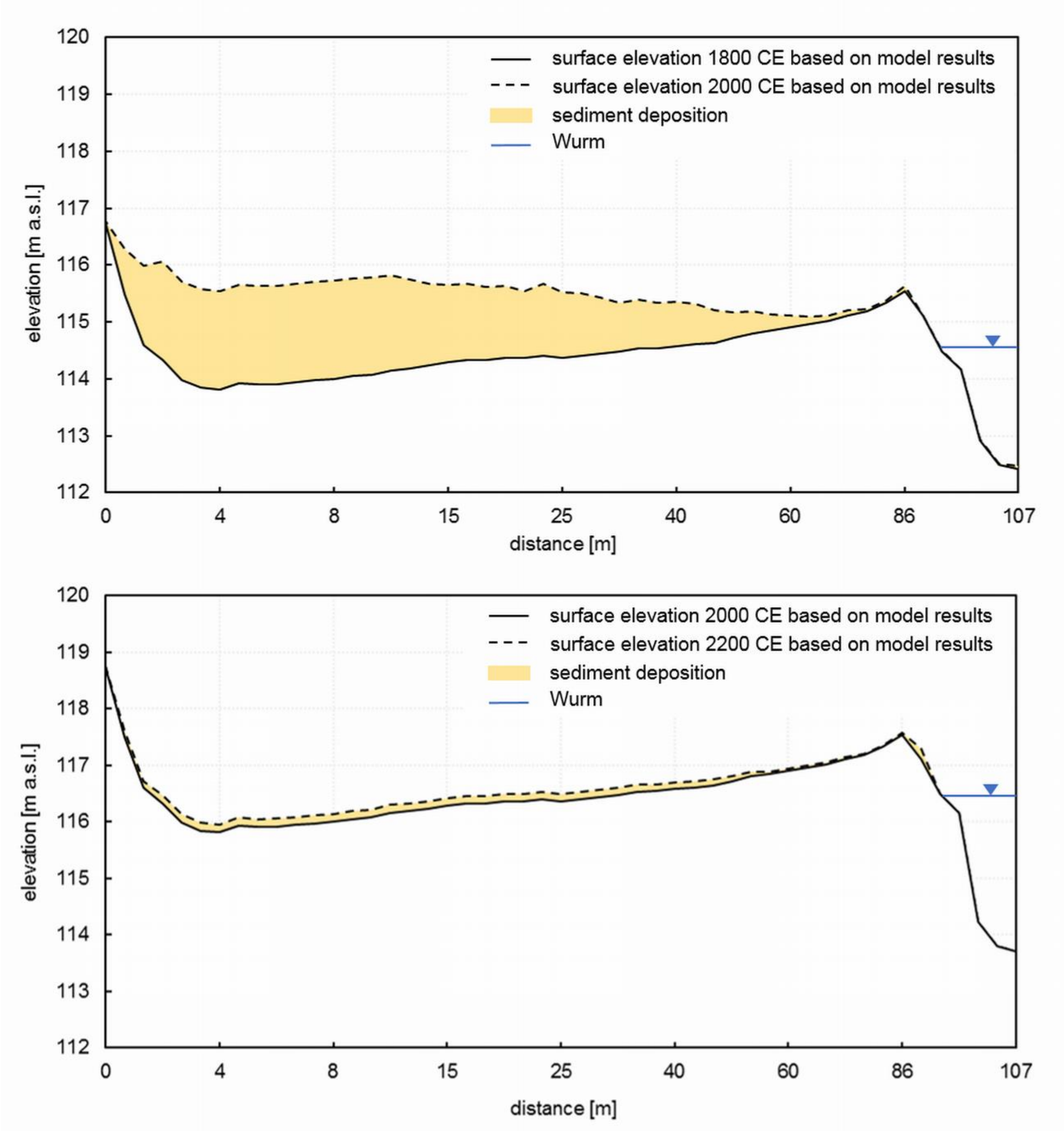

Figure 3-8: Deposition of sediment for the periods (top) 1800 AD-2000 AD and (bottom) 2000 AD-2200 AD.

From the historical numerical data from the Delft3D model in 1800 AD, the floodplain inundation begins at discharges between 10 m^3/s and 20 m^3/s, whereas in 2000 AD, floodplains are inundated at discharges between 20 m^3/s and 30 m^3/s. Under the assumption of constant sediment input, decreasing floodplain inundation rates result in decreased silt trapping efficiency of the floodplains. The difference in the sedimentation rates of 1 cm per annum for the last 200 years (see Section 3.3.4, Calibration) and 0.1 cm per annum for the next 200 years is related to the decoupling of the floodplains from the river bed. At the Wurm River, the construction and subsequent removal of water mills are another main human impact factor and cause incision of the river bed (Buchty-Lemke and Lehmkuhl 2018). Another impact factor at the Wurm River is urbanization. At the Wurm River, urbanization leads on the one hand to an increased discharge downstream of the city of Aachen where purified wastewater enters the Wurm River and on the other hand to a decreased sediment load because of the canalization and sediment trapping in the canals underneath the city of Aachen. However, the increased discharges downstream of the wastewater treatment plant (and therefore upstream of the near-natural part of the Wurm River) lead to increasing water levels and bed shear stresses and therefore to a larger erosive power. The increased erosion may also cause an incision of the river bed.

The results of the analysis of the nine subsidence scenarios show that even though mining-induced subsidence led to a local increase in the silt trapping efficiency of the floodplains, the silt trapping efficiency will significantly decrease in the next 200 years because of other human impact factors such as water mills and urbanization that led to incision of the river bed and decoupling of the floodplains from the river bed.

3.6 Conclusions

This study determined the effects of mining-induced subsidence on the trapping efficiency of floodplains in the Wurm River (Lower Rhine Embayment, Germany). This test case was exemplary because of the intense underground coal-mining since the High Middle Ages, with a peak that occurred in the 20th century. A numerical model based on the Delft3D software, using the embedded space-varying subsidence module, analyzed the effects of mining-subsidence on the trapping efficiency of floodplains. Results showed that, when subsidence occurred in the inundation area of a river, increased average floodplain sedimentation occurred independent of its size, depth, or location relative to the river. This scenario led to increased trapping efficiency of floodplains. The results were tested in a sensitivity analysis in relation to other morphodynamic changes induced by anthropogenic impacts, such as water mills and urbanization. The interaction of these different impact factors resulted in a deeply incised river bed and decoupled floodplains from the river bed at the Wurm River. Overall, when decoupling of floodplains from the river bed occurred in the old-industrial areas affected by underground coal-mining, the silt trapping efficiency of the floodplains decreased, although the mining subsidence locally and temporarily increased the deposition of fine sediment on the floodplains. The model developed in this study is applicable to rivers with similar characteristics, such as small meandering rivers with large floodplains, where suspended sediment accounts predominantly for the deposition on floodplains.

Acknowledgements

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4 A decade of fluvial morphodynamics: relocation and restoration of the Inde River (North-Rhine Westphalia, Germany)

Anna-Lisa Maaß, Verena Esser, Roy Frings, Frank Lehmkuhl Holger Schüttrumpf

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Abstract

Relocations and restorations do not only change the ecological passability and sediment continuity of a river but also its flow behavior and fluvial morphodynamics. Sediment transport processes and morphological development can be assessed with field measurements, also taking the transport of sediment-bounded contaminants as a tracer material for fluvial morphodynamics into account. The objective of this study was to determine the morphological development of the Inde River (a tributary of the Rur River in North-Rhine Westphalia, Germany) towards its pre-defined guiding principle after a relocation and restoration in 2005 AD. The fluvial morphodynamics of the Inde River were analyzed over a period of almost 15 years taking sediment samples, analyzing echo soundings of the river's bathymetry and determining the heavy metal content of the sediment as a tracer material for the morphological development. The results show that the relocation and restoration of the Inde River initiates new hydrodynamic processes, which cause morphological changes of the river widths, meander belts and channel patterns. The river bed of the new Inde River has incised into the ground due to massive erosion, which has led to increased fine sediment transport in the downstream direction. The reasons for and consequences of this fine sediment transport are discussed and correlated to the sediment continuity of a river. Overall, the new Inde River has reached its goal of being a natural river as a consequence of the relocation and restoration and has adapted its new conditions towards a dynamic morphological equilibrium.

Keywords: River relocation, River restoration, Fluvial morphodynamics, Heavy metal tracer, Fine sediment transport, Morphodynamic equilibrium

4.1 Background

Historically, anthropogenic impacts to river-floodplain systems such as stabilizing and fixing the river bed, straightening the river course or fixing the river banks have heavily modified river-floodplain systems (Gerken et al. 1988; Brown 2001; Dotterweich 2008). Consequences include changes to the natural morphological development, the sustainable disturbance of the natural bank and bed dynamics, a deterioration of the water quality, changes to the groundwater dynamics of the floodplains, loss of flooding areas and loss of habitats for aquatic and terrestrial ecosystems (Gerken et al. 1988). Contaminants might be adsorbed on fine-grained sediments (Salomons et al. 1995; Schüttrumpf et al. 2011; Brinkmann et al. 2015) and thereafter transported downstream with the water phase or deposited on the river bed or on the floodplains from where they might be remobilized by subsequent flood events (Förstner 2004; Cofalla et al. 2012; Zhao and Marriott 2013). River modifications at contaminated sites can have negative effects on the distribution of contaminants or positive effects due to the improvement of the chemical and ecological conditions (Berg et al. 2004; Berg et al. 2008).

In the twenty-first century, national and international requirements and laws define that these previous anthropogenic impacts should be undone in favor of a natural development of river-floodplain systems. It is stated in the European Union Water Framework Directive (EU-WFD) that water bodies need to be protected against negative modifications and returned to their natural or near-natural states. The objectives of river restorations are a generation of flooding/retention areas, an increase of flow lengths and flood frequencies to re-activate or activate floodplains and to enrich the ecological diversity and the reduction of anthropogenic barriers and the initiation of a natural river development (Gerken et al. 1988). The natural characteristics of a river-floodplain system are abstracted and formulated in a pre-defined guiding principle, which considers irreversible anthropogenic impacts such as alluvial clay and colluvial sediments, mainly from Medieval Times, mining-induced activity, urbanization and buildings (Patt 2016). In addition, the morphological development, the ecological passability for aquatic organisms and the sediment continuity are two main advantages of restorations (Boer and Bressers 2011; Brun 2015; Patt 2016). Pre-defined development goals should be realized within river restorations and are evaluated by comparing the current state of a river with its guiding principle.

It is always questionable if a restored river reaches its pre-defined guiding principles, how its morphological development takes place and how long it takes to adapt to new conditions. Each river reacts differently to new geometrical, hydraulic and sedimentological conditions, so that it is always reasonable to assess extensively the fluvial morphodynamics of a restored river reach. Thus, extensive field measurements and interdisciplinary cooperation can be helpful to identify, quantify and analyze such morphological adaptation processes.

The objective of this study was to determine the fluvial morphodynamics of a 13-km-long relocated and restored river reach of the Inde River (a tributary of the Rur River, North-Rhine Westphalia, Germany; see Figure 4-1). The fluvial morphodynamics of the new Inde River were determined with extensive field measurements between 2005 AD and 2018 AD. Sediment samples from the river bed for sedimentological characterization, sediment traps, echo soundings and the adjacent hillsides were analyzed, focusing on the initial morphological development of the new Inde River after its hydraulic connection to the existing river reaches. Additionally, sediment-bounded heavy metals were used as a tracer material to describe the morphological evolution of the relocation and restoration. Heavy metals are persistent substances that can be transported, relocated and accumulated with sediments (Koß 1997; Alloway 1999; Bliefert et al. 2002; Lewandowski et al. 2012). Anthropogenic activity is one reason for a significant increase in the heavy metal concentrations above the natural geogenic background (Frühauf 1992), which is especially present in old industrial regions such as the Inde River catchment (Hurley et al. 2017). Therefore, heavy metals adsorbed on fine-grained sediments were used as a tracer material to analyze the ongoing morphological development of the Inde River in the new restorations reach.

River restorations or even entire river relocations are complicated and expensive to plan and implement. Due to the fact that morphological changes can always have positive as well as negative consequences, it must be determined if such an intervention will improve the morphodynamics and the river-floodplain system as an environmental habitat. Here, the Inde River is used as a case study to analyze these consequences extensively and to learn from this example for future relocations and restorations. Initially, the results of different analyses of sediment samples and echo soundings of the Inde River are presented. Then, the results of the Inde River, focusing on the temporal scale of its fluvial morphodynamics, and its continuous sediment transport, are discussed and compared to its pre-defined guiding principles.

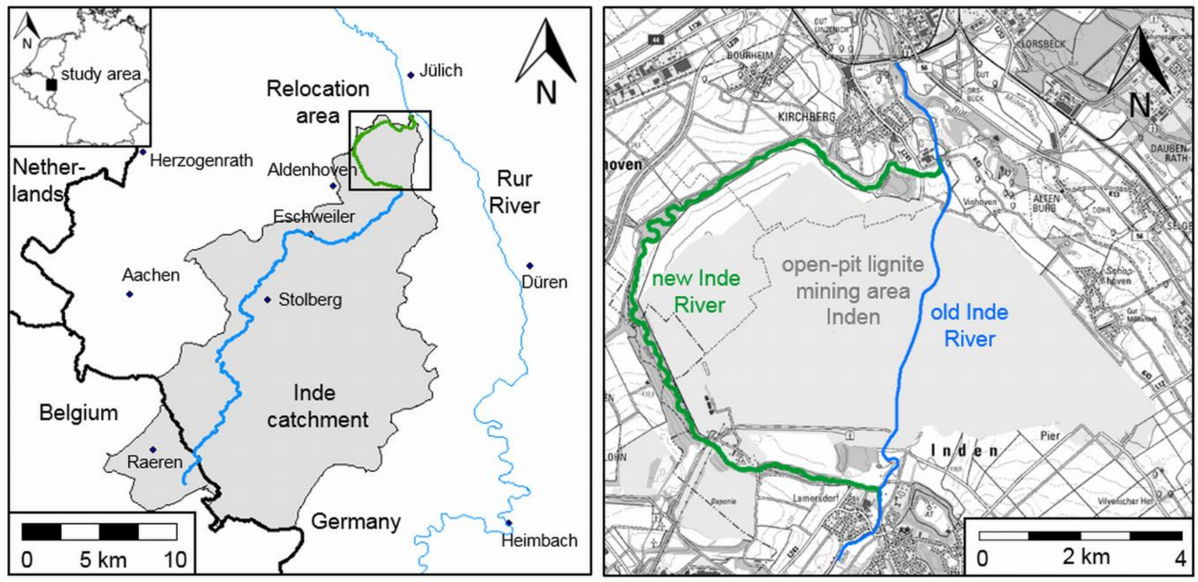

Figure 4-1: Catchment area of the Inde River (left) and relocation area (right).

4.2 Case study area

The Inde River is a 54.1-km-long river in North-Rhine Westphalia in Western Germany with a catchment area of 344 km^2. After a flow length of 2.5 km from its source in Belgium, the Inde River reaches the Belgian-German border and flows south of the city of Kirchberg into the Rur River. The main tributaries are the Vichtbach and the Wehebach. Parts of the Inde River and its tributaries have been straightened and canalized (Blümel et al. 2003; MULNV NRW 2008b, 2015). Two reservoirs are in the Inde catchment. The Wehebachtalsperre reservoir was constructed at the Wehebach (1977 AD-1981 AD) and the Dreilägerbachtalsperre at the Dreilägerbach (tributary of the Vichtbach) (1909 AD-1912 AD) to ensure a drinking water supply (MULNV NRW 2008b; Deutsches Talsperrenkomitee 2013; MULNV NRW 2015). Open-pit lignite mining is present at the Inde River. In the mining areas, the continuous pumping of groundwater is necessary to dry out the open-pit lignite mining areas to enable uninterrupted mining. Thus, mine water from the open-pit lignite mines is partly passed into the Inde River close to the communities of Lamersdorf (on average 1.0 m^3/s) and Kirchberg (on average 0.5 m^3/s) and increases the average low water discharge of the Inde River (LUA 2002). The average low water discharge of the Inde River is 0.54 m^3/s. The mean annual discharge is 2.82 m^3/s and the highest annual discharge is 89.48 m^3/s (1965 AD-2016 AD, gauging station Eschweiler) (ELWAS-WEB 2018). Generally, the widespread pumping of ground water leads to decreased flood discharges, while the high gradients and heavy rainfalls in the upper part of the Inde River result in sudden flood events especially during the wintertime (Schmidt-Wygasch 2011).

Devonian bedrock is predominant in the upper reaches of the Inde River. The middle reaches are characterized by carbonates of the Carboniferous. In the lower reaches, the river flows through the Lower Rhine Embayment with Tertiary and Quaternary sediments (Ribbert 1992; Schmidt-Wygasch 2011). In the upper part, the Inde River is characterized as a small coarse substrate dominated siliceous highland river (German Stream Type 5). Between Walheim and Stolberg, it is characterized as a small coarse substrate dominated calcareous highland river (German Stream Type 7). Between Stolberg and Eschweiler, the Inde River is defined as a mid-sized fine to coarse substrate dominated siliceous highland river (German stream type 9), whereas downstream of the city of Eschweiler until the mouth of the

Inde River, it is characterized as a mid-sized and large gravel-dominated lowland river (German Stream Type 17) (Pottgiesser and Sommerhäuser 2008).

Until 2005 AD, the lower reaches of Inde River flowed through the prospective extraction field of the open-pit lignite mining area Inden, which belongs to the Rhenish lignite-mining region in Western Germany between the cities of Aachen and Mönchengladbach (see Figure 4-2). A 5 km long reach of the Inde River (old Inde River) was relocated as the consequence of the progressing open-pit lignite mining towards a 12 km long river reach (new Inde River). The relocation includes different restoration interventions. The project was finished in 2005 AD, and the system was hydraulically connected to the existing river reaches upstream and downstream (see Figure 4-1).

Figure 4-2: Open-pit mine Inden with the Inde River (foreground) (Photo: IWW, RWTH Aachen).

The design of the new part of the Inde River followed a guiding principle that was pre-defined based on the natural characteristics of the Inde River (Ingenieurbüro Berg et al. 1998), considering some restrictions of the adjacent and ongoing open-pit mining. Realizing the guiding principle means an improvement of the current river state taking spatial, geological and other restrictions into account. Here, the restrictions are the stability of the slope of the open-pit mine, the flood protection as well as the ongoing progress of the open-pit lignite mining. It defines the geographical position of the river relocation in its spatial and temporal limits. The additional discharge of mine water into the Inde River (in Lamersdorf, approx. 1.0 m^3/s, to an average low-water discharge of 0.54 m^3/s) as well as the location of a noise abatement dam and the requirement that the river bed should consist of natural ground surface material from the open-pit mine, restricts the restoration. The natural ground surface material (so-called Forstkies) consists of a mixture of loess and gravel (silty loam) with a D_{15} of 0.06 mm, a D_{50} of 0.4 mm and a D_{90} of 3 mm (Ingenieurbüro Berg et al. 1998). Limitations of the artificial construction, using large spreaders for coal mining, without leveling to prevent soil compaction, lead to a rough and undulate surface (Schumacher et al. 2014). Vertical erosion is restricted to an artificially built sealing layer, which consists of a mixture of mineral soil materials (Forkel and Rinaldi 2008). The sealing layer restricts the infiltration of water into the ground to a certain limit, which would otherwise counteract the continuous pumping of the groundwater mentioned above. Additionally, lateral erosion is only possible in a defined development corridor with a width between 70 m and 400 m (Forkel and Rinaldi 2008). Further limitations are the adjacent forests south of Kirchberg and the smooth transitions of the river width, depth and slope at the upstream and downstream ends of the new river reach to the old river course.

In former times, the presence different geo-resources in the catchment area of the Inde River resulted in the widespread mining and treatment of iron, lead and zinc ores close to the city of Stolberg. In addition, underground coal mining and open-pit lignite mining occurred especially close to the city of Eschweiler (Förstner 2004). These anthropogenic activities led to increase in the natural, geogenic background concentrations of heavy metals, which are distributed in the landscape over different input paths (Schneider 1982). Although neither mining nor most of the metal industry exist in this area anymore (Schild and Hirsch 1981), high heavy metal concentrations from historical times can still be found in this region (Schmidt-Wygasch 2011). The water quality of the Inde River is affected by these increased concentrations (MULNV NRW 2015).

4.3 Methods

The field measurement campaign started in 2005 AD, after the completion of the relocation and restoration of the Inde River, and ended in 2018 AD. The campaign is subdivided into two parts: (1) For the years 2005 AD until 2012 AD, sediment samples from the river bed were collected for sedimentological characterization, and sediment traps, echo soundings and the adjacent hillsides were analyzed. The focus was on the initial morphological development of the new Inde River after its hydraulic connection to the already existing river reaches. (2) Different sediment samples from the river bed of the years 2017 AD and 2018 AD as well as suspended sediments sampled during a bankfull discharge were analyzed, focusing on its heavy metal content as a tracer for the ongoing morphological development of the Inde River in the restoration reach.

The first field measurement campaign (1) ended in 2012 AD because the results of the analyses showed that the new Inde River had developed towards its guiding principles and had adapted the new hydrodynamic and morphodynamic conditions. Significant changes were no longer observed. The morphological development after an additional period of 5 years was investigated in 2017 AD and 2018 AD to obtain a temporal large-scale overview of the fluvial morphodynamics of the new Inde River over an entire period of almost 15 years. Such a large-scale consideration also enables the analysis of the morphological connection of the restored river reach to the upstream and downstream older river reaches. Divided according to the different campaigns, Figure 4-3 and Figure 4-4 show all field measurement locations during the entire investigation timespan of 2005 AD to 2018 AD.

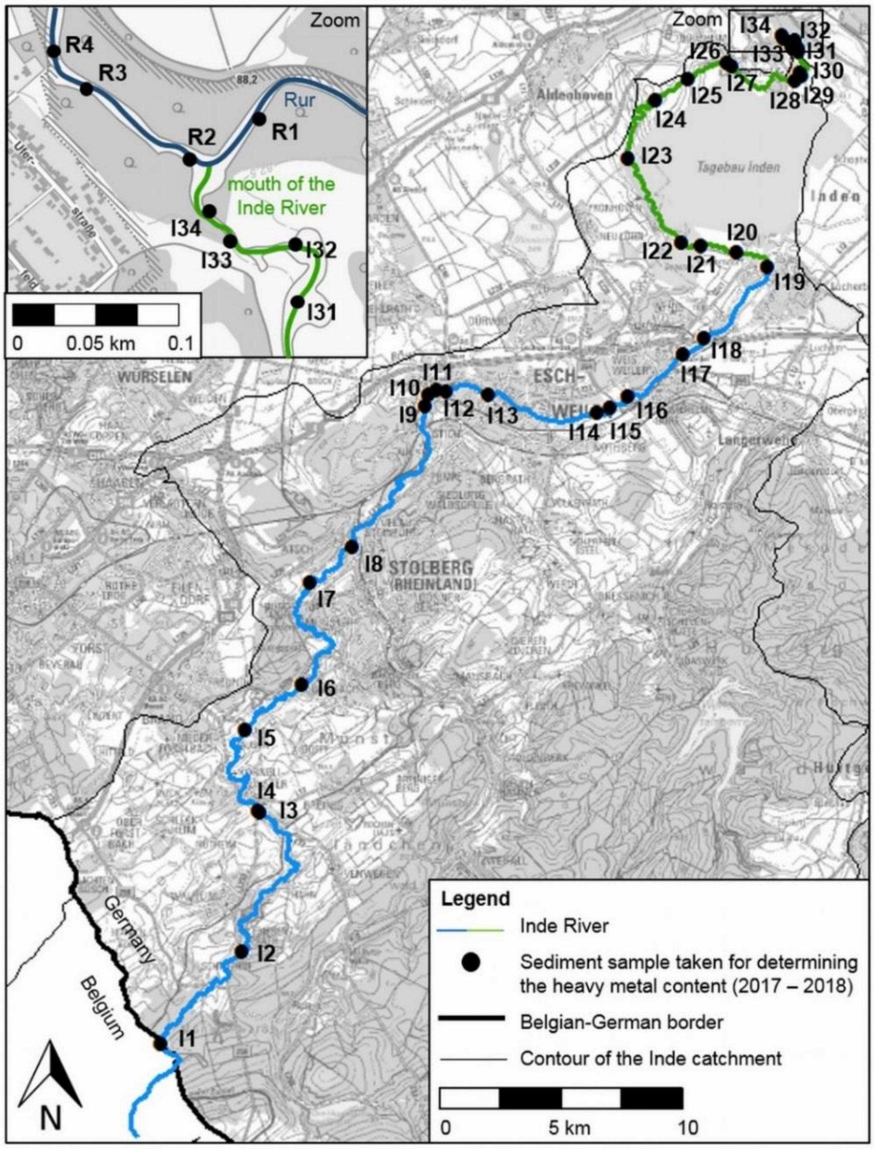

Figure 4-3: Sediment samples taken from the whole Inde River for determining the heavy metal content.

4.3.1 Sedimentological characterization

The sediment characteristics of the river bed were mapped over the entire area. 23 sediment samples were taken from the river bed: 18 samples from the new river reach, two samples from the old river reach upstream of the restoration, two samples from the Rur River and one sample from the hillside adjacent to the new Inde River at the left bank almost at the end of the new course (see Figure 4-4). Because of the sedimentological variety of the new Inde River, the sediment samples were not equally distributed over the entire new river reach. Four sediment samples were taken from the sand-dominated parts (grain size diameter between 0.063 mm and 2 mm), eight samples were taken from the gravel-dominated parts (grain size diameter between 2 mm and 63 mm) and six samples were taken from the gravel-dominated parts with a proportion of more than 5 % stones (grain size diameter larger than 63 mm). All sediment samples were dried at 105 °C and sieved to determine their grain size distribution.

The bank dynamics were mapped considering the steep erosion of the river banks or banks inside the watercourse. The hydrometry was also mapped, focusing on rapids, tributaries and branches.

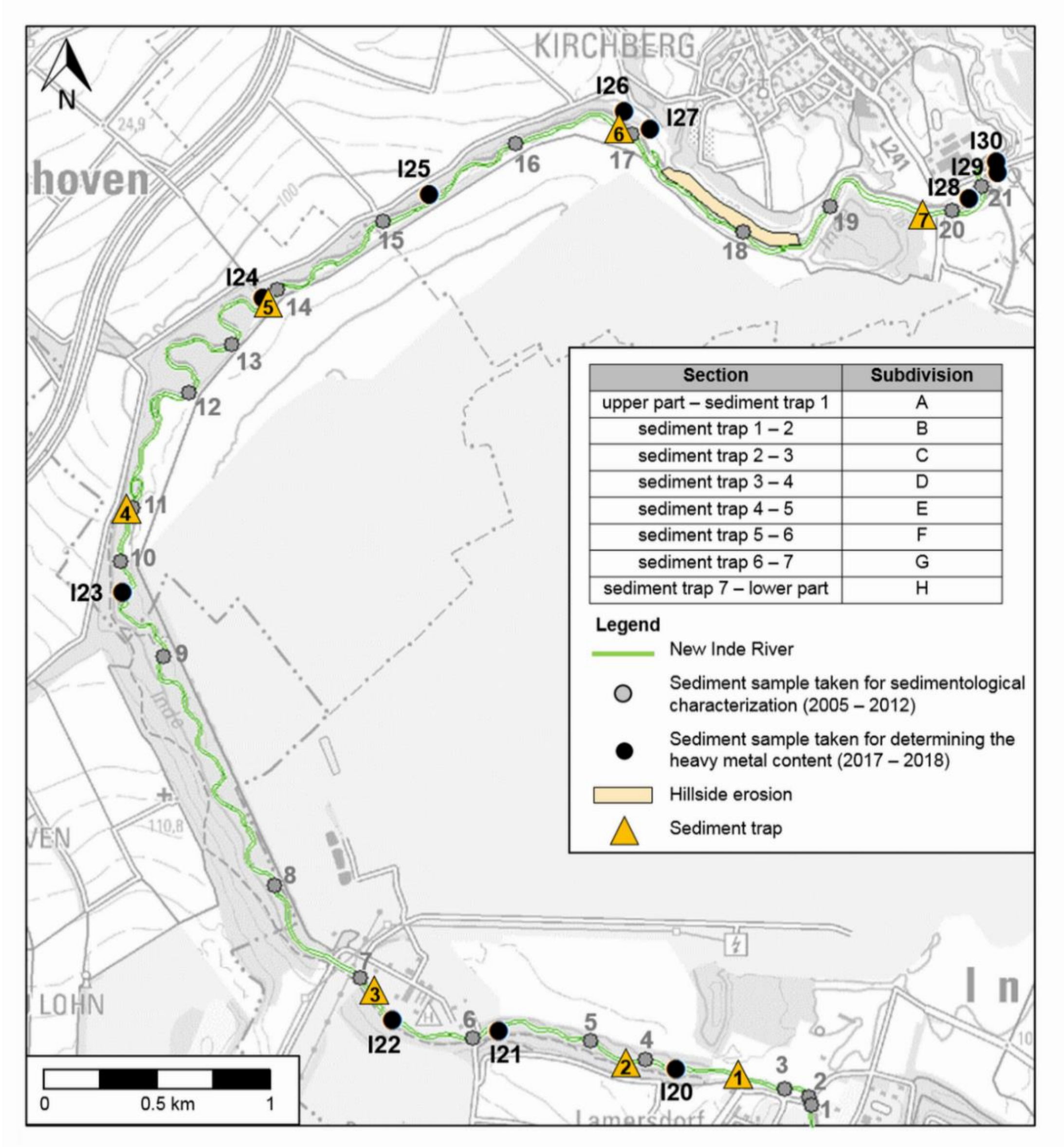

Figure 4-4: Field measurement locations inside the new Inde River reach between 2005 AD and 2018 AD.

4.3.2 Sediment traps

During the construction phase, seven structurally identical sediment traps were installed in the new Inde River reach (see Figure 4-4). Sediment traps are basin-shaped extensions or depressions located in the river, which are permanently passed through by water and sediment (Grubinger et al. 1993). Such a sediment trap traps incoming bed load and balances, in the case of the new Inde River reach, the input and output of the bed load towards an equilibrium. The hydraulic function of the sediment traps is regulated by a reduction of the current shear stress caused by reduced flow velocities. The reduced current shear stress consequently results in the deposition of sediment inside the sediment trap.

At the beginning of the measurements between 2005 AD and 2006 AD, the continuous transport of the bed load in the downstream direction was limited because of these sediment traps. In 2006 AD, an event with a discharge of 26 m^3/s and flow velocities of approximately 0.5 m/s occurred in the Inde catchment. Such an event occurs statistically five times in 1 year, especially during summer periods (Köngeter and Kammrath 2003). The sediment volume trapped in the seven sediment traps before (reference date

August 2005 AD) and after the flood event (March 2006 AD) was compared, and the sedimentological composition of each trap was analyzed. The amounts of sediment deposited in the sediment traps were also analyzed and conclusions regarding the stability of the different river reaches between two sediment traps were drawn. Trapped material can be returned into the system and potentially compensate for the vertical erosion of the river bed (Kamrath and Schweim 2006). Today, all sediment traps are emptied irregularly, which allows the continuous transport of sediments inside the restoration area.

4.3.3 Analysis of echo soundings

The erosion and sedimentation rates were determined from echo soundings. The river bed elevation of the new Inde River was determined every year between 2005 AD and 2012 AD based on echo soundings. In several cross-sections of the new Inde River, echo soundings were performed. Based on the deepest point of the sounding data of each cross-sectional profile, the longitudinal profile of the new Inde River was determined. The echo soundings were used to quantify the temporal morphological development of the restoration reach of the Inde River between 2005 AD and 2012 AD. The erosion and sedimentation rates of each cross-sectional profile as a function of time were determined for different subdivided sections (see sections in Figure 4-4).

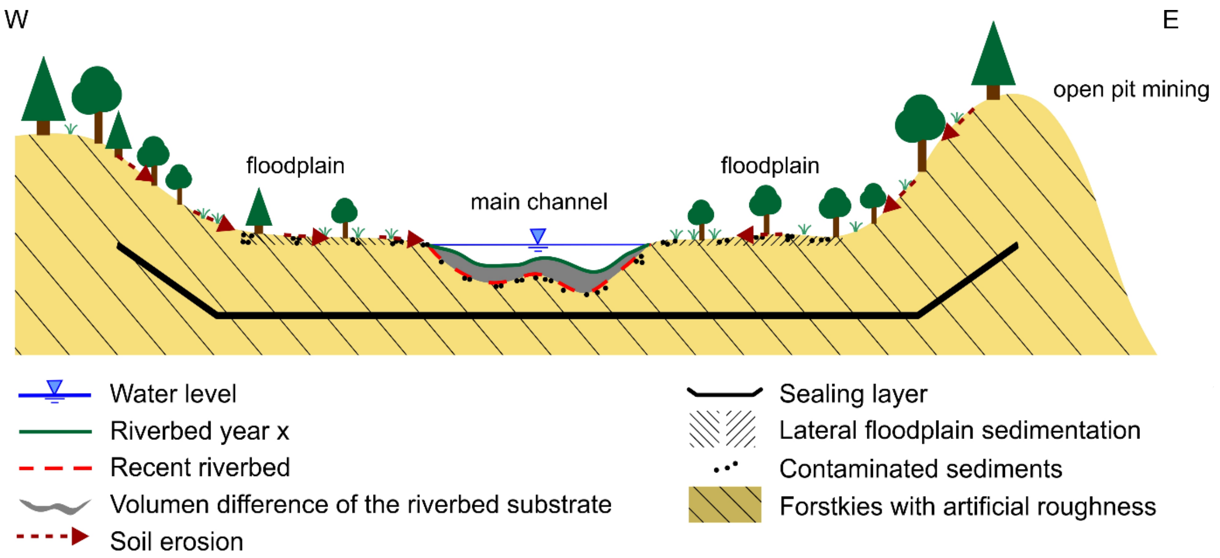

Figure 4-5: Illustration of erosion and accumulation processes in the river bed and on the floodplains.

To determine the volume of erosion or sedimentation for one section, the sounding data of one cross-sectional profile are seen as a representative data set for the adjacent river section. The erosion and sedimentation rates were quantified by comparing the elevation of the river bed in a cross-sectional profile of 1 year to the elevation of the same profile of another year (see Figure 4-5). When sounding data were missing, which is the case between 2010 AD and 2012 AD, the erosion and sedimentation rates could not be determined for all subdivisions of the new Inde River. The maximum erosion depth of the river bed was determined by analyzing the distance between the river bed elevation measured with echo soundings and the sealing layer, which was set as an erosion base during the construction phase. The echo soundings were also used to determine the local erosion of the river bed and to quantify the potentially hazardous distances to the sealing layer. The maximum depth of erosion was equal to the deepest point of each cross-sectional profile. This depth was compared to the elevation of the sealing layer to determine the minimum vertical distance between the river bed and the sealing layer.

4.3.4 Hillside erosion

One hillside, adjacent to the new Inde River at the left bank, almost at the end of the new course (see Figure 4-4), showed significant soil erosion contributing to sediment transport. During the construction phase, the ground surface of the hillside was formed using a spreader for coal mining by a wave structure with gullies (see Figure 4-6). Rainfall events led to significant hillside erosion through these gullies into the Inde River (see Figure 4-5).

Figure 4-6: Wave structure with gullies of the hillside (Photo: IWW, RWTH Aachen).

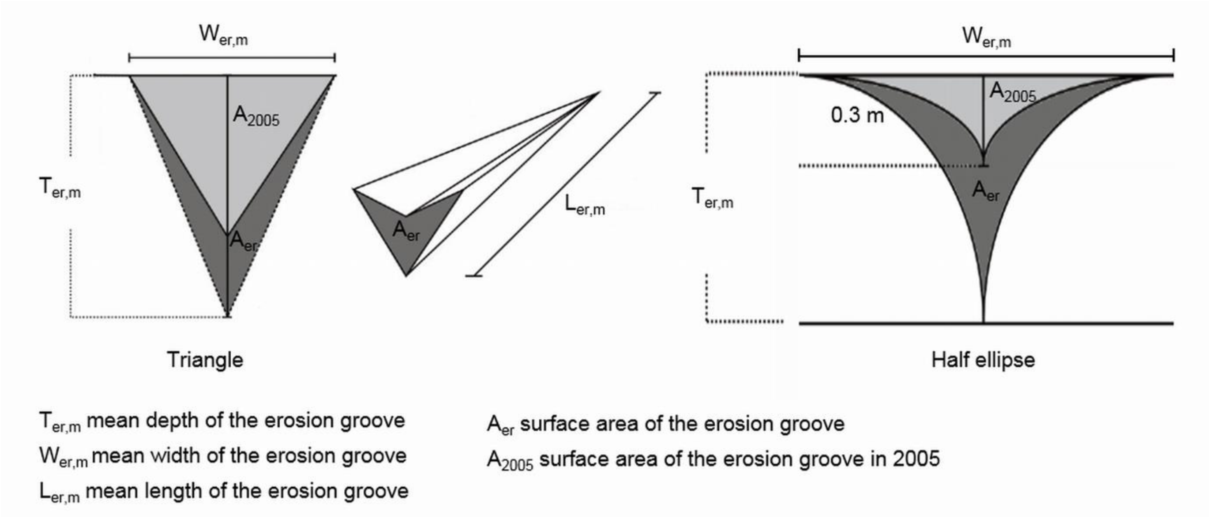

Figure 4-7: Simplification of the structure of the erosion gully (modified after Frings et al. 2013).

The amount of hillside erosion was determined by simplifying the gully surface area to two different geometrical structures: (1) a triangle and (2) a half ellipsis (see Figure 4-7). The number of erosion gullies was further counted, and their depths and lengths were measured, and it was determined if the gullies had a connection to the river bed or not. Under the assumption that the depth of the gullies is linear to the depth at the upstream end, which is the depth after finishing the restoration, the body of the eroded material in each gully is prismatic.

4.3.5 Using heavy metals as tracer for determining fluvial morphodynamics

The content of heavy metals adsorbed on the sediment particles of the samples were further analyzed and used as a tracer to determine the morphodynamic development of the new Inde River. Heavy metals can enter into the fluvial system by different processes such as weathering, erosion and transport as well as anthropogenic activities. There, hydrological processes are the driving force for their dispersion

(Foster and Charlesworth 1996). Heavy metals occur in the dissolved and particulate phases depending on different factors such as chemical parameters. Nevertheless, they are mainly bound on fine-grained sediments, especially silt and clay (< 63 µm). Thus, sediments represent an important natural transport medium for heavy metals in fluvial systems, which is controlled by recent and past morphodynamic processes such as erosion, transport and accumulation (Salomons and Förstner 1984). Due to the fact that the restoration of the Inde River consists of a 13-km-long new river bed, which was constructed with substrate [Forstkies, mixture of gravel and loess (silty loam)], showing lower geogenic background concentrations, it is possible to use sediment-bound heavy metals as a tracer for determining and analyzing the natural sediment transport and the ongoing morphological development of the Inde River in the new restorations reach.

In 2017 AD and 2018 AD, samples of the surface layer, which represents the morphologically active substrate of the river bed, and composite samples of the upper 20 cm of the river bed, were taken from the whole Inde River (see Figure 4-3, samples I1-I34). Additional samples were taken in the Rur River close to the mouth of the Inde River (see Figure 4-3, samples R1-R4). The composite samples of the upper 20 cm were sampled using a riverside auger (stainless steel) with a diameter of 6.5 cm. The samples of the surface layer were sampled using a cone-shaped pot (height: 24 cm, diameter of opening: 14 cm, stainless steel).

To determine the impact of flood events on the heavy metal distribution in the new river bed, high discharges were artificially simulated within the river channel (method after Lambert and Walling 1988). A cylinder with a height of 90 cm and a diameter of 55 cm was placed on the river bed to create an enclosed water column inside the river. Then, by whirling up the water and the surface of the river bed, the sediment was remobilized. The suspended sediment was sampled as a water sample of 20 l at each sampling site. After a settling time of 1 week, the sediment was separated from the water. These sediment samples represent the fraction that can potentially be remobilized from the river bed during high discharges.

In addition, one water sample with suspended sediment was taken during a bankfull discharge of approximately 15 m^3/s upstream of the new river reach (same sampling site as I19, see Figure 4-3). This sample was treated like the samples taken with the method after Lambert and Walling (1988).

Furthermore, four samples of the natural surface material (Forstkies) were taken in the surroundings of the river to compare its natural background of heavy metal with the content of the river bed sediments of the new Inde River.

To determine the heavy metal content, all sediment samples (fractions < 63 µm) were dried at 105 °C and analyzed with X-ray fluorescence (XRF) analysis.

4.4 Results

4.4.1 Channel pattern and sedimentology

Sediment banks develop in areas with low flow conditions (Frings et al. 2013) (see Figure 4-8). The creation of small groynes leads to changes of the main flow direction, which result in cut banks and slip-off banks and a high meander migration potential.

Figure 4-8: (A) Sediment bank, (B) steep river bank and (C) rapid of the new Inde River (Frings et al. 2013).

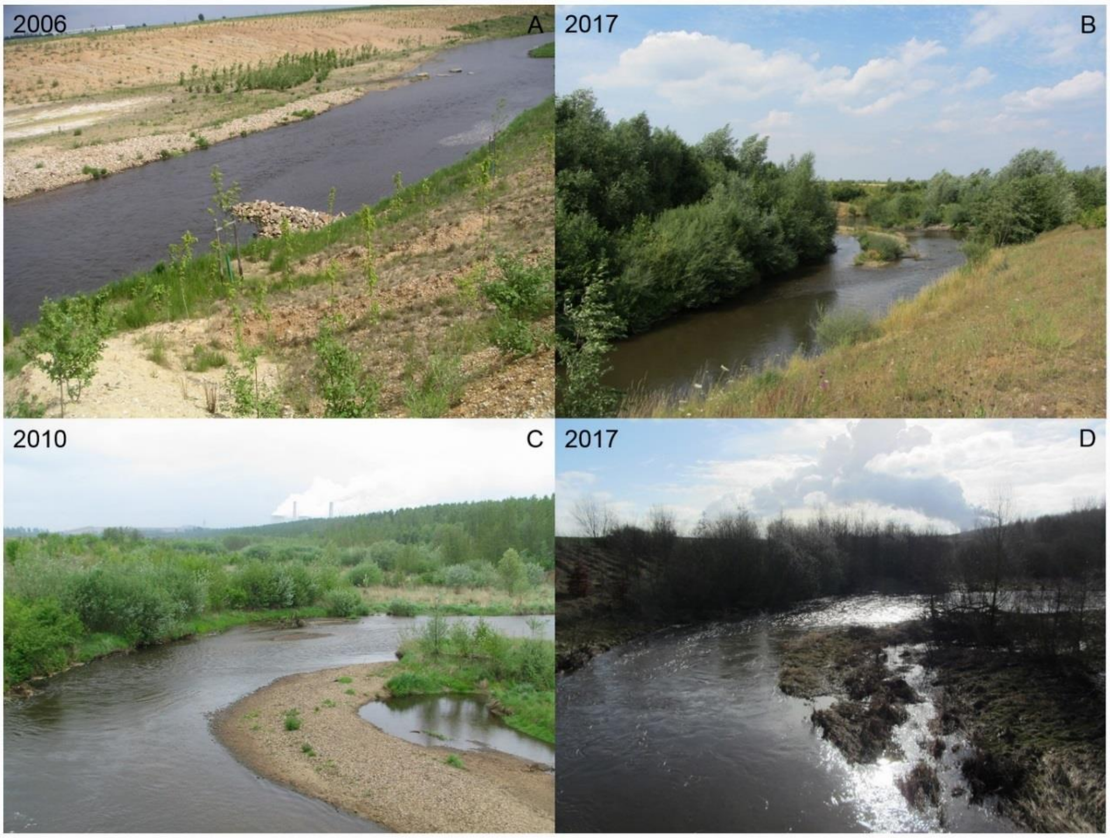

Figure 4-9: A and B: Comparable river sections. C and D: Same river section during low flow conditions and during a flood event (A and C: photos IWW, RWTH Aachen; B and D: photos PGG, RWTH Aachen).

In 2006 AD, a clear artificial structure of the adjacent hillsides, banks and groynes can be seen. In 2017 AD, the hillsides and the banks and groynes are more overgrown. An accommodated flow diversity is present (see Figure 4-9).

In addition to the geometrical adaptation, a sedimentological adaptation takes place. After the completion of the restoration in 2005 AD, the river bed consisted predominantly of sand and clay, which erodes at small shear stresses and is transported in the downstream direction into the Rur River. The erosion leads to an incision of the river bed of the new Inde River into the ground, to the formation of an armor layer and to a coarsening and washing out of the fine sediment of the river bed.

The flow velocities and grain size distributions of the river bed of the new and the old Inde River are variable. A comparison of the grain size distribution of the new Inde River with the grain size distribution of the substrate used for preparing the river bed (Forstkies) of the new reach in 2005 AD shows that the current river bed is coarser than in 2005 AD. The river bed of the new Inde River mostly consists of gravel with a proportion of sand of 20 % up to 60 %. A sandy river bed can especially be found in areas with reduced flow velocities behind roughness elements (stones), groynes, and meander belts or at slip-off banks. Scour holes with depths up to 1.5 m occur in clayey areas at steep river banks. In addition, the grain size distribution of the hillside erosion is coarser than that of the initial substrate and the sediments upstream of the restoration reach are significantly coarser than those downstream of this new reach (see Figure 4-10). The river bed of the Rur River close to the mouth of the Inde River is gravel-dominated like the river bed of the Inde River itself, but with a higher proportion of fine material (Frings et al. 2013) (see Figure 4-10).

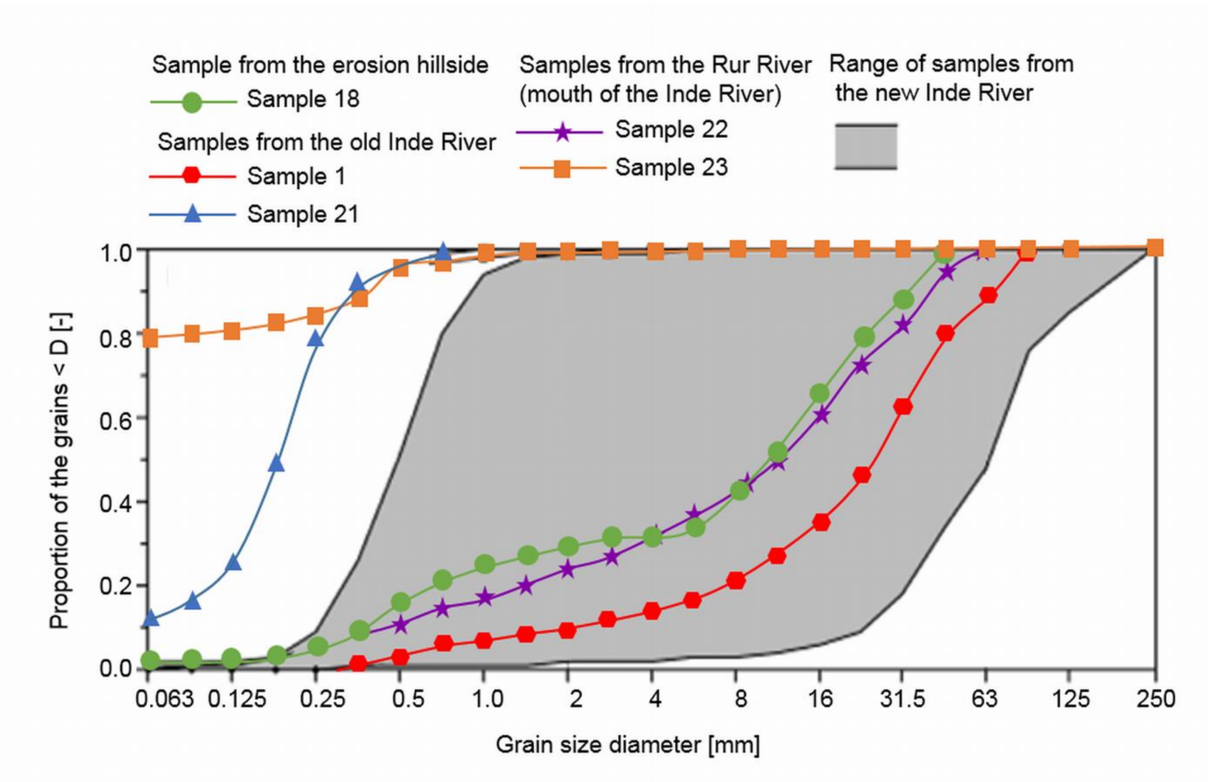

Figure 4-10: Comparison of the grain size distributions (sample locations refer to Figure 4-4; modified after Frings et al. 2013).

4.4.2 Erosion and sedimentation rates

Figure 4-11 summarizes the amounts of erosion and sedimentation for all subdivisions (A until H, see Figure 4-4) of the new Inde River reach. There are no data for subdivisions G and H between 2010 AD and 2012 AD.

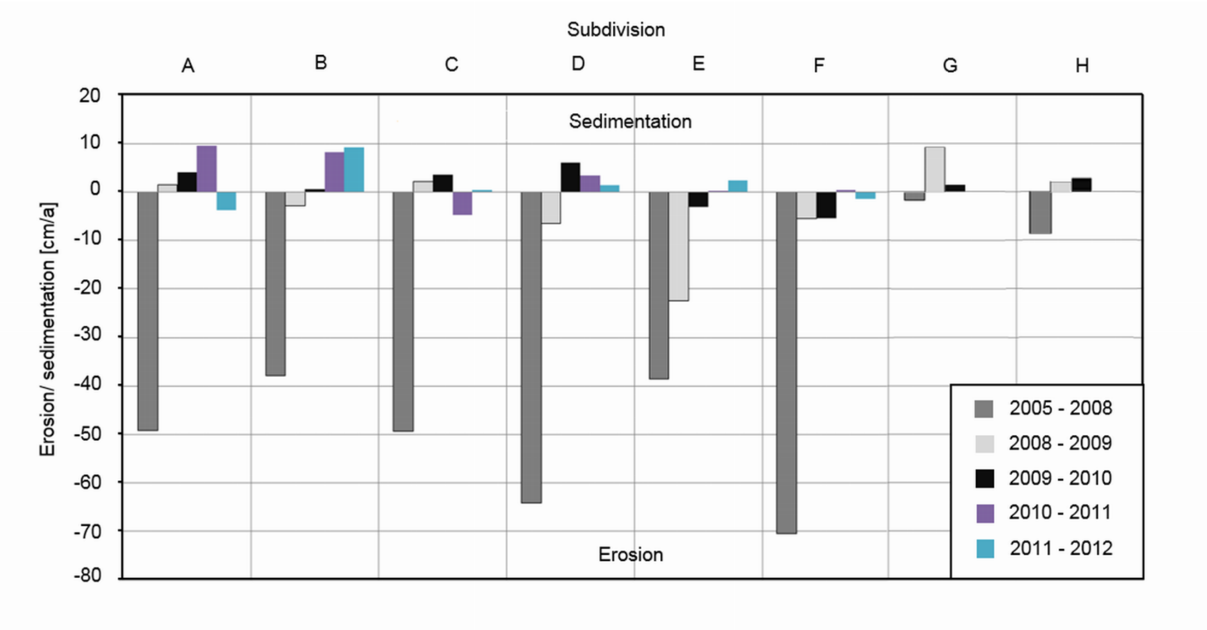

Figure 4-11: Erosion and sedimentation determined from echo soundings (modified after Frings et al. 2013).

Significant erosion took place between 2005 AD and 2008 AD. Many flood events occurred in 2007 AD, followed by an extreme flood event in 2008 AD with a discharge of more than 80 m^3/s. A flood event with a 100-year flood return interval occurs at discharges of approximately 111 m^3/s (Köngeter and Kammrath 2003), so that this flood event has a statistically smaller occurrence interval. This sequence of flood events resulted in the erosion of the river bed and a high morphological development. Between 2008 AD and 2009 AD, the erosion processes significantly decreased and changed into sedimentation of approx. 400 m^3. The analysis of the echo soundings of 2009 AD and 2010 AD shows a low erosion of approx. 300 m^3, which even changes to sedimentation, if the dredging of sediment traps 6 and 7 is considered. Although there are only a few sounding data sets for the years 2010 AD, 2011 AD and 2012 AD, the results show, as expected, a significant decrease of the fluvial morphodynamics of the Inde River compared to those in the first 5 years after finishing the restoration. Only little erosion or even sedimentation is recorded, and the river bed is on a constant level with a small trend towards sedimentation with an average rate of 2 cm/a (Frings et al. 2013).

Figure 4-12 shows the longitudinal profiles of the new Inde River between 2005 AD and 2012 AD based on the deepest point of the echo sounding results of each cross-sectional profile. A comparison of the different river bed elevations reflects the erosion or sedimentation of the river bed in the longitudinal directions. The massive erosion of sediment in the downstream direction results in the incision of the river bed into the ground and a significant sediment input into the Rur River. Despite this incision, the river bed is still located above the sealing layer, which was installed as a local erosion base during the restoration. The vertical difference in height between two echo sounding data sets is at some locations only a few decimeters (state 2012, see Figure 4-12). Only at river km 12.5 did the incision reach the sealing layer in 2008 AD and 2009 AD. Therefore, the sealing layer was repaired locally (see Figure 4-12).

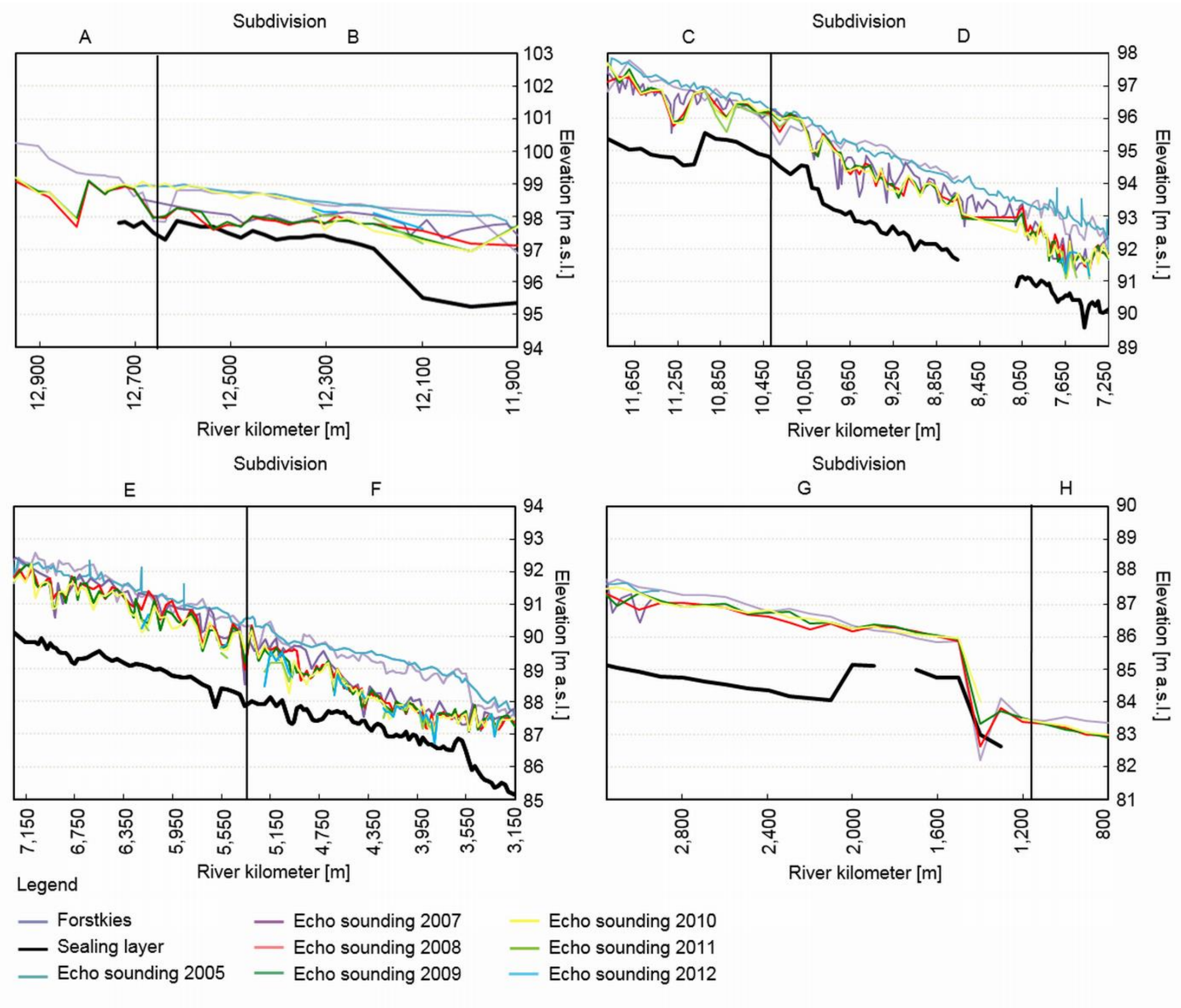

Figure 4-12: Development of the longitudinal profile of the new Inde River (modified after Frings et al. 2013).

4.4.3 Hillside erosion

Under the assumption of a triangular volume of the gullies, an erosion volume of approx. 3,500 m^3 coming from the hillside between 2005 AD and 2012 AD is determined. Under the assumption of a half ellipse shape, the total erosion volume was approx. 1,600 m^3. Here, it is assumed that the erosion volume was approx. 3,000 m^3 with a deviation of +/- 1,000 m^3 (Köngeter and Kammrath 2003). The material eroded from the hillside is characterized with a D_{10} of 0.375 mm, a D_{50} of 12 mm and a D_{90} of 31.5 mm (see Figure 4-10). Data on soil compaction, density and porosity were not collected.

The development of the vegetation cover was less than expected for the first 7 years after the completion of the restoration in 2005 AD. The risk of hillside erosion is greater due to the reduced vegetation on the surface. Vegetation would increase the resistance of the soil to erode (Köngeter and Kammrath 2003). Additionally, the gullies increase the roughness of the hillside and result in decreased flow velocities and higher water depths, which also lead to higher shear stresses (Köngeter and Kammrath 2003).

4.4.4 Sediment trapping

Table 4-1 shows the difference in the sediment trapped in the sediment traps after the event in 2006 AD to the reference date in 2005 AD.

Table 4-1: Amount of sediment and changes respective to grain size fractions in the sediment traps (modified after Kamrath and Schweim 2006).

Sediment trap	Amount of sediment [m^3]	Changes of gravel fraction [%]	Changes of sand fraction [%]	Changes of silt fraction [%]	Changes of clay fraction [%]
1	70	-0.1	+36	+34	-2
2	315	-17	+9	+8	-1
3	340	-8	+25	+10	+7
4	475	-10	-18	+26	-2
5	80	-7	+25	-16	-2
6	860	-4	-8	+17	-5
7	70	+0	+27	+65	+7

The bed load coming from upstream of the restoration is deposited in sediment trap 1 and reflects the initial sedimentological situation of the Inde River. During the event of 2006 AD, 70 m^3 of sediment was trapped in sediment trap 1. In sediment trap 2, the amount of sediment was 315 m^3. Such an increase between sediment trap 1 and 2 reflects higher sediment transport processes inside the new Inde River reach in comparison to the upstream part. Subdivision B (see Figure 4-4) is morphodynamically active. The amount of sediment in sediment trap 3 is similar to that in sediment trap 2, 340 m^3. The maximum amount of sediment, 860 m^3, is trapped in sediment trap 6, which reflects significant morphodynamic developments in terms of the erosion of banks and the occurrence of sand banks and scour holes for subdivision F (see Figure 4-4) during high-flow conditions (Kamrath and Schweim 2006). Sediment trap 6 is no longer active. The same amount of sediment, 70 m^3, is trapped in sediment traps 1 and 7 (Kamrath and Schweim 2006).

In sediment traps 2, 4, 6 and 7, the layering of the different materials and the development of an armor layer resulted in an increasing gravel fraction between 2005 AD and 2006 AD. In sediment traps 4, 6 and 7, the silt fraction increases significantly between 2005 AD and 2006 AD, and in sediment traps 1, 2, 3 and 5, the sand fraction increases significantly in 2006 AD in comparison to the reference sampling in 2005 AD (Kamrath and Schweim 2006).

An on-site inspection in 2008 AD shows that some sediment traps are completely filled up with sediment and, therefore, no longer active. Sediment is transported further downstream and is not captured inside the new Inde River reach, which results in an increased sediment input to the Rur River (Huber and Schüttrumpf 2008). In 2008 AD and 2010 AD, sediment traps 6 and 7 were dredged to restore their functionality and to counteract the massive erosion of the new Inde River reach.

4.4.5 Input and transport of heavy metals

Figure 4-13 shows the concentration profiles for zinc, lead and copper in the sediment samples used as a tracer for a further analysis of the morphological development. In the case of the missing bars, it was either not possible to sample the sediments, or to analyze them because of the grain size limitations of the X-ray fluorescence analysis.

The upper reaches and in part the middle reaches are, besides some past and recent anthropogenic impact factors, mainly characterized by the local geogenic background. There, in the samples of the surface layer, the concentrations of zinc range from 246 mg/kg up to 1,015 mg/kg, the content of lead from 38 mg/kg to 140 mg/kg and of copper from 14 mg/kg to 67 mg/kg (see Figure 4-13, samples I1-I7).

The sediment samples of the surface layer I8-I18, collected in the middle reaches and in the lower reaches (see Figure 4-13), show the highest content levels of the Inde River (Zinc: 3,924 mg/kg, see Figure 4-13, sample I16; Lead: 898 mg/kg, see Figure 4-13, sample I13; Copper: 404 mg/kg, see Figure 4-13, sample I16). Stolberg and Eschweiler were influenced by past ore mining and processing and coal mining as well as the iron and steel industry. Historical documents speculate about a beginning of mining in the study area in pre-Roman times. However, mining and ore processing are definitely postulated to have occurred since Roman times. In the 16th century, the master copper craftsmen left Aachen due to religious conflicts and moved to Stolberg. The number of brass manufacturing sites, hammer mills and wire manufacturers increased drastically (Graf 1984; Schmidt-Wygasch 2011). Coal mining between Stolberg and Eschweiler provided an energy resource, which was an important condition for the establishment of the iron and steel industry in the 18th century (Bierganz 1991). The closure of ore mining in 1919 AD was followed by the closure of the connected industries (Schneider 1982). Currently, different factories still exist.

Even though the heavy metal concentrations of the surface layer samples collected from the new relocated river bed (last part of the lower reaches, see Figure 4-13, samples I20-I28) are significantly lower than those in the middle reaches and in parts of the lower reaches (see Figure 4-13, samples I8-I19), they are higher compared to the concentrations analyzed in the samples collected in the upper reaches and partly in the middle reaches (see Figure 4-13, samples I1-I7).

The surface layer sediments of the new river bed show higher heavy metal contents than the composite samples of the upper 20 cm (see Figure 4-13, samples I20-I28). An exception is the composite sample I25.

The XRF-analyses of four natural surface material samples (Forstkies) show average concentration of 73.19 mg/kg zinc, 21.99 mg/kg lead and 15.76 mg/kg copper. Due to the fact that the composite samples include morphologically active river bed sediments with higher heavy metal enrichments in the upper part of the 20 cm, their concentration levels are slightly higher but comparable with the geogenic background of the heavy metal contents of the Forstkies samples. Thus, it is concluded that the lower part of the composite samples represents the natural background of the ground surface material (Forstkies), which was used for the construction of the new Inde River. In contrast to the other composite samples, I25 was taken in an accumulated sand bank. Its contents of zinc, lead and copper are comparable to the observations from the sediments that were suspended in the cylinder (method after Lambert and Walling 1988). Due to the recent formation of the sandbank, this sample does not represent the uncontaminated ground surface material (Forstkies), but an accumulation of surface layer sediments. The heavy metal contents of all the different sediment sample types show that the surface sediments in the whole new river bed are characterized by enrichments of zinc, lead and copper (see Figure 4-5 and Figure 4-13).

The concentrations of samples I26 and I27 are higher and are comparable to those of sample I23 (see Figure 4-13, samples I20-I27). Samples I26 and I27 belong to subdivision G (see Figure 4-11). The available data show that this part is mainly characterized by the lowest erosion rates in the restoration during the first 3 years (275 m^3/a or approx. 1 cm/a). Between 2008 AD and 2009 AD, the average sedimentation rate increased to a value of 3,500 m^3/a (approx. 10 cm/a). Although a decrease in sedimentation took place between 2009 AD and 2010 AD (250 m^3/a, approx. 1 cm/a) (Frings et al. 2013; Maaß et al. 2018b), it is assumed, that this subdivision was and still is characterized by sedimentation and thus by the accumulation of upstream eroded sediments and bounded heavy metals. The morphodynamic situation of sampling site I23 is similar.

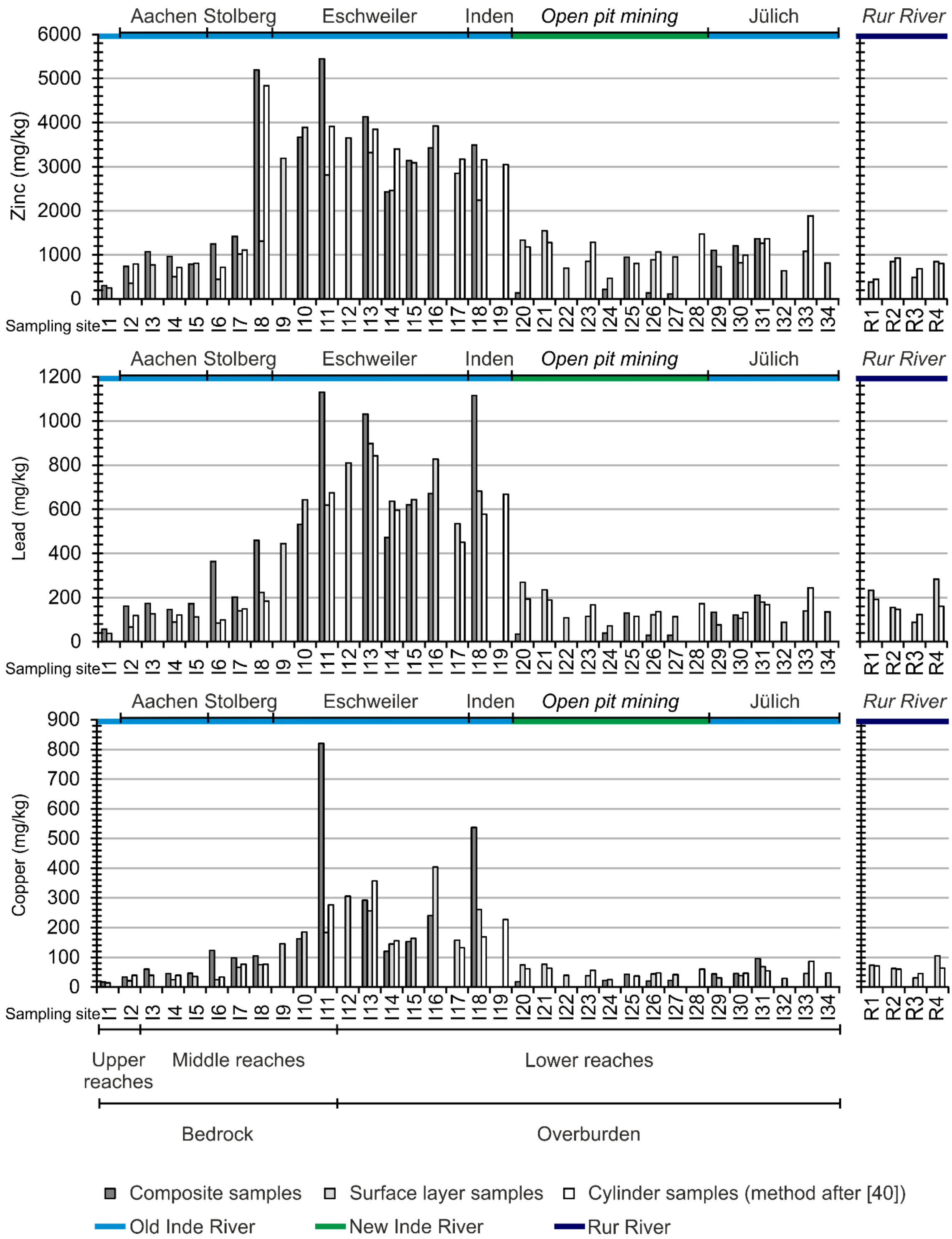

Figure 4-13: Zinc, lead and copper concentrations of Inde and Rur River (sites refer to Figure 4-3).

Samples I29 – I34 represent the reach of the old Inde River close to the mouth. Parts of this river section were changed due to the construction of another restoration (see Figure 4-3).

The sediments that were suspended in the cylinder (method after Lambert and Walling 1988) represent the fraction that can potentially be remobilized from the river bed during high discharges (Lambert and

Walling 1988). The sampled sediments show enrichments of heavy metals that are in general comparable with the surface layer samples (see Figure 4-13, site I20, I21, I23, I25, I26 and I28).

Samples R1-R4 (see Figure 4-3 and Figure 4-13) were sampled from the Rur River. R1 represents a sampling site upstream of the mouth of the Inde River. R2 is sampled directly inside the inflow of the Inde River into the Rur River. R3 and R4 are sampled 200 meters (R3) and 300 meters (R4) downstream of the mouth. The zinc content of R1 is lower than that of samples R2-R4. In the case of lead, sample R1 shows higher contents than the others, with the exception of the surface layer sediments of sampling site R4. Finally, the copper concentrations do not show clear differences. In all cases, sample R3 shows the lowest contents. Figure 4-14 summarizes all the results and shows the fluvial morphodynamics of the new Inde River from the top view and an example cross-section.

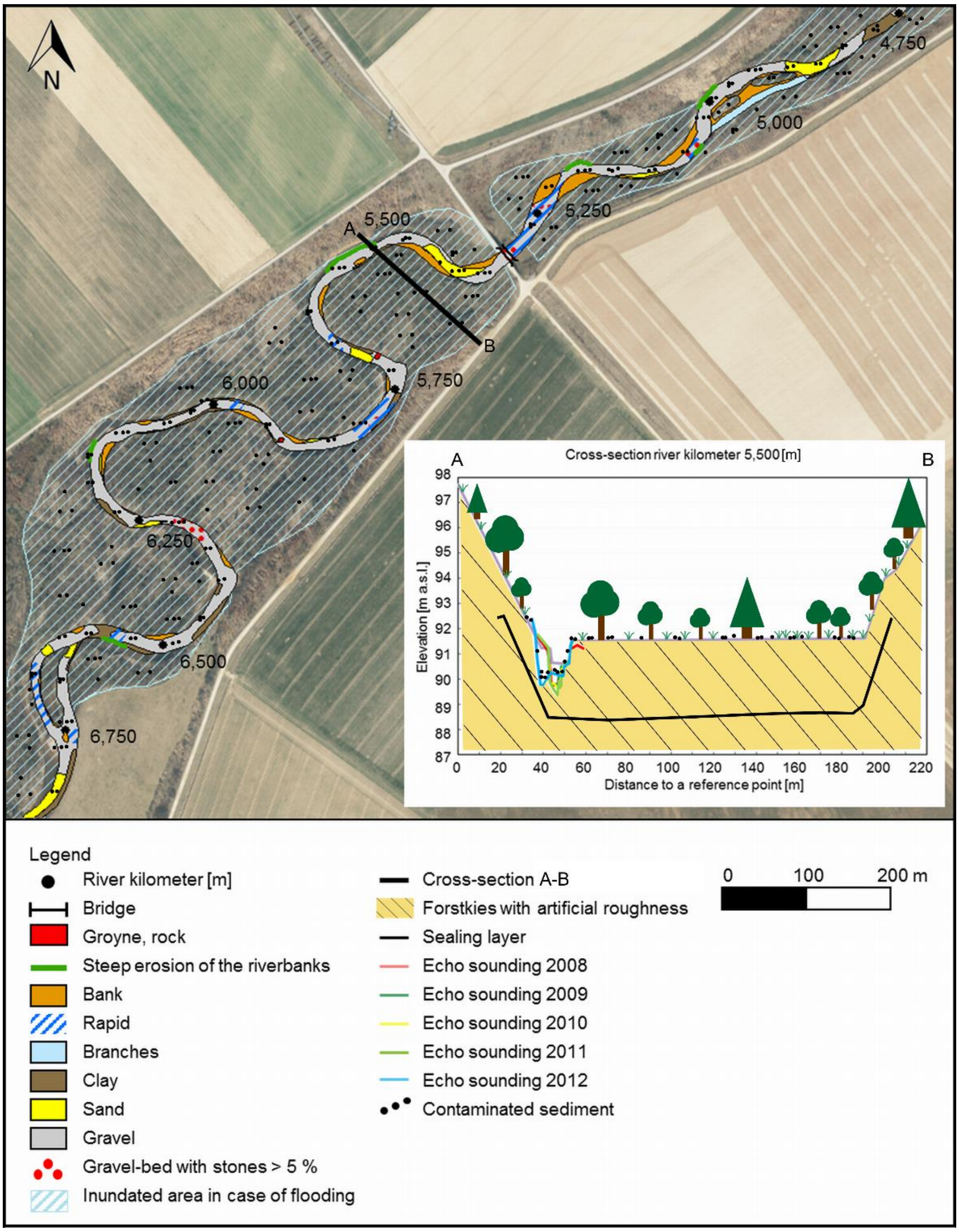

Figure 4-14: Fluvial morphodynamics of the new Inde River from the top view and an example cross-section.

4.5 Discussion

At the Inde River, a river reach of 5 km was not only restored, but also relocated and enlarged to a 13 km long reach and monitored over a time period of more than one decade. A restoration over such a length and a monitoring program over such a long time period focusing on the fluvial morphodynamics of the river are unique. Usually, restorations encompass only several hundred meters of a river. The restoration of the Emscher River, which started in 1990 AD, can be seen as an exception because it encompasses the entire course of the river. The Emscher River and its tributaries are converted from highly modified open wastewater channels with concrete beds to near-natural river systems in a large-scale restoration project of more than 30 years (Gerner et al. 2018). Such a conversion is not comparable to other restorations.

However, the monitoring of restorations deals mostly with comparisons of the pre- and immediate post restoration as case studies, but systematic studies to understand the evolution after the restoration over longer periods are missing (Pasquale et al. 2010). The results of river restorations are predominantly evaluated focusing on the biotic response of the river (e.g. (Lorenz et al. 2009)). Nevertheless, the restoration of the Thur River in Switzerland (Pasquale et al. 2010) and the restoration of Willet Creek in Canada (Chapuis et al. 2015) also focus on the morphological development of the restored river reaches. At the Thur River, the morphodynamic evolution of the restored reaches of 2 km in length was investigated in relation to the role of pioneer vegetation roots in stabilizing the alluvial sediment (Pasquale et al. 2010). At Willet Creek (restoration of 400 m flow length), a sediment budget for the watershed was developed, and the stability of the riffle-pool sequences established in the river and their effects on sediment transport processes were assessed (Chapuis et al. 2015). Both studies were conducted over a time period of only 1 or 2 years, so that the results of the morphological development strongly depend on the discharges present during this time. A monitoring program of a time period of more than one decade could not be found in the literature, which underlines the uniqueness of the field measurements at the Inde River. Long-term monitoring programs should be performed to verify the restoration success and to filter out the local effects of natural variation (van Oorschot 2017).

The morphodynamic development of a relocated and restored river with the example of the new Inde River shows that sediment transport processes depend on different parameters and especially on the hydrological and geomorphological variability of the system as well as on the vegetation growth of the adjacent landscape. The vegetation is widespread and distinctive at the new Inde River and influences its morphological development intensively and over long time-scales. In addition to the morphological development corridor (Forkel and Rinaldi 2008) and the development towards the river’s guiding principle, the ecological passability and sediment continuity (van Slobbe et al. 2013) of the new Inde River are two major benefits of the relocation and restoration. Here, achieving the guiding principles and ensuring the continuous transport of sediment through the river system mutually define each other.

The responsible water board of the Inde and Rur River (Wasserverband Eifel Rur) has measured an increasing fine sediment input of the Inde River into the Rur River after finishing the relocation and restoration in 2005 AD. A sudden and intensive transport of fine sediment in the downstream direction may cause the clogging of a downstream located river bed, here the river bed of the Rur River. Pores between gravel particles are clogged by clay, silt or fine sand (Schlächli 1993), which reduces the spawning habitats of salmonids (Sear 1993; Wood and Armitage 1997; Wooster et al. 2008). At the Inde River, there are different sources for sediment, which is eroded and then transported to the Rur River:

(1) sediment eroded in the upper part of the Inde River, (2) sediment eroded from the river bed inside the new Inde River reach, (3) sediment eroded from the floodplains inside the new Inde River reach and (4) sediment eroded from the adjacent hillsides inside the new Inde River reach (see Figure 4-5).

Concerning the sediment eroded upstream of the new Inde River reach

The river bed is stabilized with approx. 44 bed drops, 4 bed slides, 41 bottom ramps and many bridges. Therefore, the continuous transport of sediment and sediment input from the upper part of the Inde River are limited. Until now, there have been no significant hydrological, morphological or geometrical changes in the upper part of the Inde River. The enrichment of the heavy metal content in the surface layer sediments indicate that due to fluvial morphodynamic processes, the new constructed river bed of the new Inde River is characterized by ongoing and remarkable sediment and heavy metal inputs from upstream (see Figure 4-5). The differences between the heavy metal contents of the sediment samples taken upstream and those within the restoration, as well as the analysis of the suspended sediments sampled during a bankfull discharge, verify that, in fact, the sediment input from upstream is characterized by higher heavy metal concentrations than those found in the analyzed river bed sediments of the new Inde River.

Concerning the sediment eroded from the river bed and from the floodplains inside the new Inde River reach

Due to morphological processes in the river bed, the sediments of the surface layer represent a mixture of uncontaminated natural ground surface material (Forstkies) and contaminated sediment input from upstream. Thus, due to dilution effects, the heavy metal contents in the new river bed are lower than those upstream. Nevertheless, the surface sediments of the whole new river bed show heavy metal enrichments. The distribution of sediment-bound heavy metals in the entire river bed of the restoration relates to the sediment transport as well as its accumulation and indicates natural morphological processes and morphological development in the new Inde River. These results are also observed in the sedimentological characterization of the river bed, in the analyses of the sediment traps and in the measured erosion and sedimentation rates of the river bed (see Figure 4-5 and Figure 4-10).

The substrate (Forstkies) used to prepare the river bed of the new Inde River contains 72 % sand and clay (RWE 2003). The grain size distribution of the river bed is finer than the one postulated in the guiding principle of the Inde River and is eroded even during mean flow conditions, which results in an incision of the river bed into the ground (see Figure 4-5). In the first 5 years after finishing the restoration, a significant decrease in the fluvial morphodynamics of the Inde River occurred connected with a reduction of the incision and followed by an increase in the sedimentation in the whole restoration as shown in Figure 4-11 and Figure 4-12. This led towards an enrichment of heavy metals in the river bed (see Figure 4-5) and to a reduction of the dilution effect. Nevertheless, lower concentration levels of the composite samples compared with the sediments of the surface layer indicate, in general, rather low sedimentation processes or possibly even erosion during flood events.

The analysis of subdivision F (see Figure 4-4) shows morphodynamic development in regard to the erosion of banks and the occurrence of sand banks and scour holes (Kamrath and Schweim 2006). The heavy metal content of the composite sample I25 (see Figure 4-13), which was taken in a sand bank, represents more recently accumulated sediments with heavy metal enrichments. The heavy metal contents are comparable with the sediments sampled with the cylinder method after Lambert and Walling (1988) at this site. This proves that a morphodynamic analysis connected with heavy metals as a tracer is a valuable method to determine the development of the new Inde River. Future research will concentrate on the sedimentation and accumulation of contaminants on floodplains during overbank flood events.

Concerning the sediment eroded from the adjacent hillsides inside the new Inde River reach

It was noticed during an on-site inspection in 2012 AD that there is a 5 cm to 10 cm wide sediment deposition area at the bottom of the hillside, which is separated from the Inde River by an approx. 7-m-wide area with high vegetation. This indicates that the erosion of this hillside, which is also overgrown with vegetation, is decreased to almost zero and does not need any further analysis in the upcoming years. Flood events play an important role due to remobilization processes and higher erosion and accumulation rates (Förstner 2004; Cofalla et al. 2012). The analysis of a flood event in 2006 AD shows a deposition of 70 m^3 of bed load in sediment trap 1 coming from upstream. Sediment traps 2-6 show even higher amounts of trapped sediments due to erosion and sediment transport inside the new Inde River. The sediments sampled with the cylinder method represent the fraction that can potentially be remobilized from the river bed during flood events (Lambert and Walling 1988). These remobilized sediments show enrichments of heavy metals. This supports the assumption that especially high discharges and flood events contribute to the heavy metal and sediment dispersion in the new river bed. While the heavy metal concentrations in the first part of the restoration are especially influenced by a high sediment load from upstream, the remobilization, transport and sedimentation of sediment-bound heavy metals gain more importance with the increasing distance. This fact is also reflected in the data of predominating processes in the different subdivisions between 2011 AD and 2012 AD. Subdivision A (see Figure 4-4), situated in the beginning of the restoration, is characterized by a sediment input from the upper part of the Inde River and by erosion, while subdivisions B to E (see Figure 4-4) show, in general, accumulation processes.

The flood events of the years 2007 AD and 2008 AD resulted in an especially massive erosion of the river bed (Huber and Schüttrumpf 2008) and an unnaturally high amount of fine sediment input to the Rur River. Although the heavy metal enrichment in the new river bed is caused by a continuing sediment input from upstream, this sediment source and hillside erosion do not significantly increase the fine sediment input from the Inde River into the Rur River. Overall, this increased fine sediment input is definitively a consequence of the substrate used to prepare the river bed of the new river reach (Forstkies).

Due to the heavy metal content of the Rur River sediments (see Figure 4-13, sample R1) and dilution effects in the new Inde River, the Rur sediment samples (see Figure 4-13, samples R2-R4) do not show significant increases in lead and copper downstream of the mouth of the Inde River. Only the differences of the zinc concentrations of samples R1-R4 let assume that the slight increase of zinc near the mouth is connected with the sediment input of the Inde River. The differences between the heavy metal concentrations of samples R2-R4 (see Figure 4-13) can be explained by the morphodynamic processes and complex flow conditions connected with sediment transport and sedimentation in the Rur River at the mouth of the Inde River as well as with the different grain size compositions of the samples.

However, the results for the years 2010 AD until 2012 AD show that the massive erosion inside the new Inde River reach decreased towards almost zero (see Figure 4-11). It is expected that the erosion will decrease with the increasing age of the new Inde River. Because of the decreasing erosion in the river bed and on the adjacent hillsides, the accumulation of sediment-bound heavy metals increases in the restoration. This process will continue due to ongoing natural morphodynamic processes.

4.6 Conclusions

The fluvial morphodynamics of a new river reach of the Inde River (North-Rhine Westphalia, Germany) were determined after its relocation and restoration in 2005 AD with extensive field measurements between 2005 AD and 2018 AD. The results of the analysis showed the incision of the new river bed between 2005 AD and 2008 AD as well as a downstream movement of sediments, resulted in a massive sediment input at the mouth of the Inde River into the Rur River. With these morphological processes, which are connected with flood events and vegetation growth, the river system adapted its new conditions. Morphological processes decelerated with the increasing vegetation growth. The flow velocities, grain size distributions of the river bed and occurrence of fluvial forms such as banks and branches are very variable.

In 2018 AD, the new Inde River has reached a dynamic morphological equilibrium, which has improved and still improves its natural hydrological and morphological conditions as an ecological habitat. Between 2008 AD and 2013 AD, the river bed incision significantly decreased. Therefore, after almost 13 years of adaptation processes, the Inde River itself represents a dynamic equilibrium, and its new surrounding landscape has developed towards a quasi-stable system.

Currently, the predominating sedimentation processes in the river system are accompanied by an accumulation of sediment-bound heavy metals. Overall, 13 years after connecting the relocation and restoration to the consisting river reaches, the sediment samples collected from the new river bed show considerable heavy metal concentrations (see Figure 4-14).

It is concluded that the new Inde River has developed towards its pre-defined guiding principle within its anthropogenic restrictions caused by the open-pit lignite mine Inden and that it has reached its goal of being a natural river. Especially due to the length (13 km) of the new constructed river bed, the Inde River is a very good study area and a representative example showing that achieving a dynamic morphological equilibrium after a river relocation and restoration is possible after only one decade.

The results can generally be used for further investigations on fluvial morphodynamics. Overall, the results show the following:

- A new constructed river bed of a river restoration or relocation can be used to analyze the downstream movement of sediments.
- Contaminated sediments can be used as a tracer for morphological development.
- The morphological adaptation processes of a new restoration are due to hydrological and vegetation development and that
- A dynamic equilibrium can be reached only after a few years of adaptation processes, which were characterized by remarkable erosion and accumulation.

Acknowledgements

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5 Reactivation of floodplains in river restorations: Long-term implications on the mobility of floodplain sediment deposits

Anna-Lisa Maaß, Holger Schüttrumpf

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Abstract

Nowadays, national and international requirements and laws emphasize the "natural" development of river-floodplain systems. One goal is to increase the connectivity between the river and its floodplains and thus reactivate floodplains as flooding areas, which potentially increases the mobility of fine sediments. The objective of this study is to analyze the long-term effects of reactivated floodplains on the mobility of floodplain deposits of small rivers based on two river restoration scenarios: elevating the riverbed or lowering the floodplains. Past channel fixation and degradation as well as the subsequent increase in the floodplain elevation led to the decoupling of the channel and floodplain morphodynamics associated with the reduction of the habitat connectivity. Here, the floodplain sedimentation rates were determined using a numerical model based on the Delft3D software. The novelty of this numerical investigations is the morphological long-term analysis over time scales of decades, which is not comparable to other short-term hydro- and morphodynamic studies for small meandering lowland rivers. The results of 11 river restoration scenarios show that lowering the floodplain and raising the riverbed elevation both lead to an increase in the fine sediment deposition on the floodplain. However, lowering the floodplain elevation is generally more effective. Based on the numerical model results and the assumption of a fixed river channel, only anthropogenic activity might have increased the amount of fine sediments deposited on floodplains and has accelerated the decoupling of the floodplains from the riverbed in the past centuries.

Keywords: Reactivation of floodplain sediment deposits, Numerical modelling, River restorations

5.1 Introduction

Many riverbeds incise several meters below their adjacent floodplains (Surian and Rinaldi 2003; Surian et al. 2009; Ghoshal et al. 2010; Scheffers et al. 2015). In some cases, such an incision of the riverbed was constructed to reduce the flood risk and simultaneously increase the drainage of floodplains to increase the agricultural production (Kern 1998). More often, incision of the riverbed develops unnoticed over decades in our river systems for example, due to the construction and removal of transverse structures such as water mills (Buchty-Lemke and Lehmkuhl 2018; Maaß and Schüttrumpf 2019), river straightening (Frings et al. 2009), or anthropogenically increased discharges such as the input of mine, urban drainage, or industrial waters (Bizzi et al. 2015). Incised rivers have decreased water levels especially during low and mean flow conditions, and floodplain inundation suddenly occurs after heavy rainfall or snowmelt events. In Germany, only 10-30 % of the original floodplains are still available as flooding areas (Brunotte et al. 2009; Ehlert and Neukirchen 2012).

Many studies focused on the sedimentation processes on floodplains driven by hydrodynamics using event-based field measurements (e.g., Lambert and Walling 1987 or Asselman and Middelkoop 1995), numerical modelling approaches (e.g., Middelkoop and van der Perk 1998; Narinesingh et al. 1999; Lauer and Parker 2008a; Rudorff et al. 2018), or a combination of both to verify the results. For example, Middelkoop and van der Perk (1998) simulated the floodplain sediment deposition over river reaches with lengths of several kilometers using a GIS-based mathematical model and concluded that the model can be used to predict sediment deposition patterns, which are the results of the complex interaction among river discharge and sediment concentration, floodplain topography, and the resulting water flow patterns at various discharge levels. The numerical model results were compared with the sediment deposition patterns observed after the occurrence of a major flood event in the lower Rhine River in the Netherlands (Middelkoop and van der Perk 1998).

At the same time, Narinesingh et al. (1999) simulated the floodplain sedimentation along extended river reaches with a series of alternating floodplains on both sides of the main channel and verified the approach using suspended load data obtained during flood events in the Ijssel River in the Netherlands. The numerical model of Narinesingh et al. (1999) can be used as a first approximation to estimate the quantity of the suspended load deposited on floodplains along extended river reaches during floods.

Today, 20 years after these studies, the analysis of floodplain sedimentation processes is still the main objective of morphological studies and river restoration interventions. For example, Fassoni-Andrade and Dias de Paiva (2019) firstly analyzed the sediment dynamics in large lakes and rivers of the central Amazon considering different water types (white, clear, and black water) using remote sensing images.

With respect to today's river restoration interventions, national and international requirements and laws, for example, the EU Water Framework Directive or the "Room for the River" program, emphasize the "natural" development of river-floodplain systems. One goal is to increase the interconnection between rivers and their floodplains. River restorations include different interventions to counteract or eliminate the disconnection of the river from its floodplains. Generally, the deposition of fine sediment on floodplains is a natural process, whereas the disconnection of a river channel from its floodplains, for example, by an anthropogenically incised riverbed, is considered to be a negative morphodynamic change (Kern 1998). Restorations encompass the removal of river bank or bed fixings, opening of channelized river parts, restoration of natural meander belts and cross-sectional profiles, increase in the riverbed elevation, dredging of floodplains or flattening of river banks. For example, van Denderen et al. (2018) analyzed the mechanisms that influence the morphodynamic changes of side channels as a common intervention applied to increase the river's conveyance capacity and its ecological value in terms of river restorations in Europe and North America. Van Denderen et al. (2018) used a one-dimensional bifurcation model to predict the development of side channel systems and the associated timescale for a range of conditions and generalized them using stability diagrams including the most important model parameters. They showed, inter alia, that bank erosion hardly affects the equilibrium state but causes the side channel development over longer timescales depending on the bank erodibility (van Denderen et al., 2018). They concluded that the mechanisms in sand- and gravel-bed rivers are quite similar and that their results can therefore be used to assess the development and corresponding timescales of various side channel designs (van Denderen et al. 2018). Generally, restoration interventions should be sustainable, consider river dependent hydrological and morphological characteristics, and lead to dynamic sediment transport processes.

In old-industrial areas, in which a lot of fine sediment is deposited on the floodplains and the riverbed has deeply incised into the ground, river restorations may lead to an extensive reconnection and remobilization of fine sediment. For example, a restoration intervention in the Ruhr River (219.3 km long with a catchment size of 4,485 km^2) was finished in 2013 AD, which included the widespread excavation of fine sediment deposited on the floodplains and the creation of additional retention areas. A restoration in the Möhne River (65.1 km long with a catchment size of 469 km^2), a tributary of the Ruhr River, was finished in 2008 AD. The main goals of the restoration were to remove the deep incision of the river and reduce the river bank heights. The cross-sectional area of the Möhne River was increased over a length of 700 m to generate variable and dynamic flow and habitat conditions.

The objective of this study is to analyze the effects of reactivated floodplains on the availability and mobility of floodplain deposits of small rivers. A numerical model based on the Delft3D software was used to analyze the long-term response of river morphodynamics due to reactivated floodplains. Two reactivation scenarios were considered: (1) increase in the riverbed elevation and (2) lowering of the floodplains. The schematized 2D-numerical model represents small lowland rivers (river width < 20 m) with wide floodplains (floodplain width ~ 150 m each side) deeply incised into the ground (river bank heights ~ 1-3 m). The numerical model is based on the topography and bathymetry of an 11 km reach of the Wurm River (Lower Rhine Embayment, Germany).

The outline of the paper is as follows: First, the characteristics of the Wurm River are described. Subsequently, the numerical model setup using the software Delft3D and the field measurement concept for the determination of the input data for the numerical model are described. Finally, the model results and future development focusing on fine sediment deposits on floodplains are presented and discussed. The conclusions are provided in the last section.

5.2 Materials and methods

5.2.1 Study site

The Wurm River flowing through the Lower Rhine Embayment has a catchment size of 356 km^2 and length of 57.9 km (MULNV NRW 2008a). The channelization of the headwater tributaries underneath the city of Aachen leads to a significant reduction in the sediment load. In 2006 AD, approximately 2,500 m^3 sand were trapped in subsurface sand traps (personal communication: Wasserverband Eifel Rur). The mean annual discharge is 3 m^3/s and the mean flood discharge, which approximately equals the bankfull discharge, is 25 m^3/s (LANUV NRW 2004).

The Wurm River is characterized as a gravel-bed river, however, fine sediment (clay, silt, and fine sand) is predominantly transported as suspended load. Downstream of the wastewater treatment plant Aachen-Soers, the Wurm River runs as a free meandering river towards the Dutch-German border. The Wurm River flows through an 11 km long valley, which is rich in structure, and meanders over floodplains that are several hundred meters wide. The hillsides are partly forested (Fischer 2000).

Figure 5-1 shows an overview of the upper part of the Wurm River from the source in the forest of Aachen to the city of Herzogenrath. The main anthropogenic impacts of the last 200 years on the Wurm River include the presence of a minimum of 60 water mills (Vogt 1998), its location in the former underground coal mining area of Aachen, and channelization of the upper part of the Wurm River underneath the city of Aachen. The riverbed of the Wurm River is incised because of these anthropogenic effects, that is, due to the removal of the chain of water mills (Buchty-Lemke and Lehmkuhl 2018; Maaß and Schüttrumpf 2019) as well as the increased water discharge because of the inflow of purified wastewater (LANUV NRW 2004). Figure 5-1 shows the location of two turbidity sensors, which were installed in the Wurm River to determine the transport of suspended sediment.

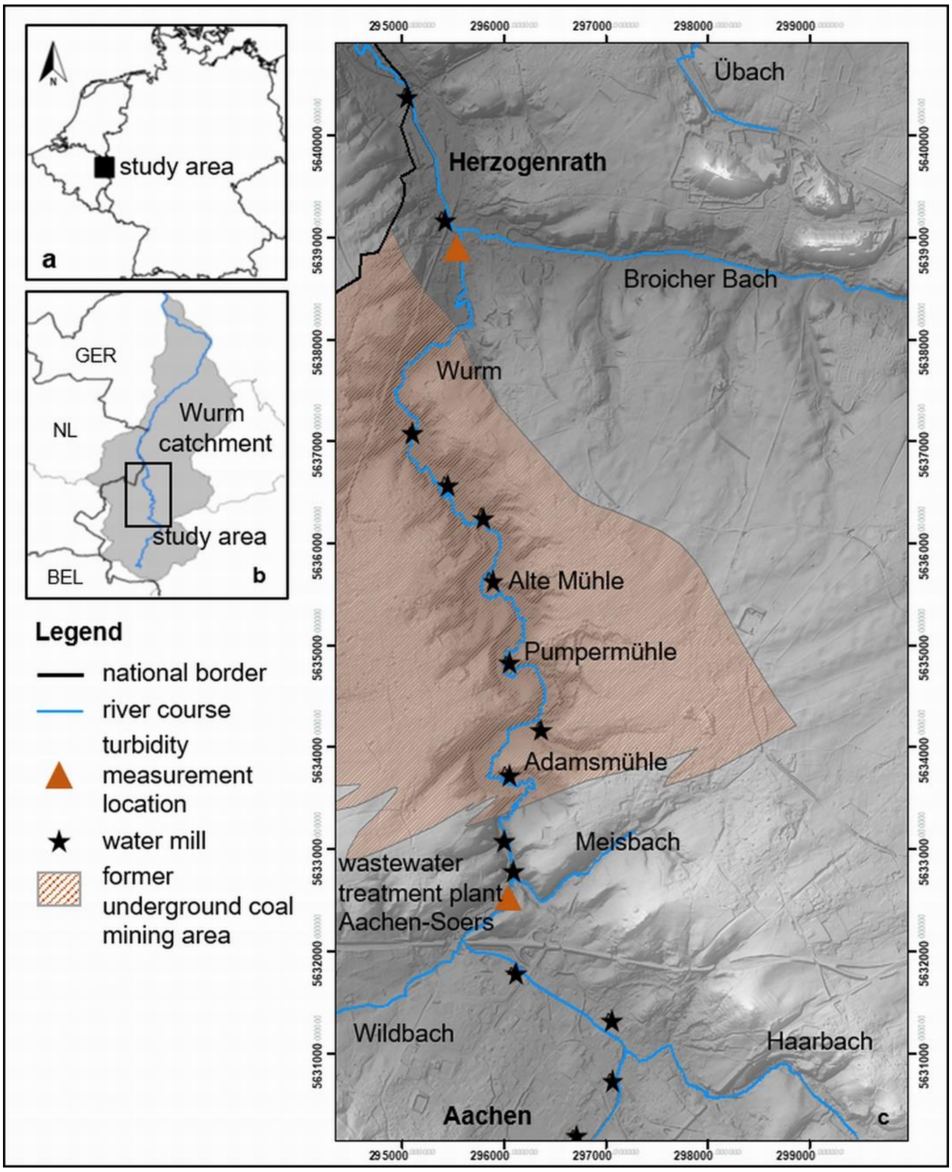


Figure 5-1: a: Map of Germany and surrounding states. b: Catchment of the Wurm River. c: Study area of the Wurm River between the wastewater treatment plant Aachen-Soers and the city of Herzogenrath.

5.2.2 Suspended sediment sampling

Data about the suspended sediment transport in the Wurm River obtained during different discharge events are not available. To collect such data, a measurement campaign consisting of two turbidity sensors, which continuously measure the turbidity in intervals of 5 min to 10 min, and suspended sediment samples, which were taken from different locations of the Wurm River, was performed. The measurement campaign started in November 2016 AD and continued for a period of two years.

Following the principles of light absorption and scattering, turbidity (in nephelometric turbidity units, NTU) is defined as an optical property of a suspension that causes light to be scattered and absorbed rather than transmitted through suspension (Gippel 1989). Turbidity in the water phase is caused by suspended particles such as clay, silt, organic, inorganic, or soluble colored organic substrate, plankton and other microscopic organisms (Gippel 1989; Gippel 1995; Marquis 2005; Habersack et al. 2008). The particle shape has only a second order effect on the turbidity (Davies-Colley and Smith 2001). Optical backscattering sensors can be used as surrogates for the high-frequency determination of suspended sediment concentrations (SSCs) in rivers (Schoelhammer and Scott 2003; Hoffmann et al. 2017). A measurement device (MPS-Qualilog 8, SEBA Hydrometrie & Co.KG) was used, which adopts optical backscatter technology to measure the turbidity. The turbidity sensor measures the unsolved suspended particles in the water phase. The scattered light of the turbidity particles is measured at an angle of 90°. Davies-Colley and Smith (2001) stated that only 1.5 % of the light in natural river systems is scattered at an angle greater than 90°. With our measurement equipment, the turbidity between 0 NTU and 1,000 NTU can be measured with a resolution of 0.01 NTU. The accuracy of the measurement device is +/- 0.3 NTU for turbidity values < 10 NTU and +/- 3 % for turbidity values > 10 NTU. The device can be used at temperatures between 0 °C and 50 °C. A wiper in front of the measuring window cleans the sensor before each measurement. One turbidity sensor was installed at the start of the nearly natural part downstream of the wastewater treatment plant Aachen-Soers. The second turbidity sensor was installed at the end of the nearly natural river section, at the gauging station Herzogenrath. The locations of the measurement devices are shown in Figure 5-1.

The SSCs were determined by taking two 1.0-L water samples at each measurement location. During the gravimetric analysis, the water samples were filtered, dried in a drying oven at 105 °C for 48 h, and weighted (with an accuracy of 0.1 mg). The SSC of these samples was determined using a smooth glass fiber filter (Macherey-Nagel, grade MN GF-6) without binder with a weight of 70 g/m^2, thickness of 0.35 mm, filtration speed of 12 s, average retention capacity of 0.6 µm, and migration distance of 140 mm/10 min. Suspended sediment samples were collected monthly and, in addition, during flood events. Only one-point sample was taken close to the turbidity sensor in the Wurm River because a high variability of the SSC in the vertical and horizontal directions of the cross-sectional profile was not expected. It is assumed that the SSC near the turbidity sensor equals the average SSC of the cross section.

Provided that most of the suspended sediment is fine grained (< 2 mm) and that the grain size distribution is always the same, there is a good relationship between the turbidity and SSC (Walling 1977; Gilvear and Petts 1985; Buchanan and Schoellhamer 1995; Lewis 1996; Christensen et al. 2000; Uhrich and Bragg 2003; Lietz and Debiak 2005; Rasmussen et al. 2005). The sediment transported in suspension during the measurement campaign in the Wurm River was always fine grained and its composition insignificantly changes, even during flood events.

A continuous time series of SSCs can be obtained from turbidity values using quadratic regression analysis (Rasmussen et al. 2005). First, the recorded turbidity data sets were validated (checked for implausible values such as negative and duplicate values and outliers). A data point was marked as outlier when the measured value was twice as high as the prior or subsequently measured values (Habersack et al. 2005). Secondly, the SSC data were also checked for implausible values. The two parameters were then correlated with each other using quadratic regression analysis. The suspended sediment load (SSL) was determined by multiplying the SSC [g/m^3] with the prevalent discharge [m^3/s] and time [s] of that discharge.

5.2.3 Long-term 2D-modelling with Delft3D

The long-term effects of reactivated floodplains on fine sediment deposits were investigated using the software Delft3D-Flow in 2D (depth-averaged) mode. In the depth-averaged mode, the velocity distribution is averaged over the depth, the vertical resolutions of the velocities and pressures are neglected, and turbulent eddies are averaged using the Navier-Stokes equations (for further details, see Lesser 2009 and Lesser et al. 2004).

A numerical model was used for the scenario analysis to determine the long-term effects of the mobility of floodplain sediment deposits. The model is based on the characteristics of the 11 km section of the Wurm River between the wastewater treatment plant Aachen-Soers and the city of Herzogenrath (see Figure 5-1 and Figure 5-2). The total number of grid cells is 98,952 and the average cell size of the entire model is 26.3 m^2. The main channel is represented by approximately four grid cells with average cell widths and lengths between 3 and 5 m. The curvilinear grid structure of the Delft3D software leads to problems in sharp bends. To avoid numerical instabilities, the course of the Wurm River was modified at several locations and sharp meander bends were cut to obtain a straight river course. Based on these simplifications, the differences in the flow conditions between the numerical model and original Wurm River were completely neglected in this analysis. Generally, a reduced flow length leads to higher flow velocities, less floodplain inundation, and thus decreased sedimentation rates. This study focused on a scenario-based analysis of different river restoration interventions and not on the Wurm River. Therefore, the exact prediction of, for example, floodplain inundation areas and amounts of sediment deposition on floodplains is not of interest. The results of the different scenarios were compared with the reference case and the course of the river was constant in all scenarios. The left part of Figure 5-2 shows the small differences in the river course between the numerical model and original Wurm River. The grid cells of the riverbed were constructed with high resolution, which does not impose any limitations on the floodplain dynamics. The sediment dynamics in the riverbed were not analyzed in detail.

The topography of the model is based on a digital elevation model (LIDAR DEM, spatial resolution of 1 m, height resolution of +/- 0.2 m, Land NRW 2017). The current bathymetry is linearly interpolated between bathymetry cross sections with an average spacing of 100 m.

The boundary conditions correspond to those recently published by Maaß and Schüttrumpf (2018): a quasi-steady time dependent inflow hydrograph at the upstream boundary (for a detailed description of this simulation management tool of Delft3D, see Yossef et al. 2008) and discharge-water depth relation at the downstream boundary. The hydrologic time series were based on discharge measurements at the gauging station in Herzogenrath performed between 1969 AD and 2016 AD. The discharge ranges from 0.13 m^3/s and 44.30 m^3/s. In this study, five quasi-steady discharge steps between 10 m^3/s and 50 m^3/s were defined.

All measurement results were used as a basis for the quasi-steady morphological modelling approach that captures characteristic flow situations such as the average flow, and bankfull conditions, and overbank flow. Each numerical modelling scenario considers a total morphological duration of 10 years.

The suspended sediment transported in the model is equal to 24.5 µm (silt), which represents the median diameter (D_{50}) of sediment cores taken from the floodplains of the Wurm River and is similar to the averaged D_{50} of sediment samples taken from the Wurm River during the turbidity measurement campaign. The transport of cohesive sediment was modelled using the Partheniades-Krone equation (Partheniades 1965). The sediment input was based on the results of the quadratic regression analysis of the turbidity and SSC measurements from November 2016 AD and November 2018 AD (see section 5.3.1 Regression results). In addition, one major assumption of the numerical model is that the entire riverbed consists of gravel with a D_{50} value of 33 mm and that the bed-load transport is negligible, even under bankfull and overbank discharge conditions. Local processes, such as riverbank erosion, vegetation, or cohesive forces (e.g., Schuurman et al. 2016; Kleinhans et al. 2018; Schuurman et al. 2018), are often simulated using a single simplified numerical model or separated numerical models. Both were not applied here. The results of the assessment of the model quality and assumptions are provided in section 5.4.3.

Generally, the backgrounds of the hydrodynamic and morphodynamic calibrations are the same as those recently published by Maaß and Schüttrumpf (2018). The critical shear stresses for the erosion and sedimentation were determined using the two median grain sizes of the floodplains ($\tau_{c,ero,floodplain}$ = 12 N/m^2; $\tau_{c,sed,floodplain}$ = 1,000 N/m^2) and riverbed ($\tau_{c,ero,riverbed}$ = 45 N/m^2; $\tau_{c,sed,riverbed}$ = 1 N/m^2). In this study, a constant roughness value is used for the river and the floodplains. The water levels with a relative maximum deviation of -0.11 %, correlation coefficient of 0.999, and Nash-Sutcliffe index of 0.96 (Nash and Sutcliffe 1970) were reproduced with a Chézy coefficient of 31 m$^{1/2}$/s.

5.2.4 Scenarios

Two types of river restorations were considered in this study, which both are suitable to enhance the connectivity of riverbeds and their floodplains. Each scenario had a total morphological duration of 10 years.

Firstly, the riverbed elevation was increased. The entire riverbed, including the elevated riverbed, consists of gravel with a D_{50} value of 33 mm. The sediment transported in suspension is silt with a D_{50} value of 24.5 µm. The increase in the riverbed elevation decreases the riverbank heights and increases the connection between the riverbed and floodplains.

Secondly, the floodplains were excavated, which also decreases the riverbank heights and increases the connection between the floodplains and riverbed. The riverbed consists of gravel with a D_{50} value of 33 mm and the sediment transported in suspension is silt with a D_{50} value of 24.5 µm. The floodplain deposits were excavated and removed. The surface of the floodplain consists of silt with a D_{50} value of 24.5 µm. Table 5-1 summarizes all scenarios and Figure 5-2 shows the scenario locations.

Table 5-1: Scenarios of river restorations focusing on the reconnection of the riverbed and the floodplains.

Scenario	Adjustment	Location	Height [m]	Length [km]	Width [m]
1	-	-	-	-	
2a	increase	straight, middle of the valley	+0.3	1	10-15 (entire riverbed)
2b	increase	straight, middle of the valley	+0.7	1	10-15 (entire riverbed)
2c	increase	straight, middle of the valley	+1.0	1	10-15 (entire riverbed)
3a	increase	meandering, close to the left valley flank	+0.3	1	10-15 (entire riverbed)
3b	increase	meandering, close to the left valley flank	+0.7	1	10-15 (entire riverbed)
3c	increase	meandering, close to the left valley flank	+1.0	1	10-15 (entire riverbed)
4a	lowering	straight, middle of the valley	-1.3	1	20 (each floodplain)
5a	lowering	meandering, close to the left valley flank	-1.3	1	20 (each floodplain)
5b	lowering	meandering, close to the left valley flank	-1 3	1	20 (each floodplain)
6	increase	entire modelling area	+0.7	7	10-15 (entire riverbed)

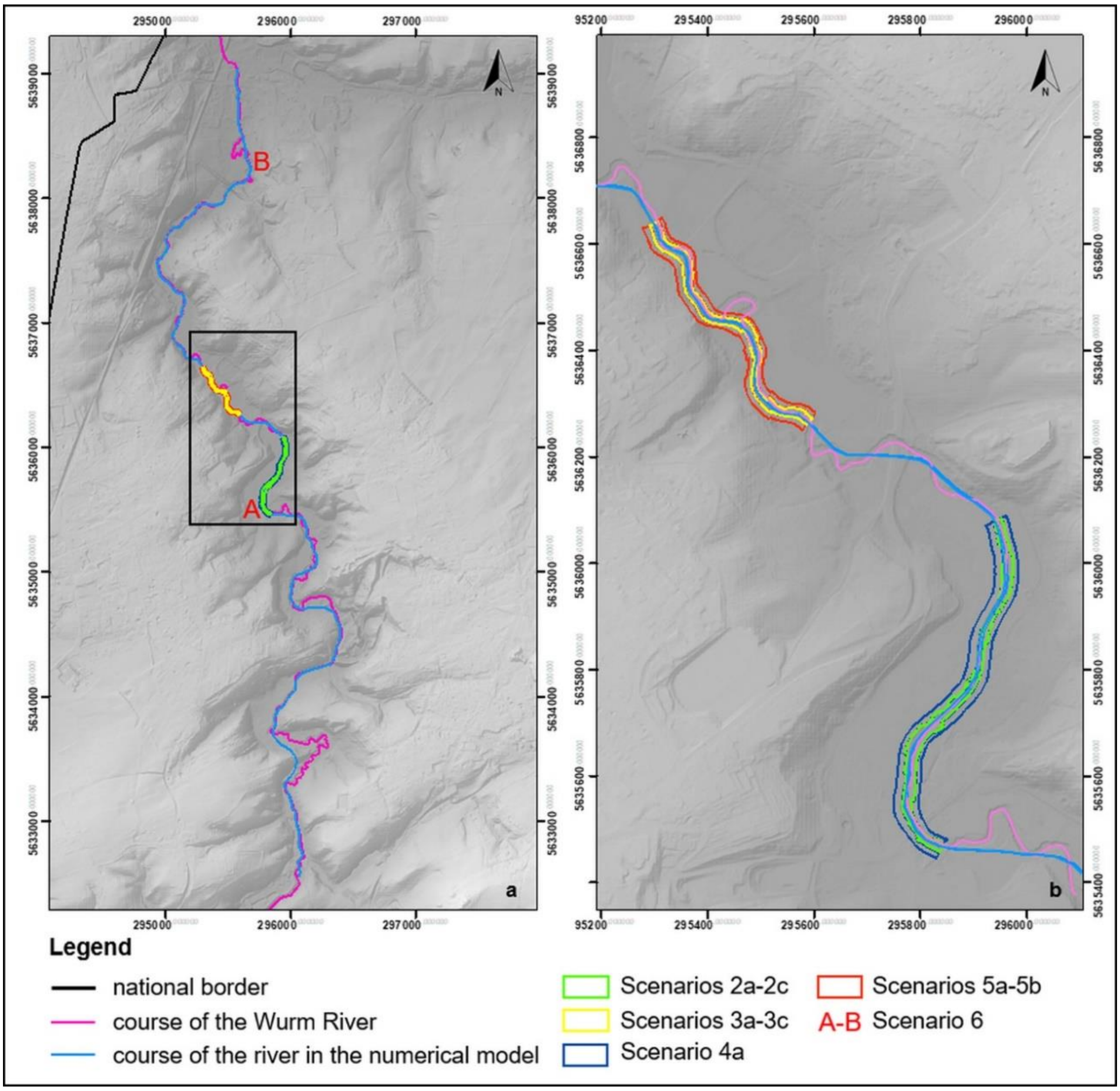


Figure 5-2: Locations of the numerical model scenarios.

Currently, there are no river restorations planned in the study area of the Wurm River. Therefore, the different scenario locations were selected based on different topographical valley settings and the characteristics of the main river channel. Scenarios 2 and 4 were set in a straight part of the Wurm River in the middle of the valley. Scenarios 3 and 5 were set in a meandering part of the Wurm River closer to the valley flanks.

Scenario 1 represents the reference scenario. In all other scenarios, the elevations of the riverbed or floodplains of the model mesh were manually increased or decreased by a defined height in a defined area. In scenarios 2a, 2b, and 2c, the riverbed elevation was partially increased by +0.3 m, +0.7 m, and +1.0 m, respectively, over a length of 1 km. In scenarios 3a, 3b, and 3c, the riverbed elevation was partially increased by +0.3 m, +0.7 m, and +1.0 m, respectively, over a length of 1 km. In scenario 4a, the floodplains were excavated by -1.3 m, with a width of 20 m on each floodplain side, over a length of 1 km. In scenario 5a, the floodplains were excavated by -1.3 m, with a width of 20 m each floodplain side, over a length of 1 km. In scenario 5b, the width of the floodplain to be lowered was increased to ~ 100 m. In scenario 6, the riverbed elevation was increased by +0.7 m over almost the entire length of the model (~ 7 km).

5.3 Results

5.3.1 Regression results

The turbidity data sets and SSCs measured between the 14th of November 2016 AD, and the 2nd of November 2018 AD were analyzed (see Figure 5-3).

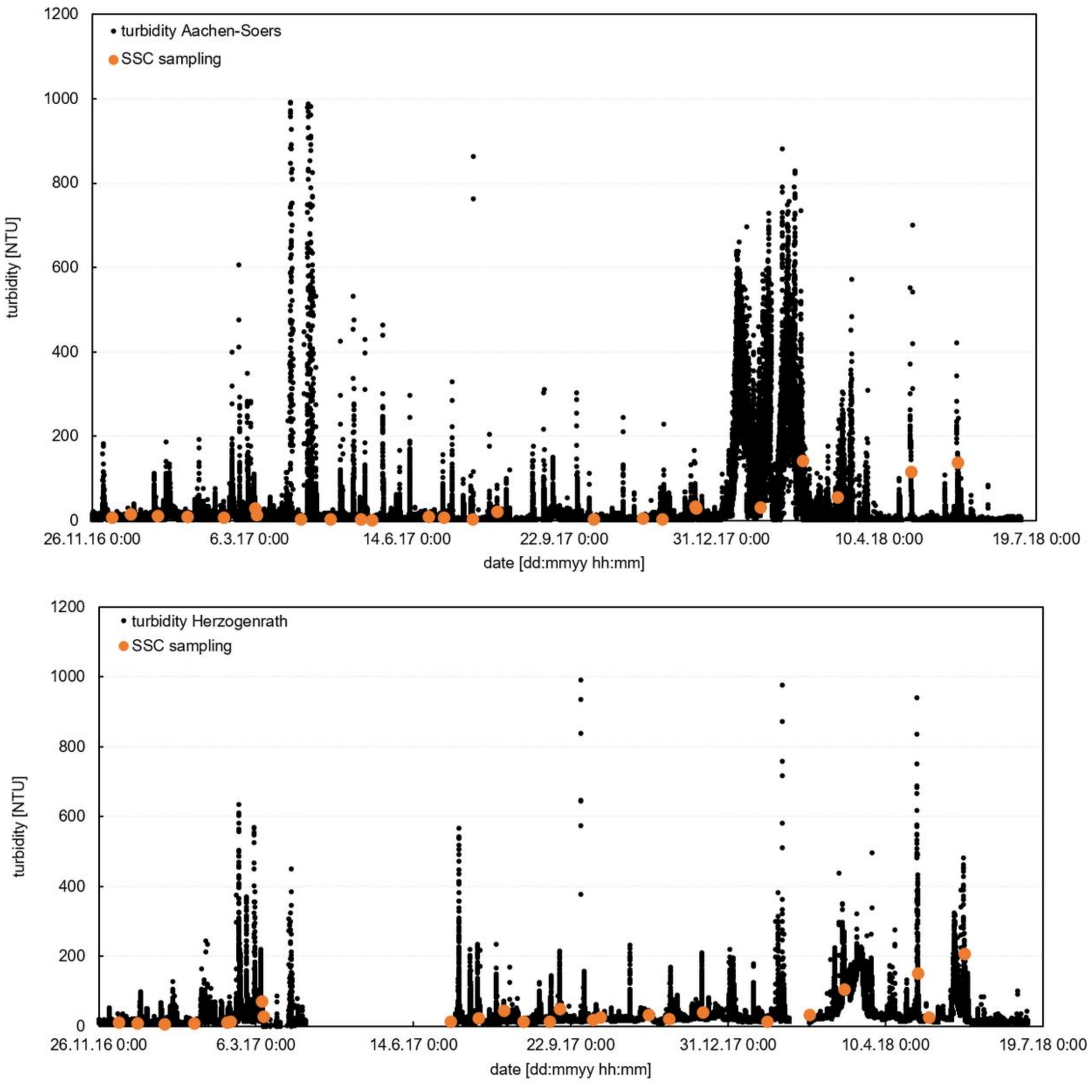


Figure 5-3: Turbidity data sets of the Wurm River in Aachen-Soers and in Herzogenrath between 2016 AD and 2018 AD.

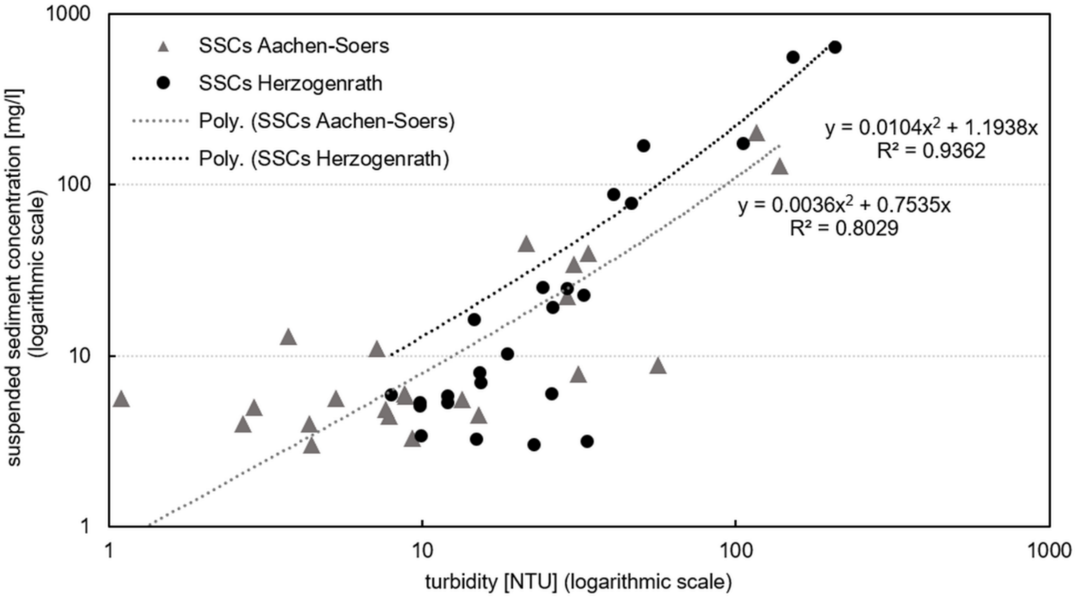
The data show a large amount of scatter and hysteresis, which are not of interest due to the long-term approach of this study. The discharge during this period ranges from 0.10 m^3/s to 37 m^3/s, with an average of 0.63 m^3/s, in Aachen-Soers and from 0.43 m^3/s to 52 m^3/s, with an average of 1.64 m^3/s, at the gauging station in Herzogenrath (LANUV NRW 2018).

For the data from Aachen-Soers, quadratic regression was performed using 27 SSCs. Four of these 27 values were marked as implausible values. For the data from Herzogenrath, the quadratic regression was performed using 27 SSCs. Three of these 27 values were marked as implausible values. Based on the data sets, different forms of fitted curves were tested to relate the measured SSCs to the turbidity values. A polynomial regression equation was used, which best describes the relation between the turbidity and SSC at the two measurement locations, that is, in Aachen-Soers (see equation 5-1, coefficient of determination (R^2) of 0.80) and in Herzogenrath (see equation 5-2, coefficient of determination (R^2) of 0.94):

$$\mathrm{SSC} = 0.0036\,\mathrm{T}^2 + 0.7535\,\mathrm{T} \qquad 5\text{-}1$$

$$\mathrm{SSC} = 0.0104\,\mathrm{T}^2 + 1.1938\,\mathrm{T} \qquad 5\text{-}2$$

where SSC is the suspended sediment concentration in mg/l and T is the turbidity in NTU, ranging from 0 NTU to 1,000 NTU. Figure 5-4 shows the results of the polynomial regression.



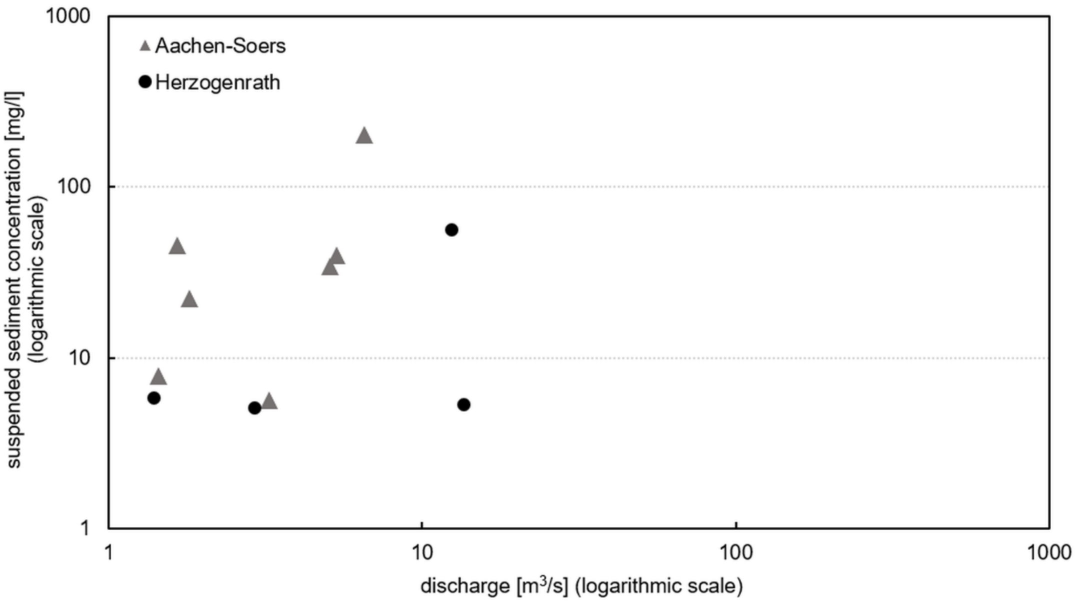


Figure 5-4: Turbidity against SSC values (upper part) as well as discharge against SSC values (lower part) measured in Aachen-Soers and Herzogenrath between November 2016 AD and November 2018 AD.

At the measurement locations in Aachen-Soers and Herzogenrath, a SSL of 21 tons per year and 43 tons per year was determined. Because of the small variability and organic content in the Wurm River, the data set was not separated into winter and summer periods. Therefore, only one SSL was calculated for the entire year. Note that two extreme flood events occurred in the Wurm River between November 2016 AD and November 2018 AD (with reoccurrence intervals of 50- and of 100-years), which led to a higher average annual SSL compared with other periods without such extreme events.

The SSCs values determined using equations 5-1 and 5-2 for both measurement locations were related to the prevalent discharge and separated according to the discharge classes of the quasi-steady hydrograph. Table 5-2 shows the average SSC for each discharge class of the quasi-steady hydrograph.

Table 5-2: Average SSC in [kg/m3] for each discharge class in the Wurm River in Aachen-Soers and in Herzogenrath measured between November 2016 AD and November 2018 AD and used in the Delft3D model as sediment input data at the upstream boundary of the model.

Discharge class [m^3/s]	**SSC [kg/m^3] in Aachen-Soers**	**SSC [kg/m^3] in Herzogenrath**	**SSC [kg/m^3] in Delft3D**
10	0.12	0.57	0.12
20	0.34	1.88	0.34
30	0.09	1.92	0.65
40	Not measured	1.94	1.02
50	Not measured	1.96	1.48

Specific study site conditions of the Wurm River due to rainwater retention basins, flood control reservoirs and sewer overflows were not included in the Delft3D model. In the numerical model, it was assumed that the sediment input generally increases with increasing discharge. Therefore, the sediment input of the Delft3D model is based on the results of the field measurements in Aachen-Soers (see Table 5-2) but was adjusted and extrapolated to reflect an increasing sediment input with increasing water discharge. Table 5-2 also shows the sediment input of the Delft3D model based on the field measurement results for the Wurm River. All scenario simulations were performed using these sediment inputs.

5.3.2 Delft3D modelling results

The average floodplain sedimentation was calculated by summing the amount of floodplain sedimentation in all grid cells of all discharge classes and divide it by the amount of grid cells in which floodplain sedimentation took place. Depositional and erosional processes close to the upstream and downstream boundaries of the model (~ 500 m) were neglected to avoid inaccuracies due to numerical boundary effects.

Figure 5-5 shows the average floodplain sedimentation of the entire model area for all scenarios. The average floodplain sedimentation of the reference scenario 1 for the upcoming 10 years is 5 cm. Generally, the results of scenario 2 show a decrease in average floodplain sedimentation in the entire model area compared with scenario 1, whereas the results of scenarios 3 to 6 show an increase in the average floodplain sedimentation in the entire model area compared with scenario 1.

Effects of the riverbed elevation

The results for scenarios 2a, b and c show that the increase in the riverbed elevation results in less sediment deposition in the modelling area (see Figure 5-5). Because of the main assumption of the numerical model that the riverbed is fixed, scouring cannot be observed.

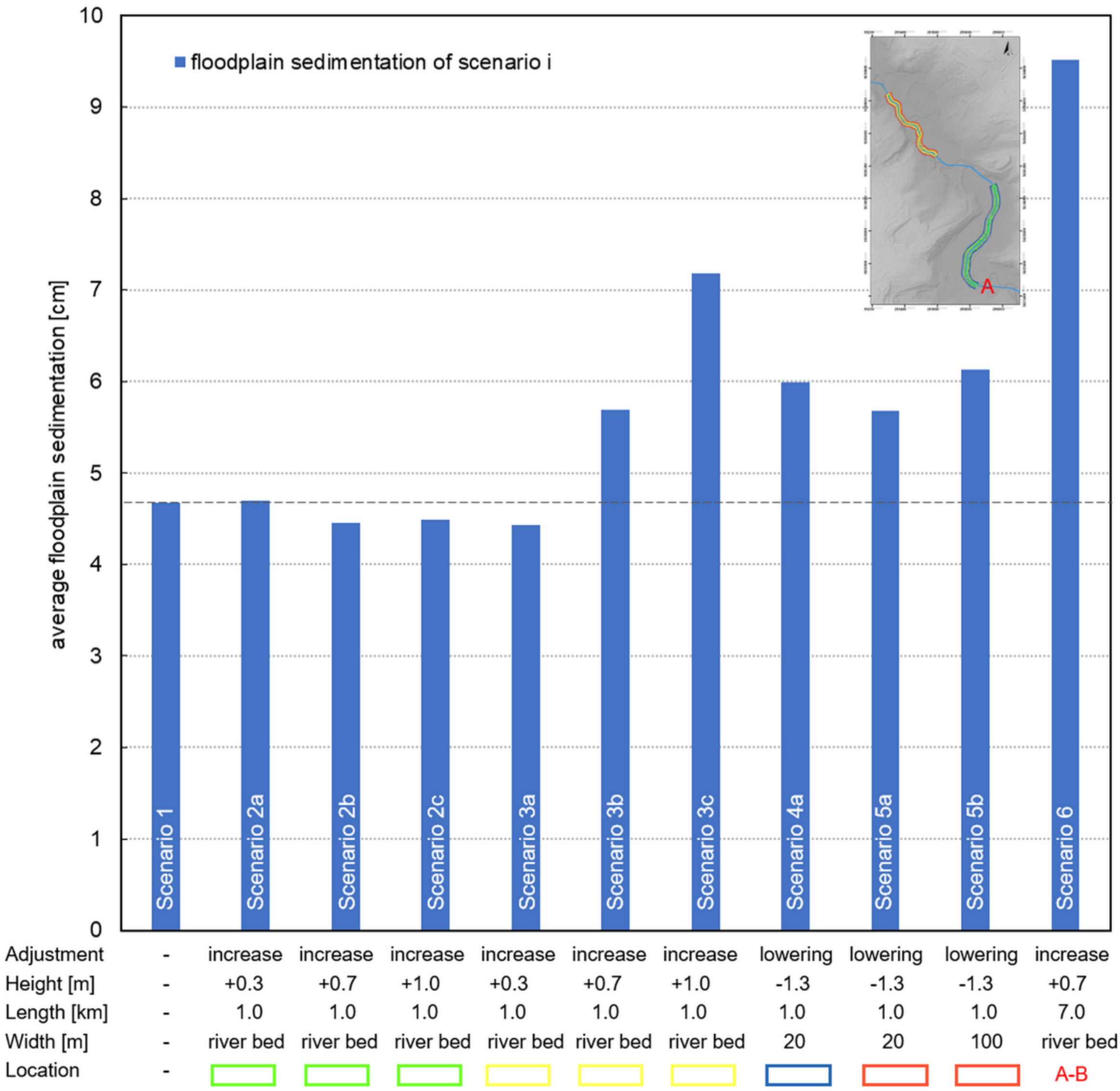


Figure 5-5: Average floodplain sedimentation of the entire model area of all scenarios.

In contrast, the numerical model results for scenarios 3b and c show that the larger the increase in the riverbed elevation is, the larger is the average floodplain sedimentation on the entire floodplain area. With respect to the impact of timing, scenarios 3b and c change the floodplain inundation frequencies and activate floodplains at lower discharges. The increase in the riverbed elevation results in longer sediment settling times on the floodplains and therefore in more floodplain sedimentation. The average sedimentation of scenario 3a (increase by +0.3 m) is > 4 cm, which is less than the average sedimentation of ~ 6 cm of scenario 3b (increase by +0.7 m) and ~ 7 cm of scenario 3c (see Figure 5-5). The spatial configuration of the sediment deposition increases with increasing riverbed elevation until the flanks of the valleys and therefore the maximum extension of the floodplain inundation is reached.

In addition to the spatial distribution of the floodplain inundation, changes in the shear stress of the floodplains lead to changes in the floodplain deposition. Regarding the shear stress of the floodplains at the maximum discharge of the quasi-steady hydrograph (Q = 50 m³/s), the shear stress in the restoration area of scenario 2 equals ~ 2 N/m² and does not change with increasing riverbed elevation compared with the shear stress in the reference area of scenario 1. In contrast, the increase in riverbed elevation of scenarios 3b and c leads to an increase in the shear stress of the floodplains from ~ 2 N/m^2 to ~ 4 N/m^2.

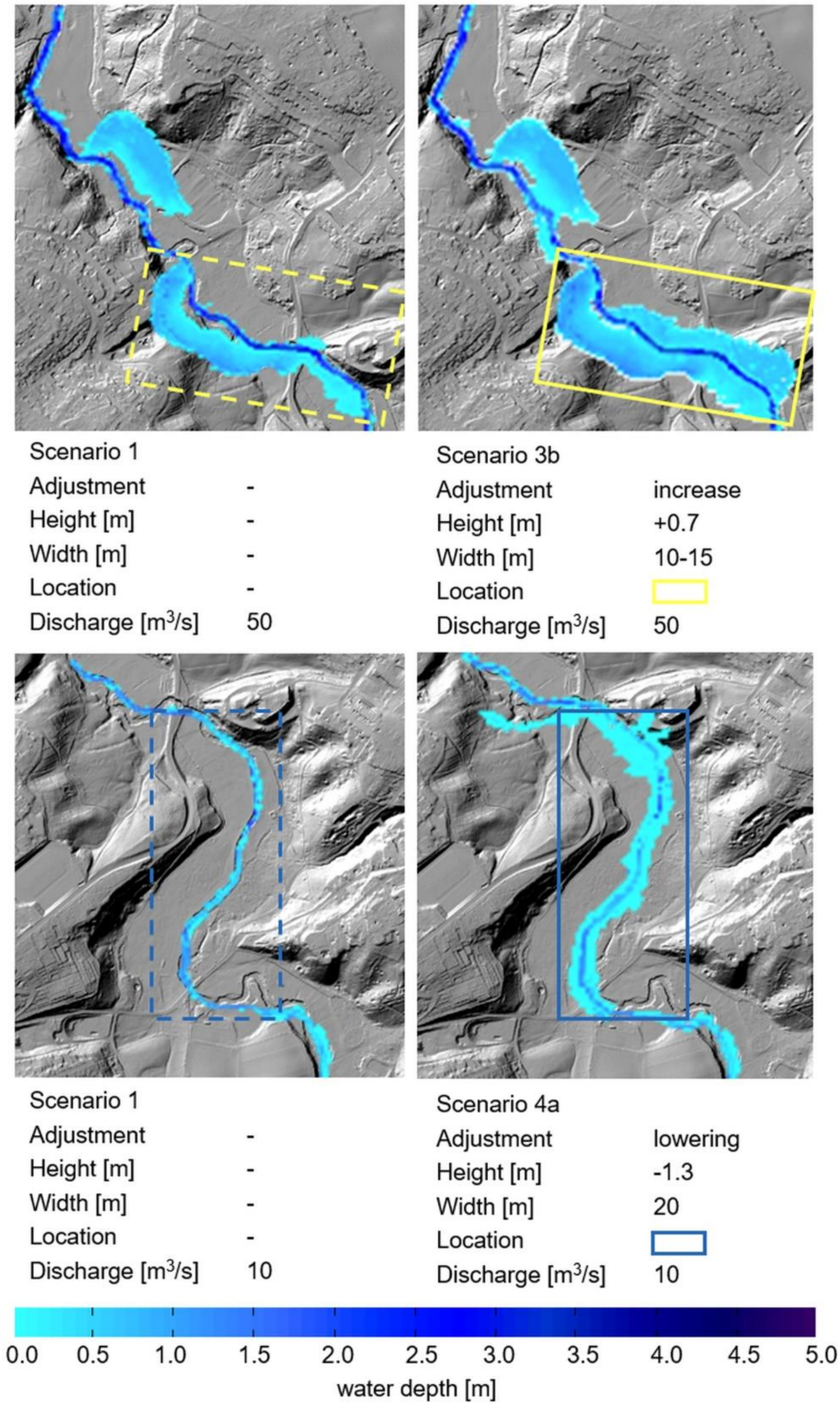


Figure 5-6: Comparison of the water depths of the reference scenario 1 and scenario 3b at a discharge of 50 m^3/s (upper part) and scenario 4a at a discharge of 10 m^3/s (lower part).

The result of scenario 6 show the greatest changes in the floodplain sedimentation after the riverbed elevation was increased. In scenario 6, the riverbed was increased over a length of ~ 7 km, that is, almost the entire length of the numerical model. Therefore, large floodplain areas are reactivated until the maximum extension of the floodplain inundation is reached. Additionally, the shear stress of the floodplains increases in almost the entire modelling area from 2 N/m^2 (scenario 1) to 4 N/m^2 (scenario 6). The average floodplain sedimentation of the entire floodplain area of the numerical model (~ 9.5 cm) increases by almost 100 % compared with the reference scenario 1 (< 5 cm; see Figure 5-5).

Generally, an increase in the riverbed elevation does not lead to floodplain inundation at lower discharges but to a greater inundation expansion during flood events, which increases the floodplain sedimentation. Figure 5-6 shows the water depths of scenario 3b compared with the reference scenario 1 at a discharge of 50 m^3/s (upper part of Figure 5-6) as example for the spatial changes in the water depth due to an elevated riverbed. Generally, further changes in the depositional rates as a result of the hydrograph patterns are of secondary importance in such a long-term analysis and cannot be determined due to the quasi-steady hydrograph approach of the scenario analysis.

Effects of floodplain lowering

The floodplain area that is lowered in scenario 5b is wider than that of scenario 5a. The comparison between scenarios 5a and b shows that the wider the lowered floodplain area is (20 m in scenario 5a compared with 100 m in scenario 5b), the larger is the average floodplain sedimentation in the entire floodplain area (~ 5.5 cm in scenario 5a and > 6 cm for scenario b, see Figure 5-5). In this study, the shear stress of the floodplains increases in all scenarios in which the floodplain elevation was lowered, from 2 N/m^2 (reference scenario 1) to 4 N/m^2 (scenarios 4a, 5a and 5b).

Generally, lowering the floodplains lead to the inundation of terraces and floodplain areas at lower discharges compared with the reference scenario 1. The lower part of Figure 5-6 shows the water depths of scenario 4a compared with the reference scenario 1 at a discharge of 10 m^3/s as example for the changes in water depth due to the lowering of floodplains.

5.3.3 Comparison of all results

The results of scenarios 2 (a,b,c) and 3 (a,b,c) with increased riverbed elevations are contrary. In scenario 2, the floodplain inundation frequencies do not change and thus the floodplains are not activated at lower discharges compared with reference scenario 1. In scenario 2, the flow paths and extension of floodplain inundation directly downstream of the restoration area change due to the increase in the riverbed elevation.

Figure 5-7 shows the average floodplain sedimentation related to the restoration area for all scenarios compared with the reference scenario 1 to analyze the effects of the restoration related to upstream and downstream effects. In contrast to Figure 5-5, the average floodplain sedimentation is only determined for the restoration area in Figure 5-7 and not for the entire model area.

The comparison of the average floodplain sedimentation with the restoration area shows that the floodplain sedimentation in the restoration area does not increase with increasing riverbed elevation. The lower the increase in the riverbed elevation is (scenario 2a: +0.3 m; scenario 2c: +1.0 m), the higher is the average amount of floodplain sedimentation in the restoration area (scenario 2a: 6 cm, scenario 2c: 3 cm; see Figure 5-7). The average floodplain sedimentation of scenario 3c (increase by 1.0 m) is smaller than the average floodplain sedimentation of scenario 3b (increase by 0.7 m; see Figure 5-7).

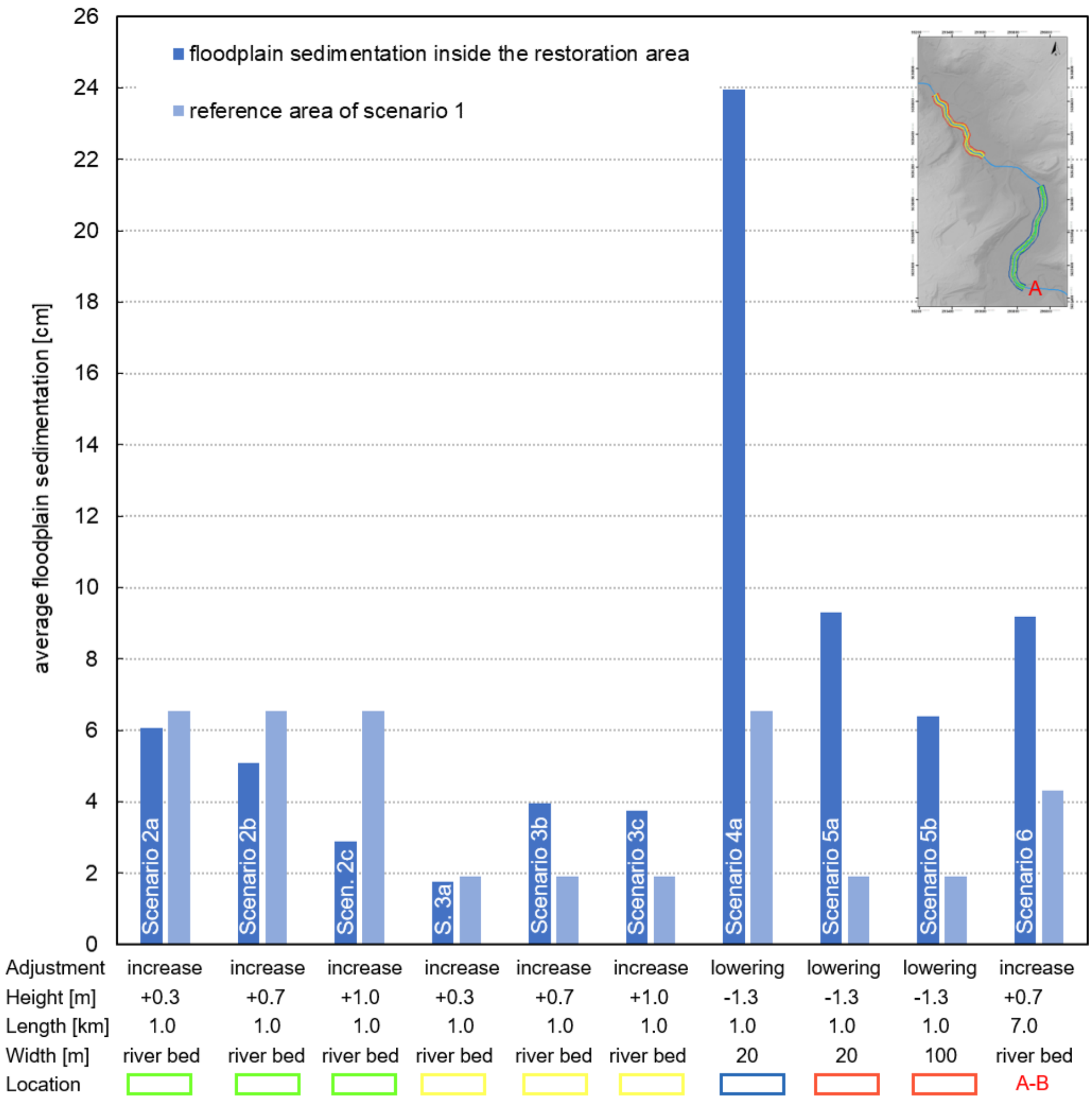


Figure 5-7: Average floodplain sedimentation inside the restoration area in comparison to the reference area of scenario 1.

The numerical model results of scenario 2 show that an increase in the riverbed elevation does not lead to the effects desired for reactivated floodplains and an increase in the fine sediment deposits on the floodplains. In contrast, the lowering of the floodplains at this location (scenario 4a) leads to a high increase of the floodplain sedimentation in the restoration area (scenario 4a: 24 cm, reference scenario 1: ~ 7 cm; see Figure 5-7).

The average floodplain sedimentation in the restoration area of scenario 5b (> 6 cm) is smaller than that of scenario 5a (~ 9 cm; see Figure 5-7). These effects are related to the different changes in the floodplain inundation of scenarios 5a and b. An analysis of the floodplain inundation frequencies of scenarios 5a and b shows that the lowering of scenario 5b leads to higher floodplain inundation frequencies in the restoration area and downstream of the restoration area, which also increases floodplain sedimentation downstream of the restoration intervention. Scenario 5a only increases the floodplain inundation frequency in the restoration area.

The increase in the floodplain sedimentation of scenario 4 is greater than the increase in the floodplain sedimentation of scenario 5, but scenarios 3b and c lead to higher floodplain sedimentation than scenarios 2a, b and c (see Figure 5-5 and Figure 5-7). Consequently, the results show that the local flow conditions become more important in case of an increase in the riverbed elevation than in case of a decrease in the floodplain elevation.

With respect to the relative influence of the valley confinement on the floodplain deposition, the results of the numerical scenarios show that an increase in the riverbed elevation does not increase the floodplain sedimentation, although scenario 2 is set in a straight part of the Wurm River in the middle of both valley flanks. In contrast, scenario 3 leads to an increase in the floodplain sedimentation on the right floodplain of the Wurm River. The position of the river close to the left valley flank increases the flow velocities and flow direction towards the right river bank. Therefore, the right floodplains are inundated earlier, and the river uses the additional floodplain area of ~ 125 m on the right floodplain.

The comparison of the average floodplain sedimentation of the entire floodplain area (see Figure 5-5) with the average floodplain sedimentation in the restoration area (see Figure 5-7) of scenarios 4a, 4b, and 5 shows that the consequences of the lowering of the floodplains are predominantly remarkable in the restoration area. The difference (scenario 4a: ~ 1 cm) between the average floodplain sedimentation of the entire floodplain area of scenario 4a (~ 6 cm; see Figure 5-5) and that of the reference scenario 1 (< 5 cm; see Figure 5-5) is smaller than the difference between the average floodplain sedimentation in the restoration area (18 cm; scenario 4a: 24 cm, scenario 1: 6 cm; see Figure 5-7).

5.4 Discussion

5.4.1 River management strategies

Restoration interventions are always in an area of tension between securing flood protection, re-establishing “natural” discharge conditions, considering urban management and the protection of historical buildings, “natural” river development and maintenance, and public perception and acceptance (Berends et al. 2018). Wohl et al. (2015) stated that the challenges with respect to river restoration are based on the large gap between the knowledge of processes, such as sediment transport, and the ability to use that knowledge for predictions or measurements in river restorations.

Focusing on the location of a river restoration within river management strategies, the results of scenarios 3 and 5 show that the reactivation of floodplains in a small, defined area has significant consequences for downstream areas because of the flow paths and floodplain inundation changes due to the reactivation of the floodplains. In both scenarios, the average floodplain sedimentation of the entire model increases compared with the reference scenario 1 (see Figure 5-5 and Figure 5-7). The results of scenario 5 show that the increase in the floodplain sedimentation is not only related to the restoration area but also to the entire river system (see Figure 5-5 and Figure 5-7). Overall, the transport of sediment in downstream direction also depends on the location of a river restoration. Generally, an increased trapping of sediment in an upstream area of a river leads to downstream depletion of sediment (unless bank erosion or other additional sediment inputs occur).

Based on the assumption of a fixed riverbed, the numerical model results do not show an increased remobilization of the sediments due to a greater degree in connectivity between the river channel and floodplains. In principle, erosion of the floodplain sediments is possible if the shear stress in the floodplains exceeds the critical shear stress of the floodplains specified during the model setup (12 N/m^2 in this study). The maximum prevalent shear stress required for the erosion of the floodplains for all scenarios is 8 N/m^2. Therefore, the critical shear stress is not exceeded during floodplain inundation and the floodplain sediment deposits are not mobilized. Consequently, the results of all scenarios indicate that the deposition of fine sediment is the dominant transport process on the floodplains.

Additionally, the numerical model results show that an increase in the riverbed elevation and the excavation of floodplains result in an increase in the fine sediment deposits on the floodplains. The contrary results of scenarios 2 and 3 (see Figure 5-5 and Figure 5-7) are due to the topographical effects of the landscape surrounding the restoration areas. In scenario 2, the steep hillsides on the left site of the river (see Figure 5-2, b) are close to the river channel and act as flow barriers in the floodplains. The flow velocities are increased at this bottleneck and the floodplain inundation changes downstream of the restoration intervention, which does not lead to the reconnection of floodplains. Neither the floodplain inundation frequencies nor the floodplain sedimentation increase. Therefore, it can be concluded that the location of the restoration strongly influences the success of the intervention.

River restoration interventions, such as removing fixed riverbeds and banks and initializing the dynamic and natural development of a river floodplain system, are not included in numerical model scenarios but lead to the reactivation of floodplains. For example, Straatsma and Kleinhans (2018) numerically analyzed the effects of side channels, vegetation roughness smoothing, floodplain lowering, embankment relocation or lowering groynes and minor embankments on the sediment transport in a river with embanked floodplains. Generally, the consequences of embankments due to the connectivity between floodplains and the riverbed are similar to those of a deeply incised river such as those analyzed in this study.

From an ecological point of view, fine sediments are often considered as negative and even substrates, which should be reduced or even removed from river-floodplain systems. For example, if the riverbed is predominantly (coarse) gravel, the fine sediment can deposit on or infiltrate the gravel riverbeds (Schruff 2018). For stream managers, it is essential to estimate the potential damage due to fine sediment infiltration, such as the increased energy consumption of pumping wells, lower survival rates of fish spawn, or reduction of the hyporheic exchange of oxygen and nutrients (Schruff 2018). In addition, contaminants might be adsorbed on fine-grained sediments (Salomons et al. 1995; Schüttrumpf et al. 2011; Brinkmann et al. 2015) and can therefore be deposited on the riverbed or floodplains and potentially be remobilized by subsequent flood events (Förstner 2004; Cofalla et al. 2012; Zhao and Marriott 2013).

River restoration interventions in old-industrial areas such as the ones analyzed in this study can have negative effects on the distribution of contaminants or positive effects because of the improvement of chemical and ecological conditions (Maaß et al. 2018a). It is important to evaluate the contamination of a study site using its “natural” state because the initiation of “natural” morphodynamics includes the transport of fine sediment as an intrinsic component of river-floodplain systems. The deposition of fine sediments is a natural process that can only be increased by anthropogenic activity.

5.4.2 Historical and present-day degree of connectivity between the riverbed and the floodplains

The analysis of the effects of river restorations, especially the effects of reactivated floodplains (in this study) on the fluvial morphodynamics leads to the following questions: What does “natural” morphodynamics actually mean? Is a greater degree of connectivity between the river channel and floodplains really “natural”? What is the evidence for a greater degree of connectivity in the past?

Channel patterns describe the planform of a river, which reflects the interaction of the river channel with its floodplains and can change depending on environmental variations (Candel et al. 2018). Consequently, they reflect the degree of connectivity between the river channel and its floodplains. Candel et al. (2018) studied a low-energy valley river in the Netherlands and reported that the river was laterally stable from the Holocene to the Late Middle Ages and that meanders were anomalies. They found that the bankfull discharge was significantly greater during the meandering phase compared with the laterally stable phase (Candel et al. 2018). They also concluded that the change from the laterally stable to meandering phases might have occurred in other rivers for which an increased Holocene fluvial activity has been reported (Candel et al. 2018). With respect to the connectivity between the river channel and its floodplains, an increased bankfull discharge results in a decreased connectivity. Therefore, “natural” morphodynamics do not reflect a meandering river-floodplain system with a great degree of river-floodplain connectivity, as assumed in many river restoration interventions.

Recently, several studies focused on the anthropogenic history of the Wurm River and rivers like the Geul River or the Inde River with similar geomorphic settings, suspended sediment loads and catchment sizes. The results of different studies by Buchty-Lemke and Lehmkuhl (2018), Hagemann et al. (2018), Maaß and Schüttrumpf (2018, 2019) and Maaß et al. (2018) show that floodplain sedimentation rates can be in an order of magnitude of 1 cm per year if the floodplains are prone to overbank flooding due to a constant impoundment of water at mill weirs and can be decreased to 0.1 cm per year due to incised riverbeds and riverbank heights of approximately 2 m. Here, the floodplain sedimentation rates of all numerical model scenarios vary between 0.5 cm per year and 1 cm per year that overall include natural as well as anthropogenic impacted floodplain accretion conditions of small river systems.

Focusing on the morphodynamic development, the results of these studies show that the Wurm River historically more dynamically meandered and that the floodplain sedimentation rates decreased. The anthropogenic impacts in terms of the construction and removal of water mills along the Wurm River led to the incision of the riverbed, disconnection of the riverbed from the floodplains, and increased bankfull discharge (Buchty-Lemke and Lehmkuhl 2018; Maaß and Schüttrumpf 2019). The comparison of the historical river course shown on Tranchot maps with the present-day river course indicated reductions in the river length, meanderin, and river gradient at a decreased sinuosity and meander migration rate (Buchty-Lemke and Lehmkuh 2018).

With respect to the connectivity between the river channel and its floodplains, “natural” morphodynamics are based on a meandering river with a low bankfull discharge and consequently a high degree of connectivity, as assumed for many river restoration interventions. Consequently, it is important and indispensable to analyze and understand the past conditions of a river and define its natural conditions. The increase in the connectivity might not always lead to a natural morphological river state.

In this study, the numerical model results lead to the conclusion that only anthropogenic activity might have increased the amount of fine sediments deposited on floodplains and accelerated the process of floodplain decoupling from the riverbed in the past centuries. The reactivation of floodplains in river restorations, for example, by increasing the riverbed elevation or lowering the floodplains reduces the anthropogenic floodplain sediment depositions and increases the degree of connectivity between the riverbed and floodplains. Within centuries to millennia, the connectivity between the floodplains and riverbed will decrease due to the increasing floodplain elevation of floodplain sediment deposits. However, if a natural river state includes a larger degree of connectivity, the reactivation of floodplains will definitely increase the fluvial morphodynamics and lead to a natural, dynamic development of the river floodplain system. However, the deposition of fine sediments on floodplains and the ongoing, potentially slow decoupling of floodplains from the riverbed are two intrinsic parts of natural river-floodplain systems and cannot be prevented in river restorations. Floodplain deposition is a natural process.

5.4.3 Assessment of model quality and assumptions

Model assumptions and schematizations are necessary and indispensable in nearly all numerical models and must be evaluated to determine their effects on the model quality (Warmink et al. 2011; Straatsma and Kleinhans 2018). E.g., Berends et al. (2018) investigated the uncertainty of model predictions of intervention effects and analyzed its effects on the predictions of flood mitigation strategies. They concluded that model uncertainty does not invalidate model-supported decision making in river management but enriches it.

The effects of schematizing initial and boundary conditions and assumptions focusing on the suspended sediment transport on long-term numerical modelling studies have been extensively described by Maaß and Schüttrumpf (2018). In this study, numerical modelling scenarios are performed on only one sediment size fraction that is transported in suspension with a median diameter (D_{50}) of 24.5 µm (silt). The critical shear stress required for erosion of the floodplain was set to 12 N/m^2 and the maximum prevalent shear stress in the floodplains is only 8 N/m^2. Therefore, remobilization of floodplain deposits does not occur. If the sediment diameter of the model is smaller than 24.5 µm, resuspension of the particles might occur, and the sediment might not be deposited on the floodplains. If the sediment diameter of the model is larger than 24.5 µm, sediment deposition might occur closer to the channel, which would change the spatial distribution of the floodplain deposition. The numerical modelling scenarios in this study focus on long-term analysis and short-term sediment transport processes, such as flocculation, resuspension, or coagulation, are not considered. Thus, the overall study results do not strongly depend on the chosen sediment diameter.

In this study, one of the main assumptions of the numerical modelling approach was that the river channel is fixed. As already summarized by Lauer and Parker (2008b), Wolman and Leopold (1957) stated that if vertical accretion on a floodplain continuously takes place without the removal of any sediment, the channel banks would grow in elevation until they eventually become too high such that the channel would rarely flood adjacent floodplains. In the long-term, this cause-effect relation would occur under the assumption of a fixed river channel. However, as meandering rivers migrate, they tend to remove material from cut-banks and deposit material in point bars and floodplains (Lauer and Parker, 2008b).

In natural river systems, local erosion phenomena and further incision of the riverbed occur over time scales of decades to centuries. These processes were not considered in the schematized numerical model, especially not in the different scenarios in this study, because the incision of the riverbed would lead to a disconnection of the floodplains from the riverbed. Neglecting these potential, locally developing erosion phenomena results in an overestimation of the reconnection of the floodplains, higher floodplain inundation rates, and higher fine sediment deposits on the floodplains.

The river bank erosion processes and river meandering were analyzed by Schuurman et al. (2016, 2018) using different numerical approaches. Schuurman et al. (2016) analyzed the interaction between bars and bends, which leads to meander initiation, and the effect of different methods on the modelled bank erosion and floodplain accretion dynamics of high-sinuosity channels with strong excitation when the inflow is periodically perturbed. Their study results show that both dynamic upstream inflow perturbation and bar-floodplain conversion are required for sustained high-sinuosity meandering (Schuurman et al. 2016). Schuurman et al. (2018) investigated the effects of higher peak discharges on the channel pattern and dynamics of bars, floodplain, and channel branches in a braided reach of the Upper Yellow River using a numerical model. Their results showed that the local-scale processes determining the channel-floodplain conversion and floodplain destruction have reach-scale effects on the braided river and they indicated the need for physics-based methods for bank erosion modelling (Schuurman et al. 2018).

In addition to riverbank erosion and meandering, the effects of the cohesion of floodplain sediments and vegetation are also not considered in this study. Kleinhans et al. (2018) extensively compared the isolated and combined effects of mud and vegetation on the river planform and morphodynamics in intermediate-size valley rivers using a numerical model for the century-scale simulation of the flow, sediment transport and morphology. They concluded that valley-flooding water levels increase with the vegetation density, causing a higher braiding intensity rather than meandering tendency (Kleinhans et al. 2018). They also concluded that an increase in the concentration of floodplain aggradation reduces the overbank flow frequency and ultimately causes the formation of single-thread channels (Kleinhans et al. 2018).

Considering such natural morphodynamic processes such as meander migration, changes in the river course, and river widening or narrowing, in a numerical model is only possible by making further assumptions and schematizations (Spruyt et al. 2011) and not applicable for numerical models with time scales of decades to centuries. Overall, the impact of natural processes and human activities on a catchment area increases with decreasing catchment size and not all impact factors can be implemented in detail in a numerical model. The schematization, discretization, and parameterization are indispensable regarding the grid approximation, course of the river, water inflow, and sediment input as well as erosion and deposition processes especially for long-term morphological modelling investigations. However, the numerical model results are always a useful tool to assess river management strategies. Based on a schematized river-floodplain system representing the main characteristics of a set of systems (here small gravel-bed rivers deeply incised with large amounts of fine sediment deposited on the floodplains), the consequences of different scenarios can be investigated in an appropriate period and the fundamental changes of fine sediment deposits on floodplains can be determined.

5.5 Conclusions

In addition to many other measures, increasing the riverbed elevation or lowering the floodplain elevation are two examples of river restoration interventions focusing on an increase of the surface water connectivity between the main channel of a river and its floodplains. Such a reactivation potentially has extensive consequences on the fluvial morphodynamics and mobility of fine sediments. The objective of this study was to analyze the long-term effects of reactivated floodplains on the mobility of floodplain deposits of small rivers. The long-term changes of the floodplain sedimentation rates were determined using a numerical model based on the Delft3D software. The characteristics of the numerical model were based on the characteristics of the Wurm River (Lower Rhine Embayment, Germany) as an example for a small meandering lowland river in Western Europe impacted by diverse natural and anthropogenic factors. The results of the model scenarios show that:

- the increase in the riverbed elevation and lowering of the floodplains generally lead to higher floodplain sedimentation rates,
- lowering the floodplains has a greater impact on the reactivation of floodplains than the increase in the riverbed elevation independent of the location of the restoration area, because floodplain inundation occurs earlier during the discharge, which leads to longer sediment settling,
- the increase in the surface water connectivity of an elevated riverbed with its floodplains strongly depends on the location and topography of the restoration area considering also depletion of sediment in downstream direction if the restoration is located in an upstream part of the river and
- river restorations can lead to increased flow velocities and alter the floodplain connectivity downstream of the restoration intervention, leading to floodplain inundation at earlier discharge stages and longer sediment settling.

Overall, based on the assumption of a fixed river channel, the reactivation of floodplains in river restorations decreases because anthropogenic activity accelerates floodplain sediment deposition and leads to a greater degree of connectivity between the riverbed and floodplains. In this study, this process is predominantly driven by the increase in floodplain inundation at earlier discharges due to lowering of floodplains. However, such a reactivation of floodplains will increase the fluvial morphodynamics and lead to a natural, dynamic development of the river floodplain system, but the deposition of fine sediments on floodplains and ongoing, potentially slow decoupling of floodplains from the riverbed are two intrinsic parts of natural river-floodplain systems and cannot be prevented by river restorations.

Acknowledgements

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6 Synthesis and outlook

6.1 Summary

In the preceding chapters, several approaches were used to meet the objective of this thesis, which was to improve the understanding of sediment transport processes and morphological changes on a river basin scale of small river-floodplain systems and to use this knowledge during the planning, realization and monitoring of river restorations (Chapter 1). The thesis focuses on the effects of three exemplary technical human impacts since the Industrial Revolution on the fluvial morphodynamics of small river-floodplain systems in Central to Western Europe.

- First, a literature review in combination with a theoretical analysis was performed to describe the life cycle of water mills and its consequences on the longitudinal river profile and the floodplain sedimentation (Chapter 2).
- Second, a literature review was performed that describes the appearance and the consequences of mining subsidence in a river catchment and its consequences on the longitudinal river profile. A 2D-numerical modelling study based on the characteristics of the Wurm River (Germany) was used to investigate the effects of mining-induced subsidence on the sediment trapping efficiency of floodplains (Chapter 3).
- Third, the fluvial morphodynamics of the relocated and restored Inde River reach were analyzed over a period of almost 15 years taking sediment samples, analyzing echo soundings of the river's bathymetry and determining the heavy metal content of the sediment as a tracer material for the morphological development (Chapter 4).
- Finally, the long-term effects of reactivated floodplains in terms of river restorations on the mobility of floodplain sediment deposits of small rivers were analyzed (Chapter 5).

The specialty of this thesis is the long-term numerical modelling approach that is not comparable to other short-term hydro- and morphodynamic research (see Chapters 3 and 5). The results of this thesis show that for long-term morphological modelling investigations, schematization, discretization and parameterization are indispensable regarding grid approximation, course of the river, water inflow and sediment input as well as erosion and deposition processes. But overall, numerical model results are always a useful tool to assess river management strategies. Here, e.g., the consequences of different scenarios can be investigated in an appropriate period and fundamental changes of the mobility of fine sediment deposits on floodplains can be determined (see Chapter 5). Besides numerical models, extensive field measurements over time scales of years (continuous turbidity measurements, see Chapter 5) or of decades (e.g., yearly echo soundings, see Chapter 4) can be conducted to analyze the long-term morphological development of a river.

The presence of water mills creates an underrated, but historically long-lasting human impact on river-floodplain systems. The effects of the construction and removal of water mills on the longitudinal river profile and the floodplain sedimentation can be seen as an example for the general effects of transverse structures. The results of a theoretical analysis complemented with field measurements and a DEM analysis showed that the construction and removal of water mills likely result in net incision of the river bed into the ground to a level below the original bed, in reduced floodplain inundation rates, and consequently in reduced floodplain sedimentation. The case studies of the Wurm River and the Geul River showed that even if the impact of water mills is primarily seen as an historical impact, the morphological changes are still present in today's river systems and the river-floodplain system does not develop on its own towards the initial situation before water mills were build (Chapter 2).

Besides the influence of water mills, mining subsidence has a long-lasting impact on the trapping efficiency of the floodplains. Land subsidence in riverine environments, which are caused by the extraction of coal in subsurface mining tunnels, results in local or large-scale ground surface irregularities, where sediment can be eroded or deposited during floods. In the Wurm River catchment, underground coal-mining was present during the 19th and 20th century. The 2D-numerical modelling results showed that if subsidence occurred in the inundation area of a river, increased average floodplain sedimentation occurred independently of its size, depth, or location relative to the river, which led to an increased trapping efficiency of floodplains (Chapter 3).

The example analysis of the fluvial morphodynamics of the Inde River (North-Rhine Westphalia, Germany) between 2005 AD and 2018 AD showed that the new Inde River has reached a dynamic morphological equilibrium, which has improved and still improves its natural hydrological and morphological conditions as an ecological habitat. After almost 13 years of adaptation processes, the Inde River itself is in a dynamic equilibrium, and its new surrounding landscape has developed towards a quasi-stable system. It is concluded that the new Inde River has developed towards its pre-defined guiding principle within its anthropogenic restrictions caused by the open-pit lignite mine Inden. Especially due to the length (12 km) of the new constructed river bed, the Inde River is an appropriate study area and a representative example showing that achieving a dynamic morphological equilibrium after a river relocation and restoration is possible after only one decade (Chapter 4).

The numerical model results of a river-floodplain system loosely based on the main characteristics of the Wurm River as an example for a small meandering lowland river impacted by diverse natural and anthropogenic factors were used to analyze the long-term effects of reactivated floodplains in river restorations on fine sediment floodplain deposits. The specialty of the numerical investigations performed in this study was the morphological long-term analysis over time scales of decades, which is not comparable to other short-term hydro- and morphodynamic research at small meandering lowland rivers. The results of all model scenarios show that lowering the floodplain and raising the riverbed elevation both lead to an increase in the fine sediment deposition on the floodplain. Independent from the location of the restoration area, lowering the floodplain has a greater impact on the reactivation of floodplains than raising the riverbed elevation. Overall, it can be concluded that numerical model results are always a useful tool to assess river management strategies. Based on a schematized river-floodplain system representing the main characteristics of a set of systems, consequences of different scenarios can be investigated in an appropriate period of time and fundamental changes of fine sediment deposits on floodplains can be determined to choose the most effective alternative (Chapter 5).

6.2 Assessment of research results

The results of this thesis contribute to a better understanding of the historical and future development of small meandering gravel-bed rivers with large floodplains, where suspended sediment accounts predominantly for the deposition of sediments on floodplains. In small river-floodplain systems, especially fine sediment (< 2 mm) is transported sometimes already during mean discharges, whereas coarse sediment is only rarely transported even during flood discharges. These transport processes greatly differ in larger river-floodplain systems, which emphasizes the importance of the consideration and analysis of fine sediment transport in small river-floodplain systems.

The results of this thesis show that consequences of historical impact factors like water mills (see Chapter 2) or mining-induced subsidence (see Chapter 3) are still present in today's river-floodplain systems due to, e.g., anthropogenically increased amounts of fine sediment deposits on floodplains (due to the construction of transverse structures), deeply incised river beds and therefore decoupled floodplains (due to the removal of transverse structures) or locally and temporarily increased floodplain sedimentation rates (due to mining-induced subsidence). This understanding helps river managers to successfully design, realize and monitor restoration interventions successfully and sometimes to answer the question, if a continuous (fine) sediment transport should be promoted or limited.

Today, many river restorations are accompanied by the removal of transverse structures to ensure better passability for fish and/or continuous transport of sediment. But, the synergy of construction and removal of these transverse structures will always result in incision of the river bed. Buchty-Lemke and Lehmkuhl (2018) also analyzed the impacts of the abandonment of historical water mills of the Wurm River. They concluded that the abandonment of the mill and removal of the weir triggered a morphological adjustment process that created terraces upstream of the mill and balanced the mill-induced knickpoint in the longitudinal profile. However, such an adjustment process can be superimposed by anthropogenic influences that control the availability of sediment and discharge conditions and channel and planform changes are different in straight, meandering and fixed river reaches. Direct human activities and the way in which the mill abandonment was conducted additionally control the fluvial morphodynamics (Buchty-Lemke and Lehmkuhl 2018). Furthermore, effects of channel instability and river widths variations are analyzed by, e.g., Downward and Skinner (2005), Chang (2008) or Bishop et al. (2011).

In literature, only a few controversial results of the impact of water mills on fluvial morphodynamics can be found. E.g., Donovan et al. (2016) focused their research on the mid-Atlantic region and stated that channel banks in close proximity to breached mill dams serve as hotspots of local erosion and deposition, but that not all sediment hot spots are mill dams and that not all mill dams are hotspots. Although historical mill dams and legacy sediments are widespread, they do not necessarily have uniform impacts on sediment yield (Donovan et al. 2016).

From a more general point of view, the impacts of increased bank heights due to water mills on the fluvial morphology are similar to those of embankments (Hesselink et al. 2003; Frings et al. 2009; Zhang et al. 2017). Due to the higher floodplains, bankfull water levels are increased in the main channel in comparison to the water levels predating mills. The increased water levels cause an increase in the shear stresses. An increase of the bed shear stress typically leads to the erosion of fine grains and coarsening of the river bed grain sizes (Frings et al. 2009). Here, incision is also associated with problems that continue today such as in the excavation of pipelines and the construction of foundations for engineering works and in navigability issues during low flow, as well as the drying of natural vegetation on the embanked floodplains.

Focusing on the numerical model results (Chapters 3 and 5), the neotectonic activity of the catchment area of the Wurm area due to the neotectonic fault (the so-called Feldbiss) is not considered in both numerical models. Due to the Feldbiss, the area is neotectonically active with an overall tilting rate of 2-10 mm/a. The Feldbiss passes northeast of Herzogenrath and is therefore not included in the numerical modeling areas. Overall, this neotectonic activity would lead to an increase in height of the entire model area in comparison to the locally arising mining subsidence.

In Germany, tectonic movement due to underground coal-mining is especially present at rivers in the Ruhr area such as the Emscher and the Ruhr River, but with a greater magnitude. Most of the river banks in these two rivers are now embanked to protect the adjacent areas from flooding, which is especially important here because urbanization is dominant in the Ruhr area (Bell et al. 2000; Harnischmacher and Zepp 2010; Harnischmacher 2012).

The consequences of subsidence due not only to underground coal-mining but also to mining of plumb or other types of soil extraction (e.g., salt) from the ground (see, e.g., Gomez and Marron 1991, Benito et al. 1998 or Bell et al. 2000) are the same as those mentioned in Chapter 3.

Today, river-floodplain systems are more often affected by uplift effects due to rising groundwater levels, but the increase in elevation due to mining uplift effects will be less than the decrease in elevation due to mining-induced subsidence (Heitfeld et al.; Rosner 2011; Harnischmacher and Zepp 2016).

Focusing on the superposition of the effects of water mills and mining subsidence, the results of this thesis show that understanding especially small river-floodplain systems means understanding their entire catchment area. Due to the variety of human activities, there might be impact factors which have greater consequences on the fluvial morphodynamics, e.g., the impact of a chain of transverse structures in contrast to the occurrence of mining-induced subsidence. The results of this thesis show that the interaction of the construction and removal of transverse structures such as water mills (see Chapter 2) results in a deeply incised river bed and that mining-induced subsidence at these river-floodplain systems plays a minor role because floodplains are rarely inundated and sediment cannot reach the subsidence areas (see Chapter 3).

Water mills and mining-induced subsidence are two examples of all the diverse anthropogenic impact factors in small river basins, whose morphodynamic consequence – of a deeply incised river with high, steep banks and decoupled floodplains containing large fine sediment deposits – is characteristic for many river-floodplain systems in Central to Western Europe and must be taken into account during river restorations to consider and evaluate the consequences of fine sediment on future river development. The results of this thesis show that assessing future morphological changes of river-floodplain systems in advance of a restoration intervention is essential for its success, e.g., focusing on the choice of sediment for the river bed to avoid unintended river bed erosion and fine sediment input in downstream direction (see Chapter 4) or focusing on the type of reconnecting floodplains (see Chapter 5). The results also show that restorations need to encompass anthropogenic restrictions of the catchment area (e.g., the presence of an open-pit lignite mine, see Chapter 4) and the general landscape development such as vegetation growth (see Chapter 4).

In the theoretical (Chapter 2) as well as in the numerical analyses (Chapter 3 and 5), vegetation is considered by a friction coefficient and does not change over time. Indeed, the results of van Oorchot (2017) and the results of Chapter 4 show that the vegetation cover affects the morphological development of a river-floodplain system to a certain extend. A monitoring program of a time period of more than one decade could not be found in the literature, which underlines the uniqueness of the field measurements at the Inde River. E.g., the studies of Pasquale et al. (2010) and Chapuis et al. (2015) were conducted over a time period of only 1 or 2 years, so that the results of the morphological development strongly depend on the discharges present during this time. Long-term monitoring programs should be performed to verify the restoration success and to filter out the local effects of natural variation such as the influence of vegetation cover (van Oorschot 2017).

6.3 Returning to a natural morphological river state

Restoration interventions are always in an area of tension between securing flood protection, re-establishing “natural” discharge conditions, considering urban management and protection of historical buildings, “natural” river development and maintenance as well as public perception and acceptance (Berends et al. 2018). Wohl et al. (2015) stated that there is a challenge for river restoration focusing on the large gap between knowledge of processes such as sediment transport and the ability to use that knowledge for prediction or measurements within river restorations.

In former times, changes in river-floodplain systems resulted from economic aspects. Today, especially ecological and nature conservation are focused. However, the overall aim of a sustainable and “natural” river management should not focus on only one of these aspects, but should include all aspects: ecological, social, economic and morphodynamic aspects (Schüttrumpf and Niemann 2016). Such an encompassing approach is already defined in the EU Water Framework Directive. To achieve these goals, it is necessary to focus more on the interactions between ecology, hydro- and morphodynamics and not on each factor individually (Schüttrumpf and Niemann 2016). Therefore, “natural” river dynamics are often wrongly perceived and classified as human-induced river dynamics. Based on the ten misinterpretations of fluvial morphodynamics (Frings and Maaß 2018) stated in Chapter 1 and the results of this thesis, the following ten interpretations of fluvial morphodynamics can be formulated:

1. Natural river systems are dynamic systems.
2. Erosion and deposition of sediment are intrinsic components of fluvial morphodynamics.
3. Sediment transport is a spatial and temporal variable process.
4. Natural rivers always transport different sizes of sediment at different discharge conditions.
5. The transport of fine sediment is present in natural rivers.
6. Historical human impacts are indispensable components of today’s river-floodplain systems and need to be considered during river restorations.
7. Restoring the sediment continuity should be decided for each river system individually in dependence of today’s river function.
8. River restoration measures should be based on the river basin scale and a river-specific sediment budget.
9. Measures at a river-floodplain system affect the entire system and their consequences should be investigated in advance.
10. Numerical model investigations and field measurements are a useful tool and necessary to analyse the long-term morphodynamic development of river-floodplain systems.

Overall, morphodynamic active rives are spatially and temporarily variable and does not represent one “natural” reference state. Rivers are dynamic systems that will not remain in one morphological state, but will continuously change due to external effects such as varying discharges even without any human impact. Understanding the history of fluvial morphodynamics and their long-term changes is essential for restoring river-floodplain systems (Wohl 2005; James and Marcus 2006). The sustainability of restorations is often neglected in restoration projects. Frings and Maaß (2018) mentioned that it is already embedded in the EU Water Framework Directive that it is not possible to achieve a "natural" morphological state. Generally, sediment should not be seen as a disturbing factor, but should be seen as an intrinsic, inseparable part of river-floodplain systems. The success of river restorations depends on substantial knowledge about historical as well as present-day fluvial morphodynamics. Such a knowledge can be acquired, e.g., with sediment fingerprinting, sediment tracing and sediment budget analyses (Frings et al. 2014a; Frings et al. 2014b; Frings and Ten Brinke 2017; Hillebrand and Frings 2017) based on analysis of historical maps as well as theoretical, physical or numerical models.

Even though it is sometimes possible to restore an initial, "natural" hydrological situation, but it is (often) not possible to achieve initial, "natural" morphodynamic conditions. Human impacts of the last decades to centuries have irreversibly changed the fluvial morphodynamics. But, ending up some human impact factors, it might be possible to restrict further unintended and negative morphological changes and to transform river-floodplain systems in a state, which is of equal value as the natural morphological state (Koenzen 2005; Frings and Maaß 2018).

6.4 Outlook

Lots of research already focuses on human impacts on large river-floodplain systems (macro-catchments) (Lewin et al. 2005; Frings et al. 2009; Hoffmann et al. 2009). Understanding fluvial morphodynamics on river basin scales is always important to investigate not only general impact factors (like sealing of the ground, deforestation, the construction of transverse structures or restoration interventions), which influence the whole river-floodplain system, but also small-scale impact factors like mining-induced subsidence, which locally influence floodplain deposition and may lead to a hotspot of (contaminated) sediments.

Even though research with a local focus has increased, there is still a lack of information of the historical development of a river catchment on a regional scale (Starkel 2002). The results of this thesis show that there is already a superposition of human impacts in river catchments classified as meso-catchments such as the ones of the Wurm, the Geul and the Inde River. This superposition results from different anthropogenic impacts present in the meso-catchment and also from impact factors affecting the tributaries (micro-catchments). A clear identification of the effects from mirco-catchments have not been reported so far. Therefore, a detailed analysis of the relationship of micro- to meso- to even macro-catchments should be subject of future research. Micro-catchments are suitable for long-term impact-based analyses because anthropogenic changes have direct consequences on the river-floodplain system and a higher spatial and temporal resolution of morphological investigations is possible (Rommens et al. 2006; Notebaert and Verstraeten 2010).

Additionally, morphological changes occur mainly during flood events. Floodplain inundation is rarely seen at deeply incised rivers with high, sharp banks and decoupled floodplains and only occurs after heavy rainfall with short leading times or snowmelt. Therefore, investigations of fluvial morphodynamics should always be carried out over long time scales to capture especially these morphologically significant events. Overall, the different human impact factors in a river catchment should be individually investigated on a micro- to a macro-catchment scale to include the entire range of river catchment sizes. In future, the interdisciplinary analysis of river catchment and landscape development combing field measurements and numerical modelling will increase and will need further research (Tarolli 2016; Verstraeten et al. 2017).

Overall, this thesis shows how different human impact factors affect sediment transport processes and fluvial morphodynamics. Sediment transport and especially morphodynamic processes are often long-lasting processes. Theoretical analyses, numerical modelling studies, continuous or repetitive field measurements over several years are useful tools to investigate these processes. All these tools require several assumptions and simplifications, which are indispensable in order to analyze time scales of decades to even centuries. It is always important to evaluate and discuss these assumptions focusing on an encompassing picture of river-floodplain systems. River systems are always (morpho-)dynamic and react to all natural and anthropogenic impact factors present inside the system. Understanding the system means understanding its history as well as its present conditions and investigating its future implications.

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Appendix

Supplementary material related to Chapter 3

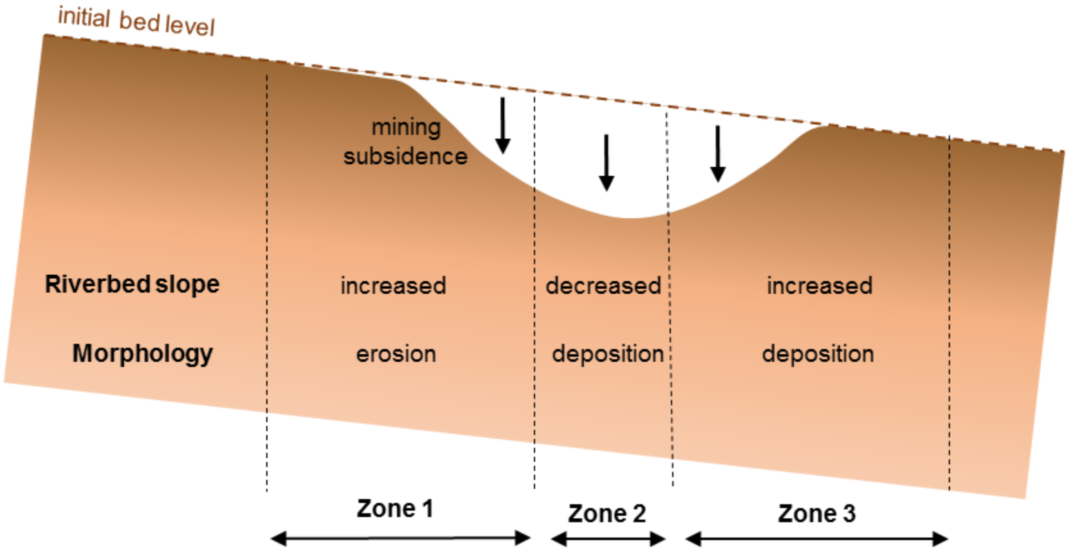

Figure A.1: Schematized effects of mining-induced subsidence on a length scale of several river widths underneath the river bed on morphology (modified after Holbrook and Schumm 1999)

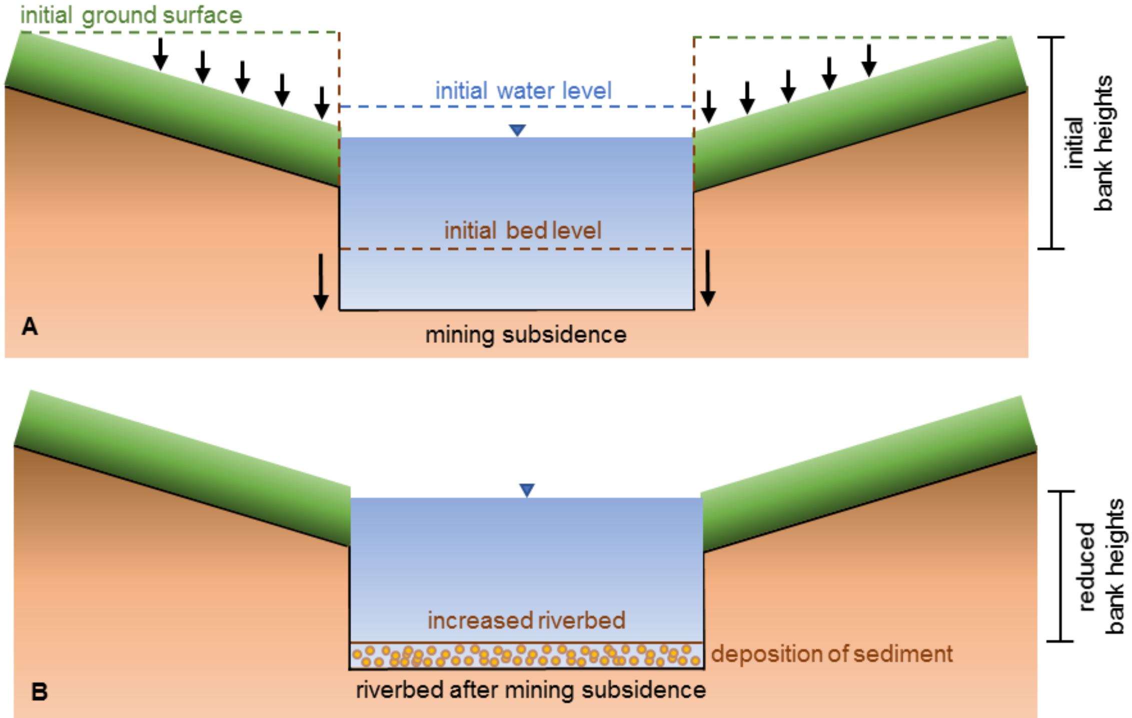

Figure A.2: Cross-sectional profile of mining subsidence underneath the river bed; B: Cross-sectional profile due to river bed aggradation inside the subsidence area.

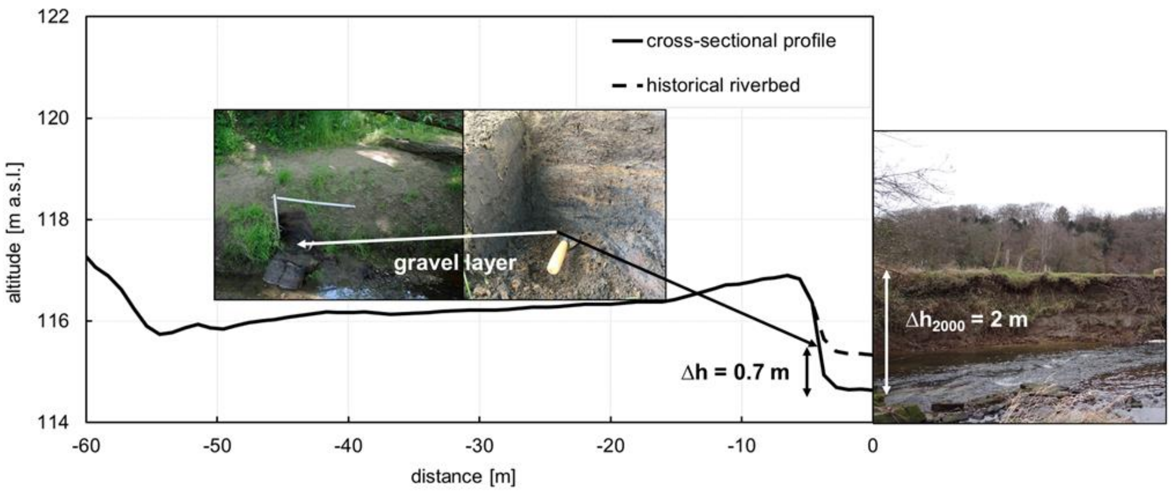

Figure A.3: Example of the relation between the actual and the historical river bed of the Wurm River

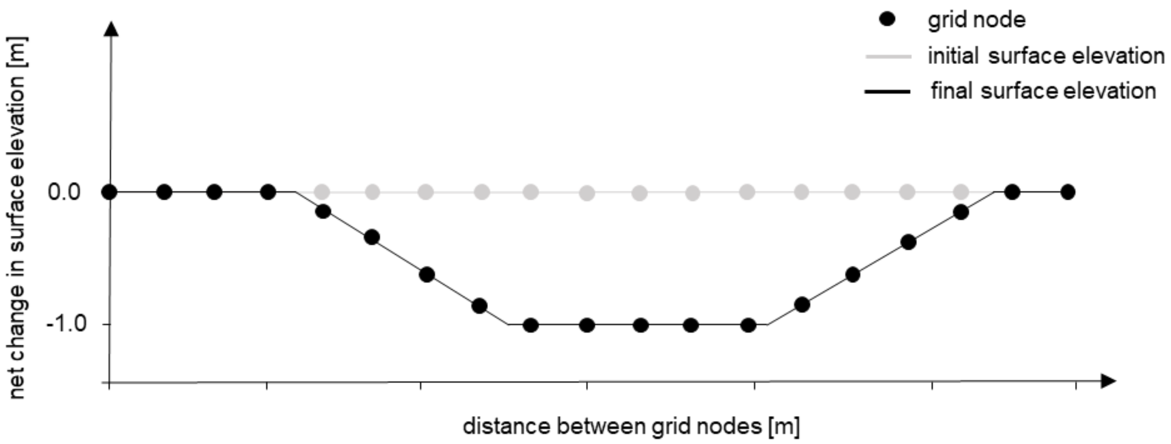

Figure A.4: Subsidence occurring on a computational grid in Delft3D (depth 1 m, slope angle 45°)

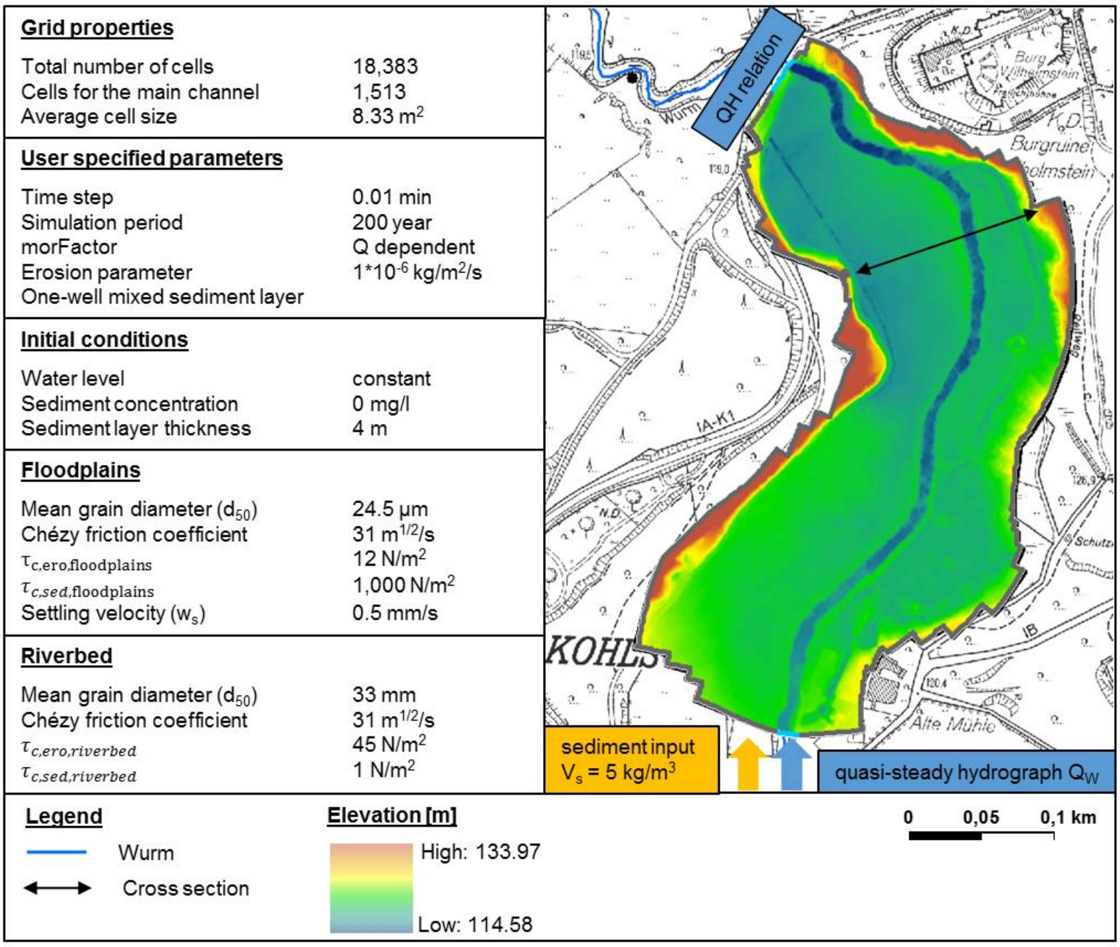

Figure A.5: Parameters used in the numerical modelling of the Wurm River study area

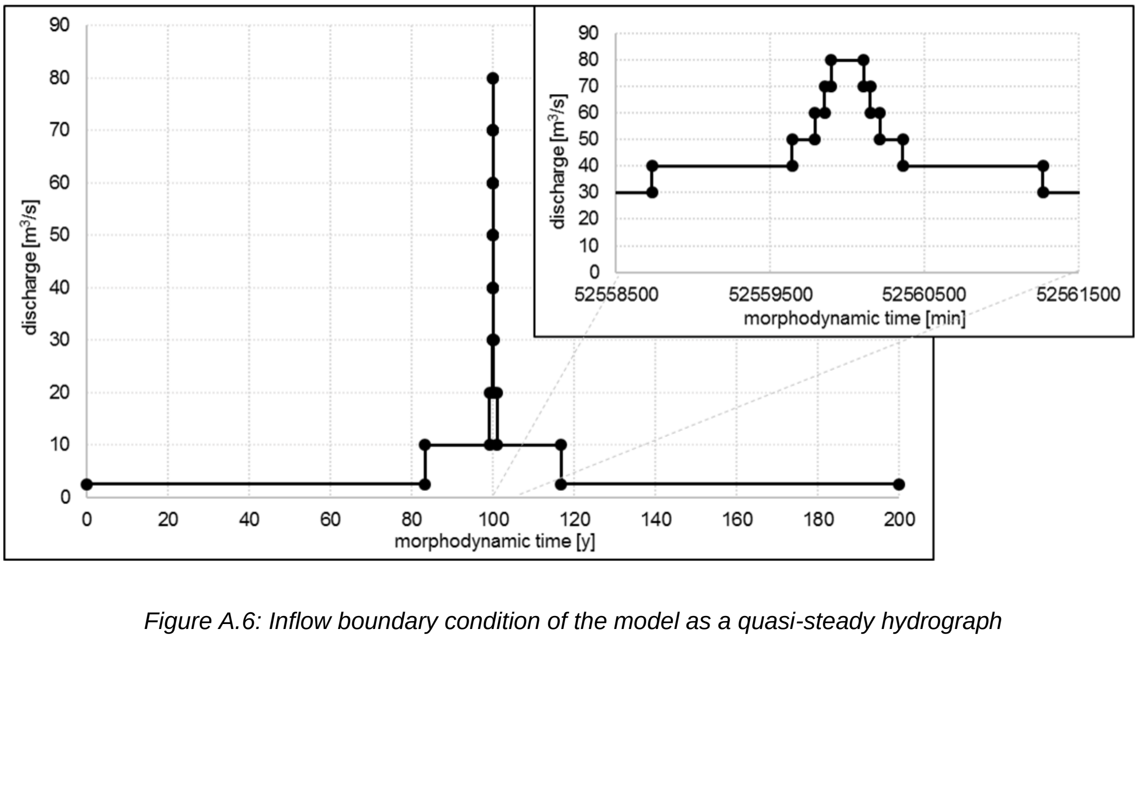

Figure A.6: Inflow boundary condition of the model as a quasi-steady hydrograph

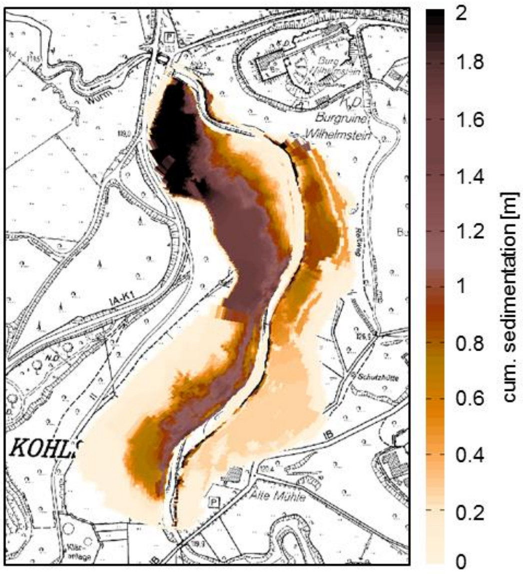

Figure A.7: Cumulative sedimentation modelled with Delft3D between 1800 AD and 2000 AD in the research area.

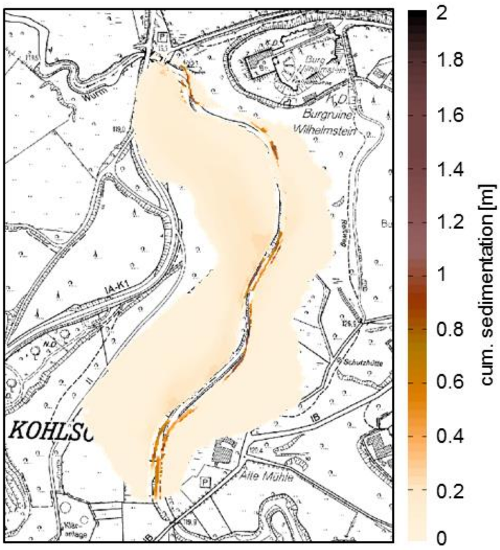

Figure A.8: Cumulative sedimentation modelled with Delft3D between 2000 AD and 2200 AD in the research area.

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Curriculum Vitae

Personal data	
Name	Anna-Lisa Maaß
Date of birth	31st December 1990
Place of birth	Gelsenkirchen
Scientific career	
11/2015-03/2019	**Research Engineer**
	Institute of Hydraulic Engineering and Water Resources Management
	RWTH Aachen University
10/2013-10/2015	**Master’s degree**
	Business Administration and Engineering: Civil Engineering
	Specialization: Water Engineering and Management
	RWTH Aachen University
	Master thesis
	Hydrodynamische Modellierung und Analyse des dispersiven, tide-beeinflussten Stofftransports zur Abbildung im Bilanzmodell OSBIMO
	Department of Engineering Hydrology
	RWTH Aachen University and Hydrotec Ingenieurgesellschaft für Wasser und Umwelt mbH, Aachen
10/2010-10/2013	**Bachelor’s degree**
	Business Administration and Engineering: Civil Engineering
	Specialization: Water Engineering and Management
	RWTH Aachen University
	Bachelor thesis
	Das Lattice-Boltzmann-Verfahren zur Beschreibung der Fluid-Partikel-Interaktion: Vorteile, Nachteile, Forschungsbedarf
	Institute of Hydraulic Engineering and Water Resources Management
	RWTH Aachen University

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7. **Maaß A.-L.**, Schüttrumpf H. (Accepted Manuscript) Reactivation of floodplains in river restorations: Long-term implications on the mobility of floodplain sediment deposits, Water Resources Research.

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