River Flow 2010 - Dittrich, Koll, Aberle & Geisenhainer (eds) -  ISBN 978-3-939230-00-7

# Morphological characteristics of the river Rhine between Iffezheim and Bingen

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ABSTRACT: The objective of the present study is an analysis of the morphological development of the river Rhine between Iffezheim and Bingen (km 335-530), focusing on the period between 1990 and 2008. This analysis forms the basis for an optimization of the existing river training structures and maintenance strategies. The input data used for the investigation are sediment transport measurements, echosounding data and dredging/sediment supply data. Potential errors in these input data are discussed. The analysis shows that in its present state, being altered by extensive engineering works during the last two centuries, the river Rhine is morphologically not in a dynamic equilibrium state. For the echosounding measurements a scale-dependent consideration of the data is required. On a large scale ($10^2$ km) the morphological development between 1990 and 2008 was characterized by general bed degradation. Only a few river sections had a stable bed, or were subject to bed aggradation. Furthermore, the analysis reveals that within the study reach, the bed load transport rate decreases in the downstream direction, whereas the transport rate for suspended load increases. A small-scale consideration ($10^1$ km) of the bed variations reveals a more frequent change between zones of aggradation and degradation, respectively. These changes express sediment movements that are linked with local effects of changing channel geometry, river training structures, sediment supply or dredging.

*Keywords: Sediment transport, Bed morphology, Field data, Numerical model, River training structures*

## 1 INTRODUCTION

The Rhine is one of the most important rivers in Europe, with a length of about 1,230 km and an average discharge of about 2,300 $m^3/s$ at the german-dutch border. Its importance is pointed out by the traffic intensity which reached values of 207.5 million tons of goods transported on the river in 2008.

The river Rhine in its present state is affected by extensive river training works that have been executed during the last two centuries. Particularly, ten barrages constructed between Basel (Rhine-km 150) and Iffezheim (Rhine-km 334) at the franco-german border between the years 1928 and 1977 had and still have a large impact on the morphological state of the river. The barrages cause a complete retention of the bed load transported from upstream. As a consequence, a bed-load deficit exists downstream of the barrages, which caused significant bed erosion in the past.

Since 1978, bed erosion downstream of the last barrage at Iffezheim is compensated successfully by artificial addition of bed load material (WSA Freiburg, 1998). Despite this success story, river correction works, dredging and sediment nourishment at other locations are still required to realize reliable conditions for safe and easy navigation of inland vessels.

The objective of the present study is an analysis of the morphological development of the river Rhine between Iffezheim and Bingen (Rhine-km 335-530). The focus is on the period between 1990 and 2008. In addition, the existing knowledge about correction works and the related morphological processes occurred during the last two centuries must be incorporated into the considerations.

A main focus of the study is the optimization of the interaction between river training structures, dredging and sediment supply activities. Consequently, the mutual influence between large-scale and small-scale effects poses a challenge to the understanding of the river system. For example, at which spatial and temporal scale this mutual influence becomes significant is an important question that needs to be considered.

In the present paper, the data base and the methodology of the study are being described and first results are presented.

Figure 1. Area of investigation

## 2 DATA & METHODS

### 2.1 *Sediment transport measurements*

The bed-load and suspended-load transported by the river Rhine have been measured systematically by the German Federal Waterways and Shipping Administration since the 1970s.

Bed-load measurements are done with the BfG bed-load sampler (a Helly-Smith like device), a sampler with an orifice of 16 cm width and 10 cm height. Since the 1990s, a sampling bag with a mesh size of 1.4 mm is used. On the sampler a camera is attached to enable an accurate positioning on the river bed. To measure the bed-load transport in a cross-section, the cross-section is divided into 5 to 10 subsections. In each subsection several bed-load samples are taken from the same anchoring position. The total sample duration per subsection typically is 15 minutes. After converting the sample volumes into subsection-averaged bed-load transport rates, these are integrated over the river width to get the total bed-load transport.

The suspended load transport is derived from simultaneous measurements of the sediment concentration (pump samplers) and flow velocity (propeller meters), carried out at 5 to 10 positions across the river width and at four different depths. After multiplication of concentration and velocity, the outcomes are integrated over the flow depth and river width to obtain the total suspended transport. With a 0.063 mm sieve, the suspended sand is separated from the finer suspended particles. Only the sand part of the suspended load contributes to morphological change. The finer particles are very scarce in the river bed of the Rhine and are considered to be wash-load.

All transport measurements are stored in the Sediment Database (SedDB) of the BfG. For this study, the measurements from the period 1996-2006, which is a period with a high data density, were analyzed. In the study area (Iffezheim-Bingen), 13 measuring sites are situated at which the transport rate was measured at least 15 times between 1996 and 2006. For these sites, a relation was established between sediment transport and flow discharge (sediment rating curves). This was done separately for bed-load and suspended sand load. An example is given in Fig. 2 for the measuring site at Nierstein (Rhine-km 484).

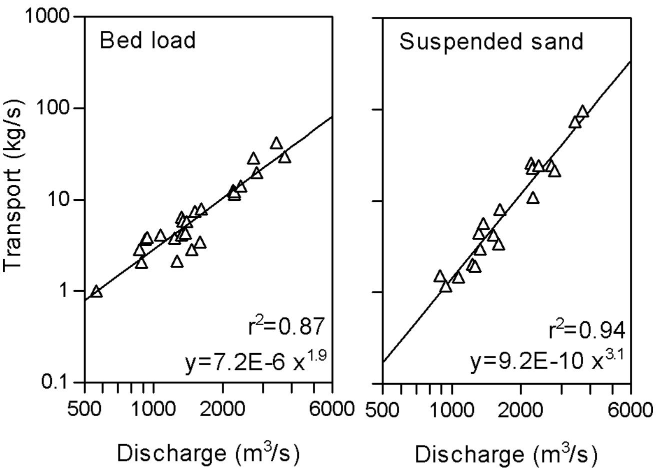

Figure 2. Rating curves for bed load and suspended sand load at Nierstein (km 484).

Power functions were used to fit the data. Other mathematical function types were tested as well, but showed a lower correlation. The rating curves were combined with time-series of daily discharges from the gauging stations of Maxau, Speyer, Worms and Mainz in order to estimate the mean annual sediment load at each of the 13 sites.

Ferguson (1986) demonstrated that annual sediment loads calculated in this way (using power functions to fit the data) are likely to be underestimated. The degree of underestimation increases with the degree of scatter about the rating curve and can reach 50%. In order to correct for this, the calculated loads were multiplied with the correction factor proposed by Ferguson (1986), which reads $c = 2.65s^2$, with $s^2$ the error variance of the rating curve.

Measurements of the sediment transport in a river are subject to stochastic errors and systematic errors. For the measurements in the river Rhine, the relative stochastic error is, according to Kleinhans and Ten Brinke (2001), 10% for suspended load and 50% for bed-load. The systematic error is, according to various tests in laboratory flumes, small. Only at locations with a relatively fine bed, a systematic underestimation of the bed-load may occur because part of the sediment smaller than 1.4 mm passes through the mesh of the sampling bag.

The accuracy of the annual load estimates depends on the accuracy of the measurements, but especially on the number and spread of data points in the transport-discharge relations. Data from (rarely occurring) extreme discharges are scarce and this makes fitting rating curves difficult. We estimate the relative error of the calculated annual loads to be 40-100%. This is a common magnitude of errors in annual loads (Crowder et al., 2007).

## 2.2 *Grain size measurements*

The grain size composition of the river bed was determined by sieve analysis using 1278 sediment samples taken from the top 10 cm of the river bed in the period 1982-2004. Additionally, the grain size composition of the transported bed-load was determined for all sediment transport measurements described above.

## 2.3 *Ecosoundings*

The bed-level elevation of the river Rhine was measured in 1990, 1992, 1996, 1998, 2000, 2002, 2004, 2006 and 2008. During each survey, detailed cross-sections were sounded at 100 m distances with singlebeam echosounders. After correcting the data for outliers, we calculated the bed-level change between subsequent years. We focused on the navigation channel (40-90% of the total river width), because in some years no measurements outside the navigation channel were done. In order to identify large-scale trends, a moving average with a window size of 10 km was applied.

Echosounding data, just as transport data, are influenced by stochastic and systematic measurement errors. Stochastic errors fully average out during the calculation of the width-averaged bed-level, but systematic errors do not. Systematic errors arise because the German authorities have changed the reference system for elevation measurements several times over the last decades. The echosounding data used in this study therefore were corrected according to the recommendations given by Sudau and Bengel (2009). The reference system DHHN 92 was used as a standard for all soundings in the river Rhine. Systematic errors in bed-level data also arise because the echosounding equipment was not always calibrated properly. Although corrections were applied, it is possible that locally a small systematic error of at most 5 cm remains. Bed-level changes of less than 5 cm, therefore, should be interpreted with care.

## 2.4 *Water level measurements*

Temporal changes in water level elevation at low flow stages can be used to reconfirm trends observed in the analysis of bed level changes, as both should be closely related. A method developed at the BfG (Busch et al., 2009) is used to identify temporal trends in stream-wise water level measurements.

## 2.5 *Dredging / Sediment nourishment*

Dredging and sediment nourishment represent direct interventions on the sediment budget of the river bed. Hence, these data are important for an interpretation of the observed morphological development. Dredging and nourishment activities in the river Rhine have been minutely recorded since the 1970s. Accurate information on the volume, date and location of all activities is stored in a database.

## 2.6 *Structures*

Knowledge about existing structures as e.g. groynes or longitudinal training walls is a prerequisite to interpret the observed bed level changes. Here, not only the structures existing at present are of interest. As the morphological development between 1990 and 2008 is in the focus of the present study, adaptations at river training structures during these years must be considered as well. Moreover, the morphological behavior of the river Rhine at its different development stages starting from the first correction works in the year 1817 are needed to improve the understanding of the interaction between structures and the morphological reaction of the river bed.

For the present study, both present and historical development stages are investigated and documented (Schmidt and Wahrheit-Lensing, 2008).

### 2.7 *Numerical models*

Field data are not only used for a direct analysis but also as a basis for numerical models. In case of the present study, both uni- and two-dimensional numerical models with a movable bed have been set up in order to systematically analyze the different factors of influence on the bed level development. Several models with wider range of spatial resolution are used in order to take into account that different effects occur in different morphological scales.

## 3 LARGE-SCALE MORPHOLOGICAL DEVELOPMENT

Geologically, the study reach consists of two parts: the subsiding Oberrheingraben (until Rhine-km 486) and the Rheingau area, which acts as a transition to the uplifting Rhenish Slate Mountains, connecting at the downstream end of the study reach. The latter forms a strong base level control, causing the river gradient in the Oberrheingraben to decrease in downstream direction (Fig. 3).

The analysis of echosounding measurements shows that the overall bed-level within the study reach is slightly degrading with an average rate of 0.5 cm per year (Fig. 4). The bed load transport decreases in stream-wise direction, while the suspended sand transport increases (Fig. 5). This suggests that most of the eroded sediments are quickly washed away in suspension.

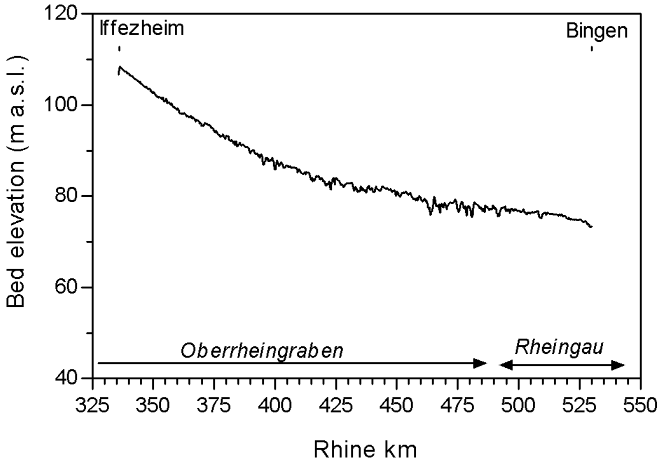

Figure 3. Bed elevation in the study reach.

The overall bed degradation shows that the river Rhine has an erosive regime, which is probably due to the extensive training works in the past and the cutting off of the sediment supply by impoundments in the river Rhine and its tributaries.

As described in Section 1, the most severe man-made alteration in recent time was the impoundment of the Rhine at Iffezheim barrage (Rhine-km 334) in 1978 and the subsequent installation of the bed-load nourishment site at Rhine-km 336 to 337.

In the upper part of the study area just downstream of Iffezheim (km 335 to 365) the transported bed load material stems mainly from the nourishment. Here the bed level is kept nearly stable with the installed nourishment scheme (Fig. 4). A slight degradation, which was observed since the mid 1980s, was eased by the mid 1990s by the means of increased nourishment after 1991.

The following reach from Rhine-km 365 to the confluence with the river Neckar (Rhine-km 428) is showing aggradation, most strongly in the upper 25 km. The transport measurements show that the bed-load transport strongly decreases in this area

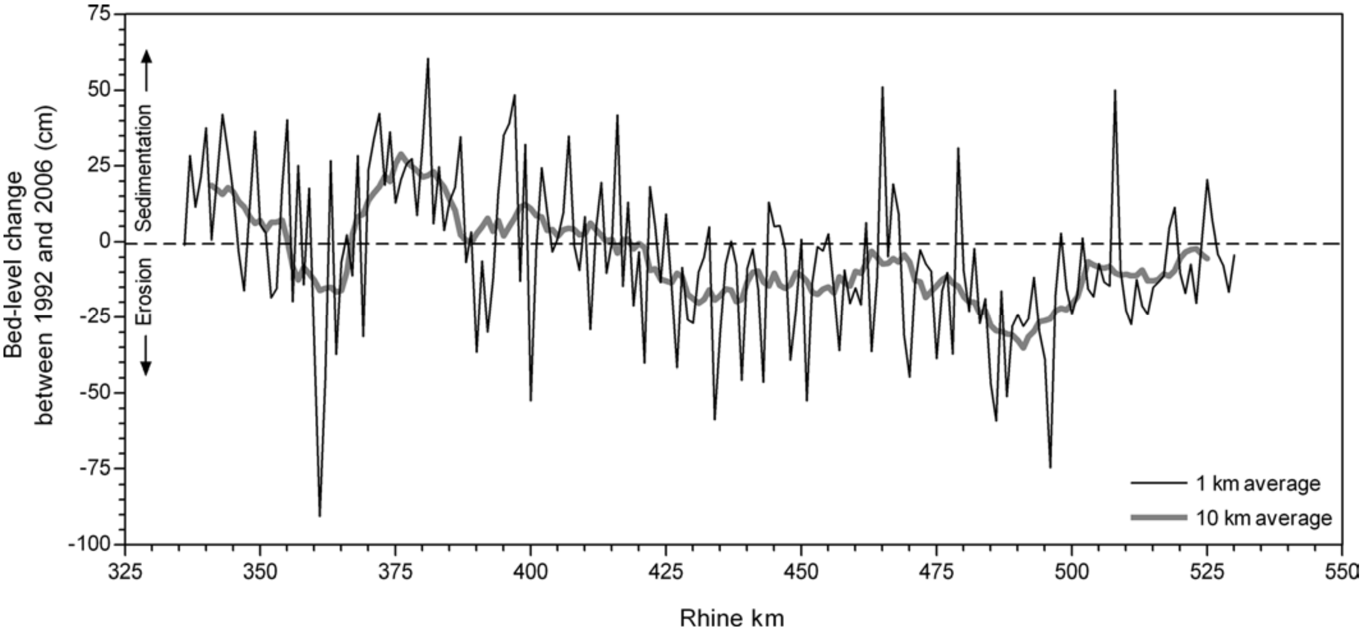

Figure 4. Development of bed levels between 1992 and 2006, averaged over a distance of 1 km and 10 km.

(Fig. 5). It is mainly the larger bed load fractions which are being deposited here, leading to a strong downstream fining (Fig. 6). The feeding of a coarser grain mixture at Iffezheim during 1981 to 1991 is supposed to have contributed to deposition along this reach. Further insight into this effect is expected from the numerical simulations described above.

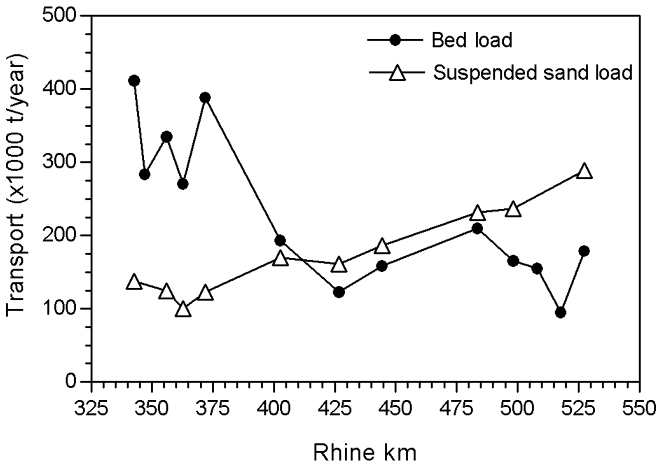


Figure 5. Bed load and suspended sand load along the study reach.

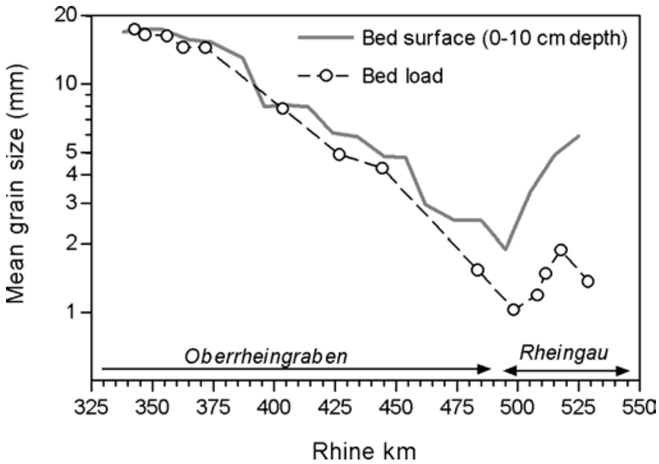


Figure 6. Grain sizes of the bed load and bed surface along the study reach.

From Rhine-km 428 until the end of the study reach, erosion is dominant since the beginning of the 1990s, with an average rate of 1.1 cm/a (period 1996 to 2006). A particular reason for this erosion can not be identified. Interaction with constructions during this period (groyne construction at km 438 in 1991/92, longitudinal training works at km 448 in 1995/96) is very likely. On the other hand, the observed bed load velocities (5.4 to 11.5 km/a for grain sizes of 4 to 8 mm) determined in tracer experiments (Gölz et al., 2006) suggest, that the exclusion of grain sizes smaller than 8 mm from the nourishment at Iffezheim between 1981 and 1991 might have contributed to the erosion by shortening the supply of bed load in this stretch.

A large scale comparison of the bed level changes with measured water level changes confirms the above mentioned trends. On the long term and on average the low-flow water level increased upstream of the confluence with the Neckar River (km 428) while there was an overall lowering of the low-flow water levels in the downstream section of the study area.

## 4 SMALL-SCALE MORPHOLOGICAL DEVELOPMENT

The mutual influence between large-scale and small-scale effects poses a challenge to the understanding of the river system. The significance of this issue is pointed out in Fig. 4, where the bed level changes between 1992 and 2006 are illustrated. Despite the general trend of bed erosion between Rhine-km 428 and 530 single spots occur that were affected by bed aggradation (e.g. km Rhine-km 480).

In the present study, these potential dredging sites are analyzed with respect to the relevant processes in different scales. Besides the influence of river training structures and maintenance activities these locations may also be affected by geomorphologic processes as e.g. sediment waves induced by discharge waves. In this connection, it is important to know for both, the temporal and the spatial scales, how active or inactive the bed morphology reacts in response to modifications at the river training structures. With this knowledge, dredging and supply activities can be analyzed and, where appropriate, adapted.

Figures 7 and 8 show volumes of sediment material extracted or supplied along the Rhine between the river section downstream of Iffezheim and Bingen. In Figure 7, the data are sorted according to years, whereas Figure 8 shows where the dredging or sediment feeding works have been located. In both figures, it is differentiated whether the dredged sediment is completely removed from the system or dredged and relocated to the river at another spot.

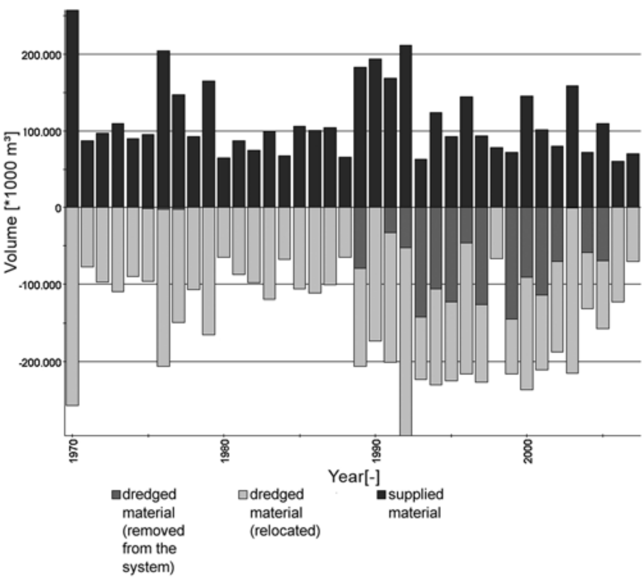


Figure 7. Dredged and supplied sediment volumes between 1970 and 2007 (Rhine-km 352-494). The data is differentiated whether the dredged material is completely removed from the system or re-added to the river at other locations. Note: the data do not include the sediment supply downstream of the barrage at Iffezheim with an average annual volume of 180,000 m³.

Note that the sediment volumes supplied downstream of the barrage at Iffezheim (average annual volume of 180,000 m³) are not included in Figure 7 and 8.

Figure 7 shows that in all years between 1970 and 2007 significant dredging and supply activities took place. However, the annual values differ significantly. The figure also demonstrates that most of the dredged material is re-added to the river at other locations.

This means that local differences in the sediment transport capacity in a relatively small scale (<$10^1$ km) lead to local bed aggradation that require dredging activities. The extracted material is needed at other locations where the sediment transport capacity increases again.

This interpretation is confirmed by the data in Figure 8. Here, it is shown that only few single spots made up the predominant portion of the dredging and supply activities between 1970 and 2007. Assuming a bulk density of 1850 kg/m$^3$, the data in Figures 5 and 8 show that e.g. at Rhine-km 422-425 the annual dredging volume is in the order of approximately 50 % of the annual bed load transport.

Starting from 1989 part of the dredged sediment was not re-added to the river but extracted and sold. In Figure 8, it is demonstrated that this process is exclusively limited to a one location at Mainz-Weisenau (Rhine-km 394).

The sediment transport capacity of a river section is mainly determined by discharge, slope, channel width, backwater effects, grain size and bed forms. The most obvious influence of groynes on the sediment transport capacity is the reduction of channel width and accordingly an increase of flow velocity and flow depth. In the following, small scale effects ($10^1$ km) of river training structures and their influence on the morphological development of the river bed are considered using an example between Rhine-km 362 and Rhine-km 371.

The river Rhine between km 362 and km 371 is characterized by series of groynes that are located alternating at the river banks. During the years 2000 – 2002 some of these groynes were adapted by increasing their length and height (Figure 9a). This resulted in a reduction of river width and consequently the sediment transport capacity increased. The changes in width and its impact on the bed level change are illustrated in Figure 9b and 9c.

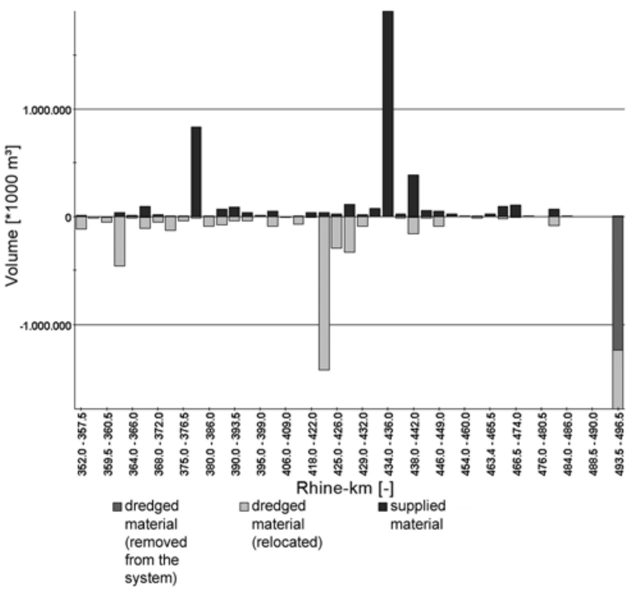


Figure 8. Dredged and supplied sediment volumes between Rhine-km 341 and 502 (for the period 1970-2007). Note: only those river sections are shown were dredging and supply activities occurred. The data is differentiated whether the dredged material is completely removed from the system or re-added to the river at other locations. Note: the data do not include the sediment supply downstream of the barrage at Iffezheim with an average annual volume of 180,000 m³.

The figure demonstrates that the locally varying reduction of the width of the movable bed has led to corresponding changes at the river bed. Those river stretches where the groynes were adapted (so that channel width decreased) are characterized by bed erosion. Contrary, the parts that were not affected by river correction works show no degrading tendency of the bed levels.

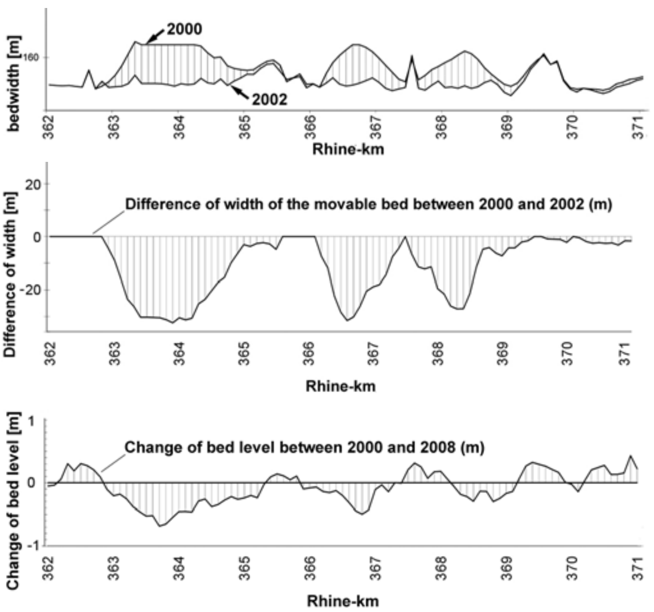


Figure 9. a) Width of the movable bed 2000 and 2002 (above), b) Difference between the width of the movable bed before (year 2000) and after adaptations at the groynes were carried out (year 2002) (middle); c) Change in bed level between 2008 and 2000, negative values represent bed erosion (below).

## 5 CONCLUSIONS

Large scale morphological development ($10^2$ km) is strongly influenced by the sum of small scale effects ($10^1$ km) of river training structures and vice versa. Consequently, a sound analysis of the interaction of these two scales is crucial for an improved understanding of the morphological development of the river Rhine. The analysis of the present study shows that due to the small-scale variability, systematic trends in the bed-level development can only be identified if long time-series of eco-sounding data are available for long river sections.

Considering the large scale development, the river Rhine downstream of the Iffezheim barrage was found to be morphologically not stable. While the bed level in the first 30 km was nearly stable, the Rhine is showing aggradation downstream of km 365 and erosion downstream of km 428. With an optimization of the bed load nourishment regarding grain sizes and volumes, both trends are tried to be further minimized.

First results considering the impact of river training structures on the bed development show that correction works executed at a small scale can lead to corresponding small-scale bed reactions. This is important as local deficits in flow depths can endanger the ease and safety of inland water navigation and consequently create a large effort for dredging and sediment supply activities. In order to optimize the maintenance strategy for the German Federal Waterways and Shipping Administration the identification and analysis of relevant spots of bed aggradation and the formulation of strategies to achieve a homogenization of the sediment transport is relevant to reduce costs.

In a next step, the existing numerical models are used as well as the field data to continue the analysis. Particularly, numerical models provide the opportunity to systematically study the factors of influence and to test the effects of possible scenarios that focus on an optimization of the maintenance strategy. The numerical models make it possible to study the temporal aspect of the morphological development of the bed in connection with the occurring discharges.

## ACKNOWLEDGEMENTS

The study is carried out by the Federal Institute of Hydrology (BfG) and the Federal Waterways Engineering and Research Institute (BAW) on behalf of and in close cooperation with the German Federal Waterways and Shipping Administration (WSV).

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