

An ex-post analysis of the German Upper Rhine: data gathering and numerical modelling of morphological changes in the 19th century

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Abstract

To ensure sustainability, long-term effectiveness and limited maintenance, river flood management practices should take into consideration the potential morphological adaptations resulting from the imposed changes to a river system. To illustrate the ability of numerical models to provide a valuable tool for flood management planners, an ex-post analysis of the Rhine during the 19th century is carried out. The Upper German Rhine has been deeply reshaped by large engineering works over this century. The initially braided reach Basel-Maxau was constricted into a single channel, while the reach Maxau-Mainz was significantly shortened by meander shortcuts. Both types of works resulted in intense erosion upstream and spread deposition downstream, with most of the changes occurring during high-flow periods. As ancient data is generally difficult to obtain, the paper shows how fragmentary ancient data may be complemented with more recent data adequately interpreted for reconstructing a realistic set of initial conditions. The study is an attempt at reproducing qualitatively the behaviour of the Upper Rhine with a dataset collected only from publicly available sources.

Keywords: ex-post analysis, data gathering, flood management, long-term numerical modelling, river morphology.

1. Introduction

Over the last two hundred years many, if not all of the large rivers worldwide have suffered intense engineering works, resulting in an alteration of their natural state. Depending on the case, the works have been done with distinct objectives in mind, e.g. flood protection, navigation improvement, irrigation or drinking water supply, energy production, with most projects combining several of those aspects together. The history of those two centuries of morphological evolution of rivers has provided new insight and a better understanding of the interconnection between imposed changes and morphological response. In order to provide solutions that are more sustainable and ecologically responsible, that reduce the risks of hazards and require less maintenance on the long term, the trend for river management practices has shifted in many cases to what is referred to as river rehabilitation projects and river renaturalisation. In any case, lessons from the past have made clear the importance of assessing the river morphological evolution resulting from any planned river management project (Schweizer *et al.* 2007). For researchers, this has led challenging questions to be answered, with a rapidly growing interest to the sphere of applied fluvial geomorphology (Newson *et al.* 2006).

The assessment of the morphological impact of river works is not straightforward, and this is especially true for a river characterized by a highly variable hydrographic regime. Sediment transport is known to relate to flow velocity, hence to river discharge, through a power law with an exponent ranging from about 3 to 5. It is thus not surprising to see that floods contribute to a large extent to morphological changes of such rivers. The morphology of some small rivers may be completely reshaped by single events, such as historic floods or other catastrophic floods as for example those induced by dam-breaks (Capart *et al.* 2007). On the other hand, the morphology of larger rivers is also known to be dictated mainly by flood events, and so-called channel-forming discharges, responsible for the morphological pattern of a river channel, may be substantially larger than the actual average discharge. In turn, morphological changes impact on the flooding risk of rivers. Furthermore, in the present context of substantial modifications of the hydrological regimes of many catchments around the world due to climate changes, the relative importance of interconnecting flood management and river morphology is expected to grow even more.

For assessing the morphological and hydraulic consequences of river works, several tools are available. Besides engineering guidelines, lessons from historical observations and analytical tools of fluvial geomorphology, numerical models may provide a valuable predictive tool. The aim of this study is to demonstrate the feasibility and the interest of an ex-post analysis of fluvial morphology evolution, where the benefits of numerical modelling are faced to historical observations. A priori, the reconstruction of what really happened in the past may seem a pure academic exercise. If the present work illustrates the feasibility of the approach, at least four benefits may be expected from such an application, even if not all of them are specifically dealt with hereafter: (1) a chance to test the models over long time scales, (2) an opportunity to calibrate some parameters in real-life situations, (3) a better understanding of the occurred phenomena by a sensitivity analysis of these parameters, and (4) the possibility of assessing the benefits and efficiency of potential new river works aimed at correcting adverse effects of previous historical works.

Conversely, the very idea of an ex-post analysis, as for any real case-study, relies on the setting up of a relevant dataset. Without reliable data about the past situation, such an analysis seems unfeasible, mainly if the period to be reconstructed is rather ancient. However, it is sometimes possible to get meaningful results with limited available data, provided that adequate simplifications are adopted to substitute for the missing data. A secondary objective of the present paper is to show the interest of complementing limited historic data with recent data to serve as input to numerical models assessing the morphological impacts of river works, by taking advantage of new technologies for data dissemination over the Internet and of the impressive sources of data available in the public domain, such as aerial and satellite images.

To illustrate the methodology, we have developed the example of the Upper German Rhine, which has a remarkable history of two centuries of large engineering works that have deeply reshaped the characteristics of the river. Since the pioneering works of engineer Tulla in the 1840's, the Rhine has evolved on the basis of a constant dialogue between multiple human interventions aimed at reducing flood risks and improving navigation, and a natural tendency to restore a stable long-term morphodynamic equilibrium.

The present work focuses on the upstream reaches of the Rhine between the city of Basel, close to the Swiss-French-German border, and the city of Mainz in Germany. These reaches have suffered intense morphodynamic changes for more than two centuries, and those changes are still active nowadays. The Upper Rhine, and the other neighbouring rivers in Southwest Germany, are characterised by a highly variable hydrograph and have suffered several extreme historical floods in the 19th and 20th century (Burger *et al.* 2007). Not only in

that region but along many similar large river catchments in Europe and elsewhere, the recent focus of flood management practices has devoted increased attention to the analysis of historical extreme floods, and the evolution of their frequency related to climate variability (Benito *et al.* 2005).

2. Two centuries of river works

In the present study, two different reaches of the Rhine (Fig. 1), characterised by a very distinct morphological behaviour, are considered: (1) the reach from Basel to Lauterburg (a few kilometres upstream of Maxau) characterised by the constriction of an initially braided pattern, and (2) the reach from Maxau to Mainz, with significant re-alignment and extensive meander shortcuts.



Figure 1. River Rhine.

2.1. Canalisation between Basel and Maxau

Before the year 1820, in the reaches from Basel to Lauterburg (close to the larger city of Maxau), the Rhine was a braided river system consisting of multiple rapidly-evolving branches, with a very low water depth at low discharges, while the river spread over a very wide area during floods. Navigation was hardly possible during low flows, and even when the water depth was sufficient the rapidly changing channel patterns required a constant adaptation of navigation pathways. With the aim of improving navigation and containing the floods, it was chosen to concentrate the flowing waters into a single channel of reduced width, confined between levees, and whose course was chosen as straight as possible. The width of this channel was no more than 250 m, and in comparison with the initial thalweg length of 195 km, the course of the river was reduced by 14 %. This confinement of the Rhine is illustrated in Fig. 2.

These works have had an immediate effect on the improvement of navigability and the reduction of flooding, but, after some years, it became rapidly evident that the confinement had severely perturbed the morphodynamic equilibrium of the Rhine. Besides the net width reduction, the increase in slope associated with the reduction of the length resulted in an increase of flow velocities and bed shear stresses. The flow gained erosive power, and the river bed started to degrade between the levees. The degradation amounted up to 10 cm per

year, and in some places the bed level was lowered by more than 7 m from 1840 to 1920 (Pardé 1959), in such an extent that, at Istein, a few kilometres downstream of Basel, bedrock outcrops were exposed, creating rapids that complicated navigation. On the other hand, the transport of intensively-eroded sediments created zones of net deposition in the lower reaches of the Rhine (downstream of Maxau), by which the flood risks were increased.

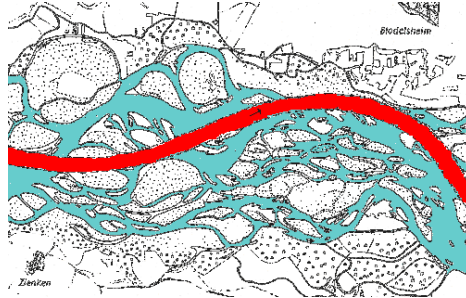


Figure 2. Confinement of the Rhine at Blodelsheim. Blue: in its natural state; red: after confinement and realignment (adapted from Casper, 1959)

The consequences of the river works were so damaging for the navigation that only the construction from 1933 of the Grand Canal d'Alsace, a completely artificial channel created aside the initial river course, was able to restore acceptable conditions for navigation. Downstream of Breisach and towards Strasbourg, it was preferred to implement the canalisation of the Rhine by a series of short derivations from the Rhine itself.

2.2. Re-alignment between Maxau and Mainz

Downstream of Maxau, the natural river bed was very different: it consisted of a single channel of very high sinuosity resulting in bank erosion along meander shorelines and frequent flooding for local neighbourhoods. Works were undertaken to face this instability of the meandering course and to decrease the risk of inundation. They consisted mainly in a re-alignment and a stabilisation of the river course by artificial meander shortcuts. Between 1827 and 1844, the course of the river along these reaches was shortened by 53 km, i.e. 38 % of the initial length (Fig. 3).

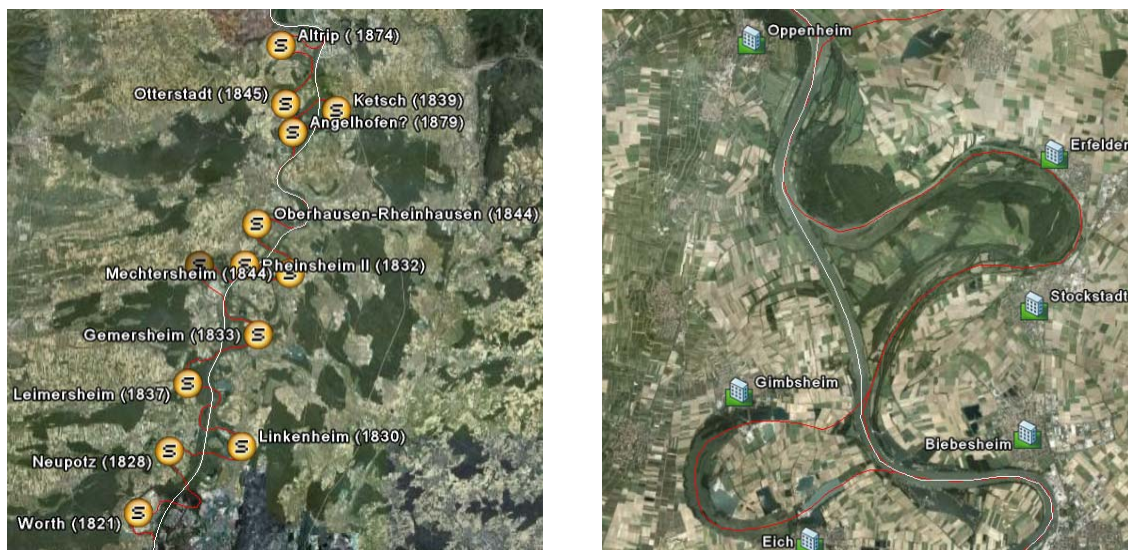


Figure 3. Meander shortcuts between Maxau and Mannheim. Left: shortcut names and years, old (red) and new (white) river courses; Right: Meander shortcut at Erfelden (Google Earth[®], 2008)

The works have had a rapid positive effect on flood protection. But considerable erosion resulted. The erosion of bank protection required multiple interventions in the nineteenth and twentieth centuries to stabilise the river course. Moreover, the increase of river slope by the multiple shortcuts had also an adverse impact on navigation, by reducing the available water depth during low flows.

3. Numerical model

The simulations reported hereafter were obtained with a one-dimensional morphological model that pertains to the family of so-called Saint-Venant-Exner models. While accounting for complex morphodynamic processes such as the migration of bedforms and bars or the effect of secondary currents may require the use of higher-dimensional models, these models are still undergoing heavy development and validation, and are often unpractical to apply at large space and time scales. In addition, the use of a one-dimensional model appears as a viable option for the present case, where the protected banks of the Rhine River largely prevented bank erosion and lateral migration.

The flow is governed by the Saint-Venant or shallow-water equations that express the conservation of flow mass and momentum:

$$\frac{\partial A}{\partial t} + \frac{\partial A_b}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\beta \frac{Q^2}{A} \right) + g A \frac{\partial h}{\partial x} + g A \frac{\partial z_b}{\partial x} + g A S_f = 0 \quad (2)$$

where A and A_b represent the wetted area and bed area, Q is the water discharge, β is the Boussinesq coefficient correcting for the non-uniformity of flow velocity along the vertical, h is the water depth, z_b is the bed level, S_f is the energy slope and g is the acceleration of gravity. Sediment transport is estimated from an empirical formula – in the present case the Meyer-Peter and Müller formula – and morphological changes are governed by the Exner equation that expresses the conservation of the sediment mass:

$$(1 - \varepsilon_0) \frac{\partial A_b}{\partial t} + \frac{\partial Q_s}{\partial x} = 0 \quad (3)$$

where ε_0 is the bed porosity and Q_s is the sediment discharge.

The equations are solved with an implicit Preissmann four-point finite-difference scheme (e.g. Correia 1992). The strength and originality of the adopted numerical approach, as opposed to explicit finite volume schemes, is that it is designed to be highly implicit. Very large time steps of integration may be used – typically one day – allowing for long-term simulations, whereas explicit Godunov-type finite volume schemes would require small time steps, leading to huge CPU times and the accumulation of numerical rounding errors.

As illustrated in Fig. 4, in the Preissmann scheme every variable is expressed as a combination of its values at one time step (index j) and at the next time step (index $j + 1$), and its values on the left (index i) and right (index $i + 1$) limits of a numerical cell:

$$\begin{aligned} f(x, t) &= \theta \phi f_{i+1}^{j+1} + \theta(1 - \phi) f_i^{j+1} + (1 - \theta) \phi f_{i+1}^j + (1 - \theta)(1 - \phi) f_i^j \\ &= \theta \phi (\Delta f_{i+1} - \Delta f_i) + \theta \Delta f_i + \phi (f_{i+1} - f_i) + f_i \end{aligned} \quad (4)$$

where $f = f^j$, $\Delta f = f^{j+1} - f^j$, and θ and ϕ are weighting coefficients for values at the next

time step and on the right interface of the element, respectively. They represent some kind of degree of implicitness and upwinding. The partial derivatives in x and t of any variable are also decomposed using a similar weighting procedure. The integration of the system of equations (1)-(3) between i and $i + 1$ can then be rewritten in a vector form of the type

$$[\mathbf{A}_{i+1}] \begin{bmatrix} \Delta A_{i+1} \\ \Delta Q_{i+1} \\ \Delta A_{b,i+1} \end{bmatrix} = [\mathbf{A}_i] \begin{bmatrix} \Delta A_i \\ \Delta Q_i \\ \Delta A_{b,i} \end{bmatrix} + [\mathbf{B}_i] \quad (5)$$

for any $i = 0 \dots m-1$. The whole domain is then solved in cascade, starting from imposed boundary conditions upstream and downstream. Typically, for subcritical fluvial regime, the discharge (hence ΔQ_0) and the bed level (hence $\Delta A_{b,0}$) are imposed upstream, and the free surface level (hence ΔA_m) is imposed downstream.

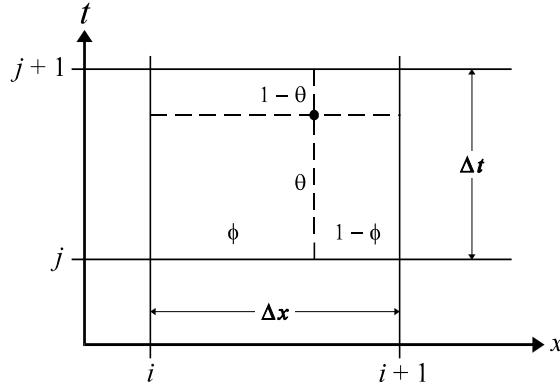


Figure 4. Sketch of the implicit four-point Preissmann scheme

4. Data collection

The objective is to attain a good degree of realism in the simulations, while maintaining a low degree of complexity in the data. For morphodynamic simulations, numerical models typically rely on different types of data: topographic data (elevations, plan form, width), hydrological data (discharges), hydraulic data (imposed water level downstream), sediment data (sizes, density, roughness). For the present simulations, these data have been collected from a variety of sources, all of them being publicly available.

4.1. Topographical data

Elevation data of the Rhine thalweg was available from the 1959 special issue of “La Houille Blanche” dedicated to the Rhine (Pardé 1959). Information about bed level changes was also available at different locations, quantifying the degradation and/or aggradation observed during the 1840-1950 period. The longitudinal profile of the Rhine in its initial situation, around 1840 (Fig. 5) shows a typical trend, with channel slopes decreasing from about 1 m per km at Basel, to 60 cm per km at Strasbourg and less than 4 cm at Mainz.

Plan-form data has been collected from aerial photographs available in the public domain, through the Google Earth® software. This includes the present river course as well as old river courses still visible through abandoned meander loops and oxbow lakes. Although the simulations presented hereafter were done with a one-dimensional model, plan form data was used in two regards: first, it allowed to assign the reductions in river length associated with the shortcuts at the correct locations, so that the elevation profiles before and immediately after the shortcuts can be compared consistently. Second, it allowed to paste one-dimensional

simulation results on the actual corresponding river plan form, so as to better visualize the impact of the shortcuts on the bed adjustments.

Values of the channel width at each location are also derived from Google Earth[®], and are cross-validated with values referenced in the literature (e.g. Casper 1959). Rectangular sections are assumed for simplicity, and cross-sections are reconstructed at intervals of about 200 to 400 m along the thalweg. Interactions with flow on the floodplains during floods were not considered.

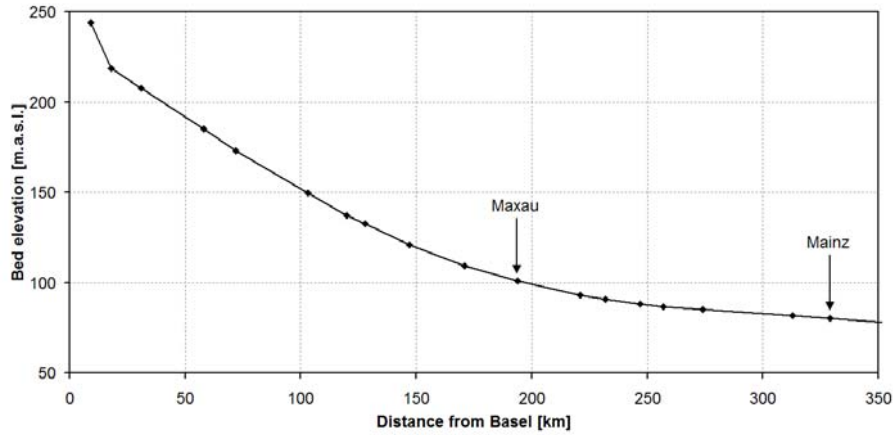


Figure 5. Longitudinal profile along the Rhine (around 1840)

4.2. Hydrologic (discharges), hydraulic (water levels) and sediment data

For simulating the reach Basel-Maxau (effect of constriction) a representative constant discharge has been assumed for simplicity. For simulating the reach Maxau-Mainz (effect of shortcuts), a more realistic simulation has been performed with real discharge data gathered from the online source “Deutsches Gewässerkundliches Jahrbuch” at <http://www.dgj.de> (last accessed Jan. 10, 2008). A series of 9 years of daily discharges measured at the station of Maxau were used, extending from 1990 to 1998 (Fig. 6). The hydrograph depicted in Fig. 6 may not be exactly representative of the one that caused the actual morphodynamic adjustments of the 19th century. However long-term changes in the hydrologic regime are deemed to be second-order to the impact of the external forcing caused by the drastic human imposed changes in the system (i.e. shortcuts), on which our analysis focuses. The chosen hydrograph serves our purpose, with a typical alternation of low-flow and high-flow periods. Several major floods are represented with discharges up to 4000 m³/s, that will allow to quantify the dynamic impact of the flood events on the ongoing morphodynamic adjustments.

As the flow remains subcritical throughout the simulation, a value for the water level has to be prescribed at the most-downstream section as a boundary condition. Water level data at the required cross-sections was also derived from actual measurements available from the “Deutsches Gewässerkundliches Jahrbuch”.

Sediment grain sizes were digitised from Casper (1959), and the values for representative diameters d_{50} and d_{90} were approximated by decaying exponentials as shown in Fig. 7. Downstream of Maxau no differentiation was made between values for d_{50} and d_{90} , and representative grain sizes were obtained by extrapolating the profile for d_{50} .

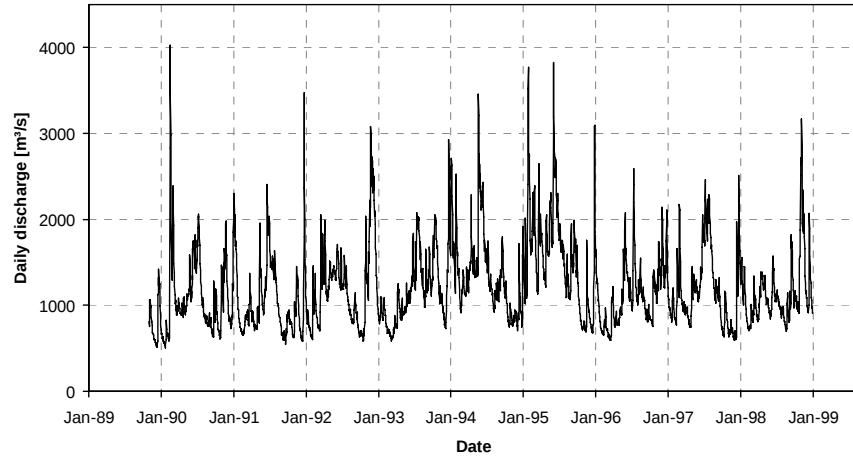


Figure 6. Daily discharges Q measured at the Maxau station over the period 1989-1999. Data obtained from the Deutsches Gewässerkundliches Jahrbuch (available at <http://www.dgj.de>).

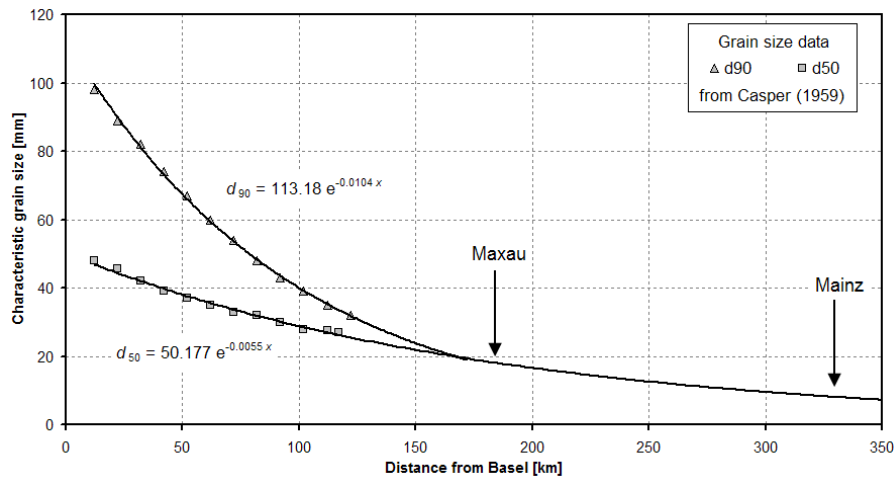


Figure 7. Representative diameters for the sediment grain sizes

5. Simulation for the reach Basel - Maxau (effect of constriction)

We consider here an idealised simulation looking at the effect of a localised constriction on morphodynamic channel adjustments. The configuration is inspired by the case of the Rhine between Basel and Maxau, where it was confined into a single narrowed channel as opposed to the original multiple braided channels. It provides a rough analogue, but due to the adopted simplifications the results are not expected to scale quantitatively with Rhine observations.

5.1. Simulation assumptions

The width of the Rhine is idealised in a relatively crude manner, with three reaches of constant width, as depicted in Fig. 8. The confinement of the Rhine has initially been the more severe between Kembs and Lauterburg. The width of the idealised channel is assumed to be 235 m at Basel, then reduced to 150 m over the confined reach, and enlarged back to 250 m downstream of Lauterburg, towards Maxau. As is the case for the real situation, the banks of the new channel are supposed to be protected against lateral erosion, so that no morphological adaptation of the channel width will be considered.

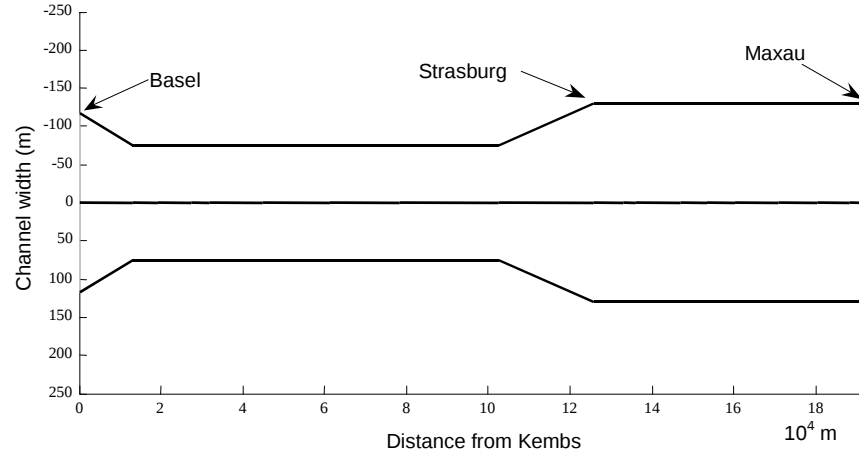


Figure 8. Simplified analogue to Basel-Maxau reach

A constant discharge of $3000 \text{ m}^3/\text{s}$ has been used for the simulation. This simplification is in line with the crude idealization of the geometry described above, and the use of actual Rhine discharge hydrographs would have made little sense for this illustrative analogue. The initial water depths at every cross-section are established by computing the backwater profile corresponding to the initial bed profile. At the downstream end, a fixed water level is imposed throughout the simulation at the level 104, i.e. an initial water depth of 3 m. Upstream of Basel, the Rhine flows out the Lake Constance, which acts as a trap for sediments coming from upstream. Between the Lake Constance and Basel, the river bed is composed of very large sediments and many rock outcrops, so that it may reasonably be assumed that few sediments were initially supplied to the reaches downstream of Basel. The simulation is thus performed on the assumption that the sediment supply at the first upstream section is simply equal to zero. Downstream of Basel, as the sediments are rather coarse, bed load is clearly the very predominant mode of transport of sediment, and thus, the classical Meyer-Peter and Müller formula is used to predict sediment transport. Except at the upstream section, sediment transport is assumed in equilibrium, equal to the transport capacities.

5.2. Simulation results

The morphological evolution was simulated over a period of 5 years (Fig. 9). As seen on the second panel of Fig. 9, the upstream reaches undergo severe erosion. This is directly related to the artificial constriction which strongly increases flow velocities and sediment transport capacities, even for the large grain sizes encountered over these reaches. Due to the lack of sediment supply at Basel, this sudden increase in sediment transport capacities initiates local scour at the narrowing. The extent of erosion at the second upstream section (Kembs) amounts to about 6 m. Even though this simulated erosion develops over a shorter time period than what was observed in reality along the Rhine, the figure is comparable to the actual erosion depth experienced at Kembs before apparition of the bed-rock outcrops at Istein.

Downstream of the constricted channel, sediments are being re-deposited in the wider reaches, as a result of the reduction in flow velocities and of the milder slopes. This is illustrated in the last panel of Fig. 9. This sedimentation process is rapidly spread over a much longer distance than the upstream localised erosion, and spans over more than 30 kilometres.

While the trend of morphological adaptations is in agreement with actual observations, the very schematic representation of the channel in the simulation (constant discharge, crude width and slope approximations, etc.) does not allow drawing firm quantitative comparisons with Rhine historical data. In particular, due to the assumption of a zero sediment supply at

the upstream end of the reach, while an equilibrium sediment transport is assumed from the next section downwards, the scour that develops over the first sections is artificially exaggerated.

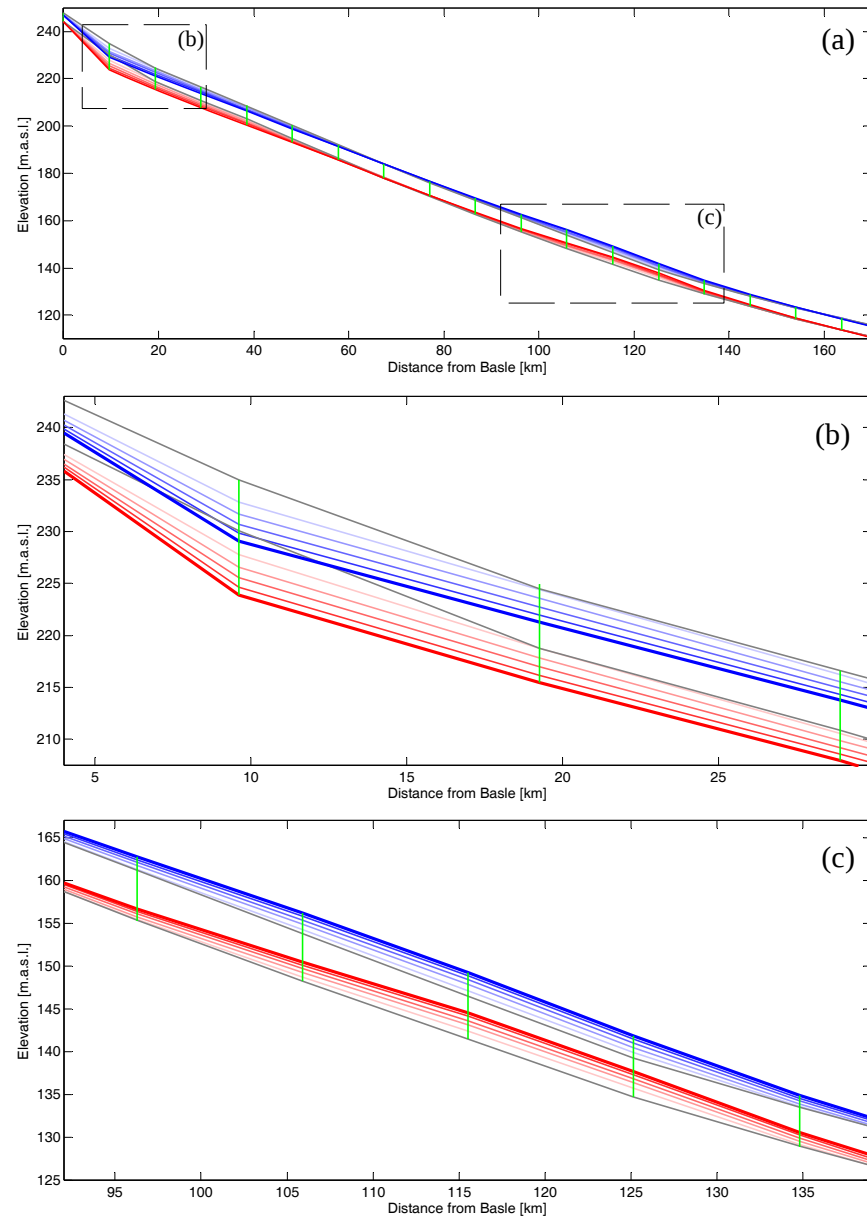


Figure 9. Reaches from Basel to Maxau: morphological evolution over 5 years. Profiles every 1 year in shades of light- to dark-blue (water) and red (bed), initial water and bed profiles in dark grey; (a) full profile, (b) and (c) close-ups in the upstream and downstream reaches, respectively.

6. Simulation for the reach Maxau – Mainz (effect of shortcuts)

The second series of simulations looks at the impact of the extensive meander shortcuts performed along the reach extending from Maxau to Mainz, mainly over the period 1820-1840. The objective of the simulation is twofold: (1) see whether the initial meandering channel may be considered in a situation of dynamic morphological equilibrium, and (2) investigate the perturbation of this equilibrium induced by the artificial shortcuts and channel

stabilisation. Indeed, the greater flow velocities induced by the greater channel slope may be expected to cause substantiated erosion.

6.1. Simulation assumptions

The bed elevations were available at several locations from Casper (1959). They were assigned at the correct river stations, and the corresponding profiles for both situations were then obtained using polynomial regressions (Fig. 10a). As elevation data was not available all along the channel but rather at some selected stations, the sudden drops at each individual cut-off are not represented as abrupt chutes, but the profiles are rather smoothed over some distance by the polynomial regression. The overall length of the shortened channel is about 135 km, as compared with the 212 km of the initial channel.

As previously, the channel width was estimated from Google Earth[®] images at selected stations, and cross-checked with figures from Casper (1959). The width at each section was also obtained by polynomial regression, as illustrated in Fig. 10b. Using the above-described elevation and width data, rectangular cross-sections were then obtained all along the channel for both situations, at intervals of about 0.5 to 1 km, with a total of 240 cross-sections for the initial channel and 209 sections for the shortened channel.

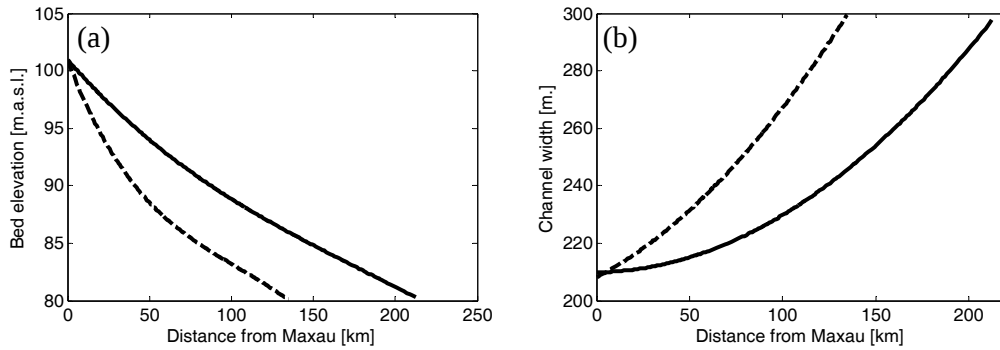


Figure 10a-b. Pre-shortcut (solid line) and post-shortcut (dashed line) profiles from Maxau to Mainz for (a) the bed elevation and (b) the channel width.

The simulations were performed with a varying discharge, using the actual daily discharge measurements of Fig. 6, taken at the Maxau station from November 1989 to December 1998, thus a duration of 9 years and 2 months. At the downstream end, a stage-discharge relationship imposing a pseudo-uniform depth for every discharge might have been the most relevant boundary condition, but such a rating curve was not available, and instead a fixed water level was imposed, corresponding to an initial uniform water depth of 5.5 m for an average representative discharge.

The Meyer-Peter and Müller formula was adopted for the estimation of sediment transport capacities. At the upstream end, an additional condition has to be imposed for the sediment supply. For the first simulation, corresponding to the initial situation before the artificial shortcuts, an equilibrium assumption is postulated, the sediment supply upstream is assumed to match exactly the sediment transport capacity at the first cross-section. The history of sediment transport rates at that location over the whole duration of the simulation is stored, and these values are then imposed as a boundary condition for the second simulation, looking at the impact of shortcuts, so that both simulations may be compared consistently.

6.2. Simulation of pre-shortcut configuration

The evolution in time of the longitudinal profile for the pre-shortcut simulation is presented in

Fig. 11, over the whole duration of the simulation, i.e. more than nine years. If one first analyses the water profiles, the effect of varying discharge on the attained flow depths is clearly visible, with uniform water depths in the upstream zone ranging from less than 3 m for the low discharges to about 10 m for the highest discharges.

But analysing the bed profiles, the major observation is the absence of any substantial zone of erosion or deposition. In fact, the local bed-level changes over the entire simulation period are less than 6 cm everywhere. That means that the erosion induced during high-flow periods is counterbalanced by the deposition at low flows. If width adjustments are disregarded, the long profile of the Rhine between Maxau and Mainz before the shortcuts may be considered in a stable morphodynamic equilibrium. This observation validates *a posteriori* the use of the Meyer-Peter and Müller formula.

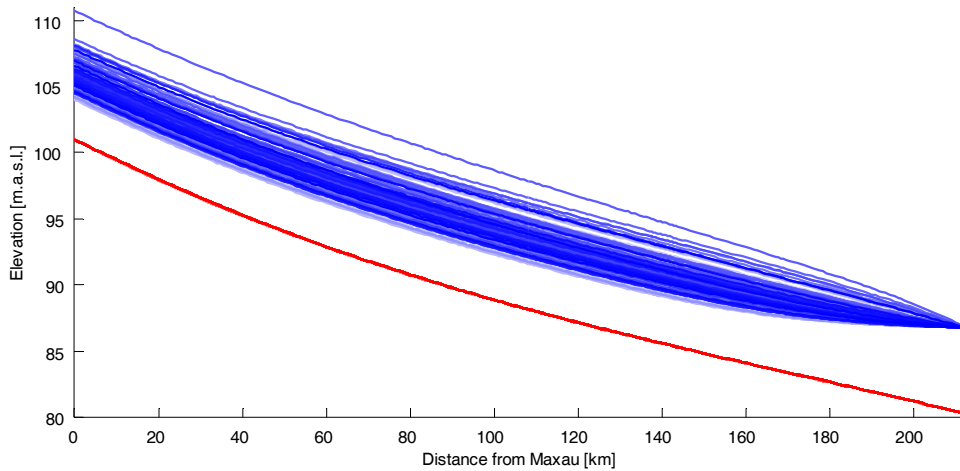


Figure 11. Evolution of water (light to dark blue) and bed (light to dark red) profiles for the pre-shortcut simulation.

6.3. Simulation of post-shortcut configuration

The impact of meander shortcuts is now investigated. The sediment discharges computed at the upstream section for the previous simulation, i.e. without shortcuts, is now supplied as a boundary condition in the shortened channel.

The evolution in time of the longitudinal profile for this post-shortcut simulation is presented in Fig. 12, over the whole duration of the simulation. Very important erosion is observed in the upstream zone. Due to the increased channel slopes (Fig. 10), the sediment transport capacities are much larger than the upstream sediment supply, and sediments are being eroded accordingly. In the intermediate reaches, the shortcut activity has been less severe, and in conjunction the channel slope is milder. As a result, limited re-deposition occurs, which is spread over several tens of kilometres. This result is close to what was really observed along the Rhine after the shortcuts.

Even if the simulation is done with a one-dimensional numerical model, the results can be visualised in two dimensions by pasting the morphological changes to the actual plan form of the Rhine River. This is presented in Figure 13. The first two panels show the pre-and post-shortcut river plan forms as tracked on Google Earth® images. One may see that the shortcuts have been mostly confined in the first half of the reach Maxau-Mainz; hence this is where most of the morphological adaptation has taken place. Panel (c) and (d) map the intensity of the simulated bed level changes on the corresponding plan form. As discussed previously, the pre-shortcut configuration is close to morphodynamic equilibrium, and hardly any bed

modification results. For the post-shortcut configuration, the erosion is confined over the first few meander shortcuts. By contrast, the zone of deposition extends over a much longer distance, even in sections at mid-distance between Maxau and Mainz, where the shortcut activity was less severe. If the simulation was run for even larger times, the extent of this zone of deposition would continue to migrate further downstream, putting those reaches under a higher risk of flooding.

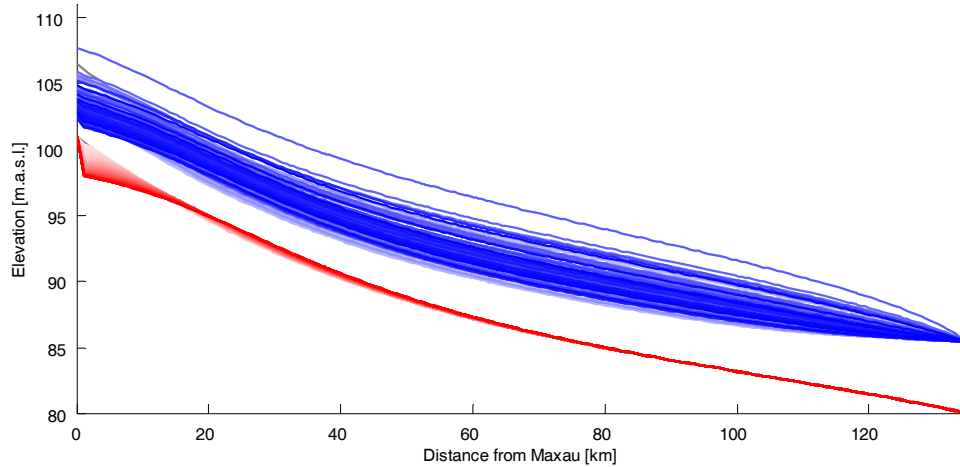


Figure 12. Evolution of water (light to dark blue) and bed (light to dark red) profiles for the post-shortcut simulation.

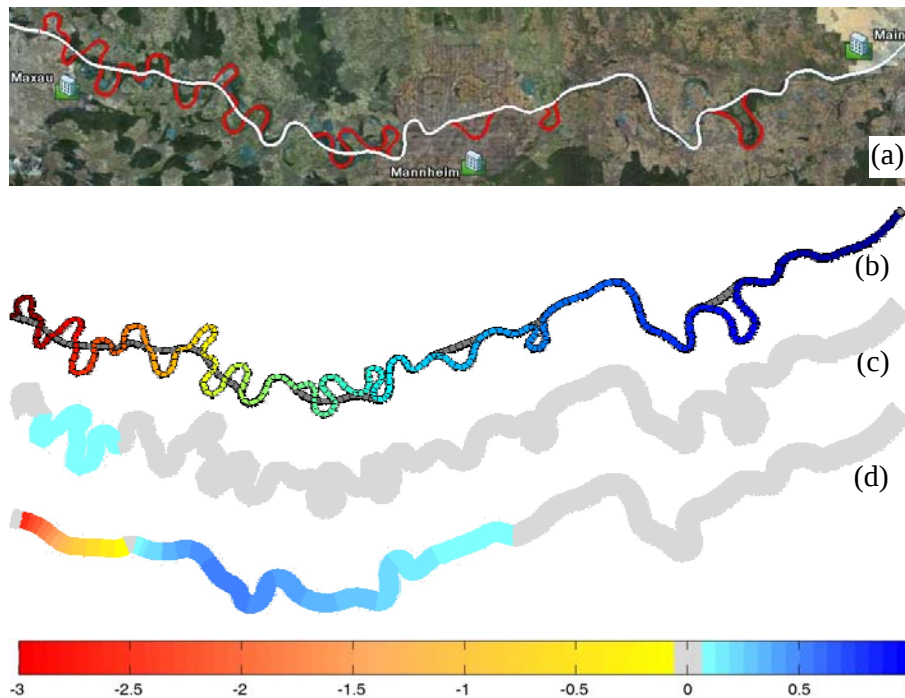


Figure 13. Planview of the simulated morphological changes due to the meander shortcuts between Maxau and Mainz. (a) Google Earth® image of the pre- and post-shortcut river courses (flow is from left to right); (b) schematic planviews; (c) and (d) simulated bed level changes for the pre- and post-shortcut configurations, respectively. Colormap is in meters (positive values for deposition).

6.4. Floods and morphology

As the simulation is carried out based on a variable hydrograph, and the rate of sediment

transport is highly dependent on the average flow velocity, morphological changes do not occur at a constant rate over the whole simulated period. Higher discharges may be expected to contribute more to the observed bed level changes. Figure 14 illustrates the impact of large floods on the rates of morphological adaptation, for an upstream section, i.e. only slightly downstream of Maxau ($x = 5$ km). One may clearly see the interconnection between discharge and rate of bed level change. Globally, the section is subject to erosion, but sequences of more intense scour are associated to peak discharges. Longer floods, even with a lesser magnitude, trigger more erosion than short but intense floods (compare e.g. the floods depicted by arrows A and C on Fig. 12 to the one shown by arrow B). Also, the mean erosion rates associated to floods decrease for later times of the simulations, as seen by comparing the floods A, B and C to later floods D, E and F on Fig. 14. This is due to the fact that, as erosion of the upstream reaches progress, the slope of the channel decreases, as do the sediment transport rates. The upstream portion of the channel is leaning towards a new equilibrium corresponding to the shortened configuration.

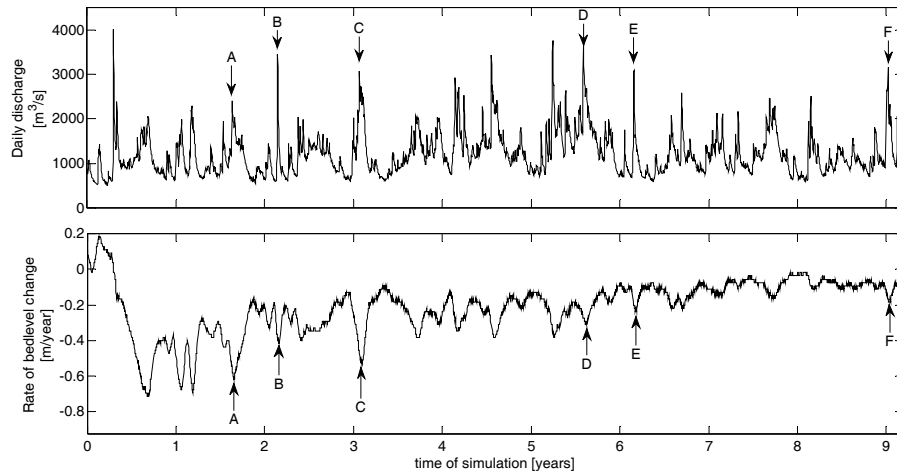


Figure 14. Impact of floods on the rate of bed level change, at a section 5 km downstream of Maxau for the post-shortcut simulation. Arrows refer to specific sections discussed in the text.

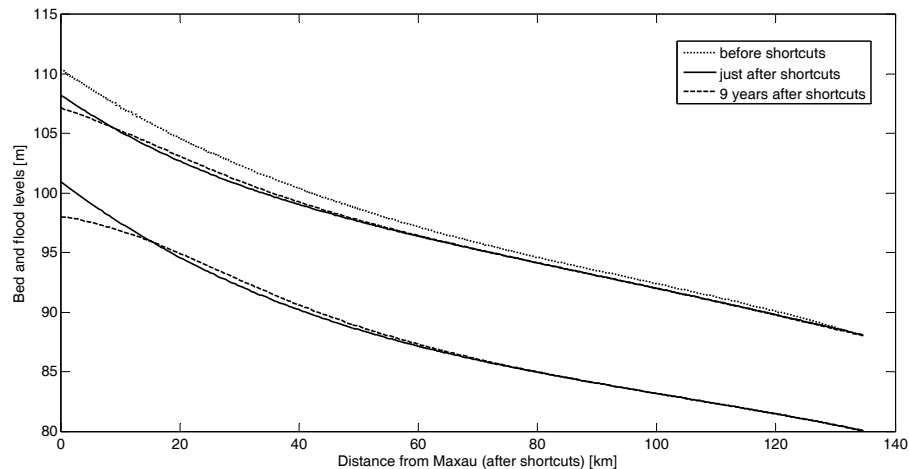


Figure 15. Flood levels from Maxau to Mainz for a flood discharge of $4000 \text{ m}^3/\text{s}$. Despite the differing length of the channels, profiles for the pre-shortcut configuration have been stretched according to the chainage of the post-flood configuration, so that corresponding river locations are made to correspond.

If floods influence largely the intensity of morphological adaptations, in turn bed level changes may have a substantial impact on flooding risks. Figure 15 illustrates this feedback

mechanism by showing the various free surface profiles corresponding to a design flood of $4000 \text{ m}^3/\text{s}$. As compared to the pre-shortcut configuration, the change in flood levels along the second half of the shortened reach, where the shortcuts were fewer, are hardly noticeable. In the most upstream part, the flood levels shortly after the shortcuts are substantially reduced, as a consequence of the increase of slope associated with the shortened channel. But after 9 years of morphological adaptations, the first 15 kilometres have suffered intense erosion, and the next 50 kilometres widespread deposition. Consequently, the water profile corresponding to the design flood is modified, with even lower flood levels over the first 7 km but higher flood levels over the next few tens of kilometres. This suppresses part of the benefit of the shortcuts for flood protection, and may put some reaches under a higher risk of flooding than initially planned. Note that due to backwater effects the zone of increased flood levels does not correspond exactly to the zone of deposition, and around $x = 12 \text{ km}$ there is a zone of erosion associated to an increase of flood levels.

CONCLUSIONS

To illustrate the interrelation between floods and river morphology, and to demonstrate the feasibility and the interest of an ex-post analysis of fluvial morphological evolution, we have developed the example of the Rhine, where two centuries of large engineering works have deeply reshaped the river.

The reconstruction of what really happened in the past has been made possible thanks to rather simple data available in the public domain and some adequate simplifications in the boundary conditions. A good degree of realism was obtained in the simulations, demonstrating that such an approach is able to predict, at least qualitatively, the long-term response of the river. In particular, the impact of floods on the morphological evolution of a perturbed river system has been exemplified. Floods impact on morphological changes by creating conditions prone to much higher rates of sediment transport. On the other hand, morphological changes impact on flood risks by potentially affecting the flood levels in an adverse way.

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