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Object: Review of the manuscript HESS-2017-435

Dear Professor Hubert Savenije,

Following up on the feedback given by the Referee#1 in RC1 and RC2, we submit a revised version of our manuscript entitled “**Long-term river trajectories to enhance restoration efficiency and sustainability on large rivers: an interdisciplinary study**” by D. Eschbach, L. Schmitt, G. Imfeld, J.-H. May, S. Payraudeau, F. Preusser, M. Trauerstein and G. Skupinski.

We have carefully considered and implemented the very helpful suggestions made by the referee. Here below, our responses to his comments are marked in blue font for a better readability. In the manuscript, we have marked all our edits in track changes mode.

Again, we would like to sincerely thank you for having given us the opportunity to submit a revised manuscript. We remain at your disposal for any further information that would be required.

Yours sincerely,

David Eschbach,
Corresponding Author (CA),
on behalf of all co-authors.

Referee #1: RC1 (11.10.2017)

CA: Please note that the title was modified by “*Long-term river trajectories to enhance restoration efficiency and sustainability on large rivers: an interdisciplinary study*”

GENERAL COMMENTS

RC1: The study deals with the long-term evolution of a reach of the Rhine River which underwent some restoration activities. Overall, I think it is a very good work: the novelty is combining reconstruction of morphological evolution with other aspects, specifically with geochemical characteristics of sediments. Some revisions are needed to make some parts more effective, especially the last section (see “specific comments”), and to put the work in a wider context (it

could be useful to summarize one or two key points that comes out from this study and this restoration project).

CA: We added the following conclusions summarizing the main findings of our study. Please see p.18, lines 25-43 in the revised version where the following section was added:

“In this study we show the relevance of considering temporal trajectories in process-based river restoration. An interdisciplinary approach deployed at different spatio-temporal scales has been developed by combining planimetric data with sedimentological, chemical and geochronological analysis, as well as a hydrological model. Prior to anthropogenic disturbances, the hydrosystem was mostly characterized by a high-energy depositional environment of braiding channels with high lateral mobility and important surfaces of gravel bars and pioneer vegetation. Correction works provoked a drastic temporal trajectory change, by intensifying filling of fine and polluted (Zn) sediments in palaeochannels and decreasing flood frequency, though some intense floods occurred. In contrast, the floodplain recorded lower deposition rates by quasi-unpolluted sediments. More recently, canalization resulted in very low sedimentation rates, but strong hydrological and hydrogeological disturbances.

Our results highlight potential risks that restoration projects may face and need to mitigate along large rivers, e.g. removal fine and potentially polluted sediments by reactivating erosion/deposition processes in former channels. On the Rohrschollen Island, this risk is reduced by the backwater effect of the agricultural dam which limit lateral erosion in the palaeochannel. On the contrary, floodplain areas outside palaeochannels show thin layers of fine sediments and appear more relevant to restore dynamic lateral channels. Managers may benefit from excavating new channels on such areas, as it has been performed on the Rohrschollen Island. They are even encouraged to develop self-erosion of lateral channels by dynamic floods.

Finally, this research underscores the necessity to base functional river restorations on an interdisciplinary knowledge of hydrosystem past-trajectories to maximize restoration efficiency and sustainability. On a practical level, we recommend managers to conduct such studies in geomorphological restoration projects, even if they are less detailed than our study presented in this article, for example in the case of financial constraints. They should at least be based on (i) planimetric analysis (old maps and photographs), (ii) sedimentological prospection (hand auger) combined to both a LIDAR DEM analysis and a rapid study of former large floods and (iii) a physico-chemical analysis of sediments, especially these filling palaeo-channels.

SPECIFIC COMMENTS

RC1: “Study area” section (pages 4 and 5). The part dealing with the restoration project could be improved. I think it could be useful to describe a little bit more in detail the restoration project and, in particular, the aims of the project. This would be very helpful for improving the last section of the manuscript (4.4) (see one of the following comments).

CA: This was done. Please see below the correction proposed in response to RC2.

RC1: Page 8, L. 2. A brief explanation of the CM diagram method would be useful.

CA: Please see p.6, lines 13-14 in the revised version. We added:

“... we characterized transport and depositional processes by plotting the median (D₅₀) and the coarsest percentile (D₉₉) of the grain-size distributions in the CM diagram according to Passega (1964, 1977) and Bravard and Peiry (1999).”

RC1: IRSL dating. I have some concerns about using this dating method within this study: is this method appropriate to the temporal scale considered in this study?

CA: Indeed, the presented IRSL ages are close to the upper dating range of the method, but it has been shown in previous papers that ages of a few years can reliably be determined using

luminescence methods (e.g. Ballarini et al. 2003, Quat. Geochron.; Madsen et al. 2005, Marine Geol.).

RC1: How much reliable are the results?

CA: This question applies in general to geochronological data, actually to any kind of data collected. For the present samples, we refer to the detailed discussion in Preusser et al. (2016, Geochronometria). Please, see also below our detailed answer to RC2.

RC1: I am specifically referring to Figure 7, which shows that dates have significant errors and reverse ages can be obtained (see pit 2, where there is a reverse relation between sediment depth and age).

CA: We cannot follow the reviewer here. What are ‘significant errors’? The ages are associated with uncertainties of ca. 10 %, i.e. lower than those related to radiocarbon dating in this time range due to calibration uncertainties. As a matter of fact, there are no reverse ages in the study, see figure 7. The ages are all in excellent agreement within uncertainties.

An additional detailed answer has also be given to RC2 (please see below).

RC1: Overall the contribution of IRSL may be considered useful for this study, since it constrains the age of fine sediment deposition, but it would be useful if authors would add some comments on such data. For instance, could alternative dating method be used in a similar context?

CA: Again, we refer to the paper by Preusser et al. (2016), providing a full overview of the topic and discussing the issues raised by the reviewer. Since such a discussion is well beyond the scope of the present study, we prefer not to repeat it here. In summary, there is no alternative dating approach.

An additional detailed answer has also be given to RC2 (please see below).

RC1: Section 4.4. This is part could be improved: considering the amount and quality of data, I think that the authors could make some efforts to make this part more effective. I think that they should try to go more in detail about the effects of the restoration project. For instance: were the project aims appropriate for this river reach?

CA: The effects of the restoration project cannot be developed here. The aim of this section is to highlight how long-term trajectory of the hydrosystem allows identifying the driving factors, amplitude and response-time of past disturbances. We show that this study is unavoidable and contributes to the construction of a restoration project. The effects of the restoration linked with the inherited morphological characteristics are developed in another paper submitted in Geomorphology. However, we will improve the text to highlight the legitimacy (efficiency and sustainability) of the restoration project, which is strengthened by considering the historical context.

An additional answer, much more detailed, has be given to RC2 (please see below).

RC1: To what extent are (or will be) those aims achieved?

CA: Again, this is developed in the paper submitted in Geomorphology. A retrospective analysis is carried out to determine the efficiency of the restoration project in the basis of a fine monitoring which is leading in short term (3 years).

An additional answer, much more detailed, has be given to RC2 (please see below).

RC1: Which are the main limitations of a restoration project carried out at reach scale, such as the one described in this study?

CA: Main limitations are developed in section 4.4.2. For instance, we showed that fine sediments could be remobilized as well as pollutants bound in such sediments.

An additional answer has also been given in the responses to RC2 (please see below).

RC1: Other examples to improve this section: “in part, this functioning has been targeted by recent restoration efforts” (Page 21, L. 11-12), this could be illustrated more in detail.

CA: By “functioning” we mean “the functioning before major engineering works”, and by “restoration efforts”, we mean the creation of hydromorphological dynamics. Aims of the restoration are twofold: reinstalling lateral and vertical dynamics into the channel and stimulating bedload dynamics and groundwater - surface water exchanges.

We propose to add the following sentence. Please see p.16, lines 16-18 in the revised version:

“In part, this functioning and processes have been targeted by recent restoration efforts. More specifically, the restoration aims have been to recover bedload transport, lateral and vertical dynamics, as well as groundwater - surface water exchanges”.

RC1: “this highlight the impact: “works are irreversible” (Page 21, L. 20-21), this statement requires further explanations.

CA: We added the following text p.17, lines 8-10 in the revised version:

“This highlight the fact that impacts of correction work and further engineering works are irreversible because the removal of very large amounts of fine sediments seems unthinkable. Furthermore, the strong hydrological alteration by the canalization works makes the functional alteration of the hydrosystem irreversible as well.”

Following this idea, we added the following text p.18, lines 8-9:

“... and/or natural fine sediment removal by the recovery of active bank erosion in lateral channels”.

RC1: I am wondering if it could be useful to add a final section (e.g. “Conclusions” or “Final remarks”) where major outcomes of this study (both specific and general) could be summarized.

CA: This was done. Please see the first comment of RC1 and p.18, lines 25-44 in the revised version.

RC1: Page 22, L. 30. This sentence is not clear: I think it would be useful to explain better what could be likely the future evolution of this reach, and I would avoid a direct reference to Lane balance (it is a concept well known among geomorphologists but, probably, not for readers with different backgrounds).

CA: This was done. We added the following text p.18, lines 16-17 in the revised version:

“For example, it will probably be necessary to balance a relative sediment deficit in the upstream section of the new channel by artificial gravel augmentations, in the next years/decades (Eschbach et al., in review).”

RC1: Figure 9. I have some concerns about this figure. Is it really meaningful to calculate sinuosity if channel configuration was multi-thread from 1743 to 1838?

CA: In braiding systems, sinuosity can be calculated by using the thalweg of the main channel.

An additional answer, much more detailed, has been given to RC2 (please see below) and the manuscript and figure 9 have been modified accordingly (calculation of a *Braiding and Anastomosing Index*).

RC1: Sinuosity is a key characteristic in single-thread channel, while less relevant in multi-thread channel. I think that it is not correct to assume that sinuosity in 1872 was 1 (it does not look like a straight channel!). I am wondering if this figure could be removed.

CA: The average axis of the active band (which corresponds roughly here to the 1872 channel) can be used as a reference to calculate the sinuosity, as this was also shown by Malavoi and Bravard (2010). Moreover, this figure cannot be removed because it summarizes the morphological planimetric evolutions driven by the engineering works, including the sinuosity.

An additional answer, much more detailed, has been given to RC2 (please see below; a *Braiding and Anastomosing Index* has been calculated; Figure 9 has also been modified) and the manuscript has been modified accordingly (please see below).

RC1: Some suggests concerning terminology: “channelization” or “channelization work” instead of “correction”;

CA: “Correction” or “correction works” are the specific terminology used in engineering reports, books or articles to consider the first engineering works in the Upper Rhine River (project of Tulla). That explains why we preferred this terminology as “channelization”. Moreover, this is previously specified in the introduction.

RC1: Page 14, L. 7. “Central bar” instead of “median bar”.

CA: This has been done.

TECHNICAL CORRECTIONS

RC1: Page 1 – L. 21. “IRSL” instead of “IRLS”

CA: This has been done.

RC1: Page 2 – L. 1. It could be better to use a chronological order where several works are cited. Please consider this comment throughout the manuscript.

CA: This has been done.

RC1: Page 4 – L. 15. Figure 3 (as well as Figure 4, page 5 L. 7) is cited within the main text before Figure 2.

CA: We removed the references to these figures.

RC1: Page 20, L. 2. What is the meaning of “NN”? Above sea level?

CA: NormalNull is a specific altimetric system reference used in the Upper Rhine. This means that the sea level reference is located in Germany (North Sea) and not in France (Mediterranean Sea).

RC1: Page 21, L. 5. “Different spatio-temporal scales”?

CA: We propose to keep this expression because it is commonly used to describe an interlocking of spatial scales and temporal scales.

RC1: Page 21, L. 32. Eschbach et al., submitted is missing in the reference list.

CA: This has been done.

RC1: Page 22, L. 33. “Short” instead of “medium”?

CA: This has been done.

RC1: Figure 4c. A legend should be add to explain the two symbols of this figure (i.e. anchor points and RMSE errors).

CA: In the figure 4c, the legend of the bold and dotted lines refers to the line style used for the vertical axis. This has been specified in the legend of the Figure 4. Please see p.9 in the revised version.

Referee #1: RC2 (10.02.2018)

RC2: I am disappointed by some of the author’s replies, also considering that my comments were not too difficult to address and aiming to improve quality and clarity of the paper.

CA: We thank you sincerely for your helpful remarks aiming to improve the paper, in quality and clarity. We are profoundly sorry that you considered our first corrections not satisfactory. We have carefully considered all your comments (RC1 & RC2) and have done our best to satisfy your and the editors requests. We sincerely hope our corrections and the revised version will be considered positively.

RC2: Specifically, I think that the author could pay more attention to the following aspects:

(1) Dating by IRSL. The authors replied that there are not reverse ages: is PIT 2 showing a “normal” relation between depth and ages of sediments (figure 7)? I understand that this could be the only option for dating: on the other hand, I think it could be useful to say that there were no other options.

CA: The IRSL ages shown in Figure 7 for PIT 2 are 179 ± 35 (at 40 cm), 170 ± 26 (58 cm) and 165 ± 22 (97 cm) years. First, it is important to note that these ages all overlap well within the given uncertainties. For a set of three ages there are $n * (n-1)$ possibilities (6 in our cause) of how these ages can be arranged. The end members would be 1-2-3 and 3-2-1 (where 3 is the youngest and 1 is the oldest age). We have computed the likelihood for the different possible combinations based on their uncertainties using the following MATLAB code (by courtesy of Prof. S. Hergarten, Freiburg):

```
n = 1000000;
a = randn(3,n);
a(1,:) = 179 + a(1,:) * 35;
a(2,:) = 170 + a(2,:) * 25;
a(3,:) = 165 + a(3,:) * 22;
[~,index] = sort(a);
index = 100*index(1,:)+10*index(2,:)+index(3,:);
h = hist(index,1:1000);
% probabilités of the 6 possible orders in percent
h = 100*h(h~=0)/n
```

For this we received the following results:

% 1 2 3	1 3 2	2 1 3	2 3 1	3 1 2	3 2 1
% 11.47	15.22	10.08	22.51	15.00	25.72

This indicates that the observed order of values has a likelihood of more than 10% and, indeed, we are considering this a statistically likely enough case to be regarded as “normal” (from a statistical point of view). In other words, the only information we can deduct from the dates of PIT 2 is that they reveal a rapid phase of sediment deposition - with an absence of a significant correlation between depth and ages -, which corresponds to the phase of correction works of the Rhine at the Rohrschollen site.

Furthermore, in order to follow your suggestion, we added a sentence to specify that the IRSL method is the only option for dating in this context. Please see p.7 lines 8-9 in the revised version: “, ... as any other alternative approach is achievable in this context (Preusser et al., 2016)”

RC2: (2) Section 4.4. The authors replied that “... effects of the restoration project cannot be developed here...”. If so, why in the “Introduction” they say “...and to assess potential benefits and limits of the restoration” (page 3, line 5) and “...evaluate efficiency and sustainability of the restoration effects...” (page 3, line 13)? I understand that they want to avoid overlapping between this paper and another one submitted to “Geomorphology”: in this case, my suggest would be to make some change in the “Introduction” to make the whole work more consistent.

CA: We fully understand the remark of RC2 and we thank him for this helpful comment. From a general point of view, the aim of the paper is to show that long-term trajectory of the hydrosystem is useful to improve the efficiency and the sustainability of the Rohrschollen restoration project (and potentially of other river restoration projects). This is presented in the introduction, as well as in the discussion (section 4.4). We discuss the general knowledge produced thanks to the historical study, and which is useful in the restoration context (limits, benefits, efficiency, sustainability), but we don’t aim to show the post-restoration changes observed in the Rohrschollen Island with large detail, because we believe that (i) this would be beyond the scope and topic of the paper, and (ii) would make the paper unnecessarily long. Furthermore, these detailed results have been published by Eschbach et al. (2017) and may be published in the near future (Eschbach et al., in review). Nevertheless, we fully agree with RC1 and RC2 that the restoration project and the morphological evolution of the restored channel should be better presented in the Study area section, notably to strengthen the discussion.

Consequently, we added / modified several sentences in the introduction and the discussion, both modifications being linked together.

Please see p.2 lines 37-39 in the revised version. We modified the objectives in order to make them coherent with the discussion (“evolutionary trends” is more general than “evolution”; the objective (v) opens avenues towards other river restorations):

“..., (iv) deduce post-restoration evolutionary trends and (v) propose operational outlook to improve efficiency and sustainability of Rohrschollen’s restoration, and by extension of other river restoration projects (Sear et al., 1994; Grabowski and Gurnell, 2016)”.

And p.4 lines 3-9, we added some details on the restoration and post-restoration adjustments:

“As the bankfull discharge of the new channel is $20 \text{ m}^3 \cdot \text{s}^{-1}$, flooding in the Island occurs when the discharge exceed this threshold. A three years monitoring showed that bedload transport, active lateral and vertical morphodynamics occur along the new channel (active bank erosion, formation of bars and logjams, enhancement of pool-riffle sequences, increase of groundwater – surface water exchanges...; Eschbach et al., 2017; Eschbach et al., in review), but not along the Bauerngrundwasser which is affected by the hydraulic backwater of the agricultural dam (Eschbach et al., 2017; Eschbach et al., in review; see also the pictures of Fig. 1).”

In the Discussion, p.16, lines 17-18, we added:

“More specifically, the restoration induced, in the new channel, the recovery of bedload transport, lateral and vertical dynamics, as well as groundwater - surface water exchanges.”

P.17, lines 9-15, we completed (two more sentences) and modified the end of the section:

“... because the removal of very large amounts of fine sediments seems unthinkable. Furthermore, the strong hydrological alteration by the canalization works makes the functional alteration of the hydrosystem irreversible as well. In this constrained context, the main challenge of the restoration was to recover processes as dynamic floods (on the whole island) and an active morphodynamic gravel bed channel in a relatively restricted environment (new channel; see also below). On the basis of an environmental monitoring conducted during three years after the end of the restoration works, it appears that these restoration objectives are attained (Eschbach et al., 2017; Eschbach et al., in review) and that the restoration choices were relevant (see also below).”

P.17, lines 25-26, we added:

“This demonstrates once again the relevancy of the principles of this restoration.”

P.17, line 39, we added:

“... as it is the case on the Rohrschollen Island (new channel).”

P.17, line 42, we added:

“... (as it has been performed on the Rohrschollen Island),...”

P.18, lines 9-10, we added:

“... (which could be made more difficult if sediments are polluted) and/or natural fine sediments removal by the restoration of active bank erosion in lateral channels.”

P.18, lines 16-17, we added:

“... to balance a relative sediment deficit in the upstream section of the new channel by artificial gravel augmentations, in the next years/decades (Eschbach et al., in review).”

P.18, lines 22-23, we added:

“...and modelling, both in the frame of fluvial hydrosystem temporal trajectories.”

RC2: (3) Sinuosity (Figure 9). Yes, I agree that sinuosity can be measured in a braided rivers: the point is that if you are analyzing a multithread river (braided, wandering; see figure 4) other indices would be more useful to be taken into account (e.g. braiding index).

CA: In order to take into account the remarks RC1 and RC2 of the Reviewer#1, we have calculated the thalweg's sinuosity on the basis of the straight length of the reach (p.16, Fig. 8). So, the sinuosity in 1872 is 1.09 rather than 1.00, which was effectively wrong. Furthermore, we have added a *Braiding and Anastomosing Index* (BAI; table of Fig. 8, p.16) which corresponds to the mean number of these two types of channels (channels showing stagnant water have been excluded). Indeed, this index shows in a relevant way the modifications of the channel pattern (BAI decreased from 7.90 to 1.00).

As a consequence, the following changes in the revised version are also proposed:

P.3, line 14, we added:

"Before engineering works, it was a braiding and anastomosing fluvial hydrosystem."

P.8, lines 7-8, we added:

"The braiding and anastomosing index ranged between 7.9 and 5.4 (Fig. 8)"

P.11, line 7, we added:

"... , the braiding and anastomosing index decreased from 5.36 to 2.45"

P.11, line 10, we added:

"(...; the braiding and anastomosing index decreased to 1 in 1872)"

At the end of the title of Figure 9 (p.16 in the revised version), we added:

"... BAI is a Braiding and Anastomosing Index which corresponds to the mean number of these two types of channels (channels showing stagnant water have been excluded)".

CA: In addition, we propose additional modifications in the revised version (modifications of only one to three words are not listed below):

P.3, line 3, we added:

"...from braiding to anastomosing and meandering..."

P.3, line 14, we added:

"Before engineering works, it was a braiding and anastomosing fluvial hydrosystem."

Long-term river trajectories to enhance restoration efficiency and sustainability on large rivers on the Upper Rhine: an interdisciplinary study (~~Rohrschollen Island Upper Rhine, France~~)

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15 **Abstract.** While the history of a fluvial hydrosystem can provide essential knowledge on present functioning, historical context remains rarely considered in river restoration. Here we show the relevance of an interdisciplinary study for improving restoration within the framework of a European LIFE+ project on the French side of the Upper-Rhine (Rohrschollen Island).
Investigating the Planimetric-planimetric evolution combined with historical high flow data enabled to reconstruct pre-disturbance hydromorphological functioning and major changes that occurred on the reach. A deposition frequency assessment
20 combining vertical evolution of the Rhine thalweg, chronology of deposits in the floodplain, and a hydrological model revealed that the period of vertical incision in the main channel corresponded to high rates of narrowing and lateral channel filling. The
aAnalysis of filling processes by using Passega diagrams and IRLS dating highlight that periods of engineering works were closely related to fine sediment deposition, which present also concomitant heavy metal accumulation. In fact, current fluvial
25 forms, processes and sediment chemistry around the Rohrschollen Island directly reflect the disturbances that occurred during past correction works, and up to today. Our results underscore the advantage of combining functional restoration with detailed knowledge of past-trajectory to: (i) understand the functioning of the hydrosystem prior anthropogenic disturbances, (ii) characterize the human-driven morphodynamic adjustments during the two last centuries, (iii) characterize physico-chemical sediment properties to trace anthropogenic activities and evaluate the potential impact of the restoration on pollutant remobilization, (iv) deduce post-restoration evolution tendency and (v) evaluate efficiency and sustainability of the restoration
30 effects. We anticipate our approach to expand the toolbox of decision-makers and help orientating functional restoration actions in the future.

1 Introduction

During the two last centuries, numerous engineering works (e.g. channelization or damming), aimed at flood control, navigation improvement, expansion of agriculture or hydropower production, have altered the functioning of European large
35 rivers (Brookes, 1988; Petts et al., 1989; Kondolf and Larson, 1995; ~~Petts et al., 1989~~), including aquatic and riparian habitats and biodiversity (Bravard et al., 1986; Amoros and Petts, 1993; ~~Bravard et al., 1986~~; Dynesius and Nilsson, 1994). In order to balance these impacts by recovering fluvial processes (Bravard et al., 1986; Naiman et al., 1993, 1988; Hering et al., 2015; Naiman et al., 1993, 1988) and ecosystem services (Loomis et al., 2000; Acuña et al., 2013; Large and Gilvear, 2015; ~~Loomis et al., 2000~~), an increasing number of restoration projects have been carried out over the last decades (Kondolf and Micheli,
40 1995; Wohl et al., 2005). In Europe, this trend has been supported by the Water Framework Directive (IKSR-CIPR-ICBR, 2005; WFD, 2000). Restoration activities progressively target hydromorphological processes and functioning rather than

‘static’ fluvial forms (Jenkinson et al., 2006; Beechie et al., 2010; Arnaud et al., 2015; Beechie et al., 2010; Jenkinson et al., 2006). Numerous studies have shown that current river functioning results from complex long-term trajectories driven by natural and anthropogenic factors at different spatio-temporal scales (e.g. Brown, 1997; Bravard and Magny, 2002; Brown, 1997; Gregory and Benito, 2003; Starkel et al., 2006; Ziliani and Surian, 2012). These trajectories provide a relevant basis to infer future trends and management principles (Bravard, 2003; Sear and Arnell, 2006; Bravard, 2003; Fryirs et al., 2012). In order to understand the complete range of functional changes, a comprehensive understanding of human-driven channel adjustments over the last centuries therefore appears crucial in river restoration. Despite significant research efforts over the last two decades, however, integrating pluri-secular temporal trajectories into restoration projects remain an exception (Sear and Arnell, 2006; Fryirs et al., 2012; Sear and Arnell, 2006).

In large modified hydrosystems such as the Upper Rhine River, current lateral extent of the floodplain results from past disturbances that occurred during engineering works (Herget et al., 2005, 2007). Hydromorphological dynamics, chemical pollutions and depositional processes were strongly impacted by diking along the main channel and disconnecting of lateral channels since the beginning of the 19th century (Tümmers, 1999). Several studies have focused on the storage and remobilization of heavy metals (Schulz-Zunkel and Krueger, 2009; Ciszewski and Gryar, 2016; Falkowska et al., 2016; Grygar and Popelka, 2016; Schulz-Zunkel and Krueger, 2009) and/or organic pollutants in major floodplains worldwide (Lair et al., 2009; Berger and Schwarzbauer, 2016; Zimmer et al., 2010; Lair et al., 2009; Berger and Schwarzbauer, 2016). Most studies concerned with the Rhine focused on the industrialized Lower Rhine region including the Rhine-Meuse Delta (de Boer et al., 2010; Evers et al., 1988; Middelkoop, 2000; Goth et al., 2001; de Boer et al., 2010; Middelkoop, 2000). In comparison, the Upper Rhine region is two times less contaminated than the lower parts of the Rhine with respects to total concentrations of both polychlorinated dibenzo(p)dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) in sediments and tracers of industrial activities (Evers et al., 1988). However, contamination histories are still not well known and reference studies considering functioning or disturbance histories are missing.

Studying past functioning and disturbance histories as keys to understanding current forms and processes of floodplains can provide insights into current functioning and hydromorphological sensitivity to changes (Kondolf and Larson, 1995; Mika et al., 2010). Historical hydromorphological adjustments should be evaluated on an accurate spatial scale and a high temporal resolution to identify past evolutionary processes and causal relationships (Bogen et al., 1992; Horowitz et al., 1999). Interdisciplinary and retrospective studies, however, rarely combine different data sources to obtain a comprehensive view of functional changes (Bravard and Bethemont, 1989; Trimble and Cooke, 1991; Lawler, 1993; Gurnell et al., 2003; James et al., 2009; Rinaldi et al., 2013; Lawler, 1993; Lespez et al., 2015; Rinaldi et al., 2013; Trimble and Cooke, 1991). Furthermore, historical studies rarely consider sediment dating and pollution (Bogen et al., 1992; Garban et al., 1996; Horowitz et al., 1999; Woitke et al., 2003).

Within the framework of a functional geomorphological restoration project on the Rohrschollen Island, we embarked for an interdisciplinary and retrospective pluri-secular study to provide a holistic understanding of the functional temporal trajectory of the fluvial hydrosystem, rather than to determine reference states. We hypothesized that long-term temporal trajectories allow to identify driving-factors, amplitude and response time of disturbances, and to provide key-information to manage functional restoration actions, notably in terms of potential benefits and limits assess potential benefits and limits of the restoration. This approach bears potential to accompany actions of functional restoration in order to maximize efficiency and sustainability, and infer future evolutionary trends. To test these hypotheses, this study combines horizontal (planimetric) and vertical (thalweg evolution, filling chronology) dynamics to: (i) understand-show the functioning of the hydrosystem prior anthropogenic disturbances, (ii) characterize-characterise the human-driven morphodynamic adjustments during the two last centuries including sediment transport and deposition processes as well as geochronology, (iii) characterize-assess physio-chemical sediment properties (e.g. heavy metals and organic contaminant concentrations) to trace anthropogenic activities and

evaluate the potential impact of the restoration on pollutant remobilization (Middelkoop, 2000; Fedorenkova et al., 2013; IKS-CIPR-ICBR, 2014; Middelkoop, 2000), (iv) propose operational outlook in order to improve efficiency and sustainability of future restoration projects deduce post restoration evolution and (v) evaluate efficiency and sustainability of the restoration effects (Sear et al., 1994; Grabowski and Gurnell, 2016; Sear et al., 1994)-(iv) deduce post-restoration evolutionary trends and (v) propose operational outlook to improve efficiency and sustainability of the Rohrschollen's restoration of Rohrschollen Island, and by extension of other river restoration projects (Sear et al., 1994; Grabowski and Gurnell, 2016).

2 Study area

With a total length of 1,250 km and a drainage basin of about 185,000 km², the Rhine is the third largest river of Europe. Located between Basel and Bingen (Fig. 1-a), the Upper Rhine Graben is 35-50 km wide and 310 km long. Hydrology in the southern part of this sector is characterized by a nivo-glacial regime and a mean discharge of 1,059 m³.s⁻¹ (1891-2011; Basel gauging station; Uehlinger et al., 2009). Slope decrease and inherited geomorphological factors explain the longitudinal evolution of the channel pattern from braiding to anastomosing and meandering (Carbiener et al., 1983; Schmitt et al., 2016; Fig. 1-b). Since the middle of the 19th century, three successive engineering works modified drastically the hydrosystem: (i) the correction stabilized the main channel between two artificial banks and the floodplain between two high flow dikes, (ii) the regularization consisted to build alternative in-channel groyne fields to improve navigation and (iii) the canalization by-passed the corrected main channel in many areas south of Strasbourg. Nowadays, the river consists of a single channel which is locally by-passed by artificial canalised sections. North of Strasbourg, the canalization concreted the Rhine bed itself.

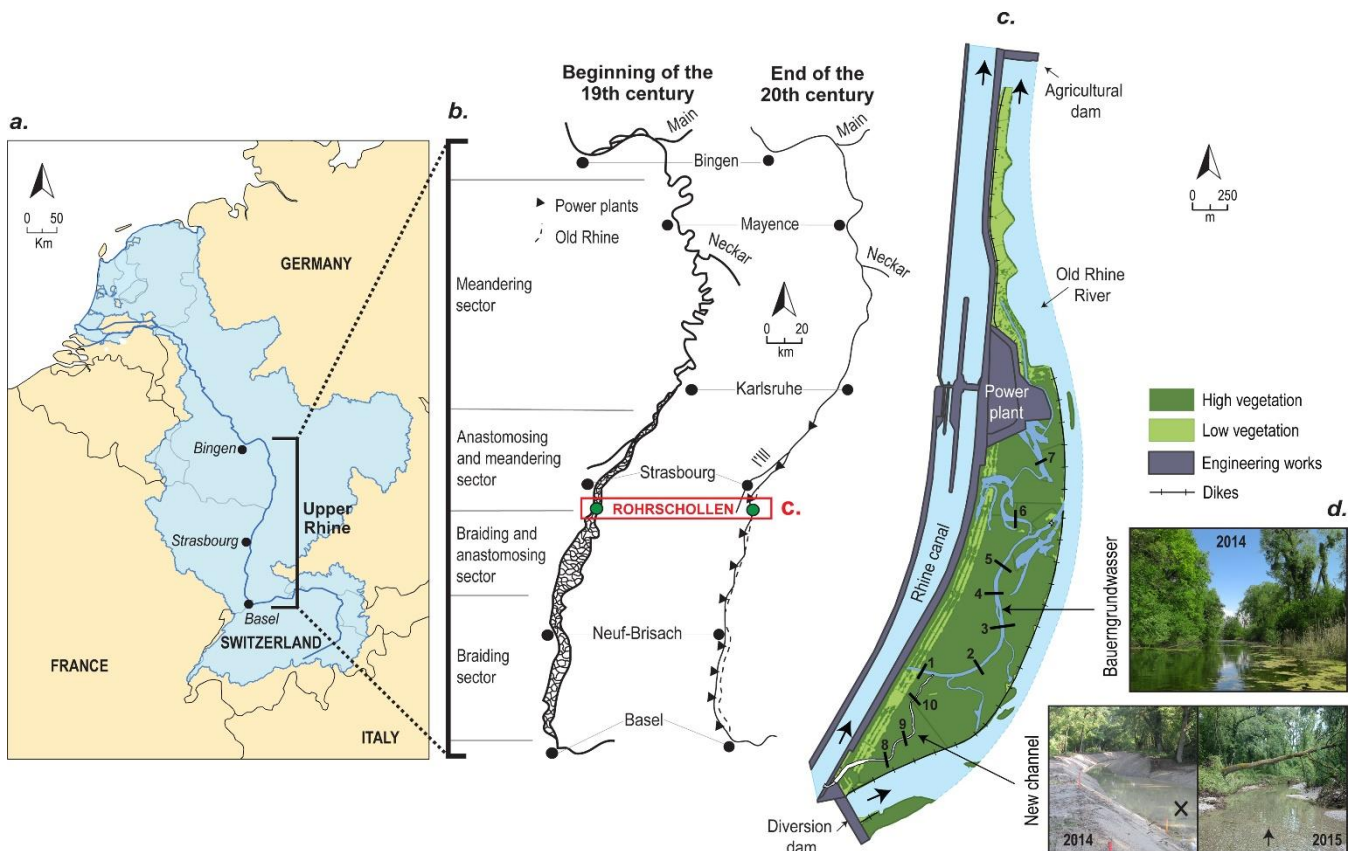


Figure 1: (a) Location of the Upper Rhine Graben, (b) channel pattern sectorization and evolution from the 18th century to present (Schmitt et al., 2009), (c) location of the study site and map of Rohrschollen Island, (d) pictures of the Bauerngrundwasser and evolution of the new channel.

The ~~artificial~~ Rohrschollen ~~artificial~~ Island is located 8 km ~~South-East~~SE of the city of Strasbourg and owes its existence to the construction of a power plant in 1970. ~~Before engineering works, it was a braiding and anastomosing fluvial hydrosystem.~~ The ~~Island-island~~ is enclosed by the Rhine canal to the west and the Old Rhine River to the east, which corresponds to ~~a-the~~ by-passed ~~of-the~~ corrected Rhine (Fig. 1-c). On the southern part, a diversion dam diverts up to $1,550 \text{ m}^3 \cdot \text{s}^{-1}$ for usage by the power plant. When the discharge is less than $1,563 \text{ m}^3 \cdot \text{s}^{-1}$, an instream discharge of $13 \text{ m}^3 \cdot \text{s}^{-1}$ flows to the Old Rhine. On the northern part of the island, an agricultural dam built in 1984 maintains a constant water level in the Old Rhine at 140 m NN (NormalNull) in order to increase groundwater level for agricultural purpose. When floods exceed $2,800 \text{ m}^3 \cdot \text{s}^{-1}$ (2-year instantaneous flood), the agricultural dam ~~can be~~is raised for flood retention (IKSR-CIPR-ICBR, 2012), but flooding remains static ~~and only a part of the island is flooded.~~ The island is crossed by an anastomosing channel (Bauerngrundwasser), which is disconnected from the Rhine canal at its upstream extremity and connects to the Old Rhine further downstream (Fig. 1-c & d). Further north an additional minor channel flows towards the Rhine Canal. The water level of the entire length of the Bauerngrundwasser is artificially maintained by the hydraulic backwater of the agricultural dam ~~(Fig. 3-e)~~. Classified as a natural reserve since 1997, the island has recently been restored (European LIFE+ project) in order to recover typical alluvial processes and biodiversity, including dynamic floods, bedload transport, active morphodynamics, ~~or~~ and hygrophilous tree species. ~~To attain these objectives, the project aims to restore the alluvial functionality by recreated dynamics floods. In the southern part of the island~~ a large floodgate was built in 2013 ~~in the southern part of the island~~ and a new upstream channel of 900 m length was excavated (Fig. 1-c & d). The downstream end of this channel is connected to the Bauerngrundwasser channel. Water input from the flood gate ranges ~~between-from~~ $2 \text{ m}^3 \cdot \text{s}^{-1}$ (when $Q_{\text{Rhine}} < 1550 \text{ m}^3 \cdot \text{s}^{-1}$) ~~and-to~~ $80 \text{ m}^3 \cdot \text{s}^{-1}$ (when $Q_{\text{Rhine}} > 1550 \text{ m}^3 \cdot \text{s}^{-1}$). ~~As the bankfull discharge of the new channel is $20 \text{ m}^3 \cdot \text{s}^{-1}$, flooding in the island occurs when the discharge exceed this threshold. A three years long-monitoring showed that bedload transport and active lateral and vertical morphodynamics occur along the new channel (active bank erosion, formation of bars and logjams, enhancement of pool-riffle sequences, increase of groundwater—/surface water exchanges...; Eschbach et al., 2017; Eschbach et al., in review), but not along the Bauerngrundwasser, which is affected by the hydraulic backwater of the agricultural dam (Eschbach et al., 2017; Eschbach et al., in review; see also the pictures of Fig. 1).~~ Our study addresses embedded spatial scales: (i) the entire study site, which corresponds to the fluvial hydrosystem area around the natural reserve (about 1-3 km beyond the perimeter of the later), (ii) the Rohrschollen Island which corresponds to the natural reserve area, (iii) seven transects on the Bauerngrundwasser used to characterize sediment transport and depositional processes, and (iv) two sediment pits excavated near the new and the old channels ~~(Fig. 4 a, 2010)~~ in order to date sediment deposition and assess sediment pollution.

3 Material and methods

In this study, we have adopted an interdisciplinary approach that combines hydrological retrospective modelling with limnimetric, topographic (levelling and DEM) and hydrogeologic data as well as data on sediment filling processes, depositional chronology and geochemical characteristics (Fig. 2).

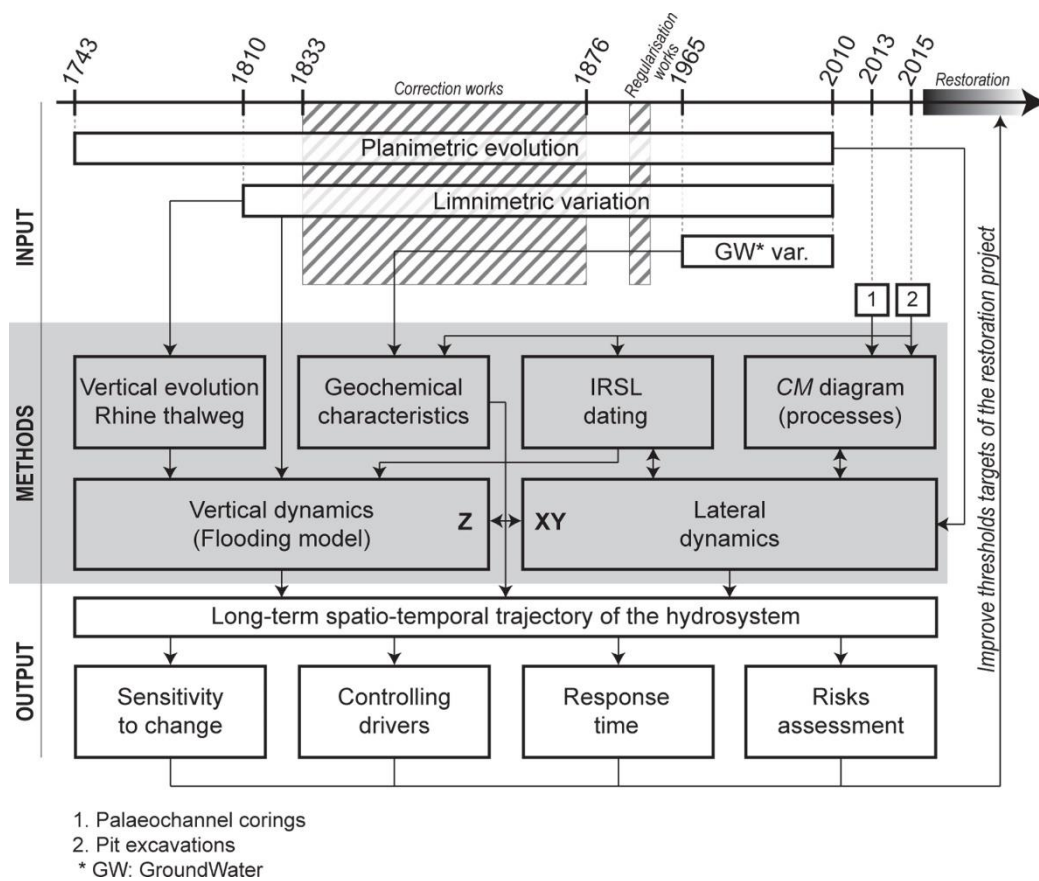


Figure 2: Methodological approach to analyse long-term spatio-temporal trajectory of the hydrosystem by combining historical multi-source data with *in situ* morpho-sedimentary prospections and geochemical investigations.

3.1 Planimetric analysis

5 The historical planimetric analysis covers a period of about 260 years (from 1743 to 2010) and was carried out in ArcMap (ESRI v.10.3) using six historical maps and two sets of aerial photographs. The map from 1828 compiled during the demarcation of the Franco-German border was georeferenced on the IGN BD ortho 2007 base map and used as a base layer for georeferencing of the 1743, 1778, 1838, 1872 and 1926 maps. Aerial photographs were georeferenced using the 2007 orthophotograph as a base layer. Fixed position objects such as churches, road crossings or bank protection structures were used as control points. Between nine and twelve control points were selected for each historical map, and between five and seven for the aerial photographs. Total root mean square error (RMSE) ranged from 0.94 to 25 m and increased with the distortion and the imprecision of the oldest maps, especially the 1743 and 1778 maps (Fig. 4-c). However, the RMSE distortion is satisfactory considering the inherent relative imprecision of these maps and the difficulty to determine anchor points between old maps and 2007 orthophotography. Aerial photographs were selected at low flow water level to enable comparison between morpho-ecological surfaces and active channel and gravel bar surfaces which are particularly sensitive to discharge variations (Rollet et al., 2014). Morpho-ecological units were then manually digitized at the detailed scale of 1:1000 to 1:2000 based on 8 maps. According to the typology developed by Dufour (2005), four classes and fourteen subclasses were determined. Surface areas of each class and time slice were calculated to quantify the planimetric evolution. The results of the surface analyses were converted to a percentage ratio to facilitate regional interpretation of the morpho-ecological evolution. Two scales were considered: the study area of the Rohrschollen Island with a total surface of 2,181 ha and the area of the natural reserve with a total surface area of 314 ha.

3.2 Analysis of vertical data

3.2.1 Limnimetric and piezometric analysis

The vertical evolution of the Rhine thalweg was studied based on historical limnimetric data and bibliographic references (Bensing, 1966; Bull, 1885; CECR, 1978). Limnimetric data were compiled for low water discharge ($\sim 540 \text{ m}^3 \cdot \text{s}^{-1}$) at the Marlen gauging station (Kilometre Point 295; [Jeanpierre, 1968](#); Felkel, 1969; [Jeanpierre, 1968](#)). The piezometric analysis was achieved using a German database (LUBW: Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg) and the French regional groundwater database (APRONA, Association pour la PROtection de la Nappe phréatique de la plaine d'Alsace), by selecting datasets close to the Rohrschollen reach.

3.2.2 Palaeochannel corings

Seven coring transects were distributed along the Bauerngrundwasser to cover the different morphological characteristics of the study area (e.g. Fig. 3). Six sediment cores per transect were hand-augered on both channel banks to measure the thickness of the post-correction deposits. From the 42 cores, a total of 81 sediment samples were taken at different depth of the filling layer. Two additional samples were extracted from the channel bottom at transects two and four with a piston sampler.

3.2.3 Pit excavations

In addition to the transect-based prospection, two pits were excavated up to the gravel bottom, on the right bank of the two channels. Locations of the pits were determined by (i) identifying main filling sectors revealed by old maps and corings survey, and (ii) the proximity to the potential future erodible banks (concave banks; Fig. 3-a). Stratigraphical Units (SU) were defined in the field on the basis of colour and textural differences. Two large topographical cross-sections (600 m for the pit 1 and 800 m for the pit 2) intersecting both pits were extracted from the DEM to interpret the dynamics of fine sediment deposition in relation to the initial elevation of each pit, the thickness of the stratigraphical units and the flooding regime (Fig. 3-b).

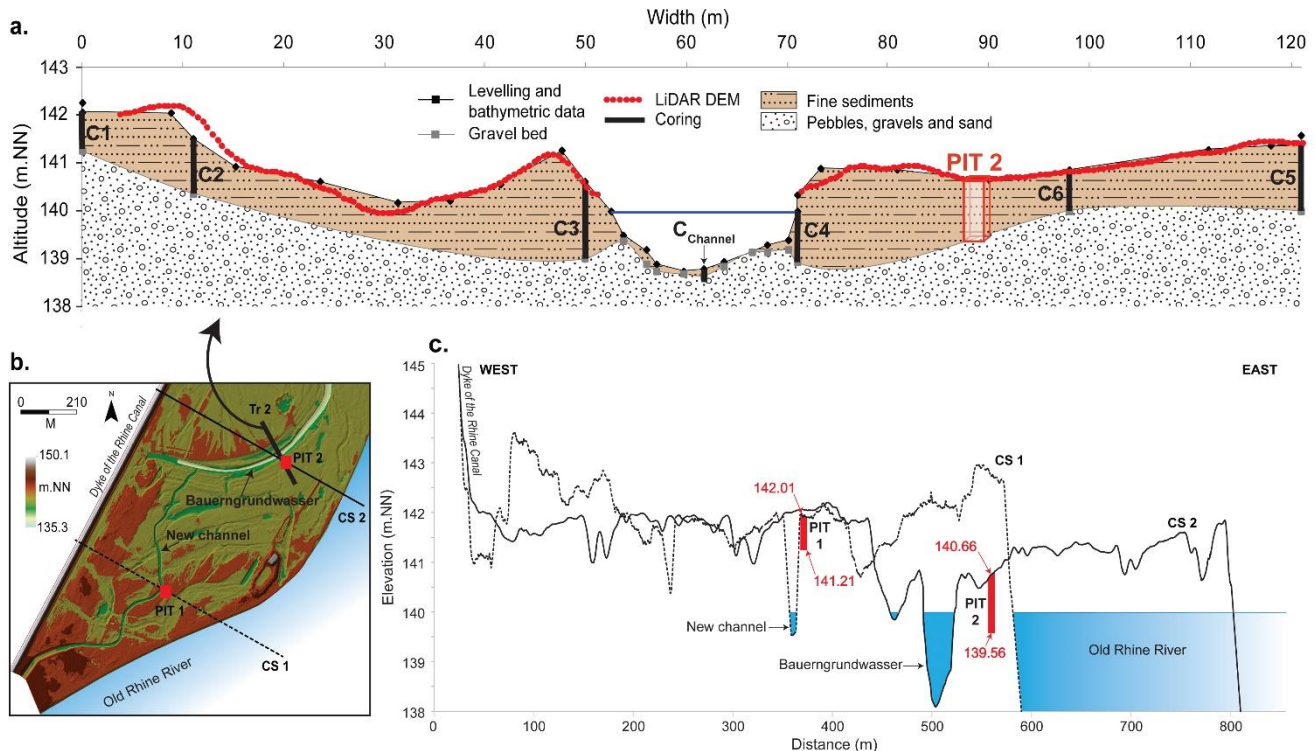


Figure 3: (a) Example of a transect (Tr 2) based on levelling and bathymetric data. Levelling data are compared to LIDAR DEM data. Location of corings and Pit 2 is also given, (b) location of Tr 2, the two excavation pits (red squares) and topographical profiles crossing the two pits, (c) overlaying of the two topographical profiles.

3.3 Characteristics of the sediments

3.3.1 Grain size analysis

Depending on width and thickness of the filling, 31 samples from three coring transects distributed along the entire length of the Bauerngrundwasser (2, 4 & 5 in figure 1) and two samples from the channel bottom (2 & 4 in figure 1) were selected for grain size analysis. In addition, one sample per SU were taken from each excavated pit (Fig. 7). Munsell colour and qualitative SU description were completed in the field. Cumulative grain size distribution and a sorting index were obtained from measurements with a Beckman Coulter laser diffraction particle size analyser. Then, the soil organic carbon ratio was determined by the loss on ignition method (375°C during 16 hours). ~~To further~~ We characterized transport and depositional processes, ~~we used the CM diagram method (Bravard and Peiry, 1999; Passega, 1964, 1977), determine the competence of palaeochannel deposits by plotting the median (D_{50}) and the coarsest percentile (D_{99}) of the grain-size distributions in the CM diagram according with~~ to Passega (1964, 1977) and Bravard and Peiry (1999).

3.3.2 Geochemical and organic pollutants analyses

The 10 samples from the two pits (Fig. 7) were air-dried at 20 °C and sieved (<2 mm). Dried sediments were pulverized (<63 µm) using an agate disk mill prior to alkaline fusion and total dissolution by acids. Measurement of elemental concentrations was done as described previously (Duplay et al., 2014) by inductively coupled plasma atomic emission spectrometer and mass spectrometer analysis (ICP-AES and ICP-MS) using the geological standards BCR-2 (US Geological Survey, Reston, VA, USA) and SCL-7003 (Analytika, Prague, Czech Republic) for quality control. An enrichment factor (EF) was used to compare changes of Zn, Cr, Ni, Cu, Pb and Cd concentrations in the pit 1 and pit 2 profiles with the reference soil collected in the deepest SU of the considered pit:

$$EF_{HM} = \frac{\left(\frac{HM_{sample}}{Ti_{sample}}\right)}{\left(\frac{HM_{reference}}{Ti_{reference}}\right)} \quad (1)$$

where HM and Ti are, respectively, the concentrations of the considered heavy metal and Ti (mg kg⁻¹ d.w.) in the SU sample of the pit and the reference soil. Concentrations of heavy metals were normalized relative to titan (Ti) as a conservative element to limit EF variations due to local heterogeneities as it displays a low relative standard deviation (<0.03) over both pits (Reimann and de Caritat, 2005).

Based on previous studies dedicated to the contamination of the Rhine sediments (Fedorenkova et al., 2013; van Helvoort et al., 2007), 38 legacy and modern organic pollutants (including 30 pesticides, the hexachlorobenzene and 7 polychlorinated biphenyls) were analysed by liquid chromatography and gas chromatography mass spectrometry (LC-MS and GC-MS) with quantification limits ranging from 0.015 and 0.05 µg.g⁻¹ (see Tables S1).

3.3.3 Depositional chronology

Dating of sediments sampled from both pits was carried out using Infrared Stimulated Luminescence (IRSL). ~~as any other alternative approach is achievable in this context (Preusser et al., 2016).~~ The detailed procedures and methodological aspects are discussed in Preusser et al. (2016). ~~This paper shows that any other alternative approach are achievable in this context.~~ In summary, IRSL (stimulated at 50°C) of sand-sized feldspar grains was measured applying both small aliquot (ca. 100 grains) and single-grain techniques. When applying the Minimum Age Model (MAM) on single-grain data sets, the estimated ages coincides with the expected age of the sediment. At the same time, MAM ages calculated for the small aliquot data sets overestimate the known age by up to 200 years (>100 %). This is explained by partial resetting of the IRSL signal prior to deposition and masking effects when measuring several grains at the same time. Presented here are the results previously published by Preusser et al. (2016) from pit 1 together with additional samples taken from pit 2 (Table S1). For the new data,

we again observed significant older ages when measuring several grains at the same time for most of the samples. Only for sample IDEX2-107, multiple and single-grain approaches gave the same result. However, for this sample too small grains (100-150 μm) were measured using Risø single-grain discs. This results in accumulating a few (ca. 5) grains being measured at the same time and likely similar averaging effects as observed for larger aliquots. Hence, we consider these ages as maximum estimates.

3.3.4 Flooding frequency assessment

To determine the depositional chronology of the two pits and reconstruct flooding frequency over time, we developed a simple flooding model based on (i) the results of the vertical evolution of the corrected Rhine thalweg close to the Rohrschollen Island, (ii) the thickness of fine sediments at both pits, and (iii) IRSL dating. Elevation of the pits at each time slice was determined by the gradual sediment accumulation and the corresponding elevation increase between the two adjacent IRSL dates. Active channel width in vicinity to the pits was measured from the 1828, 1838 and 1872 maps. Flooding water depth was determined by subtracting the elevation of the pits from the thalweg elevation for each time slice (Fig. 5-c). For the three dates corresponding to the 1828, 1838 and 1872 maps, we determined the maximum discharge using the hydrogram (Q_{max}) at Basel and the limnimetric data at the Kehl bridge, which is located about 7 km downstream the study area. We calculated for these dates and the corresponding bankfull discharges the sections (S), the mean water slopes (I), the hydraulic radius (Rh) and the roughness (k) close to the pits. This allowed to estimate flood discharges ($Q_{flooding}$) for both pits during the entire period from 1828 to 1970 (end of the canalization) using the Manning-Strickler equation (Eq. 2):

$$Q_{flooding\ pit_x\ at\ date_n} = S_{date_n} \times I^{1/2}_{date_n} \times Rh^{2/3}_{date_n} \times k \quad (2)$$

Finally, we compared these results with the limnimetric variations (historical hydrogram) to determine the frequency and the intensity of historical floods in each pit (Fig. S2; Fig. 5-c).

4 Results and discussion

4.1 Hydromorphological dynamics before the beginning of the correction works (up to ca. 1833)

Analysis of the three earliest historical maps (Fig. 4-a, 1743, 1778 and 1828) at the scale of the entire study site documents the natural morphodynamics along the Upper Rhine before the beginning of the correction works. At that time, the Rhine was a wide and braiding channel system (width ranging from 500 m to 1,500 m) characterized by numerous in-channel gravel bars, which is consistent with the descriptions from Schäfer (1973) and Herget et al. (2005) and Schäfer (1973). Multiple anastomosing channels also existed along the floodplain (Carbiener, 1983), at a maximum distance of about 5 km from the thalweg. The braiding and anastomosing index ranged between 7.9 and 5.4 (Fig. 8). The period 1743-1828 is characterized by marked changes and strong channel shifting of about 1 to 2 km. Across the entire study area, gravel bar surface areas increased (+100 ha; +128%) while vegetated areas changed only slightly (low vegetation: -45 ha; -18.4%; high vegetation: +124 ha; +11%; Fig. 4-b). In 1828, more than 70 % of the present natural reserve area was occupied by the active channel (running water and gravel bars). The high morphodynamic activity may be caused by the high frequency of flood events (four 10-years floods from 1810 to 1828) characterizing the beginning of the 19th century (Fig. 5-c). These dynamics could be an effect of the Little Ice Age (Martin et al., 2015; Schmitt et al., 2016), which may have had a considerable impact on discharge, bedload transport and flood regime intensifying lateral dynamics (Schirmer, 1988; Rumsby and Macklin, 1996; Schirmer, 1988). A similar phenomenon has been observed previously, for example, by Bonnefont and Carcaud (1997) on the River Moselle, or by Bravard (2003) for the Rhône Basin. However, this hypothesis has not been validated for the Rhine yet and awaits further testing (Wetter et al., 2011; Schmitt et al., 2016; Wetter et al., 2011).

In-At the scale of the natural reserve, the reach was located on the left bank of the Rhine in 1743. It was almost completely occupied by the thalweg from 1778 to 1828 as it shifted towards the western direction. According to the location of pit 1 (Fig. 4-a, median-central bar on 1828 map) and the depositional history deduced from historical maps, the resetting of the IRSL signal in basal sediments of pit 1 resulted from this major lateral migration (Preusser et al., 2016). In accordance with the IRSL dates, deposition of fine grained sediments in the lower part of pit 1 took place between 1778 and 1806 (Fig. 5-a) after the Rhine thalweg had moved over the area. The maximum age of the investigated sediments in pit 1 is therefore 238-210 years (i.e. 1777-1805; Preusser et al., 2016). The 1828 map in figure 4-a shows that pit 2 is located in the 1828 main channel and accumulation of fine sediments must have commenced after this time. Despite local diking on the floodplain and across some lateral channels as revealed by the planimetric analyses (essentially in 1828), it seems that fluvial morphodynamics and lateral channel shifts before 1828 were (quasi) not influenced by anthropogenic disturbances.

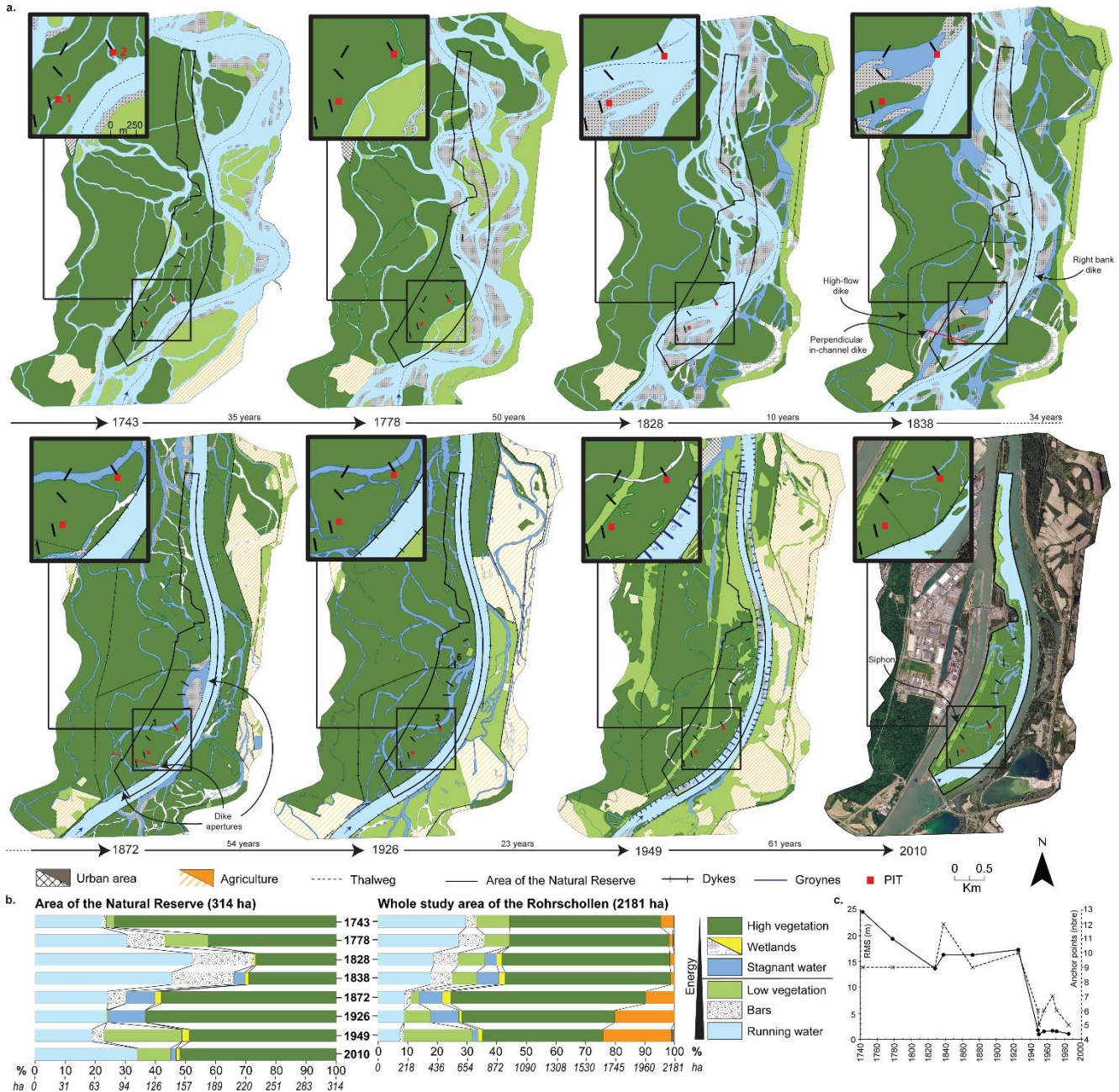


Figure 4: (a) diachronic evolution of the whole study area. The black-boxes are zooms of (scale 1:2) in the surroundings of the two pits. (b) Surface evolutions of the morpho-ecological units in the natural reserve (1743-2010) and in the whole study area (1743-1949). (c) Number of anchor points used to georeferenced old maps (1743/1778/1828/1838/1872/1926) and aerial photographs (1949/1956/1966/1971/1985 dotted line) and values of RMSE errors (continuous line).

4.2 Hydromorphological disturbances during the correction works (1833-1876)

4.2.1 Main channel adjustments

The correction works commenced between 1828 and 1838 (around 1833) and induced major changes ~~of~~to the hydrosystem (Herget et al., 2005). A detailed map based comparison of the 1828 and 1838 maps shows that the left bank was eroded in the southern part of the study area (maximum of about 50 m) after 1828 and before (possibly during?) the building of the *perpendicular in-channel dike* (Fig. 4-a, 1838). This is in agreement with the current position of the upstream part of the Bauerngrundwasser (Fig. 9, period A). Subsequently, the Rhine thalweg was artificially shifted ~~in~~towards a western direction by the *right bank dike*, and then to the east by the *perpendicular in-channel dike* and the *high-flow dike*. A large flood ($Q \sim 3800 \text{ m}^3 \cdot \text{s}^{-1}$; 10-years floods; Fig. 5-c) occurred in 1831, which was thoroughly documented due to the important damages it caused (Champion, 1863 — ~~Testimony of M. Coumes~~). We hypothesize that this event intensified the morphological adjustments during this period. In 10 years (1828-1838) the surface of running water decreased ~~of~~by 20 ha (-5%) in the entire study area, while the surface area of stagnant water increased correspondingly ~~(+plus 75 ha or +equal to 85 %)~~.

~~From 1840 onwards~~During the 1838-1872, about 40 years after the beginning of the correction works, the ~~new~~-corrected Rhine channel began to incise (1 cm ~~per~~per year on average; Fig. 5-a) in response to channel narrowing (250 m wide), slope increase and bank stabilization (Fig. 4-c, 1872). In addition, areas of gravel bars, flowing water and low vegetation surfaces decreased (by -110 ha ~~or~~- 70 %; -194 ha ~~or~~- 50 %; -121 ha ~~or~~- 67 %, respectively), while areas of high vegetation and agricultural surfaces increased (by +218 ha ~~or~~+ 18 %; +183 ha ~~or~~+ 700 %, respectively; Fig. 4-b). This is interpreted as the consequence of sediment deposition in the disconnected parts of the main channel, inducing channel narrowing, and forest and agriculture expansion, as intended by the correction works (Bernhardt, 2000). These types of morphodynamic disturbances driven by channel correction were also observed by David et al. (2016) on the River Garonne ~~River~~, Magdaleno et al. (2012) on the River Ebro ~~River~~ and Habersack et al. (2013) on the River Danube ~~River~~.

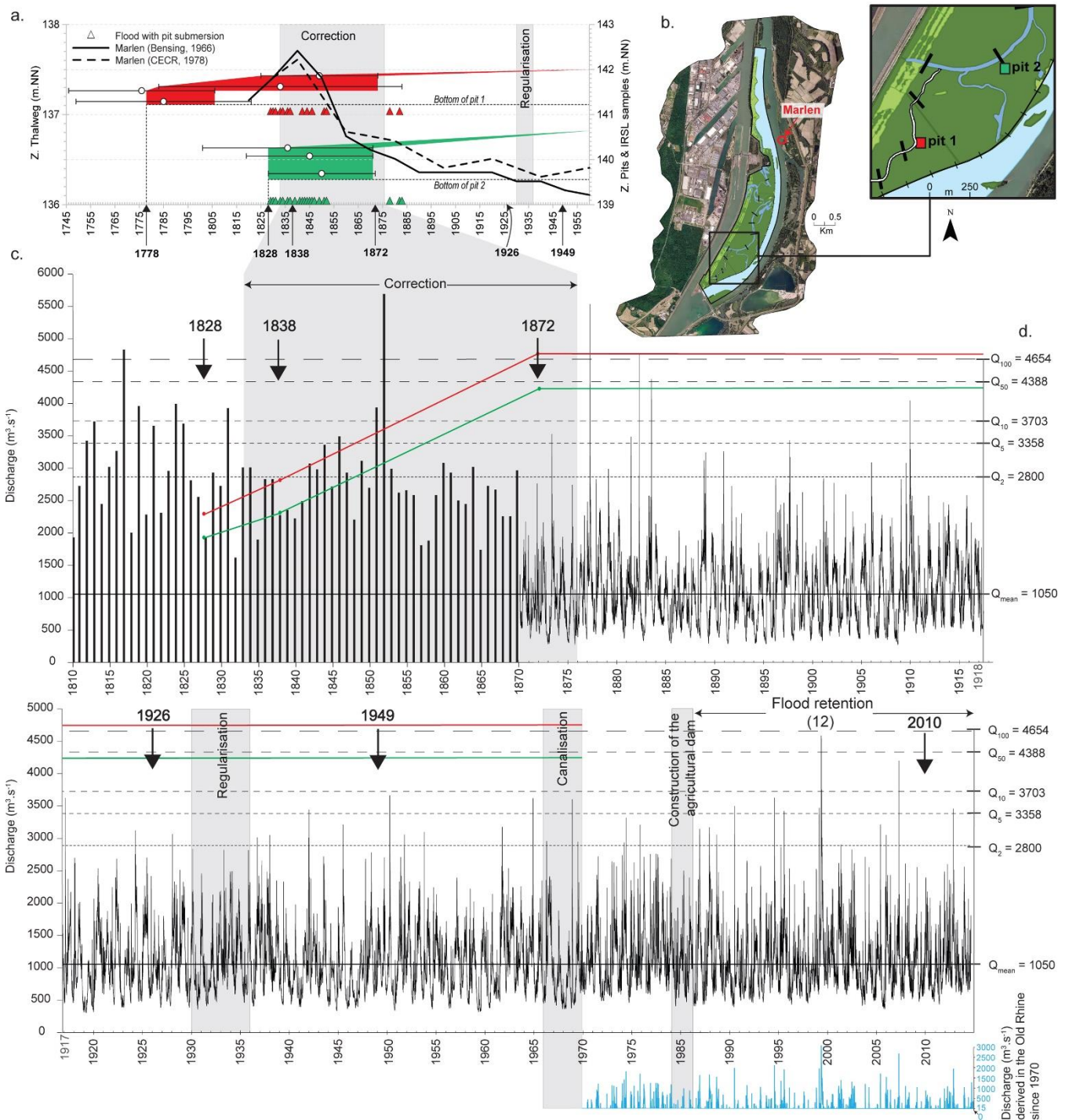


Figure 5: (a) Vertical evolution of the Rhine thalweg from 1815 to 1960 based on low water levels ($Q \sim 540 \text{ m}^3 \cdot \text{s}^{-1}$) recorded at the Marlen gauging station (Bull, 1885; Bensing, 1966; CECR, 1978). Vertical evolution of the pits linked to the age-depth model and number of floods which attained each pits (triangle), (b) location of the two pits and of the ancient gauging station of Marlen, (c) discharge of the Rhine at the gauging station of Basel. The period 1810-1870 corresponds to maximum instantaneous annual flows. The period 1870-2015 corresponds to the highest mean daily flow (OFEV: Office Fédéral de l'Environnement). The dates with arrows corresponds to old maps or aerial photographs (see figure 4). The red and green lines correspond to the submersion discharges for the pits 1 and 2 respectively, (d) flood return periods at Basel between 1870-2015 ($\text{m}^3 \cdot \text{s}^{-1}$; Adjustment of Pearson III, OFEV).

4.2.2 Lateral channel adjustments and filling processes

At the scale of the natural reserve, from 1828 to 1838, the braiding and anastomosing index decreased from 5.36 to 2.45, surface areas of running water decreased (by 21 ha \Rightarrow 13 %), while stagnant water and high vegetation areas increased. In particular, vegetation populated median-central bars (Fig. 4-a). This general trend became even more marked during the 1838-1872 period (Fig. 4-b: the braiding and anastomosing index decreased to 1 in 1872), running water and gravel bar areas declined (by 65 ha \Rightarrow 47% and: -45 ha \Rightarrow 71 %, respectively), and high vegetation and stagnant water areas increased (by +90

ha ~~or \pm 101 %~~ and \pm 19 ha ~~or \pm 166 %~~, respectively). This supports the idea that the sequential impacts induced by the correction works along the floodplain (i.e. channel narrowing, expansion of vegetation) were especially dynamic in the upstream part of the Bauerngrundwasser. The channel filling dynamics are detailed in a *CM* diagram (Fig. 6-a) which shows that graded suspension deposition (QR segment) of sandy loam occurred at the transect 2. In addition, Figure 6-a shows a general and concomitant decrease in grain size and sediment sorting from the bottom to the surface, which reveals a decline in flood energy likely induced by channel diversion following the correction. Furthermore, residual T2 samples are located on RS segment (uniform suspension). They correspond to fine sediments (silt) with sorting and depth are not correlated. These have been deposited on the left bank of the Bauerngrundwasser in low turbulence conditions likely due to site-specific factors such as topography or vegetation, whose general importance has been underlined by [Bravard et al. \(2014\)](#), [Toonen et al. \(2015\)](#), [Bravard et al. \(2014\)](#) and [Riquier et al. \(2015\)](#). Such kind of depositional filling processes in newly bypassed channels have also been documented by [Passega \(1964, 1977\)](#) and [Bravard and Peiry \(1999\)](#) and [Passega \(1964, 1977\)](#).

The analysis of the evolution of the middle part of the natural reserve from 1838 to 1872, revealed that a large gravel bar was deposited behind the left dike of the corrected Rhine channel (Fig. 4-a). This clearly resulted from an extreme hydrological event, which occurred during the Rhine diking and probably corresponds to the 1852 flood (above 300-years flood; Fig 5-c and Fig. 9, period B). This flood event, referred as the “*flood of the century*” (6.63 m at the Basel gauging station, i.e. 5.78 m higher than the mean low flow water level), has been documented in detail, especially by [Wittmann \(1859\)](#), [Pardé \(1928\)](#), [Champion \(1863\)](#), [Eisenmenger \(1907\)](#) and [Pardé \(1928\)](#) [Wittmann \(1859\)](#). After this flood event, embankment of the Rhine continued but local dike apertures remained open in order to feed some old channels and to enhance filling dynamics (Fig. 4-a, 1872). In addition, the downstream part of the Bauerngrundwasser (middle part of the natural reserve) presented an important connection to the Rhine, until its probable disconnection in 1876 ([Fischbach, 1878](#); [Casper, 1959](#); [Fischbach, 1878](#)). This specific hydrological condition impacted the depositional filling processes, as shown by the processes observed at the downstream part of the Bauerngrundwasser which are mainly characterized by graded suspension (Fig. 6-a; T4 and T5 transects). Indeed, *CM* diagram shows that energy is higher at T5 than at T4 although T4 is located upstream. Furthermore, the complexity is reinforced by the absence of upward fining in grain size at the surface as shown in the upstream part of the Bauerngrundwasser (Fig. 6-b). Similar to the T2 samples, the position of the other T4 samples in the *CM* pattern corresponds to the mean level of turbulence in the uniform suspension (RS segment) and are located on the left bank (Fig. 6-a). These T4 samples depend on the great distance from the main channel, as previously observed ([Bravard and Peiry, 1999](#)). Generally, the disconnection of the Bauerngrundwasser with the Rhine was reinforced by the total closure of the dike apertures after 1876 (Fig. 4a; 1872, 1926).

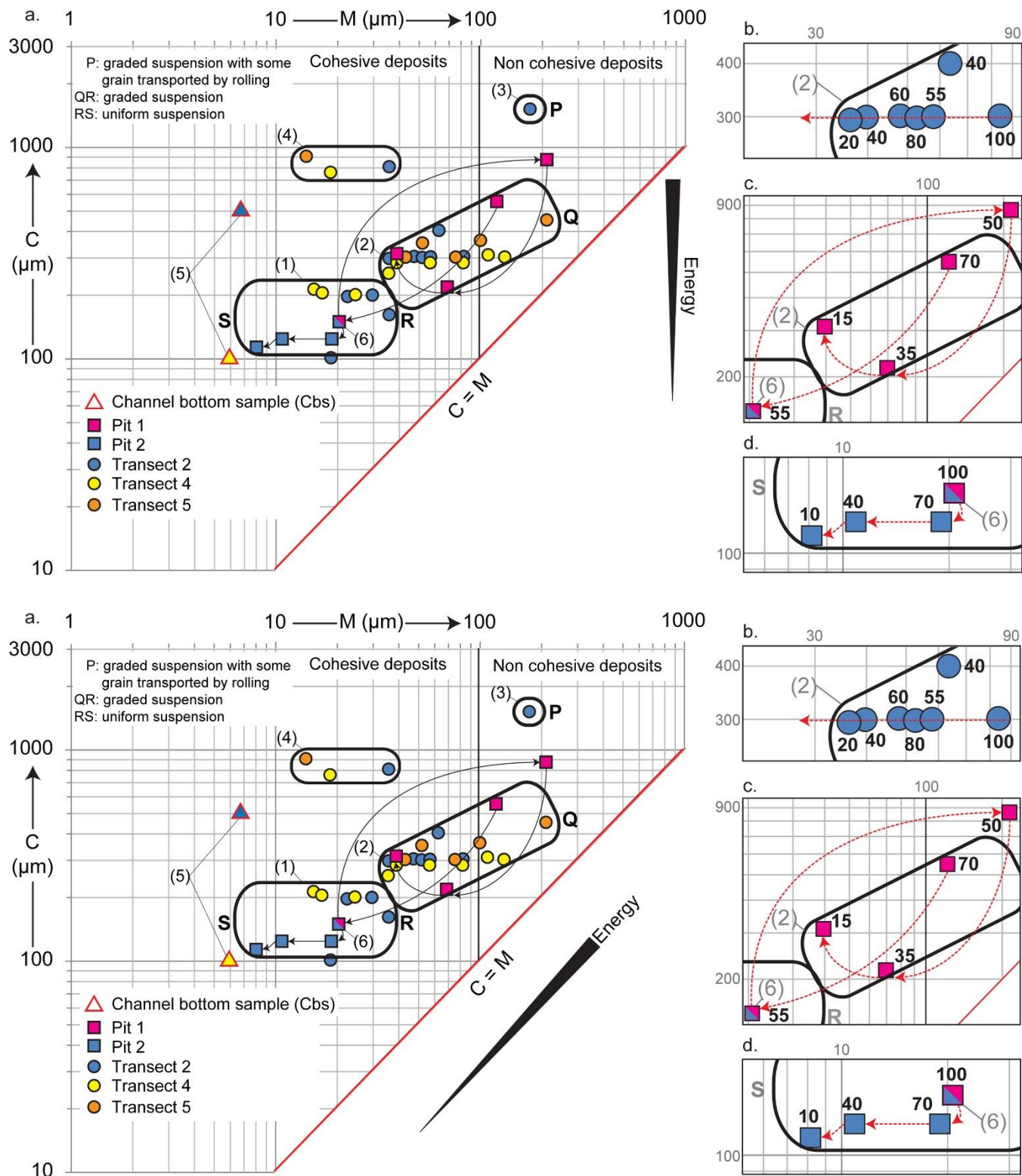


Figure 6: a. Floodplain CM diagram and patterns according to Passega (1964, 1977). Numbers between brackets help for the presentation of the results and the discussion; b. isolated samples with the indication of the samples depth for transect 2, pit 1 (c) and pit 2 (d). Red arrows show the deposition chronology.

In figure 6-a, square tag 6 corresponds of two overlapped samples from the pit 1 – SU 3 and pit 2 – SU 2 (Fig. 7). These samples are composed by the same grain-size characteristics. Square tag 6 is reported on Fig. 6-c & d. Planimetric results combined with CM diagram and IRSL ages show imply that cohesive sediments which compose the two overlapped samples were likely deposited during the same flood, probably the 1831 flood. Pit 1 is located on a former large gravel bar in 1828 (Fig. 4-b, 1828). According to our chronology, pit 1 - SU 2 was already deposited at this time (Preusser et al., 2016).

This SU is composed of silt deposited during low energy conditions (tag 6; Fig. 6-c). It means that pit 1 likely consists of two depositional filling periods: the first started before 1828 (probably in 1778 for SU 2, 3 & 4; Fig. 7), while the second started with the beginning of the correction works (for SU 5 & 6, Fig. 7; Preusser et al., 2016). Conversely, pit 2 is located on the 1828 main channel (Fig. 4-b, 1828), which became an overbank area or low energy depositional environments in close vicinity of the main channel in 1838 (Fig. 4-a, 1838). Thus, if any deposits of fine sediments existed in 1828, the filling period in pit 2 have begun after 1828, as also shown by the IRSL ages (min.: 1828; Fig. 5-a), and was relatively regular. The end of the depositional filling periods at both pits occurred around 1872 as shown by the IRSL ages and is reflected in a grain size refinement and sorting decrease (Fig. 5-a). It coincides with a clear increase in vegetation areas shown by the 1872 map (Fig. 4-a, 1872). Depositional filling differences (periods and processes) between the two pits are mainly controlled by the elevation and the location of the pits in the floodplain (Fig. 3-c), which in turn determine the frequency of flooding (Fig. 5-a & c) and mean sedimentation rates (from 0.9 cm / year in pit 1 and 6 cm / year in pit 2; Fig. 5-a and Fig. 7). This may also explain the heterogeneity of depositional filling processes at pit 1 (Fig. 6-c) in contrast to pit 2 where grain size generally decreases with increasing elevation; Fig. 6-d). This phenomenon has been observed for disconnected lateral channels by several studies (e.g. Bravard et al., 1986; Hooke, 1995; Riquier et al., 2015).

4.2.3 Geochemistry of the sediment filling

Geochronological data combined with geochemical data confirmed changes in the hydrosystem and sediment deposition dynamics of the Rohrschollen from the beginning of the correction works. Quartz (SiO_2) ~~was~~is the dominant mineral (ranging ~~e-from~~ 54 % to 63 %; Fig. 7), ~~and~~ and does not show any particular trend down the profile in pit 1 and pit 2. MnO , TiO_2 and P_2O_5 ~~were~~are least abundant in both pits. This shows that the patterns of mineral composition are not directly related to grain size and likely reflect a common sediment source to both pits (Grygar et al., 2016). However, lower ratios of Al/Si, especially in the lower sediment layers of SU 2 and 3 in both pits 1 and 2, reflect a general low clay content with dominant sandy (pit 1) or silty (pit 2) sediment textures. This suggests relatively weak soil development and chemical weathering. The uppermost sediment layers of pit 1 and pit 2 differed in organic carbon (C) (16.4 and 27.0 g.kg^{-1} , respectively) while organic matter content and organic carbon gradually decrease with depth in both pits. This suggests different temporal trajectories of deposition of organic-rich sediments on the two sites, i.e. the gravel bar (pit 1) and the Bauerngrundwasser (pit 2) until 1838 (pit 2).

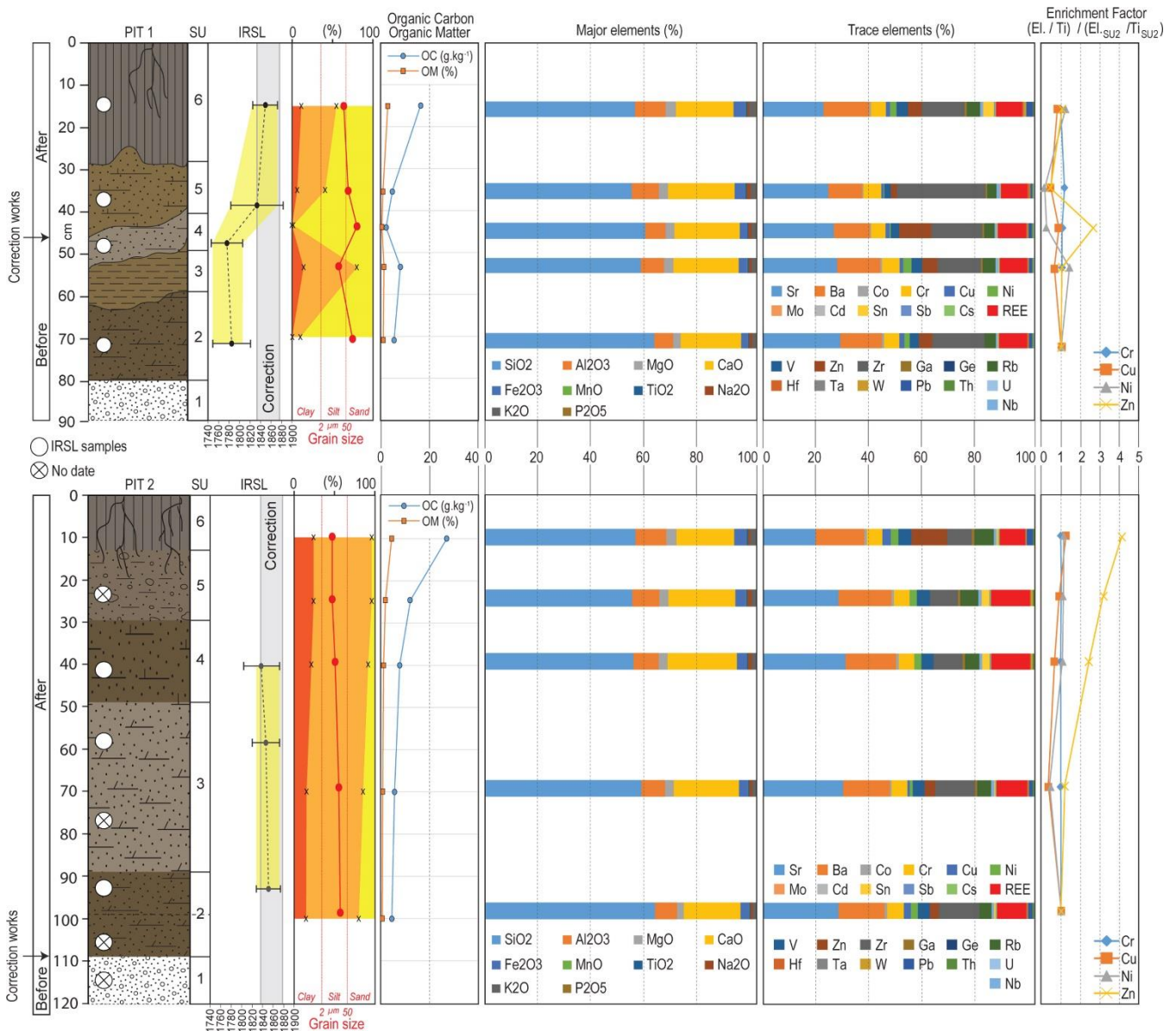


Figure 7: Stratigraphical log of the two pits including datings, organic contents, sedimentological and geochemical results.

Regarding pollution histories, polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB), hexachlorocyclohexanes (HCH) and pesticides (Table S1) could not be detected in both pits. This is in agreement with the proposed chronology of pits filling because the first massive use of modern organic pollutants in the whole Rhine catchment gradually increased in the Rhine after 1940, followed by a strong reduction of these pollutants due to the Rhine Action Plan since 1970 (Evers et al., 1988; Middlekoop, 2000; Goth et al., 2001; Middlekoop, 2000). Similarly, the normalized REE patterns did not show any significant changes with depth in both pits (Fig. S3). Massive use of REE started after 2000 (Klaver et al., 2014), when sedimentation rates were low on the Rohrschollen compared to the period during and immediately after the correction works (Fig. 5).

To evaluate the potential metal pollution resulting from anthropogenic activities, the relative enrichment in minor element concentrations in the sediments was evaluated in the pits accounting for the geochemical background. Depth-distribution of minor elements in both pits followed a $Sr > Ba > Zr > Cr > REE > Zn$ pattern. Heavy metal concentrations in pit 1 and pit 2 ranged from 31 to 196 mg.kg⁻¹ for Zn, 64 to 91 mg.kg⁻¹ for Cr, 10 to 46 mg.kg⁻¹ for Cu, 6 to 42 mg.kg⁻¹ for Ni, 12 to 35 mg.kg⁻¹ for Pb, and 0.23 to 1.24 mg.kg⁻¹ for Cd. Cu, Ni, and Cr enrichment factors in pit 1 and pit 2 remained within the natural background (i.e., normalized concentration profiles showed no enrichment in both profiles). This suggests low industrial use of these heavy metals upstream the study site in the 19th century, which is in agreement with previous results (Goth et al., 2001; Middlekoop, 2000; Goth et al., 2001).

In contrast, Zn enrichment factors decrease with depth in pit 2 (from about 4 to 1), which probably reflects anthropogenic inputs of Zn in the SU 4 to 6 (up to 196 mg.kg⁻¹ in SU 6). This is in agreement with previous observations (Ciszewski and Gryar, 2016) insofar metal pollution is expected to be greater at a shorter distance from the main channel thalweg (as for pit 2 until 1838) or from a secondary channel that are hydrologically connected (as for the Bauerngrundwasser after 1838 for pit 2), compared to a site that is further and less frequently flooded (as for pit 1 after 1828). From about 1860 to the early 1930s, heavy metal concentrations in the Rhine gradually increased in relation to the progressive industrialization-industrialisation (Middlekoop, 2000). Heavy metal enrichment, which is particularly marked for Zn, is therefore likely caused by changes in both heavy metal pollution of the Rhine over the past centuries and sedimentation rates. Although the main depositional filling at pit 2 ended around 1872, it was still flooded at least four times after this date (1876, 1881, 1882 and probably 1910), whereas pit 1 was more rarely and intensively flooded (1876 and probably 1881; Fig 5-c). Moreover, flow patterns during flooding from 1872 onwards likely controlled sedimentation rates of heavy metal-bound to suspended solids. Overall, our results suggest that Zn may be a proxy of anthropogenic deposition histories in the Rhine floodplain, as previously shown in large fluvial systems (Grygar and Popelka, 2016, Lintern et al., 2016).

In addition, water table fluctuation and regular water saturation by flooding may have changed Zn speciation and mobilization in the SU 1-3 of pit 2, whereas pit 1 remained non-saturated (Fig. 8). In the period between floods, under non-saturated conditions and in the presence of oxygen, oxidation of metal-sulfur, organic carbon and Fe-Mn oxyhydroxide in the upper SU may release heavy metals. High flood frequency possibly increased vertical transport of suspended solids and chemical redistribution in pit 2, which smoothed changes of Zn concentrations with depth (Middelkoop, 1997). During flood events, heavy metals can thus not only move between the SU but also be partly transported into the river water in association with suspended solids, by local surface erosion (Tao et al., 2005). This emphasizes that, in a restoration context, Zn may be mobilized and transported into the Rhine by groundwater table elevation (Ciszewski and Gryar, 2016) linked to flooding frequency increase as well as by bank and surface erosion.

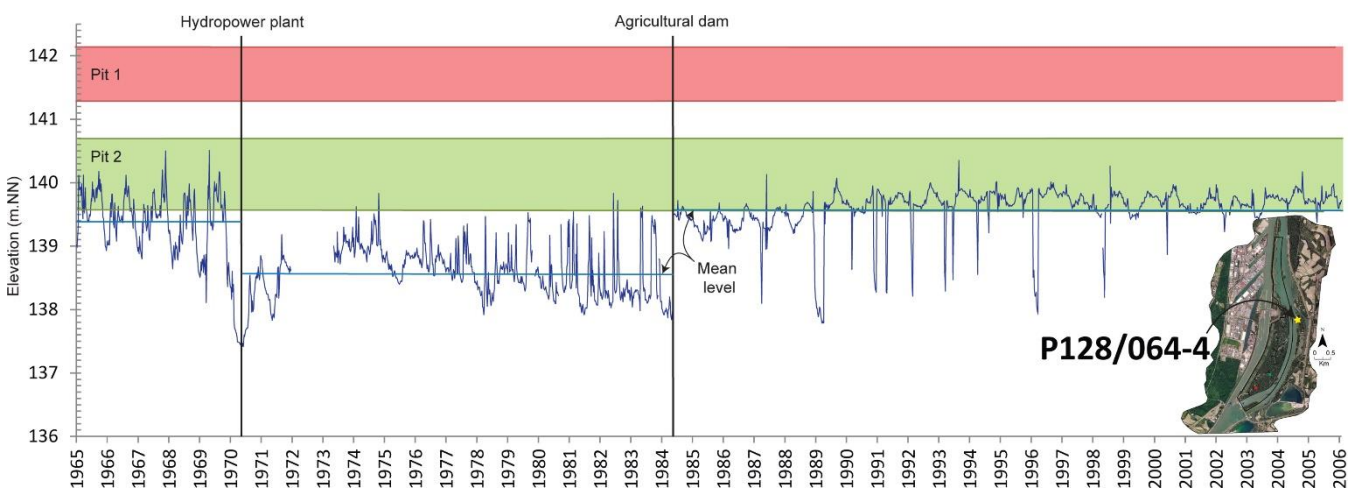


Figure 8: Hydrogeological variation between 1965 and 2006. After 1984, the lowest peaks correspond to periods during which the Old Rhine is empty.

4.3 Adjustments since the end of the correction works (after 1876)

Results of the CM pattern (Fig. 6-a) show one sample in group 3 and three samples in group 4 that correspond to the left bank of the Bauerngrundwasser (surface layer). This last depositional filling-period is linked to several large floods (1876, 1882; > 300 and 100 years return periods, respectively; Fig. 5-c) of high transport energy leading to suspension (Fig. 6-a, group 4) and rolling processes (Fig. 6-a, group 3-P). The 1876 flood, which was the major hydrological event during this period, fed the Bauerngrundwasser from upstream. The flood induced relative high flow conditions with increased sediment transport capacities, which caused grain size decrease along the channel. This process was particularly pronounced in the coarser P sample, which was deposited on the left-bank of the channel close to T2 (Fig. 4-a, 1926). As identified on the 1926 map, the

flood probably opened a dike near the upstream part of the Bauerngrundwasser (Fig. 4-a), which increased flow through the channel. During the same period (1872-1926), last major planimetric and geomorphic changes occurred downstream the Bauerngrundwasser close to the transect 6 (Fischbach, 1878—~~Testimony of M. Schante~~). In this area, the 1876 flood breached the downstream part of the high-flow dike (Fig. 4-a, 1872, 1926), and widened and accentuated channel bends (Fig. 9, period C). The present morphology of the Bauerngrundwasser results from this event. After this flood, all dike apertures were closed, thereby reinforcing the disconnection between the floodplain and the main channel. This situation was exacerbated by the progressive incision of the corrected Rhine channel (Casper, 1959). Gravel bar surfaces were progressively covered by high vegetation (more than 60 % of the natural reserve area in 1926; Fig. 4-b).

The ~~regularization~~-regularisation works (1930-1936) induced a ~~last~~/second phase of incision (Casper, 1959; Marchal and Delmas, 1959), accentuating the gradual conversion of the Bauerngrundwasser into a wetland (+ 7 ha). At the same time gravel bars appeared on the groyne fields which extended into the corrected Rhine channel (+ 13 ha between 1926 and 1949; Fig. 4-b). In 1970, this Rhine channel was by-passed by the Rhine canal on which a power plant was constructed. A continuous discharge up to $1,550 \text{ m}^3 \cdot \text{s}^{-1}$ is diverted towards the Rhine canal, altering the hydrology of the Old Rhine River drastically (Fig. 5-c, blue hydrogram). Therefore, groundwater level was lowered by about 0.8 m (Fig. 8). In 1984, the construction of the agricultural dam raised and stabilized the water level of the Old Rhine River at 140.00 m NN , and the groundwater level around 139.60-140.00 m NN , while the amplitude of groundwater fluctuation decreased suddenly from 1.5 to 0.4 m NN (Fig. S3). The entire Bauerngrundwasser was ~~impacted~~-influenced by this backwater effect, which increased the stagnant water surface (+7 ha in 2010; Fig. 4-b). To avoid drying of the Bauerngrundwasser during low flow and drought periods along the Old Rhine River, an input of $1.5 \text{ m}^3 \cdot \text{s}^{-1}$ from the Rhine canal feeds the channel by a siphon (Fig. 4-b, 2010, siphon). This explains the specific modern dynamics of sediment suspension at the bottom of the Bauerngrundwasser (group 5; Fig. 6-a). Energy decreases along the channel as shown by the differences between T2-Cbs ($C = 500$; $M = 7$) and T4-Cbs ($C = 100$; $M = 6$). Similar dynamics were also observed by Peiry (1988) and underscore that in-channel deposition and filling was a current process until the start of the restoration.

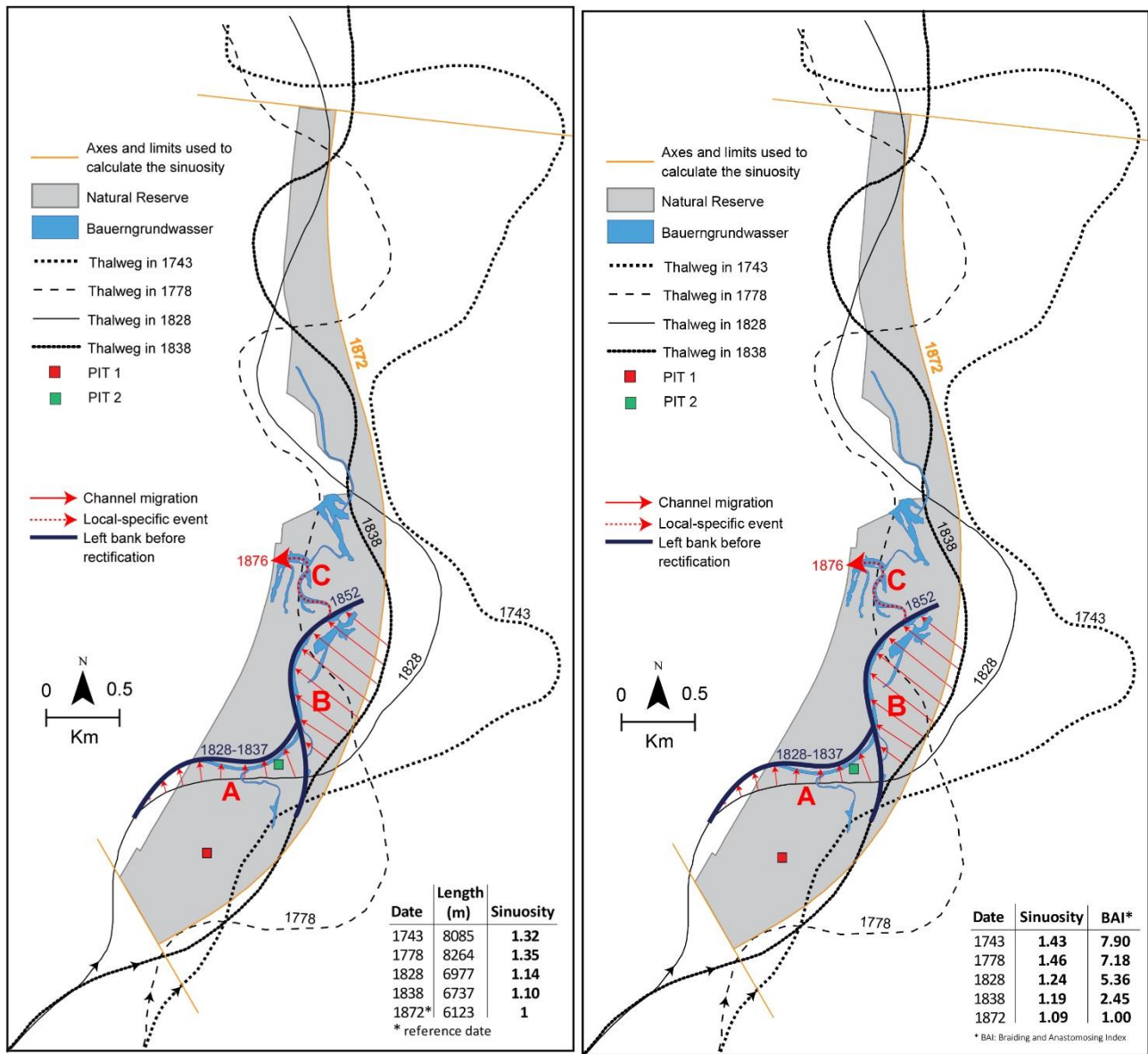


Figure 9: Rhine thalweg evolution from 1743 to the end of the correction works in 1876. (A) Area of lateral channel mobility during the 1828-1837 period. (B) Area of lateral channel mobility during the 1851-52 flood. (C) Area impacted by the 1876 flood. **BAI is a Braiding and Anastomosing Index which corresponds to the mean number of these two types of channels (channels showing stagnant water have been excluded).**

4.4 Using Rhine long-term trajectory to enhance efficiency and sustainability: learning from the past to infer restoration guidelines

Combining spatial and temporal scales by overlapping multiple data sources in an interdisciplinary approach appears of crucial importance to (i) determine pre-disturbance dynamics of the hydrosystem, (ii) improve the understanding of the history of the hydrosystem in fine spatio-temporal scales (Brierley and Fryirs, 2008; Belletti et al., 2014; Bouleau and Pont, 2014; Brierley and Fryirs, 2008), and (iii) provide key information to manage restoration projects in efficient and sustainable ways. Indeed, these results allow validating our three working hypotheses:

4.4.1 Long-term temporal trajectories allow to identify driving factors, amplitude and response-time of disturbances

The pre-disturbance functioning of the Rhine hydrosystem in our study area, as identified by historical map analysis, sedimentological and geochronological data, was characterized by a high energy depositional environment with active braiding-anastomosing, lateral channel mobility and important surface areas of gravel bars and pioneer vegetation. In part, this

functioning has been targeted by recent restoration efforts. More specifically, the restoration induced, in the new channel, aims have been to the recovery of bedload transport, lateral and vertical dynamics, as well as groundwater—/surface water exchanges. Our results also highlight that the system has been drastically disturbed from the beginning of the correction works. In addition, the flood regime is an additional and crucial driving factor, inducing important and rapid changes in morphodynamics and sediment deposition, especially in low elevation areas where floods are relatively frequent, long and intense (palaeochannels; e.g. pit 2). The hydrosystem remained morphologically sensitive to floods throughout the duration of the correction works. From the end of the correction, changes were less marked and also related to a decrease in flood energy and frequency. The volume of fine sediment deposition is higher in the upstream part of the Bauerngrundwasser, with a maximum thickness of 1.8 m and a volume of about 400,000 m³ (estimated by combining diachronic planimetric analysis with thickness of sediment layer close the Bauerngrundwasser). A volume of about 800,000 m³ of fine sediments with a mean thickness of about 0.4 m was deposited in the entire Rohrschollen Island up to today. This highlight the fact that impacts of correction works and further engineering works are irreversible because the removal of very large amounts of fine sediments seems unthinkable or extremely difficult. Furthermore, the strong hydrological alteration by the canalization works makes the functional alteration of the hydrosystem irreversible as well. In this constrained context, -Hence-the main challenge of the restoration was to recover processes as dynamic floods dynamics-(on the whole island) and an active morphodynamic gravel bed channel in a relatively restricted environment (new channel; see also below). On the basis of an environmental monitoring conducted during three years after the end of the restoration works, it appears that these restoration objectives are attained (Eschbach et al., 2017; Eschbach et al., in review) and that the restoration choices were relevant (see also below).

4.4.2 Assessing potential benefits and limits of the restoration

Fine sediments are mainly located along the Bauerngrundwasser and represent a limitation for restoration purposes, because of the risk of their remobilization from both banks and channel bottom. As shown by Boulton et al. (1998) and Richards and Bacon (1994), and Boulton et al. (1998), fine sediments (e.g. sand) are a limiting factor for many aquatic biological species. This point is important because fine sediments were relatively scarce in the braiding-anastomosing Rhine hydrosystem previous ~~to~~ the initiation of correction works (Ochsenbein, 1966). Furthermore, another risk concerns potential remobilization of pollutants bound to fine sediments. This risk has also been identified and characterized on the Rhône River by Bravard and Gaydou (2015), Desmet et al. (2012), and Provansal et al. (2012), and Bravard and Gaydou (2015). However, ~~partial~~ backwater effects induced by the agricultural dam control the water level on the Bauerngrundwasser, even during ecological floods (partly), and thus ~~may~~ limit bank erosion (Eschbach et al. submitted). Thus, in the specific case of the Rohrschollen Island, both risks are drastically lowered by this local hydraulic constraint. This demonstrates once again the relevancy of the principles of the Rohrschollen's restoration.

Conversely, the new channel dug on a large former in-channel gravel bar (Fig. 1-d) exposes a thinner layer of fine sediments along its banks, which are mainly composed of coarse sediments (gravels, pebbles) inherited from the pre-correction Rhine and represent a historical in-channel gravel bar. The backwater effect of the agricultural dam does not affect this channel (except the 100 downstream meters; Eschbach et al., 2017). Consequently, the restoration of this channel induces a recovery of bedload dynamics, lateral channel mobility, morphodynamic and habitat diversification (Eschbach et al., in review), which stimulate notably key-processes as downwelling/upwelling hydrological exchanges (Eschbach et al., 2017).

4.4.3 Provide key-information to manage functional restoration actions in order to maximize efficiency and sustainability, and infer future evolutionary trends

Efficiency and sustainability are key issues in restoration projects (Bouleau and Pont, 2014; Loomis et al., 2000). For management strategies, knowledge of temporal trajectories is relevant for targeting pre-disturbance processes (Cairns, 1991) and performing hydromorphological process-based restorations (Mika et al., 2010; Rinaldi et al., 2015). It also allows to identify floodplain areas with high hydromorphological functional potentials, i.e. sectors with thin layers of fine sediments located outside palaeochannels, notably on former gravel bars as its ist the case on the Rohrschollen Island (new channel). In such geomorphological areas, where the efficiency of restored lateral channels may be the highest, managers are encouraged to excavate new channels and enhance morphodynamics by floods (as it has been performed on the-Rohrschollen Island), which even may erode self-formed lateral channels in some cases, rather than reconnecting filled palaeochannels directly. However, the latter restoration measure has dominantly been carried out on large rivers including the Rhine, which raises the question regarding its wider relevance and sustainability (Schmitt et al., 2009; Schmitt et al., 2012; see also below).

Concerning the floodplain compartment, the sedimentation rate is relatively low on ~~the~~ Rohrschollen Island (about 0.1 cm/year), but it is higher (of about one order of magnitude) on areas where flood intensities and frequencies have been less impacted than ~~the~~ Rohrschollen Island, along the non-canalized section of the Upper Rhine (Dister et al., 1990; Frings et al., 2014; Dister et al., 1996) and in the Rhine delta (Hudson, 2008). This floodplain geomorphological evolution reduces flood retention capacities. It probably will require in the future innovative flood management strategies (Hudson, 2008) that may notably be based on floodplain artificial excavations of fine sediments (which could be made more difficult if sediments are polluted) and/or natural fine sediments removal by the recoveryrestoration of active bank erosion in lateral channels. This also should allow recovery of coarse sediments in the floodplains, a texture which is currently lacking. The long term (> 100 years) sustainability of the hydro-geomorphological management of the Upper Rhine appears as a key-question, which is coming more and more important, and is complexified by possible fine sediment pollutions.

Morphodynamic (and ecological) fluvial functionality requires relatively high, intense and long flood events superimposed on the natural-mean hydrological regime (Bayley, 1991; Dister, 1992). This is the case on Rohrschollen Island, but following the first flooding events after restoration, a further question arises, among other: how to manage such a highly dynamic environment on median/long terms? For example, it will probably be necessary to equilibrate-balance the-Lane-balance-a relative sediment deficit in the upstream section of the new channel by upstream-artificial gravel augmentations, in the next years/decades (Eschbach et al., in review)-in order to consider a likely future sediment deficit in the upstream extremity of the channel.

The sustainability of functional restoration efforts and their management remains an open question: on which time scale, for which compartment and over which spatial scales should they be considered? In this context, it appears crucial to continue the post-restoration monitoring over medium-short (3-5 years) and long-median (> 5-10 years) time scales to evaluate restoration success (Jähnig et al., 2011; Kondolf and Micheli, 1995; Palmer et al., 2005; Jähnig et al., 2011). This opens up avenues for developing integrative methodological approaches to improve pre-restoration knowledge and to implement post-restoration monitoring and modelling, both in the frame of fluvial hydrosystem temporal trajectories.

5 Conclusions

In this study we show the relevance of considering temporal trajectories in process-based river restoration. An interdisciplinary approach deployed at different spatio-temporal scales has been developed by combining planimetric data with sedimentological, chemical and geochronological analysis, as well as a hydrological model. Prior to anthropogenic disturbances, the hydrosystem was mostly characterized by a high-energy depositional environment of braiding channels with high lateral mobility and important surfaces of gravel bars and pioneer vegetation. Correction works provoked a drastic temporal trajectory change, by intensifying filling of fine and polluted (Zn) sediments in palaeochannels and decreasing flood

frequency, though some intense floods occurred. In contrast, the floodplain recorded lower deposition rates by quasi-unpolluted sediments. More recently, canalisation resulted in very low sedimentation rates, but strong hydrological and hydrogeological disturbances.

Our results highlight potential risks that restoration projects may face and need to mitigate along large rivers, e.g. for example the removal of fine and potentially polluted sediments by reactivating erosion/deposition processes in former channels. On the Rohrschollen Island, this risk is reduced by the backwater effect of the agricultural dam which limits lateral erosion in the palaeochannel. On the contrary, floodplain areas outside palaeochannels show thin layers of fine sediments and appear more relevant to restore dynamic lateral channels. Managers may benefit from excavating new channels on such areas, as it has been performed on the Rohrschollen Island. They are even encouraged to develop self-erosion of lateral channels by dynamic floods. Finally, this research underscores the necessity to base functional river restorations on an interdisciplinary knowledge of hydrosystem past-trajectories that includes the physico-chemical characterization of sediments in order to maximize restoration efficiency and sustainability. On a practical level, we recommend managers to conduct such studies in geomorphological restoration projects, even if they are less detailed than our study presented in this article, e.g. for example in the case of financial constraints. They should at least be based on (i) planimetric analysis (old maps and photographs), (ii) sedimentological prospection (hand auger) combined to both a LIDAR DEM analysis and a rapid study of former large floods and (iii) a physico-chemical analysis of sediments, especially these filling palaeo-channels. Therefore, to improve pre-restoration project, we recommend to the manager to conduct, at least, (i) a diachronic historical mapping compared with DEM data, (ii) basic sediment prospection (carried out by hand-augered) and, if possible, (iii) geochemical analysis of the filling material.

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67 References

- Acuña, V., Díez, J.R., Flores, L., Meleason, M., Elozegi, A., 2013. Does it make economic sense to restore rivers for their ecosystem services? In *Journal of Applied Ecology* 50, 988–997. doi:10.1111/1365-2664.12107
- Amoros, C., Petts, G.E. (Eds), 1993. *Hydrosystèmes fluviaux*, Masson. Paris, 301 p.
- Arnaud, F., Piégay, H., Schmitt, L., Rollet, A.J., Ferrier, V., Béal, D., 2015. Historical geomorphic analysis (1932–2011) of a by-passed river reach in process-based restoration perspectives: The Old Rhine downstream of the Kembs diversion dam (France, Germany). In *Geomorphology* 236, 163–177. doi:10.1016/j.geomorph.2015.02.009
- Babcsanyi, I., Chabaux, F., Granet, M., Meite, F., Payraudeau, S., Duplay, J., Imfeld, G., 2016. Copper in soil fractions and runoff in a vineyard catchment: Insights from copper stable isotopes. In *Science of the Total Environment* 557–558, 154–162. doi:10.1016/j.scitotenv.2016.03.037
- Bayley, P.B., 1991. The flood pulse advantage and the restoration of river-floodplain systems. In *Regulated Rivers: Research & Management* 6, 75–86. doi:10.1002/rrr.3450060203
- Beechie, T.J., Sear, D.A., Olden, J.D., Pess, G.R., Buffington, J.M., Moir, H., Roni, P., Pollock, M.M., 2010. Process-based principles for restoring river ecosystems. In *BioScience* 60, 209–222.

- Belletti, B., Rinaldi, M., Buijse, A.D., Gurnell, A.M., Mosselman, E., 2014. A review of assessment methods for river hydromorphology. In *Environmental Earth Sciences* 73, 2079–2100. doi:10.1007/s12665-014-3558-1
- Bensing, W., 1966. Gewässerkundliche Probleme beim Ausbau des Oberrheins (Problèmes hydrologiques liés à l'aménagement du cours supérieur du Rhin). *Deutsche Gewässerkundliche Mitteilungen*, 85–102.
- 5 Berger, M., Schwarzbauer, J., 2016. Historical Deposition of Riverine Contamination on Terrestrial Floodplains as Revealed by Organic Indicators from an Industrial Point Source. In *Water, Air, & Soil Pollution* 227. doi:10.1007/s11270-015-2708-8
- Bogen, J., Bolviken, B., Ottesen, R.T., 1992. Environmental studies in Western Europe using overbank sediment. In *Erosion and Sediment Transport Monitoring Programmes in River Basins (Proceedings of the Oslo Symposium, August 10 1992)*, 317–325.
- Bonnefont, J.-C., Carcaud, N., 1997. Le comportement morphodynamique de la Moselle avant ses aménagements/The morphodynamic behaviour of Moselle river before its harnessings. In *Géomorphologie: relief, processus, environnement* 3, 339–353. doi:10.3406/morfo.1997.932
- Bouleau, G., Pont, D., 2014. Les conditions de référence de la directive cadre européenne sur l'eau face à la dynamique des 15 hydrosystèmes et des usages. In *Natures Sciences Sociétés* 22, 3–14. doi:10.1051/nss/2014016
- Boulton, A.J., Findlay, S., Marmonier, P., Stanley, E.H., Valett, H.M., 1998. The functional significance of the hyporheic zone in streams and rivers. In *Annual Review of Ecology and Systematics*, 59–81.
- Bravard, J.-P., 2003. Dynamiques à long terme des systèmes écologiques ou de l'Eden impossible à la gestion de la variabilité. In: Lévêque C., Van Der Leeuw S. (eds), *Quelles Natures Voulons-Nous ?*, 133-139.
- 20 Bravard, J.-P., Amoros, C., Pautou, G., 1986. Impact of Civil Engineering Works on the Successions of Communities in a Fluvial System: A Methodological and Predictive Approach Applied to a Section of the Upper Rhône River, France. In *Oikos* 47, 92. doi:10.2307/3565924
- Bravard, J.-P., Bethemont, J., 1989. Cartography of rivers in France, in: Petts G. E. (ed), *Historical Change of Large Alluvial Rivers: Western Europe*.
- 25 Bravard, J.-P., Gaydou, P., 2015. Historical Development and Integrated Management of the Rhône River Floodplain, from the Alps to the Camargue Delta, France, in: Hudson, P.F., Middelkoop, H. (Eds.), *Geomorphic Approaches to Integrated Floodplain Management of Lowland Fluvial Systems in North America and Europe*. Springer New York, New York, NY, pp. 289–320, 289–320p.
- Bravard, J.-P., Goichot, M., Tronchère, H., 2014. An assessment of sediment-transport processes in the Lower Mekong River 30 based on deposit grain sizes, the CM technique and flow-energy data. In *Geomorphology* 207, 174–189. doi:10.1016/j.geomorph.2013.11.004
- Bravard, J.-P., Magny, M., 2002. Les fleuves ont une histoire. Paléo-environnement des rivières et des lacs français depuis 15 000 ans. Errance édition.
- Bravard, J.-P., Peiry, J.-L., 1999. The CM pattern as a tool for the classification of alluvial suites and floodplains along the 35 river continuum. In *Geological Society, London, Special Publications* 163, 259–268.
- Brierley, G.J., Fryirs, K.A., 2008. *River Futures: An Integrative Scientific Approach to River Repair*. Island Press, 325 p.
- Brookes, A.B., 1988. *Channelized rivers: Perspectives for environmental management*. Chichester, UK.
- Brown, A.G., 1997. *Alluvial Geoarchaeology: Floodplain Archaeology and Environmental Change*. Cambridge University Press, 404 p.
- 40 Bull, F., 1885. Technisch-statistische Mittheilungen über die Stromverhältnisse des Rheins längs des elsass-lothringischen Gebietes (Atlas). In: *C.F. Schmidt (ed). Ministerium für elsass-lothringen, Strassburg*, 193 p.

- Carbiener, P., Carbiener, R., Vogt, H., 1993. Relations entre topographie, nature sédimentaire des dépôts et phytocénose dans le lit alluvial majeur sous forêt du Rhin dans le fossé rhénan : Forêt de la Sommerlet (commune d'Erstein). In *Revue de géographie de l'Est* 4, 207–312.
- Carbiener R., 1983. Le grand ried central d'Alsace : écologie et évolution d'une zone humide d'origine fluviale rhénane. In *Bulletin Ecologie*, 249–277.
- Cairns, J., 1991. The status of the theoretical and applied science of restoration ecology. In *Environmental professional* 13, 186–194.
- Casper, M., 1959. L'aménagement du parcours allemand du Rhin : mesures exécutées, en cours et en projet. In *La Houille Blanche*, 229–248. doi:10.1051/lhb/1959037
- CECR, Ministère de l'Agriculture, Service Régional d'Aménagement des Eaux d'Alsace, 1978. Rapport finale de la Commission d'Etude des Crues du Rhin. Colmar, 87 p.
- Champion, M., 1863. Les inondations en France depuis le VI^{ème} siècle jusqu'à nos jours. Dunod, Paris, 501 p.
- Ciszewski, D., Grygar, T.M., 2016. A Review of Flood-Related Storage and Remobilization of Heavy Metal Pollutants in River Systems. In *Water, Air, & Soil Pollution* 227. doi:10.1007/s11270-016-2934-8
- Corenblit, D., Tabacchi, E., Steiger, J., Gurnell, A.M., 2007. Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: A review of complementary approaches. In *Earth-Science Reviews* 84, 56–86. doi:10.1016/j.earscirev.2007.05.004
- David, M., Labenne, A., Carozza, J.-M., Valette, P., 2016. Evolutionary trajectory of channel planforms in the middle Garonne River (Toulouse, SW France) over a 130-year period: Contribution of mixed multiple factor analysis (MFAmix). In *Geomorphology* 258, 21–39. doi:10.1016/j.geomorph.2016.01.012
- De Boer, J., Dao, Q.T., van Leeuwen, S.P.J., Kotterman, M.J.J., Schobben, J.H.M., 2010. ~~Thirty-year~~ **Thirty-year** monitoring of PCBs, organochlorine pesticides and tetrabromodiphenylether in eel from The Netherlands. In *Environmental Pollution* 158, 1228–1236. doi:10.1016/j.envpol.2010.01.026
- Desmet, M., Mourier, B., Mahler, B.J., Van Metre, P.C., Roux, G., Persat, H., Lefèvre, I., Peretti, A., Chapron, E., Simonneau, A., Miège, C., Babut, M., 2012. Spatial and temporal trends in PCBs in sediment along the lower Rhône River, France. In *Science of The Total Environment* 433, 189–197. doi:10.1016/j.scitotenv.2012.06.044
- Dister, E., Gomer, D., Obrdlík, P., Petermann, P., Schneider, E., 1990. Water management and ecological perspectives of the upper rhine's floodplains. In *River Research and Applications* 5, 1–15.
- Dister, E., 1992. La maîtrise des crues par la renaturation des plaines alluviales du Rhin supérieur. In *Espaces naturels rhénans - Bulletin de la société industrielle de Mulhouse* 1, 10.
- Dufour, S., 2006. Contrôles naturels et anthropiques de la structure et de la dynamique des forêts riveraines des cours d'eau du bassin rhodanien (Ain, Arve, Drôme et Rhône). Université Jean Moulin Lyon 3, 244 p.
- Dufour, S., Piégay, H., 2009. From the myth of a lost paradise to targeted river restoration: forget natural references and focus on human benefits. In *River Research and Applications* 25, 568–581. doi:10.1002/rra.1239
- Duplay, J., Semhi, K., Errais, E., Imfeld, G., Babcsanyi, I., Perrone, T., 2014. Copper, zinc, lead and cadmium bioavailability and retention in vineyard soils (Rouffach, France): The impact of cultural practices. In *Geoderma* 230–231, 318–328. doi:10.1016/j.geoderma.2014.04.022
- Dynesius, M., Nilsson, C., 1994. Fragmentation and flow regulation of river systems in the northern third the world. In *Science* 266, 753–762.
- Eisenmenger, G., 1907. Études sur l'évolution du Rhin et du système hydrographique Rhénan et propositions données par la faculté. Université de Paris, 512 p.

- Eschbach, D., Piasny, G., Schmitt, L., Pfister, L., Grussenmeyer, P., Koehl, M., Skupinski, G., Serradj, A., 2017. Thermal-infrared remote sensing of surface water-groundwater exchanges in a restored anastomosing channel (Upper Rhine River, France). In *Hydrological Processes* 31, 1113–1124. doi:10.1002/hyp.11100
- Eschbach, D., Grussenmeyer, P., Schmitt, L., Koehl, M., Guillemin, S., submitted. Combining geodetic and geomorphological methods to monitor restored dynamic mid-sized channels. *Geomorphology*.
- 5 Evers, E.H.G., Ree, K.C.M., Olie, K., 1988. Spatial variations and correlations in the distribution of PCDDs, PCDFs and related compounds in sediments from the river Rhine — Western Europe. In *Chemosphere* 17, 2271–2288. doi:10.1016/0045-6535(88)90140-3
- Falkowska, L., Reindl, A.R., Grajewska, A., Lewandowska, A.U., 2016. Organochlorine contaminants in the muscle, liver and brain of seabirds (*Larus*) from the coastal area of the Southern Baltic. In *Ecotoxicology and Environmental Safety* 133, 63–72. doi:10.1016/j.ecoenv.2016.06.042
- 10 Fedorenkova, A., Vonk, J.A., Breure, A., Hendriks, A.J., Leuven, R., 2013. Tolerance of native and non-native fish species to chemical stress: a case study for the River Rhine. In *Aquatic Invasions* 8, 231–241. doi:10.3391/ai.2013.8.2.10
- Felkel, K., 1969. Die erosion des oberrhein zwischen Basel und Karlsruhe. In *GWF (Wasser - Abwasser)* 30, 801–810.
- 15 Fischbach, G., 1878. Compte rendu des séances de la société - Séance ordinaire du 3 juillet 1878 présidée par M. de Turckheim. In *Société des sciences, agriculture et arts de la basse-Alsace - Bulletin Trimestriel- Tome XII - 3ième fascicule. Travaux sur les eaux entre Erstein et Strasbourg présentés par M. Schanté*, 118 p.
- Fryirs, K., Brierley, G.J., Erskine, W.D., 2012. Use of ergodic reasoning to reconstruct the historical range of variability and evolutionary trajectory of rivers. In *Earth Surface Processes and Landforms* 37, 763–773. doi:10.1002/esp.3210
- 20 Garban, B., Ollivon, D., Carru, A.M., Chesterikoff, A., 1996. Origin, retention and release of trace metals from sediments of the river seine. In *Water, Air, and Soil Pollution* 87, 363–381. doi:10.1007/BF00696848
- Gocht, T., Moldenhauer, K.-M., Püttmann, W., 2001. Historical record of polycyclic aromatic hydrocarbons (PAH) and heavy metals in floodplain sediments from the Rhine River (Hessisches Ried, Germany). In *Applied Geochemistry* 16, 1707–1721. doi:10.1016/S0883-2927(01)00063-4
- 25 Grabowski, R.C., Gurnell, A.M., 2016. Using historical data in fluvial geomorphology, in: Kondolf, G. M., Piégay, H. (Eds.), *Tools in Fluvial Geomorphology*. John Wiley & Sons, Ltd. 21p.
- Gregory, K.J., Benito, G., 2003. *Paleohydrology: Understanding Global Change*. University of Southampton, 396 p.
- Grygar, T., Popelka, J., 2016. Revisiting geochemical methods of distinguishing natural concentrations and pollution by risk elements in fluvial sediments. In *Journal of Geochemical Exploration* 170, 39–57. doi:10.1016/j.gexplo.2016.08.003
- 30 Gurnell, A.M., Bertoldi, W., Corenblit, D., 2012. Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers. In *Earth-Science Reviews* 111, 129–141. doi:10.1016/j.earscirev.2011.11.005
- Gurnell, A.M., Peiry, J.-L., Petts, G.E., 2003. Using Historical Data in Fluvial Geomorphology, in: Kondolf, G. M., Piégay, H. (Eds.), *Tools in Fluvial Geomorphology*. John Wiley & Sons, Ltd, pp. 77–101
- 35 Habersack, H., Jäger, E., Hauer, C., 2013. The status of the Danube River sediment regime and morphology as a basis for future basin management. In *International Journal of River Basin Management* 11, 153–166. doi:10.1080/15715124.2013.815191
- Harman, W., Starr, R., Carter, M., Tweedy, K., Clemmons, M., Suggs, K., Miller, C., 2012. Function-based framework for assessment and restoration projects. (Oral presentation).
- 40 Herget, J., Bremer, E., Coch, T., Dix, A., Eggenstein, G., Ewald, K., 2005. Engineering Impact on River Channels in the River Rhine Catchment (Menschliche Eingriffe in Flussläufe im Einzugsgebiet des Rheins). In *Erdkunde* 59, 294–319.
- Herget, J., Dikau, R., Gregory, K.J., Vandenberghe, J., 2007. The fluvial system — Research perspectives of its past and present dynamics and controls. In *Geomorphology* 92, 101–105. doi:10.1016/j.geomorph.2006.07.034

- Hering, D., Aroviita, J., Baattrup-Pedersen, A., Brabec, K., Buijse, T., Ecke, F., Friberg, N., Gielczewski, M., Januschke, K., Köhler, J., Kupilas, B., Lorenz, A.W., Muhar, S., Paillex, A., Poppe, M., Schmidt, T., Schmutz, S., Vermaat, J., Verdonschot, P.F.M., Verdonschot, R.C.M., Wolter, C., Kail, J., 2015. Contrasting the roles of section length and instream habitat enhancement for river restoration success: a field study of 20 European restoration projects. In *Journal of Applied Ecology* 52, 1518–1527. doi:10.1111/1365-2664.12531
- Hooke, J.M., 1995. River channel adjustment to meander cutoffs on the River Bollin and River Dane, northwest England. In *Geomorphology* 14, 235–253.
- Horowitz, A., Meybeck, M., Idlafkih, Z., Biger, E., 1999. Variations in trace element geochemistry in the Seine River Basin based on Foodplain deposits and bed sediments. In *Hydrological Processes* 13, 1329–1340.
- Hudson, P.F., Middelkoop, H., Stouthamer, E., 2008. Flood management along the Lower Mississippi and Rhine Rivers (The Netherlands) and the continuum of geomorphic adjustment. In *Geomorphology* 101, 209–236. doi:10.1016/j.geomorph.2008.07.001
- IKSR-CIPR-ICBR, 2005. État des lieux DCE, partie A.
- IKSR-CIPR-ICBR, 2012. Plan d'action contre les inondations 1995 - 2010 : objectifs opérationnels, mise en œuvre et résultats - Bilan synthétique. Coblenz.
- IKSR-CIPR-ICBR, 2014. Mise en œuvre du Plan de gestion des sédiments Rhin. Commission Internationale pour la Protection du Rhin (CIPR). ISBN 978-3-941994-54-6.
- Jähnig, S.C., Lorenz, A.W., Hering, D., Antons, C., Sundermann, A., Jedicke, E., Haase, P., 2011. River restoration success: a question of perception. In *Ecological society of America*, 21, 2007–2015.
- James, L.A., Singer, M.B., Ghoshal, S., Megison, M., 2009. Historical channel changes in the lower Yuba and Feather Rivers, California: Long-term effects of contrasting river-management strategies, in: Geological Society of America Special Papers. James, L.A., Rathburn, S.L., and Whittecar, G.R., (eds) Geological Society of America, pp. 57–81 doi:10.1130/2009.2451(04)
- Jeanpierre, D., 1968. L'érosion des fonds : conséquence secondaire de la protection de la plaine d'Alsace par l'endiguement longitudinal du Rhin, in: Société Hydrotechnique de France. Presented at the XIème journées de l'hydraulique, Paris, 8 p.
- Jenkinson, R.G., Barnas, K.A., Braatne, J.H., Bernhardt, E.S., Palmer, M.A., Allan, J.D., 2006. Stream restoration databases and case studies: a guide to information resources and their utility in advancing the science and practice of restoration. In *Restoration Ecology* 14, 177–186.
- Jones, C.J., Johnson, P.A., 2015. Describing Damage to Stream Modification Projects in Constrained Settings. In *Journal of the American Water Resources Association* 51, 251–262. doi:10.1111/jawr.12248
- Knighton, A.D., 1984. Fluvial forms and processes, Edward Arnold Editions (ed). London, 218 p.
- Kondolf, G.M., Larson, M., 1995. Historical channel analysis and its application to riparian and aquatic habitat restoration. In *Aquatic Conservation: Marine and Freshwater Ecosystems* 5, 109–126. doi:10.1002/aqc.3270050204
- Kondolf, G.M., Micheli, E.R., 1995. Evaluating stream restoration projects. In *Environmental Management* 19, 1–15. doi:10.1007/BF02471999
- Lair, G.J., Zehetner, F., Khan, Z.H., Gerzabek, M.H., 2009. Phosphorus sorption-desorption in alluvial soils of a young weathering sequence at the Danube River. In *Geoderma* 149, 39–44. doi:10.1016/j.geoderma.2008.11.011
- Large, A.R.G., Gilvear, D.J., 2015. Using Google Earth, a virtual-globe imaging platform, for ecosystem services-based river assessment. In *River Research and Applications* 31, 406–421. doi:10.1002/rra.2798
- Larras, J., 1977. Fleuves et rivières non aménagés. In *Revue de géographie alpine* 65, 228–229.
- Lawler, D.M., 1993. The measurement of river bank erosion and lateral channel change: A review. In *Earth Surface Processes and Landforms* 18, 777–821. doi:10.1002/esp.3290180905

- Leopold, L.B., Wolman, M.G., Wolman, M.G., Wolman, M.G., 1957. River channel patterns: braided, meandering, and straight. US Government Printing Office Washington (DC). 50 p.
- Lespez, L., Viel, V., Rollet, A.J., Delahaye, D., 2015. The anthropogenic nature of present-day low energy rivers in western France and implications for current restoration projects. In *Geomorphology* 251, 64–76. doi:10.1016/j.geomorph.2015.05.015
- Lintern, A., Leahy, P.J., Heijnis, H., Zawadzki, A., Gadd, P., Jacobsen, G., Deletic, A., McCarthy, D.T., 2016. Identifying heavy metal levels in historical flood water deposits using sediment cores. In *Water Research* 105, 34–46. doi:10.1016/j.watres.2016.08.041
- Loomis, J., Kent, P., Strange, L., Fausch, K., Covich, A., 2000. Measuring the total economic value of restoring ecosystem services in an impaired river basin: results from a contingent valuation survey. In *Ecological economics* 33, 103–117.
- Magdaleno, F., Anastasio Fernández, J., Merino, S., 2012. The Ebro River in the 20th century or the ecomorphological transformation of a large and dynamic Mediterranean channel. In *Earth Surface Processes and Landforms* 37, 486–498. doi:10.1002/esp.2258
- Marchal, M., Delmas, G., 1959. L'aménagement du Rhin à courant libre du Bâle à Lauterbourg. In *La Houille Blanche*, 177–202. doi:10.1051/lhb/1959032
- Martin, B., Drescher, A., Fournier, M., Guerrouah, O., Giacona, F., Glaser, R., Himmelsbach, I., Holleville, N., Riemann, D., Schonbein, J., Vitoux, M.-C., With, L., 2015. Les évènements extrêmes dans le fossé rhénan entre 1480 et 2012. Quels apports pour la prévention des inondations ? In *La Houille Blanche*, 82–93. doi:10.1051/lhb/20150023
- Middelkoop, H., 2000. Heavy-metal pollution of the river Rhine and Meuse floodplains in the Netherlands. In *Netherlands journal of geosciences* 79, 411–427.
- Mika, S., Hoyle, J., Kyle, G., Howell, T., Wolfenden, B., Ryder, D., Keating, D., Boulton, A., Brierley, G., Brooks, A.P., others, 2010. Inside the “black box” of river restoration: using catchment history to identify disturbance and response mechanisms to set targets for process-based restoration. In *Ecology and Society* 15, 8 p.
- Miller, S.O., Ritter, D.F., Kochel, R.C., Miller, J.R., 1993. Fluvial responses to land-use changes and climatic variations within the Drury Creek watershed, southern Illinois. In *Geomorphology* 6, 309–329. doi:10.1016/0169-555X(93)90053-5
- Naiman, R.J., Décamps, H., Pastor, J., Johnston, C.A., 1988. The Potential Importance of Boundaries of Fluvial Ecosystems. In *Journal of the North American Benthological Society* 7, 289–306. doi:10.2307/1467295
- Naiman, R.J., Decamps, H., Pollock, M., 1993. The Role of Riparian Corridors in Maintaining Regional Biodiversity. In *Ecological Applications* 3, 209–212. doi:10.2307/1941822
- Ochsenbein, G., 1966. La végétation sur les bords du Rhin. In *Saisons d'Alsace*, 383–398.
- Palmer, M.A., Bernhardt, E.S., Allan, J.D., Lake, P.S., Alexander, G., Brooks, S., Carr, J., Clayton, S., Dahm, C.N., Follstad Shah, J., Galat, D.L., Loss, S.G., Goodwin, P., Hart, D.D., Hassett, B., Jenkinson, R., Kondolf, G.M., Lave, R., Meyer, J.L., O'Donnell, T.K., Pagano, L., Sudduth, E., 2005. Standards for ecologically successful river restoration: Ecological success in river restoration. In *Journal of Applied Ecology* 42, 208–217. doi:10.1111/j.1365-2664.2005.01004.x
- Pardé, M., 1928. Périodicité des grandes inondations et crues exceptionnelles. In *Revue de géographie alpine* 16, 499–519. doi:10.3406/rga.1928.4457
- Passega, R., 1964. Grain Size Representation by Cm Patterns as a Geological Tool. In *Journal of Sedimentary Research* 34.
- Passega, R., 1977. Significance of CM diagrams of sediments deposited by suspensions. In *Sedimentology* 24, 723–733. doi:10.1111/j.1365-3091.1977.tb00267.x
- Peiry, J.-L., 1988. Approche géographique de la dynamique spatio-temporelle des sédiments d'un cours d'eau intra-montagnard : l'exemple de la plaine alluviale de l'Arve (Haute-Savoie). Lyon 3.
- Petts, G.E., Moeller, H., Roux, A.L. (eds), 1989. Historical change of large alluvial rivers: Western Europe.

- Preusser, F., May, J.-H., Eschbach, D., Trauerstein, M., Schmitt, L., 2016. Infrared stimulated luminescence dating of 19th century fluvial deposits from the upper Rhine River. In *Geochronometria* 43, 131–142. doi:10.1515/geochr-2015-0045
- Provansal, M., Raccasi, G., Monaco, M., Robresco, S., Dufour, S., 2012. La réhabilitation des marges fluviales, quel intérêt, 5 quelles contraintes ? Le cas des annexes fluviales du Rhône aval. In *Méditerranée* n° 118, 85–94.
- Reimann, C., de Caritat, P., 2005. Distinguishing between natural and anthropogenic sources for elements in the environment: regional geochemical surveys versus enrichment factors. In *Science of The Total Environment* 337, 91–107. doi:10.1016/j.scitotenv.2004.06.011
- Richards, C., Bacon, K.L., 1994. Influence of fine sediment on macroinvertebrate colonization of surface and hyporheic stream 10 substrates. In *The Great Basin Naturalist* 54, 106–113.
- Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2015. A methodological framework for hydromorphological assessment, analysis and monitoring (IDRAIM) aimed at promoting integrated river management. In *Geomorphology* 251, 122–136. doi:10.1016/j.geomorph.2015.05.010
- Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2013. A method for the assessment and analysis of the hydromorphological 15 condition of Italian streams: The Morphological Quality Index (MQI). In *Geomorphology* 180–181, 96–108. doi:10.1016/j.geomorph.2012.09.009
- Riquier, J., Piégay, H., Šulc Michalková, M., 2015. Hydromorphological conditions in eighteen restored floodplain channels of a large river: linking patterns to processes. In *Freshwater Biology*, 19 p. doi:10.1111/fwb.12411
- Rollet, A.J., Piégay, H., Dufour, S., Bornette, G., Persat, H., 2014. Assessment of consequences of sediment deficit on a gravel 20 river bed downstream of dams in restoration perspectives: application of a multicriteria, hierarchical and spatially explicit diagnosis. In *River Research and Applications* 30, 939–953. doi:10.1002/rra.2689
- Rumsby, B.T., Macklin, M.G., 1996. River response to the last neoglacial (the “Little Ice Age”) in northern, western and central Europe. In *Geological Society, London, Special Publications* 115, 217–233. doi:10.1144/GSL.SP.1996.115.01.17
- Schäfer, W., 1973. Der Oberrhein, sterbende Landschaft. In *Natur und Museum*, 1–29.
- Schirmer, W., 1988. Holocene valley development on the upper Rhine and Main, in: Lang, R. & Schlijchter, C. (Eds) *Lake, Mire and River Environments*. Balkema, Rotterdam, pp. 153–160
- Schmitt, L., Trémolières, M., Blum, C., Dister, E., Pfarr, U., others, 2012. 30 years of restoration works on the two sides of the Upper Rhine River: feedback and future challenges, in: *Int. Conf. Integrative Sciences and Sustainable 30 Development of Rivers*. Lyon, France. pp. 101–103
- Schmitt, L., Houssier, J., Martin, B., Beiner, M., Skupinski, G., Boës, E., Schwartz, D., Ertlen, D., Argant, J., Gebhardt, A., Schneider, N., Lasserre, M., Trintafillidis, G., Ollive, V., 2016. Paléo-dynamique fluviale holocène dans le compartiment sud-occidental du fossé rhénan (France). In *Revue Archéologique de l'Est* 42è supplément, 15–33.
- Schmitt, L., Lebeau, M., Trémolières, M., Defraeye, S., Coli, C., Denny, E., Dillinger, M., Beck, T., Dor, J.-C., Gombert, P., 35 Gueidan, A., Manné, S., Party, J.-P., Perrotey, P., Piquette, M., Roeck, U., Schnitzler, A., Sonnet, O., Vacher, J.-P., Vauclin, V., Weiss, M., Zacher, J.-N., Wilms, P., 2009. Le “polder” d’Erstein : objectifs, aménagements et retour d’expérience sur cinq ans de fonctionnement et de suivi scientifique environnemental (Rhin, France). In *Ingénieries n° spécial*, 67–84.
- Schulz-Zunkel, C., Krueger, F., 2009. Trace Metal Dynamics in Floodplain Soils of the River Elbe: A Review. In *Journal of 40 Environment Quality* 38, 1349. doi:10.2134/jeq2008.0299
- Sear, D.A., Arnell, N.W., 2006. The application of palaeohydrology in river management. In *Catena* 66, 169–183. doi:10.1016/j.catena.2005.11.009

- Sear, D.A., Darby, S.E., Thorne, C.R., Brookes, A.B., 1994. Geomorphological approach to stream stabilization and restoration: Case study of the Mimmshall brook, hertfordshire, UK. In *Regulated Rivers: Research & Management* 9, 205–223. doi:10.1002/rrr.3450090403
- Starkel, L., Soja, R., Michczyńska, D.J., 2006. Past hydrological events reflected in Holocene history of Polish rivers. In *CATENA*, Past Hydrological Events Related to Understanding Global Change 66, 24–33. doi:10.1016/j.catena.2005.07.008
- Steiger, J., Tabacchi, E., Dufour, S., Corenblit, D., Peiry, J.-L., 2005. Hydrogeomorphic processes affecting riparian habitat within alluvial channel-floodplain river systems: a review for the temperate zone. In *River Research and Applications* 21, 719–737. doi:10.1002/rra.879
- Tao, F., Jiantong, L., Bangding, X., Xiaoguo, C., Xiaoqing, X., 2005. Mobilization potential of heavy metals: A comparison between river and lake sediments. In *Water, Air, & Soil Pollution* 161, 209–225.
- Toonen, W.H.J., Winkels, T.G., Cohen, K.M., Prins, M.A., Middelkoop, H., 2015. Lower Rhine historical flood magnitudes of the last 450 years reproduced from grain-size measurements of flood deposits using End Member Modelling. In *CATENA* 130, 69–81. doi:10.1016/j.catena.2014.12.004
- Trimble, S.W., Cooke, R.U., 1991. Historical Sources for Geomorphological Research in the United States. In *The Professional Geographer* 43, 212–228. doi:10.1111/j.0033-0124.1991.00212.x
- Tulla, J.G., 1825. Ueber die Rectification des Rheins, von seinem Austritt aus der Schweiz bis zu seinem Eintritt in Hessen. Karlsruhe.
- Tümmers, H.J., 1999. Der Rhein: ein europäischer Fluß und seine Geschichte, 2. Überarbeitete und aktualisierte Auflage. Beck (ed), München, 481 p.
- Uehlinger, U., Wantzen, K.M., Leuven, R.S.E.W., Arndt, H., 2009. Tockner K. (eds), The Rhine river basin, in: Rivers of Europe. Academic Press, Amsterdam; London, pp. 199–245
- van Helvoort, P.-J., Griffioen, J., Hartog, N., 2007. Characterization of the reactivity of riverine heterogeneous sediments using a facies-based approach; the Rhine–Meuse delta (The Netherlands). In *Applied Geochemistry* 22, 2735–2757. doi:10.1016/j.apgeochem.2007.06.016
- Wetter, O., Pfister, C., Weingartner, R., Luterbacher, J., Reist, T., Trösch, J., 2011. The largest floods in the High Rhine basin since 1268 assessed from documentary and instrumental evidence. In *Hydrological Sciences Journal* 56, 733–758. doi:10.1080/02626667.2011.583613
- WFD, 2000/60/EC, 2000. Directive 2000/60/EC of the European parliament and of the council of 23 October 2000 establishing a framework for Community action in the field of water policy.
- Wittmann, J., 1859. Chronik der niedrigsten Wasserstände des Rheins vom Jahre 70 ?? Chr. Geb. bis 1858 und Nachrichten über die im Jahre 1857 - 58 im Rheinbette von der Schweiz bis nach Holland zu Tage gekommenen Alterthümer und Merkwürdigkeiten, insbesondere die damals sichtbaren Steinpfeilerreste der ehemaligen festen Brücke bei Mainz und die unfern dieser Stadt im Rheinstrome gemachten Entdeckungen. Seifert, Mainz, 142 p.
- Wohl, E., Angermeier, P.L., Bledsoe, B., Kondolf, G.M., MacDonnell, L., Merritt, D.M., Palmer, M.A., Poff, N.L., Tarboton, D., 2005. River restoration. In *Water Resources Research* 41, W10301-1-W10301-12. doi:10.1029/2005WR003985
- Woitke, P., Wellmitz, J., Helm, D., Kube, P., Lepom, P., Litheraty, P., 2003. Analysis and assessment of heavy metal pollution in suspended solids and sediments of the river Danube. In *Chemosphere* 51, 633–642. doi:10.1016/S0045-6535(03)00217-0
- Ziliani, L., Surian, N., 2012. Evolutionary trajectory of channel morphology and controlling factors in a large gravel-bed river. In *Geomorphology*, 104–117.

Zimmer, D., Kiersch, K., Jandl, G., Meissner, R., Kolomiitsev, N., Leinweber, P., 2010. Status Quo of Soil Contamination with Inorganic and Organic Pollutants of the River Oka Floodplains (Russia). In *Water, Air, & Soil Pollution* 211, 299–312. doi:10.1007/s11270-009-0301-8