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Review

Insights in Processes and Modelling of the Morphological Evolution of the Lower Rhine

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Abstract

Human interferences have set off a multitude of morphological responses of the lower Rhine in Germany and the Netherlands. We share insights from thirty years of studies on these responses in the Niederrhein below Xanten and the branches in the delta. Elementary analyses of the 1D Saint-Venant–Exner equations explain the downstream flattening and upstream steepening of the longitudinal bed profile due to retrogressive erosion in response to river training, bend cut-offs and sediment mining. Three reasons make a 2D approach necessary for modelling the seemingly 1D problem of large-scale morphological response: (i) transverse variations in bed sediment composition, (ii) sediment division at river bifurcations, and (iii) the possibility that non-erodible layers in bends cause either erosion or sedimentation of the longitudinal bed profile. The Pannerdense Kop and IJsselkop bifurcations are in a state of quasi-equilibrium, essentially unstable but developing slowly. Considerable spatiotemporal variations in the sediment composition of the riverbed surface pose a challenge to stabilizing the longitudinal bed profile by matching gradients in flow velocity to gradients in bed sediment composition. As these variations form a major knowledge gap, we recommend research on the state and dynamics of sediment size and layer structure in the upper metres of the riverbed.

Keywords: river morphology; mixed-size sediment; bifurcations; Rhine

1. Introduction

The River Rhine has been heavily modified by human interferences since Roman times and at an accelerated pace since 1850 [1]. Dikes have narrowed its floodplains; river training works have turned migrating channels with islands into a single-thread main channel; bends have been cut off; new courses have been excavated; dams and weirs have been constructed in the upstream reach, in tributaries and across outlets to the sea; bifurcations have been realigned or relocated; sand and gravel have been mined from its riverbed; dredging and deposition have become part of regular maintenance; and recently aspects of the original river have been restored by removing bank revetments and by implementing the Room for the River programme in the Netherlands. All interferences have set off morphological responses in the riverbed. This poses a challenge to unravelling the causes of ongoing developments and to predicting future changes as a result of delayed response and new interventions and mitigation. We have addressed this in the past thirty years for the free-flowing Rhine downstream of Xanten, to which we refer here as the ‘lower Rhine’. It consists of the Rhine branches of the delta in the Netherlands and a part of the Niederrhein in Germany (Figure 1). We exclude the regulated Nederrijn branch, the downstream



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IJsselmeer reservoir, which has no fluvial character, and the Rhine–Meuse estuary where morphological development is affected by the Delta Works, seaport development, tides, density currents, cohesive sediment, and deep scour after breaking of thin erosion-resistant bed layers [2–4].

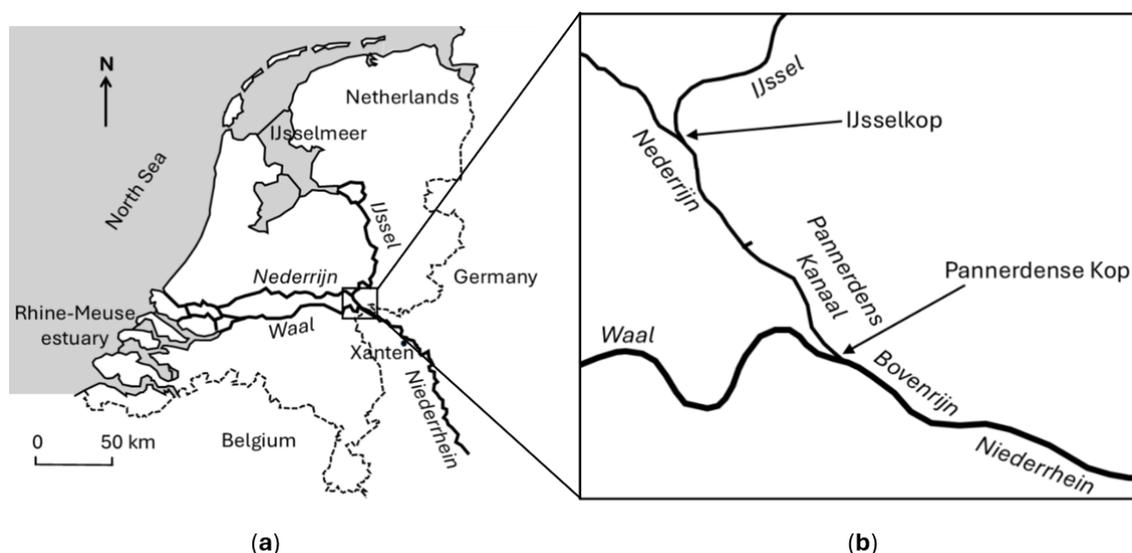


Figure 1. Map of branches of the lower Rhine. (a) Overview; (b) Area with bifurcations.

The objective of this review is to share insights gained from the thirty years of our studies on morphological development of the lower Rhine and to communicate the corresponding documentation, which has been published partly in peer-reviewed scientific articles and partly in research reports reviewed by experts at Rijkswaterstaat and Deltares. Rijkswaterstaat commissioned the studies for river management issues of flood safety, navigability, freshwater supply and riparian nature. These issues require a large-scale system perspective because local interventions have effects over long distances. Main study projects were the numerical modelling of the Rhine bifurcation at Pannerden [5–10], the Niederrhein-Bovenrijn border project [11], the DVR project for sustainable fairway management of the Rhine delta [12–20], the final evaluations of the pilots with longitudinal training walls in the Waal [21] and sediment nourishments on the Bovenrijn, the Room-for-Living-Rivers plan, the IRM project for selecting a policy for riverbed levels, the current Room for the River 2.0 programme, and the current WSV-Rijkswaterstaat working group to analyze the Rhine waterway in the border region (references to reports in Supplementary Materials). The corresponding field data, referenced and visualized by Ylla Arbós et al. [22,23] and Chowdhury et al. [24], were provided by Rijkswaterstaat, TNO-NITG, Wasserstraßen- und Schifffahrtsamt Rhein, Bundesanstalt für Gewässerkunde and Bundesanstalt für Wasserbau.

Our review complements articles in *Water* by Havinga [25] and Krapesch et al. [26]. Havinga gives an overview of management and interventions in the Dutch part of the lower Rhine. Krapesch et al. review sediment-related knowledge on the Rhine catchment for the lower Rhine with a focus on recent PhD research. We see the three articles in *Water* together as a triptych for knowledge on sediment management, morphology and engineering in the lower Rhine.

We focus on the insights gained in the morphological system behaviour of the lower Rhine rather than on overviews of observed evolution, measurements and model results. These insights are relevant for the current Room for the River 2.0 programme that aims at stabilizing the eroding longitudinal riverbed profiles [27–32] as well as the discharge distributions at the Pannerdense Kop and IJsselkop bifurcations [6,9,10]. Section 2 reviews

established notions of elementary large-scale morphological response that help in evaluating cause–effect relationships for observed erosion and sedimentation. Section 3 explains the finding that two-dimensional (2D) numerical models are a necessity for simulating the large-scale morphological development of longitudinal riverbed profiles of the lower Rhine. One-dimensional (1D) numerical models appear to be inadequate for this. Section 4 discusses aspects of bed sediment composition that shed light on difficulties in numerical modelling and motivate priorities for further research. Section 5 addresses the development of bifurcations. The insights are wrapped up in the conclusions and recommendations of Section 6.

2. Elementary Large-Scale Morphological Response

The elementary large-scale morphological response of longitudinal bed profiles of alluvial rivers can be understood from a set of partial differential equations. For simplicity this section assumes a river with a uniform width and rectangular cross-sections so that 1D conservation equations can be formulated per unit of width. Accordingly, the volumetric mass balance for sediment can be written as

$$\frac{\partial z_b}{\partial t} + \frac{\partial q_s}{\partial x} = 0 \quad (1)$$

in which z_b (m) denotes bed level, q_s (m^2/s) denotes sediment transport rate per unit width, t (s) denotes time, and x (m) denotes the coordinate along the river. It is assumed that sediment transport magnitude depends on how fast the water flows. This means that q_s represents the transport rate of gravel and sand that are also found on the riverbed, excluding silt and clay that are transported as wash load independent of the strength of the flow. It is furthermore assumed that the transport rate adapts immediately to changes in the flow, without lags in time or space, which is fair if adaptation lengths are small with respect to the scale of the phenomena considered or the space steps or grid cells in numerical models [33]. Sediment transport rate can then be written as a function of flow velocity, u (m/s): $q_s = q_s(u)$. Substitution in Equation (1) and application of the chain rule for differentiation results in the Exner [34] equation:

$$\frac{\partial z_b}{\partial t} + \frac{dq_s}{du} \frac{\partial u}{\partial x} = 0 \quad (2)$$

which Exner postulated without derivation from Equation (1) and with a constant factor, a , instead of dq_s/du . Acknowledging that sediment transport rate also depends on bed sediment grain size, D (m), leads to the extended Exner equation:

$$\frac{\partial z_b}{\partial t} + \frac{dq_s}{du} \frac{\partial u}{\partial x} + \frac{dq_s}{dD} \frac{\partial D}{\partial x} = 0 \quad (3)$$

This equation assumes that bed sediment composition can be characterized by a single representative grain size. Numerical models for the lower Rhine follow a more sophisticated approach by considering transport and mass conservation of different size fractions in mixtures of sediment [35]. We come back to this in Section 4.

The Exner equation relates erosion and sedimentation to gradients in the longitudinal flow profile which are commonly computed using 1D steady Saint-Venant equations [36] for gradually varied flow [37], colloquially referred to as backwater curve equations. The resulting set of 1D quasi-steady Saint-Venant–Exner equations has been analyzed extensively for rivers with uniform sediment. For lowland rivers like the lower Rhine, with Froude numbers below 1, these equations require conditions for incoming discharge and sediment load at the upstream boundary, and water level at the downstream boundary [38].

De Vries [39] and Ribberink and Van der Sande [40] study the system response to changes in boundary conditions by linearizing the equations and applying Laplace transformation. A stepwise change in downstream water level is felt immediately over a long river reach through backwater effects, to which the riverbed responds according to a diffusion equation [39]. A stepwise increase in upstream sediment load first produces only local sedimentation at the boundary. Its front initially moves downstream according to a wave equation [40]. De Vries, Ribberink and Van der Sande call the diffusive response to downstream boundary conditions “parabolic” and the wave propagation response to upstream boundary conditions “hyperbolic”, a terminology based on similarity between the characteristic equations of linear second-order partial differential equations and the discriminants of conic sections.

The different characters of responses to upstream and downstream conditions help in identifying causes of observed changes. If, for instance, the immediate morphological response to an extreme event extends over a longer distance, it is likely that this response has a downstream cause. If the immediate response is only local, it likely has an upstream cause. The response to modification of a reach can be understood in a similar way. The upstream and downstream ends of the modified reach generate wavelike morphological responses from upstream to downstream and diffusive responses from downstream to upstream. This is shown in the conceptual diagrams of Figure 2. Reduction in the sediment load from upstream leads initially to erosion immediately downstream of a bedrock reach (Figure 2a). This erosion progressively expands as a rarefaction wave, flattening the longitudinal bed profile (Figure 2b). Narrowing of a reach leads initially to erosion inside the narrowed reach and sedimentation upstream. The erosion expands as a rarefaction wave from the upstream end of the reach and as a diffusive process from the downstream end, together tending to a flatter longitudinal bed profile (Figure 2c). As time proceeds, continuing erosion in the narrow flattening reach draws down water levels. The initial sedimentation upstream then turns into erosion which expands upstream through diffusion and steepens the upstream longitudinal bed profile (Figure 2d). Eventually the retrogressive erosion will reach the upstream bedrock and incise the non-narrowed part of the river to a profile with the same slope as it had before implementing the narrowing.

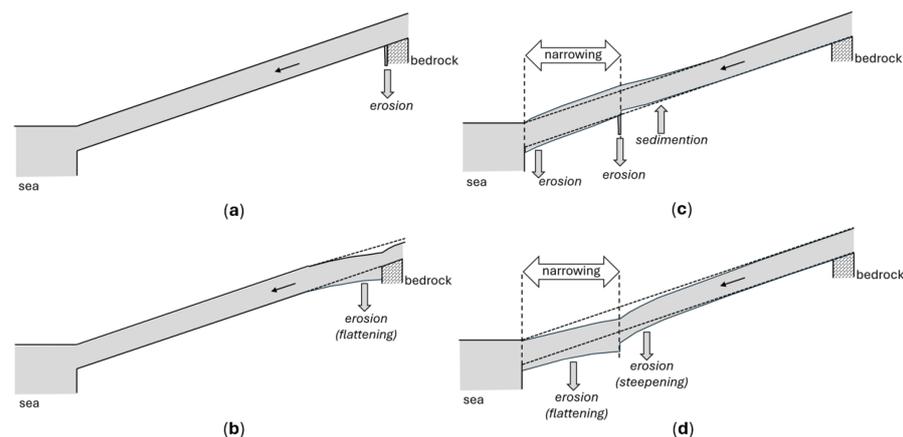


Figure 2. Conceptual diagrams of longitudinal bed profile responses according to Saint-Venant–Exner equations for uniform sediment. (a) Initial response to reduced sediment load upstream; (b) Progressing response to reduced sediment load upstream; (c) Initial response to narrowing; (d) Progressing response to narrowing.

The pattern of downstream flattening and upstream steepening in panel d of Figure 2 can be recognized in the erosion of the Niederrhein, Bovenrijn and Waal in Figure 3. This erosion is mainly caused by river training, bend cutoffs and sediment mining although

other factors play a role as well [41] (p. A-3). Numerical computations [42] show that sediment nourishment at the German–Dutch border would not be able to counter the erosion in the Netherlands, in line with the primarily local sedimentation and wavelike development predicted by theoretical analysis [40].

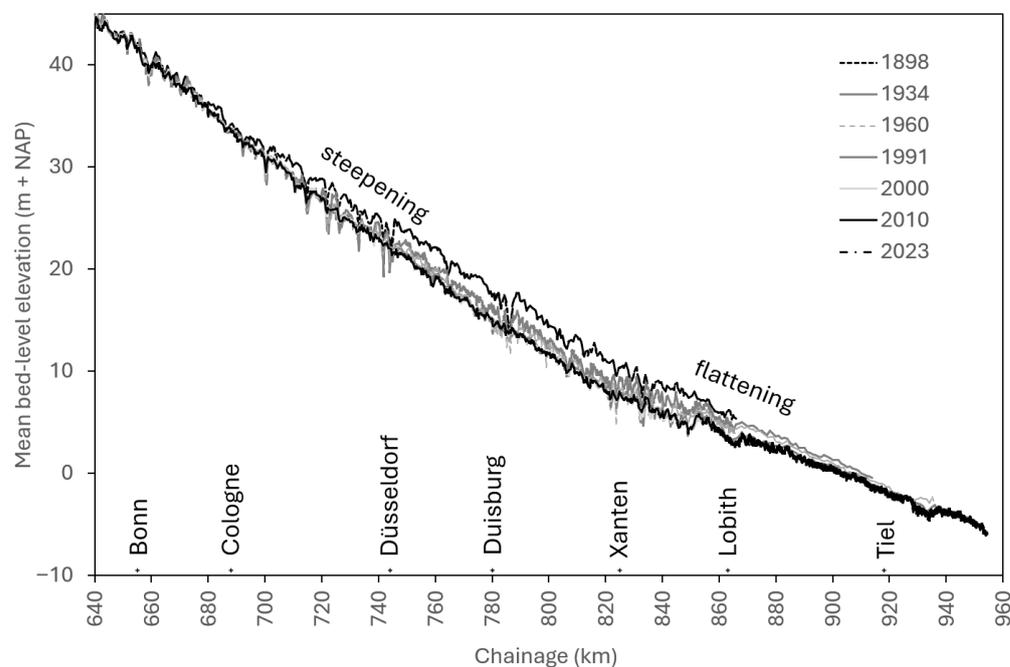


Figure 3. Signature of retrogressive erosion in development of longitudinal bed profile along Niederrhein, Bovenrijn and Waal. Data from Rijkswaterstaat and [43].

The response to widening a river reach forms a mirror image of the response to narrowing in Figure 2. If widening aims at stabilizing an eroding riverbed, like in the Room for the River 2.0 programme, implementation over a limited distance enhances erosion upstream by water level drawdown, which opposes the intended effect of reducing sediment transport capacity. In the river Meuse, such widening-induced erosion damaged pipeline crossings and ferry landings during the 2021 summer flood [44]. Morphological processes at different locations along the river are connected through backwater effects. Accordingly, morphological impact assessment requires analyzing river systems comprehensively over long distances.

3. Necessity of 2D Numerical Modelling for Large-Scale Morphological Response

The equations for large-scale morphological response in Section 2 are one-dimensional (1D). They relate to a single average bed level for every cross-section. The topography of bars and pools in transverse direction, however, is relevant for navigation. That is why Rijkswaterstaat developed 2D numerical models for river morphology in the 1930s, solving the corresponding equations by hand and mechanical devices before the advent of electronic computers [45,46]. A Dutch–Danish research team [47] developed a numerical morphological model for electronic computers in the 1980s, which evolved into Mike21C in Denmark and Delft3D in the Netherlands. Delft3D was developed further in the next 40 years, with computational acceleration techniques and simulation of dredging and deposition strategies especially for application to the lower Rhine [14].

In these 40 years three reasons emerged as to why a 2D morphological model is also a necessity for the seemingly 1D problem of the evolution of longitudinal riverbed profiles. The first reason is that bed sediment composition varies considerably in transverse direction

(Figure 4) [48]. This is not just a challenge for selecting a single representative composition at each cross-section. It has implications for the validity of 1D model concepts that have been derived from experiments in narrow laboratory flumes. We address this further in Section 4.

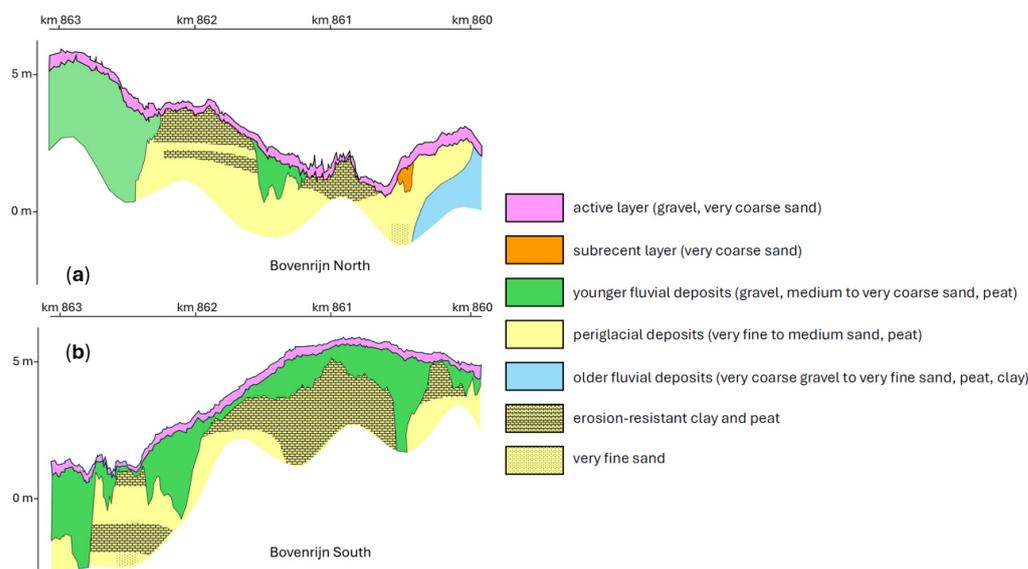


Figure 4. Longitudinal profiles of subsurface sediment composition in the Bovenrijn between km 860 and 863 in 2001, based on [48]. Elevation datum is NAP. The layer annually reworked by erosion and sedimentation is thicker than the active layer. (a) 70 m from right bank (North); (b) 70 m from left bank (South).

The second reason is that the development of river bifurcations depends on how sediment load from upstream is divided over the two branches downstream. This is governed by 2D and 3D processes in local river geometry that are not captured by 1D models. In 1D models, the division of sediment load is represented by an empirical nodal point relation. Several researchers have attempted to derive a physics-based nodal point relation for application in 1D models. Bolla Pittaluga et al. [49,50] insert a locally 2D representation in an otherwise 1D model and assume that, close to the bifurcation, the bed level in the left half of the upstream river connects to the bed level in the left branch, and in the right half to the bed level in the right branch. This may be physically plausible if horizontal dimensions are at most about one order of magnitude larger than vertical dimensions, like in the laboratory experiments of Bolla Pittaluga et al. For prototype-scale rivers, however, slopes over short distances form merely steps in bed levels at the entrances of the bifurcated branches. Elaboration of the Saint-Venant–Exner equations shows that no information on bed level can pass from the downstream branches to the relevant area of the upstream river. These theoretically predicted steps are clearly visible in measured bed levels at the Pannerdense Kop and IJsselkop bifurcations [24] (p. 7). The approach with a locally inserted 2D model is therefore not valid for bifurcations in the lower Rhine. Its effects on bifurcation stability are even opposite to those of more physics-based formulations [51]. Van der Mark and Mosselman [52] derive a physics-based nodal point relation for the effect of helical flow on bedload in idealized river geometries. This relation showed reasonably good agreement with measurements but took such a complex form that the authors see no prospect for developing a generic relationship with broader validity. Hence none of the attempts [49,50,52] were successful. One-dimensional models appear inadequate for applications where sediment division at bifurcations matters. We come back to bifurcations in Section 5.

The third reason why 2D morphological models are a necessity regards the effects of implementing or removing non-erodible layers in river bends (Figure 5). These layers have the purpose of improving navigability. By raising the bed in the over-deep outer-bend pool, they reduce the cross-sectional flow area and thereby increase flow velocities. Resulting erosion of the inner bend is supposed to make navigable depth available over a larger width. Non-erodible layers, however, have two effects [12]. Not only do they increase discharge and, hence, sediment transport capacity in the inner bend, they also let helical flow move sediment from the non-erodible layer to the inner bend by preventing the formation of a transverse bed slope that would keep sediment in the outer bend. The net result of the opposed effects of higher sediment load and higher sediment transport capacity can be either erosion or sedimentation in the inner bend. This also determines whether a non-erodible layer leads to erosion or sedimentation of the longitudinal bed profile. One-dimensional models cannot reproduce this. Two-dimensional models originally developed for bed topographies in navigability studies thus appear necessary for understanding and assessing large-scale evolution of longitudinal riverbed profiles too.

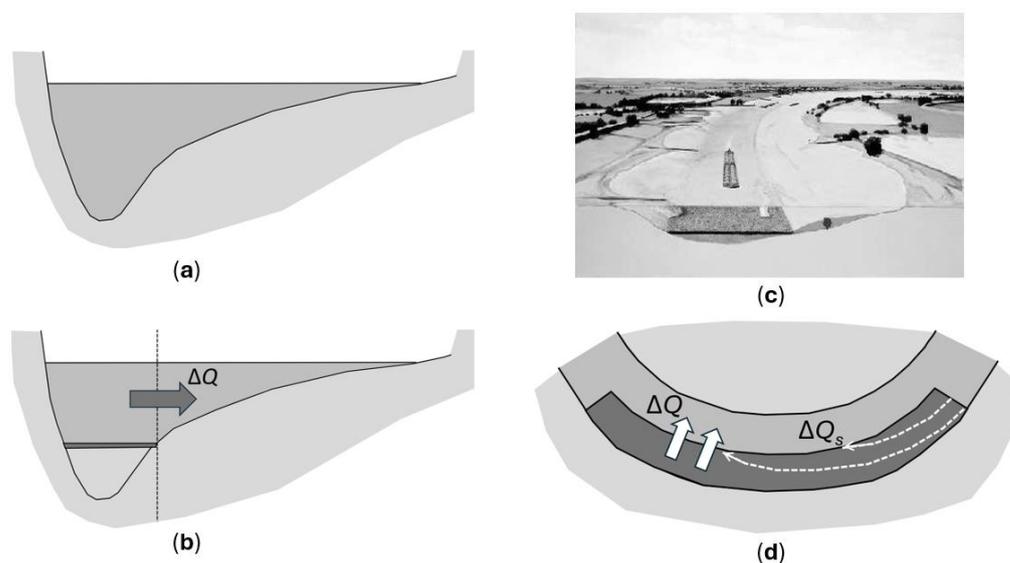


Figure 5. Effects of non-erodible layers in river bends. (a) Cross-section with over-deep outer-bend pool and shallow inner bend; (b) Redistribution of discharge towards inner bend by non-erodible layer in outer bend; (c) Artist impression of non-erodible layer; (d) Increase in both discharge (block arrows) and sediment load (dashed arrows) in inner bend.

4. Bed Sediment Composition

The alluvial deposits of the Rhine–Meuse delta over the past 10,000 years are known in great detail thanks to fieldwork by more than 1400 students of Utrecht University in the period 1959–2001 [53]. This has resulted in a database of over 200,000 lithological borehole descriptions. Additional information was available in the form of more than 1200 ^{14}C dates and 36,000 archeological artefacts. Fluvial deposits from main channels and pointbars of the Rhine and the Meuse constitute the Betuwe Formation of fine to coarse sand and gravel [54]. The gravel–sand bed of the Waal has coarsened by winnowing during erosion over the past 900 years, before 1870 mainly due to river confinement between dikes and after 1870 mainly due to river training and dredging [55]. Gravel and sand do not form a homogeneous mixture but segregate into areas and layers of different composition [56]. Sediment patches of different grain sizes develop on the surface of the riverbed [57]. Gravel accumulates in the troughs of dunes and may be buried when dunes decline, and re-exposed and entrained when dunes grow again [58]. Different pathways of sediment grains lead to lateral sorting in river bends [59–61]. Bed-level variations due to discharge variations

mix sediment in a thicker active layer than just the height reworked by bedforms in a laboratory flume, slowing down the rate of changes in bed sediment composition [8,62]. The coarsest sediment grains can become immobile at low discharges, which influences the transport and arrangement in bedforms of finer grains still in motion [63–65]. Engineered non-erodible layers to improve navigability [12] affect sediment in a similar way.

The mixing and segregation of grain sizes, including burial and re-exposure, cause large spatial and temporal variations in composition of the surface of the riverbed [66]. This explains the scatter in bed sediment composition from grab samples and is visible when studying the riverbed in a diving bell (Figure 6). It poses a challenge to the current Room for the River 2.0 programme that aims at stabilizing the riverbed ($\partial z_b / \partial t = 0$) by designing river geometry in such a way that it adapts gradients in flow velocity ($\partial u / \partial x$) to gradients in bed sediment composition ($\partial D / \partial x$). From Equation (3):

$$\frac{dq_s}{du} \frac{\partial u}{\partial x} + \frac{dq_s}{dD} \frac{\partial D}{\partial x} = 0 \quad (4)$$

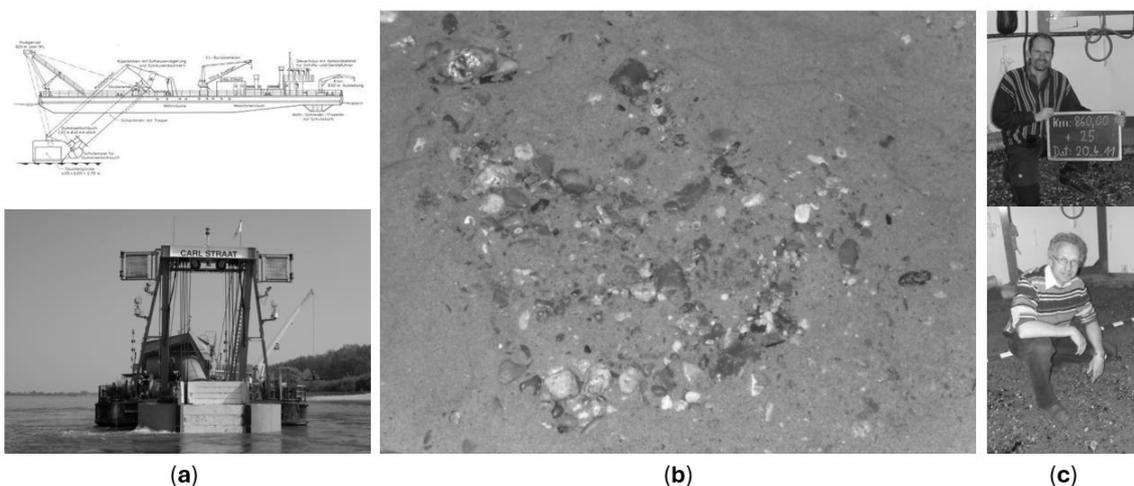


Figure 6. Study of riverbed sediment composition of the lower Rhine in diving bell [27,28]. (a) Carl Straat diving bell, drawing reproduced with permission of Wasserstraßen- und Schifffahrtsamt Rhein; (b) Gravel and sand on the bed of the Bovenrijn; (c) The authors on the riverbed of the lower Rhine.

Room for the River 2.0 seeks to realize this adaptation through spatial design of a multichannel system. Fluctuations in bed sediment composition also carry the risk of finding trends that are spurious due to undersampling (Figure 7).

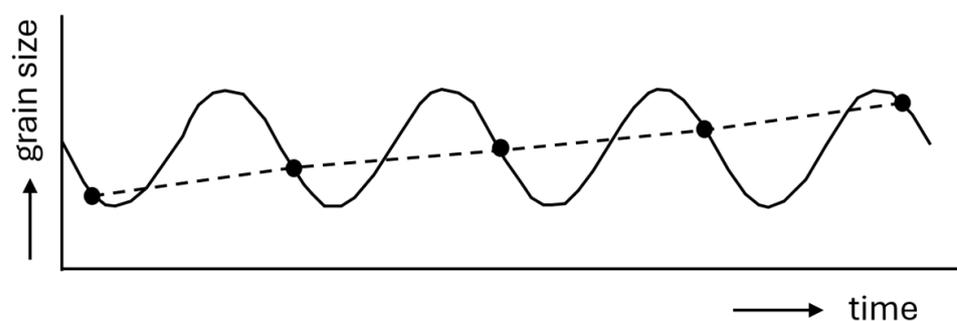


Figure 7. Schematic representation of spurious coarsening trend due to undersampling. Wavy line represents true grain size variations. Dots represent observed variations. Dashed line represents spurious trend derived from observations.

The overall composition of the active layer is less variable than the composition of the mere surface but nonetheless poorly known. Trends could be assessed and model concepts could be improved if the composition and layer structure of the upper metres of the riverbed would be measured in more detail, for instance by combining data from multibeam echosounders with data from borings and sub-bottom profilers.

The 2D morphological models for the lower Rhine simulate the evolution of bed sediment composition by (i) dividing the sediment mixture into separate size fractions, (ii) employing transport formulas and mass conservation equations for each of the separate fractions, (iii) applying hiding-and-exposure corrections to the critical shear stress of each of the fractions [67], and (iv) defining a thickness of the active layer in which the composition changes [35]. This approach yields satisfactory results. Remaining limitations, nonetheless, are the strong dependence of results on active-layer thickness, the assumption of constant porosity, and the applicability of hiding-and-exposure corrections [62]. Hiding and exposure in well-graded (poorly sorted) unimodal mixtures might differ from the mechanisms in poorly graded (well-sorted) bimodal mixtures with the same mean grain size and standard deviation. Moreover, hiding and exposure occur only if different grain sizes interact within a sediment mixture, not if different grain sizes are segregated in different vertical layers, bed surface patches, or zones in transverse direction. Two-dimensional models do distinguish between mixing and transverse segregation; one-dimensional models do not. Deeper insight into the interactions between different grain sizes and the evolution of composition and structure of the active layer might be obtained from 3D direct numerical simulation of sediment transport [68–70].

Another limitation of the modelling approach has been in the past that the hyperbolic character of the equations, explained in Section 2, can become elliptic [62,71]. This renders the set of equations ill-posed because its solution would require not only initial conditions but also final conditions, implying that the present would depend on the future. Chavarrías resolved this limitation for 1D models by altering timescales in a way similar to applying morphological acceleration factors [72,73], and for 2D models by adding diffusion [74].

5. Development of Bifurcations

The lower Rhine splits into branches at two main bifurcations (Figure 1). At the Pannerdense Kop bifurcation, the Bovenrijn splits into Waal and Pannerdens Kanaal, which changes name into Nederrijn at km 873.5. The IJssel splits off from the Nederrijn at the IJsselkop bifurcation. The morphological stability of river bifurcations can essentially be understood from a non-linear phase-plane analysis that traces the evolution in time of the water depths, h_1 and h_2 , of the two downstream branches. The analysis uses (i) the 1D quasi-steady Saint-Venant–Exner equations, (ii) a power-law formula, $q_s = mu^b$ with empirical coefficient m and empirical exponent b , to describe how sediment transport rate, q_s , depends on depth-averaged flow velocity, u , and (iii) a nodal point relation to describe how the sediment load from upstream is divided over the two branches. The flow is assumed uniform without backwater effects, and erosion and sedimentation are assumed to be spread evenly over the length of each branch. Flokstra [75] carries out the analysis for a nodal point relation that divides sediment load in proportion to the widths of the downstream branches and a relation that divides the load in proportion to the discharges into the two branches. He finds in both cases that bifurcations are unstable and tend to close one of the two branches [75] (p. A.3). Wang et al. [76] perform the analysis for a nodal point relation $q_{s1}/q_{s2} = (q_1/q_2)^p$ where q_{s1} and q_{s2} (m^2/s) are sediment transport rates per unit width into branches 1 and 2, respectively, q_1 and q_2 (m^3/s) are discharges per unit width into branches 1 and 2, respectively, and p is an exponent. They find that bifurcations are stable if $p > b/3$ but unstable if $p < b/3$ (Figure 8). Thus two tipping points arise in

behaviour of the system. One tipping point is related to passing the threshold $p = b/3$ between stable and unstable bifurcations. The other tipping point is passed if a trajectory towards closure of one branch turns into a trajectory towards closure of the other branch by a change in the depths h_1 and h_2 of the quasi-equilibrium in Figure 8a.

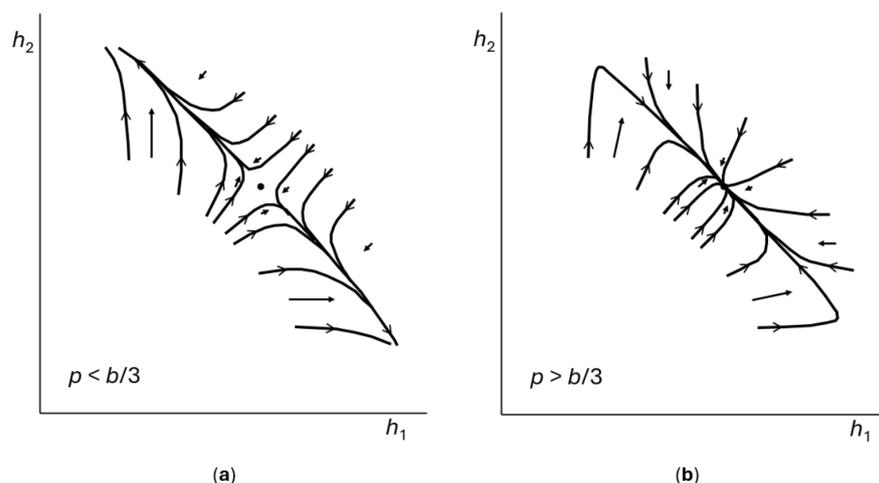


Figure 8. Evolution trajectories of river bifurcations in phase-plane analysis. Symbols h_1 and h_2 denote water depths in each of the two downstream branches. The central circular dot represents equilibrium. Size and direction of separate arrows indicate rate and direction of change. (a) Unstable equilibrium; (b) Stable equilibrium.

The 1D phase-plane analyses reveal essential aspects of system behaviour, but they cannot capture the complexity of the division of sediment. Physics-based nodal point relations are too complex even for highly idealized bifurcation geometries (Section 3). Moreover, they are not constant in time. Two-dimensional numerical simulations show that p can increase over time as morphology evolves and thereby stabilizes an initially unstable bifurcation [9]. The intense navigation on the lower Rhine makes the picture even more complex. Eerden and Mosselman [77] observed that return currents around a ship leaving the IJssel at the IJsselkop bifurcation sucked water from the downstream Nederrijn, which must have transported sediment from the Nederrijn in upstream direction first and then downstream into the IJssel (<https://www.youtube.com/watch?v=E7rBUVrkhbA>, accessed on 3 February 2026).

Bifurcations in the delta of the lower Rhine were unstable in the past 10,000 years, creating numerous avulsions [53]. The speed at which a bifurcation loses stability depends on how far away the system is from the unstable quasi-equilibrium. Numerical simulations [9] and the 1D phase-plane analyses (Figure 8a) show that nearly balanced bifurcations develop much slower than bifurcations further away from quasi-equilibrium. Trial and error [78] have brought the Pannerdense Kop and IJsselkop bifurcations into states of quasi-equilibrium. To maintain these states, Rijkswaterstaat follows a policy of compensating any measures to increase conveyance in one branch with equivalent increases in conveyance in the other branch. Remaining weak trends of change are addressed in the current Room for the River 2.0 programme. Gradually increasing discharges to the Waal might be related to the riverbed erosion set off by implementing a non-erodible layer (Figure 5) at Nijmegen (1986–1988) and bendway weirs at Erlecom (1994–1996), and to the gradual increase in dredging to accommodate a least available depth for navigation of 2.8 m (after 1999). Instability driven by a perturbation in the sediment division is relatively easy to manage because the morphological effect is local, in accordance with the hyperbolic wavelike character explained in Section 2. Instability driven by a perturbation in discharge

is more challenging, because the morphological response has a parabolic diffusion character, extending over the lengths of backwater effects.

Notwithstanding the quasi-equilibrium of the lower Rhine bifurcations, morphological effects of an extreme flood event might change the division of discharges suddenly during the event in such a way that a design discharge on the Bovenrijn would in one of the branches produce a discharge that exceeds the values for which dikes have been designed [79]. This possibility has been identified for erosion due to flows of 2 m/s over a floodplain at the IJsselkop bifurcation [80]. Whether or not this floodplain would erode depends on strength and smoothness of the grass cover. The owner of the land on the floodplain knows this and keeps the grass in good shape by mowing every year before the flood season [81].

6. Conclusions and Recommendations

6.1. Conclusions

We have shared insights from about thirty years of studies on the morphological evolution of the free-flowing Rhine downstream of Xanten, substantiated by references to corresponding literature. The elementary large-scale morphological response to changes in upstream sediment load has another character than the response to changes in downstream water level. Changes in upstream sediment load cause an initially local response that gradually propagates downstream. Changes in downstream water level immediately affect a longer reach and gradually extend their influence further upstream. Similar patterns of response are generated at the entrance and exit of a modified reach, generating waves that propagate downstream and diffusive bed level changes upstream. Upstream of the modified reach, initial sedimentation flips later into erosion or vice versa. On the lower Rhine this erosion after initial sedimentation created a typical profile of downstream flattening and upstream steepening due to retrogressive erosion in response to river training, bend cut-offs and sediment mining.

The large-scale morphological response of longitudinal bed profiles seems to pose a 1D problem that could be solved using a 1D morphological model. We presented three reasons, however, why a 2D morphological model is necessary for this seemingly 1D problem. First, bed sediment composition varies considerably in transverse direction, invalidating 1D model concepts for the interaction between different sediment size fractions. Second, 1D morphological models cannot calculate the division of sediment at river bifurcations. Third, non-erodible layers in river bends cause either erosion or sedimentation of the longitudinal bed profile, depending on 2D features.

The sediment composition of the surface of the riverbed varies considerably in time and space. This poses a challenge to stabilizing the longitudinal bed profile by matching gradients in flow velocity with gradients in bed sediment composition. The composition forms a major gap in our knowledge.

One-dimensional phase-plane analyses provide insight into key aspects of bifurcated river systems, but the division of sediment over different branches requires a 2D approach. The Pannerdense Kop and IJsselkop bifurcations are in a state of quasi-equilibrium. They are essentially unstable, but the instability develops slowly. Rijkswaterstaat has managed to maintain this state by compensating the measures to increase conveyance in one branch with equivalent increases in conveyance in the other branch.

6.2. Recommendations

We recommend prioritizing research on state and dynamics of sediment size and layer structure in the upper metres of the riverbed, as this forms the main knowledge gap for designing interventions to stabilize the longitudinal river profile based on the extended Exner

equation (Section 4). For this, we recommend both field measurements and detailed numerical modelling. Recommended field measurements follow the method of Van Dijk et al. [82] for determining bed levels and subsurface composition and layer structure. They collected high-resolution data along four 7 km tracks of (i) multibeam echo sounding recordings of bed levels and (ii) parametric echosounder recordings of subsurface layer structure in the Waal branch of the lower Rhine, interpreted using 16 vibrocore sediment composition samples of 4.5 m depth. Direct measurement of transport by intercepting sediment particles is notoriously inaccurate [33,83]. Effective indirect ways to obtain information about sediment dynamics are monitoring of the evolution of a dredged cross-trench [66,84] and dune tracking. Short secondary dunes provide more accurate information on sediment transport than long primary dunes, but their tracking requires a high spatiotemporal resolution [85,86]. For the modelling we recommend direct numerical simulation of grain sorting, hiding and exposure in a 3D setting with mixed-size sediment and varying discharges. To this end, Nabi's model [69,70] could be extended with sediment grains of different sizes, tested and calibrated on the laboratory experiments of Blom et al. [58], and then applied to simulate the development of bed levels and subsurface composition and layer structure recorded by Van Dijk et al. [82]. These simulations would aim at deeper physical understanding as well as improved parameterizations for the 2D morphological models routinely used.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w18030407/s1>, File S1: List of project reports.

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