Title:	River morphology
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This document is intended to become an annex in the final report. It includes the texts of the following memoranda prepared previously:

- *River bed degradation of the Rhine branches*
- *The Room-for-the-River programme in the Netherlands*
- *Development of navigation bottlenecks*

River morphology

1. River bed topography and navigability

Water depths for navigation depend not only on discharge but also on the topography of the river bed. Figure #.1 illustrates that spatial bed level variations can lead to insufficient depth for navigation even if the average water depth would be sufficient. Furthermore, the mathematical equations for water flow imply that the average depth at a given discharge is smaller if the longitudinal bed profile is steeper. This is seen most easily in the Chézy equation and the continuity equation for steady uniform flow:

$$u = C\sqrt{h i_x} \tag{1}$$

$$Q = Bhu \tag{2}$$

in which u denotes flow velocity, C is the Chézy coefficient for hydraulic roughness, h is the water depth, i_x is the longitudinal slope, Q is the discharge and B is the width of the river. Combination yields:

$$Q = BCh^{3/2} i_x^{1/2} \tag{3}$$

This relation shows that steeper longitudinal river-bed slopes correspond to shallower rivers for given constant values of discharge, width and roughness. A flat slope might hence seem favourable for navigation at first glance. A flatter slope of the Rhine, however, implies that bridging the elevation difference between Rotterdam and, say, Duisburg or Basel requires locks that are navigation obstacles to a certain extent by themselves.

River bed topographies usually display a whole spectrum of river bed variations, from ripples and dunes at the smallest scales to bars and longitudinal bed level profiles at the largest scales. Figures #.2 to #.4 show some examples.

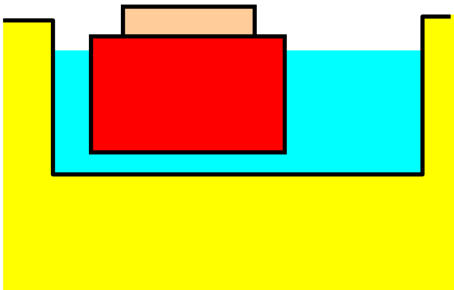

Figure #.1. Effect of spatial bed level variations: sufficient (left) and insufficient (right) depth for navigation at the same average water depth.

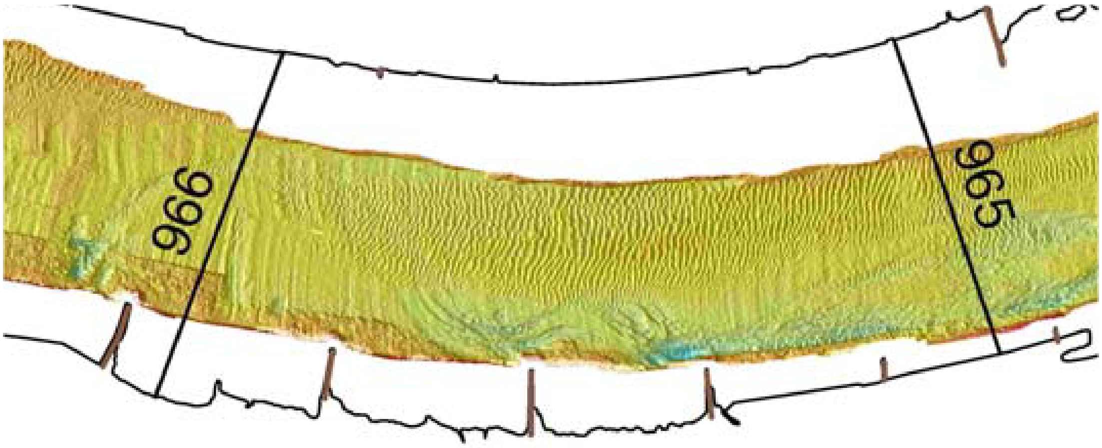

Figure #.2. Dunes on the bed of the Nieuwe Merwede.

Figure #.3 Dunes on top of a bar exposed at low discharge in a branch of the Amazon River near Iquitos, Peru.

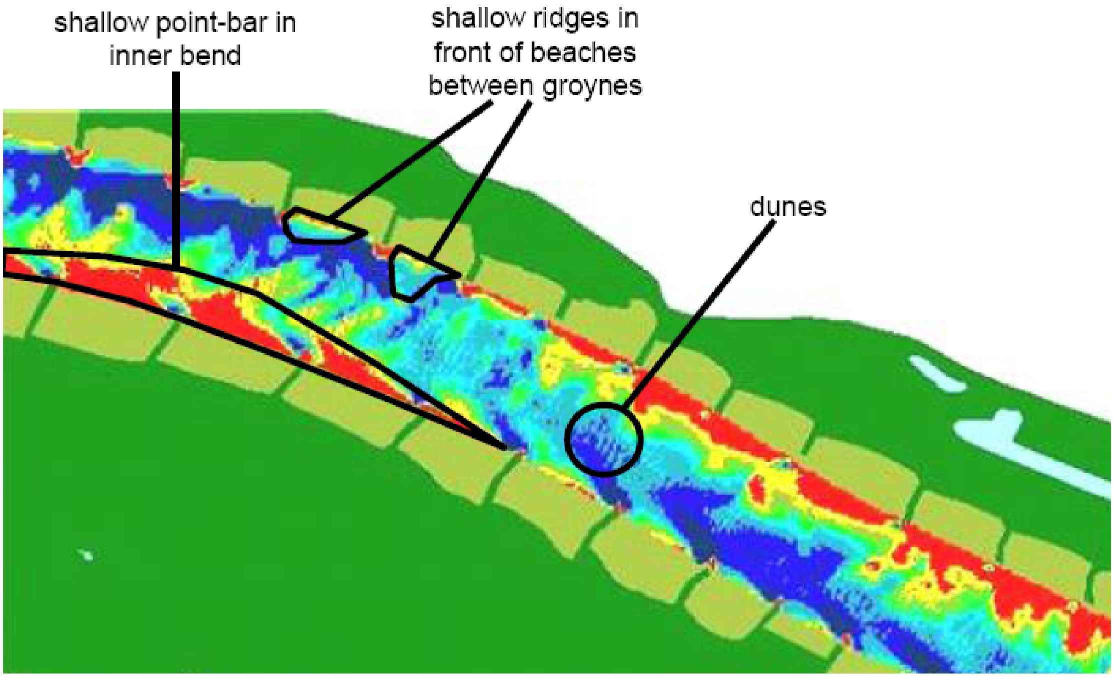

Figure #.4. Different bed topography features in the river Waal at Winssen (km 895).

The bed topography of a river results from processes of erosion and sedimentation. Hydrological changes, such as those owing to climatic change, as well as engineering interventions, such as damming, river training, bend cutoffs and re-landscaping of floodplains, affect these processes and hence produce changes in river bed topography. River morphology is the science of studying, modelling and forecasting these changes. Morphological changes are a separate, distinct source of navigation bottlenecks, in addition to extended periods of low flows and the limited space under bridges during river floods or storm surges.

2. Historical training of the river Rhine

The river Rhine has seen enormous changes over the past centuries. Tributary rivers have been dammed, the river has been trained, weirs have been constructed, bends have been cut off and all kinds of interventions have been implemented for hydropower, navigation and other beneficiaries of its resources. Two examples of river training are given below to illustrate the dimensions and the impacts of the interventions.

The first example regards the correction of the Oberrhein between 1817 and 1876, under the leadership of Johann Gottfried Tulla who became notorious for his statement that “as a rule, no stream or river needs more than one bed”. This correction reduced the number of channels to one, reduced the overall width of the river substantially and shortened the river stretch between Basel and Worms by 80 km from 355 km to 275 km (Figure #.5). The correction caused severe erosion of the river bed, degrading the bed by several metres, up to 10 m locally, until it stopped by armouring and by reaching the inerodible bedrock. As the surfacing bedrock rendered navigation impossible, the parallel 50 km long Grand Canal d'Alsace (or Rheinseitenkanal) was constructed between Kembs and Vogelgrun in the years 1932-1959. The purpose of this canal was not only navigation but also hydropower, on which France had received the exclusive right at the Treaty of Versailles after Germany's defeat in World War I. The remaining Vieux Rhin or Rest-Rhein at the French-German border still testifies of the impact of Tulla's river training (Figures #.6-#.8).

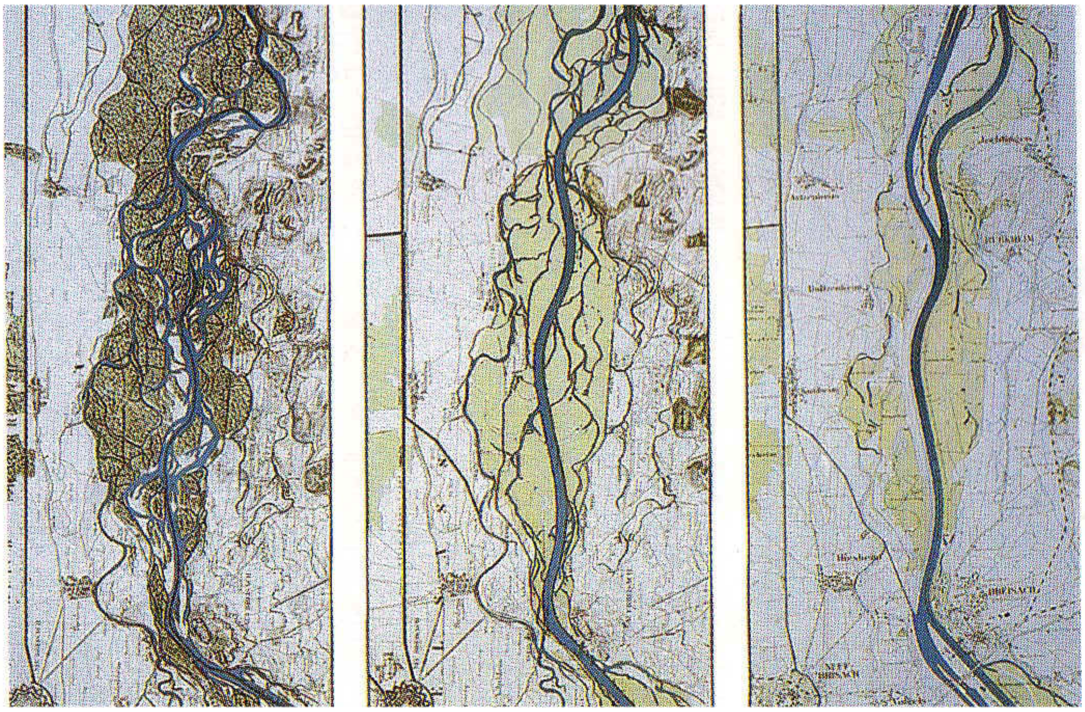

Figure #.5. The Oberrhein at Breisach: before river training (1828, left), after Tulla's correction (1872, centre) and after further canalisation (1963, right).

Figure #.6. Incised Rest-Rhein with cars on the old floodplain.

Figure #.7. Rapids due to a bedrock sill in the Rest-Rhein.

Figure #.8. Ship locks in the Grand Canal d'Alsace at Ottmarsheim.

The second example of historical river training regards the Waal. Figure #.9 shows the progress of river training works in the period 1830-1890, whereas Figure #.10 shows the present situation. Lambeek & Mosselman (1998) report that the main-channel width of the Waal was about 400 to 700 m in 1800 and about 200 to 300 m in 1998, which implies a reduction by more than 50%.

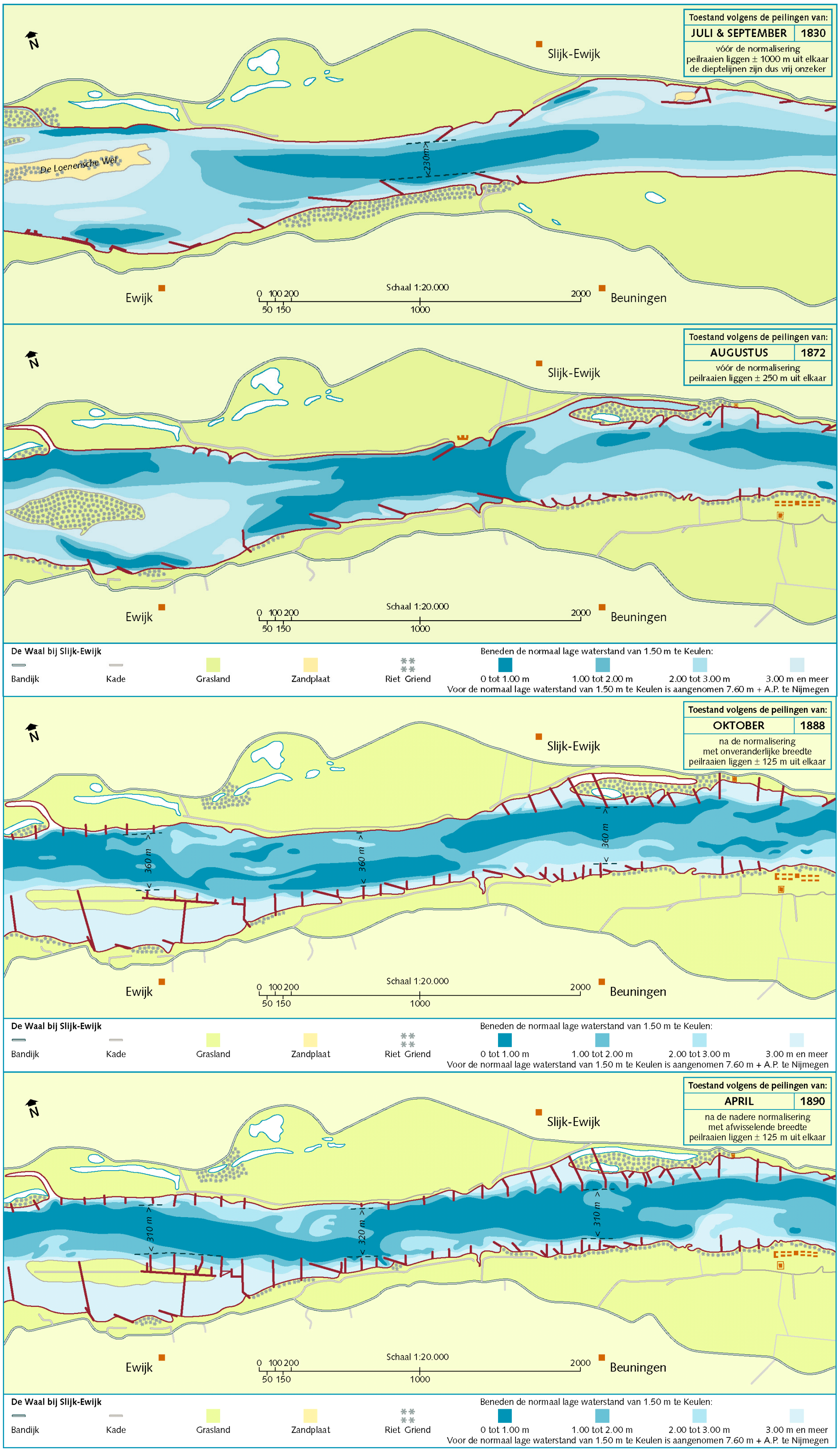

Figure #.9. Waal river evolution near Ewijk as a result of river training in the period 1830-1890.

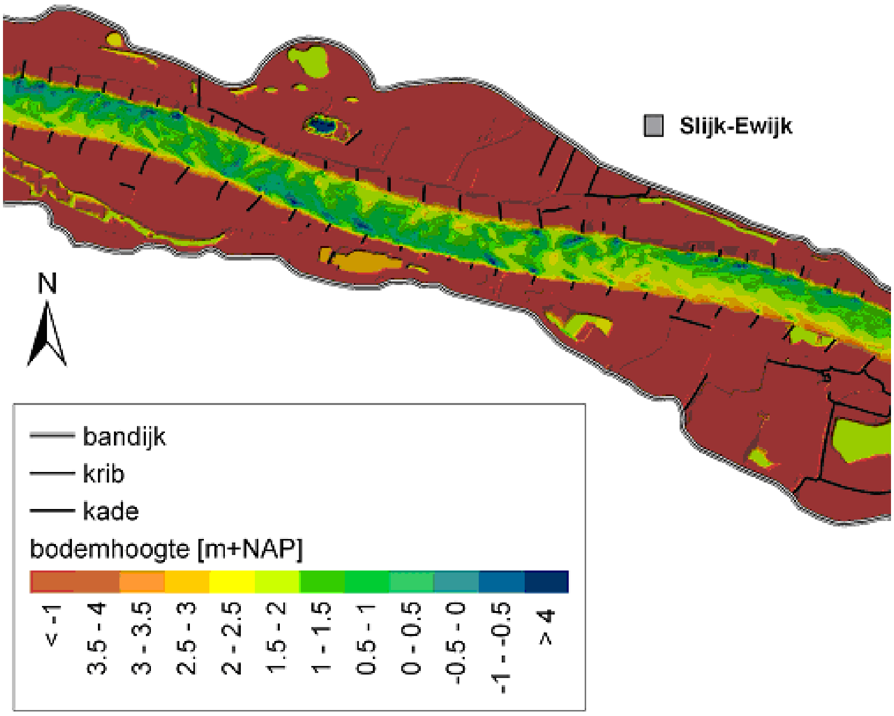

Figure #.10. Present situation of Waal river at Ewijk.

The morphological impact of river narrowing can be evaluated on the basis of its effect on sediment transport capacity. Equations (1) and (2) can be combined into the following flow equation:

$$u^3 = u^2 u = \left(C^2 h i_x\right)\left(\frac{Q}{Bh}\right) = \frac{QC^2 i_x}{B} \qquad (4)$$

The sediment transport capacity formula and the sediment balance for steady uniform conditions are given by

$$q_S = mu^n \qquad (5)$$

$$Q_S = Bq_S \qquad (6)$$

where q_S denotes sediment transport capacity per unit width, m is an empirical coefficient, n is an exponent expressing the degree of nonlinearity and Q_S is the sediment transport capacity over the full cross-section. The degree of nonlinearity is always larger than 3 and usually assumes values around 4 to 5 in situations of ample sediment mobility. Combination of Equations (4) to (6) yields

$$Q_S = B^{1-n/3} m Q^{n/3} C^{2n/3} i_x^{n/3} \qquad (7)$$

Figure #.11 shows the resulting ratio of new sediment transport capacity to reference sediment transport capacity as a result of 50% river width reduction, assuming constant values for discharge, roughness, longitudinal slope and parameters of the sediment transport capacity formula. The increase in sediment transport capacity amounts to 25% if $n = 4$ and 59% if $n = 5$. The erosion due to this increased transport capacity produced substantial bed degradation. This degradation appears still active, because Mosselman & Wijbenga (2007) find that recent lowering of the Boven Merwede river bed cannot be explained from sand mining alone.

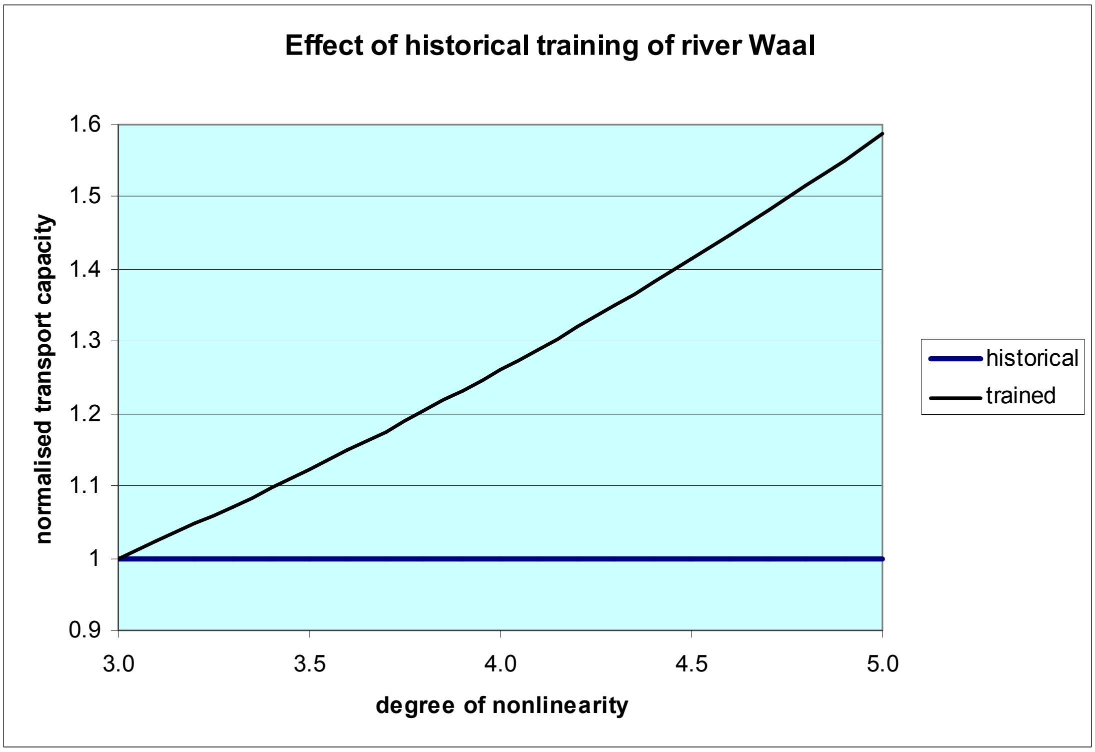

Figure #.11. Ratio of new to historical sediment transport capacity after 50% width reduction as a function of the degree of nonlinearity, *n*, for the river Waal.

3. Waal Programme and DVR project

The 200 to 300 m wide main channel of the river Waal contains a 150 m wide navigation profile where the water depth must be at least 2.5 m at OLR ("Overeengekomen Lage Rivierstand"), i.e. at the low-water level that is exceeded during 95% of the time. The OLR criterion has been established internationally in 1947 and corresponds to a Rhine discharge of 1020 m^3/s at Lobith. Maintaining this navigation profile requires about 600 000 m^3 of dredging annually (Osté, 2004, p.12). The *Toekomstvisie Hoofdtransportas Waal* concluded in 1993 that safe, fast and efficient navigation in 2010 would require enlargement of the navigation profile to accommodate the expected traffic growth. The present 150 m × 2.5 m profile would have to be enlarged to a profile of 170 m × 2.8 m at OLR.

Alternative strategies to achieve this enlargement of the navigation profile were elaborated in the *Waal Programme*. In 1996, Rijkswaterstaat selected a preferred strategy, composed of groyne extensions, maintenance dredging and, above all, structural measures in river bends. The latter comprised bendway weirs, fixed layers and bottom vanes (Figures #.12 - #.14).

Figure #.12. Bendway weirs to correct the cross-sectional profile in bends of the river Waal.

Figure #.13. Fixed layers to correct the cross-sectional profile in bends of the river Waal.

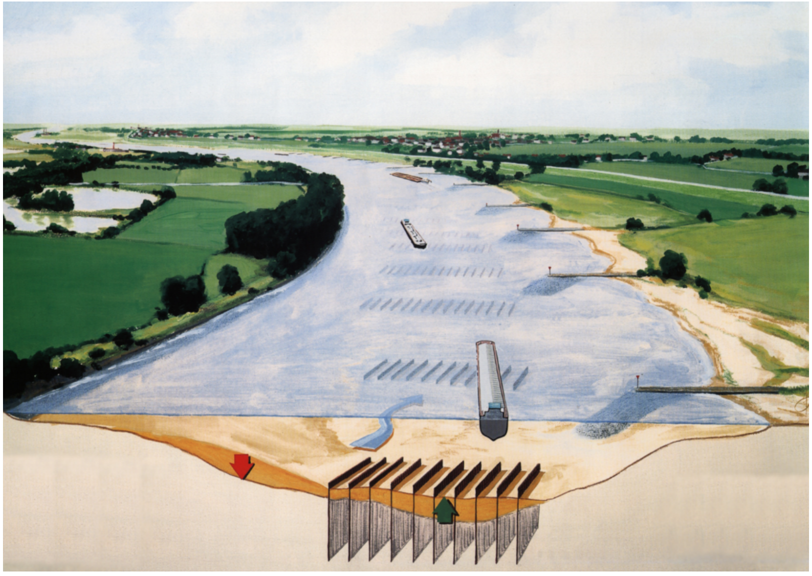

Figure #.14. Bottom vanes to correct the cross-sectional profile in bends of the river Waal.

Subsequently, the bendway weirs were realised in the bend at Erlecom and fixed layers were constructed in the outer bend pools of the bends at Nijmegen and Sint Andries. Implementation of the bottom vanes, however, was cancelled because a pilot field application in the bend of the river IJssel at Fortmond had not been successful (Asmerom & Jörissen, 2003; Vrijburcht, 2003) and because the shipping sector feared that ships touching the bottom vanes might be cut open by the sheet piles of these vanes.

Meanwhile, however, another navigability issue had gained importance. The original time horizon of the Waal programme was the year 2010. As this year was coming near, Rijkswaterstaat extended the horizon by 50 years for reasons of waterways sustainability. This revealed that the ongoing overall bed degradation of the river Waal poses a problem, because the fixed layers in the outer-bend pools do not follow the degradation and hence become obstacles for navigation (Figure #.15). Finding ways to stop this process is becoming imperative. The bed degradation results from a deficit in the sediment supply from upstream, from excessive dredging in the past, from a retarded adaptation to river training works and from an inland shift of the erosion base (river mouth), but the relative contribution of each of these causes is still unknown. The Waal is in this respect a particular case of a much wider problem, because most rivers in Europe and the USA exhibit overall bed degradation due to dams, torrent control works, aggregate mining, river training, lateral embankments, shortening of river courses, afforestation, vegetation encroachment and cessation of wood cutting and grazing (Marston et al, 1995; Kondolf, 1997; Bravard et al, 1999; Liébault & Piégay, 2002; Surian & Rinaldi, 2003). River bed degradation can be seen as a typical manifestation of global change, but it does not result from climate change. Nonetheless, it needs to be considered as an important boundary condition in any assessment of the effects of climate change. Table #.1 presents the geographical distribution of the overall river bed degradation in the Netherlands. Taking an even wider perspective, the deficit in sediment supply from upstream along with the confinement of river floods between embankments could be held responsible for part of the overall subsidence of the Netherlands (cf. Syvitski et al, 2009), and hence for part of the relative sea level rise.

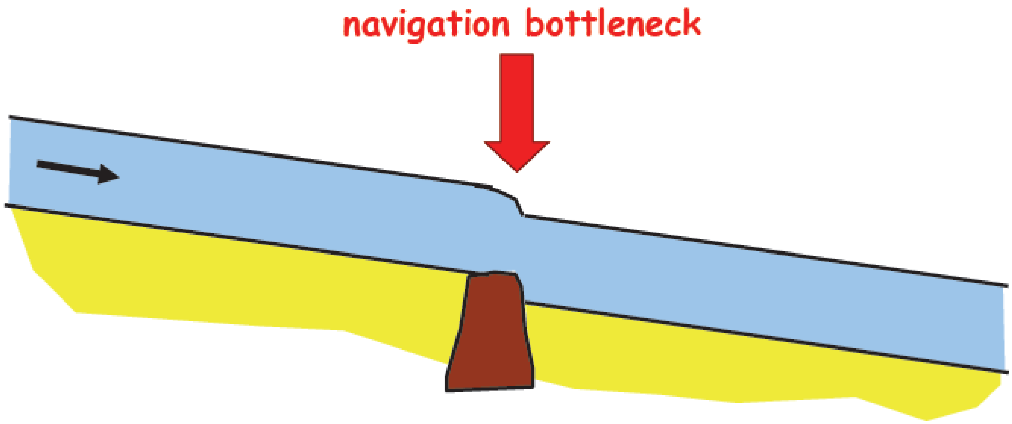

Figure #.15. Development of fixed layer into obstacle for navigation due to overall river bed degradation downstream.

Table #.1. Bed degradation for the Rhine branches in the Netherlands (Van Vuren & Sloff, 2006).

River reach	**Chainage (km)**	**Annual bed level change (m/year)**		
		1950-1970	**1970-1990**	**1990-2000**
Bovenrijn	859-867	-0.03	-0.03	-0.01
Boven-Waal	868-886	-0.02	-0.02	-0.03
Midden-Waal	887-915	-0.01	-0.01	-0.01
Beneden-Waal	916-951	0.00	-0.01	-0.01
Pannerdensch Kanaal	868-879	-0.02	-0.04	-0.03
Nederrijn, reach 1	880-891	-0.01	-0.01	-0.02
Nederrijn, reach 2	892-922	-0.01	-0.02	-0.02
Nederrijn, reach 3	923-947	-0.03	0.00	0.01
Lek	948-989	0.00	-0.02	-0.02
Boven-IJssel	880-930	0.01	-0.01	0.01
Midden-IJssel	931-970	0.02	-0.02	0.01
Beneden-IJssel	971-1000	0.01	0.00	-0.01

A new view of sustainable waterways maintenance and improvement has emerged which assigns a key role to sediment management strategies. Deltares developed a two-dimensional numerical model to optimise sediment management strategies and structural measures within the DVR project, where “DVR” stands for “Duurzame Vaardiepte Rijndelta”.

4. Quick scan of problems due to overall river bed degradation in the Netherlands

HKV (2006, 2007) predicts that further overall bed degradation in the rivers Bovenrijn and Waal will be on the order of 0.50 m in 2036 and 0.75 m in 2066. The bed degradation in the Pannerdensch Kanaal is predicted to be on the order of 0.75 m in 2036 and 1.0 m in 2066.

HKV (2007) provides an overview of the problems that may arise due to continued overall bed degradation. HKV based this overview on an inventory by Brouwers (2000) and a non-referenced study by Lievense, noting that cables and pipelines require 3 to 4 m sediment cover as a safety margin. The overview regards 60 river crossings that are in use. Out of these 60 crossings, 7 crossings have sufficient cover, 34 crossings do not have sufficient cover and 19 crossings are characterised by missing or unreliable information that hampers a further assessment. Tables #.2 to #.5 show the structures and river crossings under threat from erosion. Additionally, bed degradation poses an erosion threat to 510 groynes on the Bovenrijn and the Waal, and to 68 groynes on the Pannerdensch Kanaal.

Figure #.16. Groynes on the Pannerdensch Kanaal.

Table #.2. Banks protected with riprap along Bovenrijn and Waal under threat from erosion (adapted from HKV, 2007)

Chainage (km)	Bank	Description
861.5 – 862.5	left	quay at Tolkamer
868.5 – 871.5	left	quay at Millingen (Kolenbranderbos)
870.5 – 871.5	right	bank protection at Hulhuizen
874.5 – 875.5	left	bank protection at Erlecom
879.5 – 880.5	right	bank protection at Bemmel
894 (500 m)	left	bank protection of flood-free terrain at Druten
900 (500 m)	left	bank protection of flood-free terrain at Deest
906 – 908	right	bank protection at IJzendoorn
910.0 – 911.5	left	bank protection at bridge of N323

Table #.3. Cables and pipelines under Bovenrijn and Waal under threat from erosion (adapted from HKV, 2007)

Chainage (km)	Number of cables and pipelines
867	2
871	1
872	1
876	1
876.5	2
879.5	1
886	3
889.5	1
890.5	1
891	1
891.2	1
891.6	1
893	1
894	1
903	1

Table #.4. Banks protected with riprap along Pannerdensch Kanaal under threat from erosion (adapted from HKV, 2007)

Chainage (km)	Bank	Description
867.5 – 872.0	left	bank protection
869.5 – 873.5	right	bank protection

Table #.5. Cables and pipelines under Pannerdensch Kanaal under threat from erosion (adapted from HKV, 2007)

Chainage (km)	Description
868 – 869	Gasunie NV Groningen
869 – 870	PGEM NV Arnhem
872 – 873	PGEM NV Arnhem, Gasunie NV Eindhoven, Gasunie NV Groningen
873 – 874	NV Prorail (Betuweroute)
874 – 875	Gasunie NV Groningen
876 – 877	PTT Telecom Amersfoort, Telekabel Gelderland-Zuid Nijmegen, KPN-Telecom BV Arnhem
877 - 878	Vitens NV Doetinchem

As a representative of the river management authority, Havinga (2009) adds the following points of concern:

1. Discrepancy between the degrading bed in the Netherlands and the stabilised bed in Germany. Continued bed degradation in the Netherlands will create a nautical bottleneck between Lobith and Emmerich within 5 to 10 years. The main reason for stabilising the river bed in Germany was the increasing difference between the water levels on the river Rhine and the water levels in the connecting canals;

2. Stability of hydraulic structures and cable and pipeline crossings;
3. Stability of discharge distributions at the Pannerdensche Kop and IJsselkop bifurcations;
4. Increased propagation speed and, hence, decreased attenuation of flood waves, producing higher design flood levels (*Maatgevende Hoog Waterstanden, MHW*) in the Netherlands.

5. Theoretical analysis to identify measures to arrest overall bed degradation

Mosselman et al (2004) present the following analysis to identify measures to arrest overall bed degradation. The lowering of the longitudinal profile of a river can be understood as a decrease in the longitudinal river gradient. A mathematical relation for this gradient can be derived from three fundamental equations for a trained river in regime: the continuity equation, the momentum equation and the sediment balance (Jansen et al, 1979). The continuity equation (2) represents conservation of water mass and expresses for a river in regime that the amount of water flowing through each cross-section is equal to the discharge of the river. The equation is recalled here for clarity:

$$Q = Bhu \tag{8}$$

where

B = river width (m)
h = water depth (m)
u = depth-averaged flow velocity (m/s)
Q = river discharge (m^3/s)

The momentum equation (1) for a river in regime expresses that the water neither accelerates nor decelerates because the hydraulic resistance is exactly equal to the driving component of gravity. This equation is recalled here for clarity too:

$$u = C\sqrt{hi_x} \tag{9}$$

where

C = Chézy coefficient for hydraulic roughness ($m^{1/2}$/s)
i_x = longitudinal river slope (-)

The sediment balance represents conservation of sediment mass. For a river in regime, it expresses that the sediment transporting capacity equals the total sediment load:

$$Q_s = B\frac{m'}{\Delta^p D^q}u^n \tag{10}$$

where

D = sediment grain diameter (m)
m' = empirical coefficient in sediment transport formula ($s^{n-1} \cdot m^{p-n-2}$)
n = empirical exponent of u in sediment transport formula (-)
p = empirical exponent of Δ in sediment transport formula (-)
q = empirical exponent of D in sediment transport formula (-)
Q_s = total sediment load (m^3/s)
Δ = relative submerged sediment mass density (-)

The exponents p and q satisfy $p > 1$ and $q > 1$. It can be demonstrated theoretically that the exponent of u should always satisfy $n > 3$.

The fundamental Equations (8) to (10) can be combined into

$$Q_s = B \frac{m'}{\Delta^p D^q} \left(C^2 \cdot h \cdot i_x \frac{Q}{B \cdot h} \right)^{n/3} \tag{11}$$

as well as

$$Q_s = B \frac{m'}{\Delta^p D^q} \left(\frac{Q}{B \cdot h} \right)^n \tag{12}$$

Furthermore, the following geometrical relation holds:

$$z_b(x) = z_w(0) - h(0) + i_x \cdot x \tag{13}$$

where

x = distance along river to erosion base in river mouth (m)
z_b = river bed level (m + datum)
z_w = water level (m + datum)

Combination of Equations (11) to (13) yields the following longitudinal profile of the river bed:

$$z_b(x) = z_w(0) - \frac{m'}{Q_s \Delta^p D^q} \frac{Q^n}{B^{n-1}} + \left(\frac{Q_s \Delta^p D^q}{m'} \right)^{3/n} \left(\frac{B^{1-3/n}}{C^2 Q} \right) \cdot x \tag{14}$$

This means that overall bed degradation can be arrested by increasing B, Δ, D, Q_s, x or $z_w(0)$, or by decreasing C or Q. Increasing B is not desirable because that would induce an overall shallowing of the navigation channel. A change in $z_w(0)$ is not effective as it does not affect the longitudinal river gradient. Furthermore, C is a parameter that is difficult to control. Thus the following options to arrest overall bed degradation remain:

- Replacement of bed sediment by denser material (Δ);
- Replacement of bed sediment by coarser material (D);
- River bed nourishment by artificial sediment supply (Q_s);
- Decrease of river discharges (Q);
- Increase of sinuosity and hence increase of the length of the river (x).

River bed nourishment is the solution selected in Germany, where it has become routine practice. Figure #.17 shows an overview of amounts and locations in recent years. In the Netherlands, sediment from the intensely dredged lower reaches might be transported upstream by ships. A four-barge push tow could transport about 7000 m^3 of sediment at a time. If the supplied sediments are coarser or denser than the sediments of the river bed, the amount of required sediment supply will eventually decrease. It should be noted, however, that the latter development into a more sustainable situation may require a very long time. A supply of a 1 m thick layer of sediments to 100 km of the 250 m wide river Waal corresponds to a volume of 25 million m^3. Currently Austria is preparing similar granulometric bed improvement in the Danube by adding a 25 cm thick layer of 40 to 70 mm coarse gravel to the bed surface in the deeper parts of the river (Habersack, 2010).

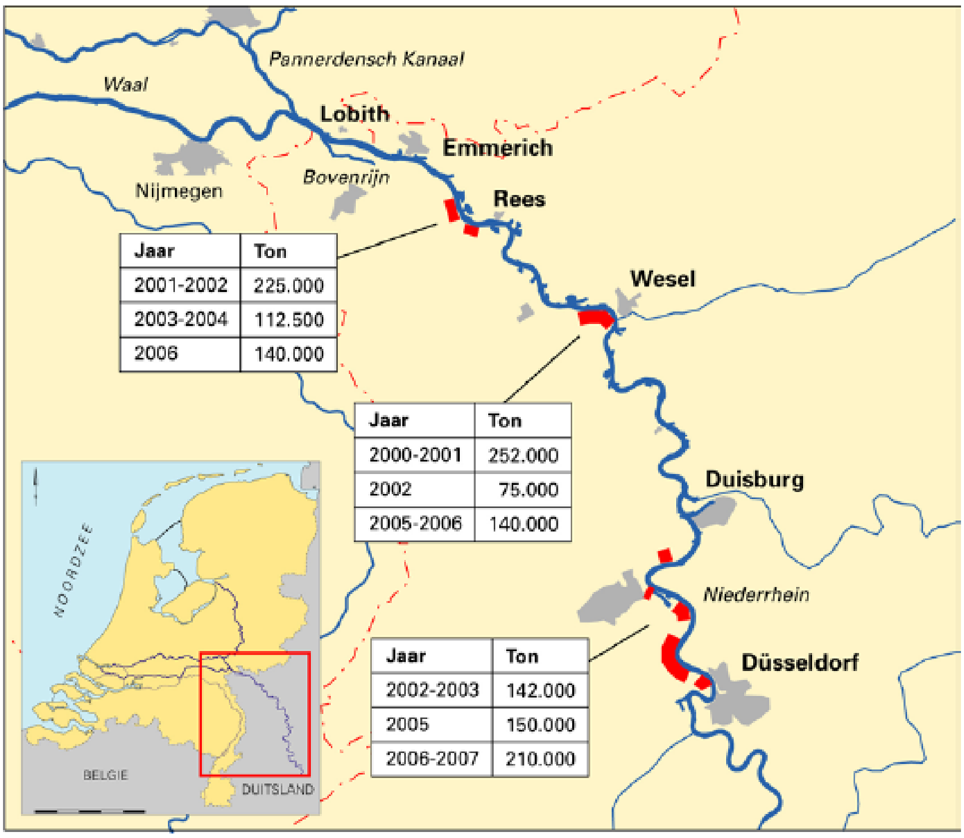

Figure #.17. Amounts and locations of river bed nourishments along the Niederrhein in Germany in recent years (HKV, 2007).

The longitudinal profile might also be maintained by structural measures. Canalisation of the river by means of dams, weirs or sills prevents overall bed degradation, although it may enhance the erosion downstream of the canalized reach. This solution has been applied to the Rhein upstream of Iffezheim. The busy navigation traffic on the river Waal makes that canalisation is not a desirable option.

The analysis leads to the conclusion that river bed nourishment by artificial sediment supply seems to be the most feasible way to arrest overall bed degradation. This should be part of a sediment management strategy in which sediment is removed from local shoals by dredging and supplied to deeper pools by dumping.

6. The Room-for-the-River programme in the Netherlands

Dike raising and reinforcement projects along the Dutch Rhine branches in the 1970s and 1980s encountered massive protests from the population, because these projects involved demolition of houses and straightening of the sinuous dike alignments that were much appreciated as a characteristic element in the Dutch riverine landscape. When new statistical analyses after the 1993 and 1995 floods, along with considerations of expected climate change, led to the conclusion that the design flood discharge at Lobith needed to be increased from 15,000 m^3/s to 16,000 m^3/s, it was decided to refrain from further raising of the dikes and to realize safety at the new design flood by giving more space to the rivers. The basic idea was that water levels at a given discharge are lower when the cross-section (or “conveyance capacity”) of the river is larger. As an additional objective, more space for the rivers would also provide opportunities for ecological rehabilitation and thus enhance the spatial quality of the river landscape. Measures to give more space to the river are floodplain excavation, creation of secondary channels and flood channels, dike set-back, lowering of groynes, lowering of summer levees, removal of obstacles and deepening of the main channel. Various stakeholders proposed about 700 measures to give more space to the rivers. All these measures were thoroughly evaluated on effectiveness, costs, number of houses to be demolished and spatial quality. This resulted in a selection of about 35 measures that now constitute the Room-for-the-River programme (“*Spatial Plan Key Decision Room for the River*”). Figure #.18 gives an overview of the measures along the Bovenrijn and Waal branches.

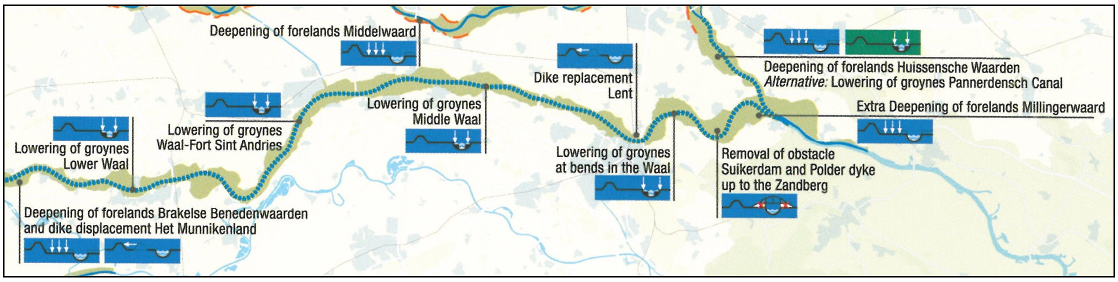

Figure #.18. Overview of measures along Bovenrijn and Waal in Room-for-the-River programme in the Netherlands.

Most measures of the Room-for-the-River programme come down to increasing the space in the floodplains. Discharges of frequently occurring floods will hence increase on the floodplains and decrease in the main channel. The resulting decrease of annual sediment transport capacity in the main channel induces sedimentation. Uniformly distributed sedimentation along the river is not the largest problem and might even be beneficial for navigation as it might reduce or arrest the ongoing problematic overall bed degradation of the Rhine branches. The problem is that the Room-for-the-River measures, and hence the sedimentation they produce, are not uniformly distributed along the river. They give rise to local prominent shoals.

The effects of non-uniform Room-for-the-River measures can be understood from Fig. #.19. The increased space in the floodplain is schematised by extracting part of the flood discharge from the main channel upstream of the measure and by supplying this discharge back to the main channel downstream of the measure. The longitudinal profile in the upper part of the figure shows how water levels during floods are lowered and how water depths in the main channel decrease. The decreasing water depth just upstream of the water extraction point makes flow lines converge. The corresponding accelerating flow produces erosion. The flow velocity decreases abruptly, however, immediately downstream of the water extraction point. This produces marked sedimentation that gradually expands itself downstream with a steep front. The water depth increases in the area further downstream within the reach of increased space. The corresponding decelerating flow produces sedimentation too. The flow velocity increases abruptly at the point where the extracted water re-enters the main channel. This produces an erosion wave that gradually expands downstream with a flattening front. As soon as the discharge has dropped below bankfull, thus stopping the floodplains from conveying water, the hole and the shoal formed during the flood start to migrate freely downstream. They disappear gradually as the river reworks its bed by erosion and sedimentation, but for some time the shoal remains a hindrance for navigation that might require dredging. Furthermore, a residual effect of the sedimentation remains despite this reworking, so that the river bed aggrades on the long run as shown in the longitudinal profile below in Figure #.19.

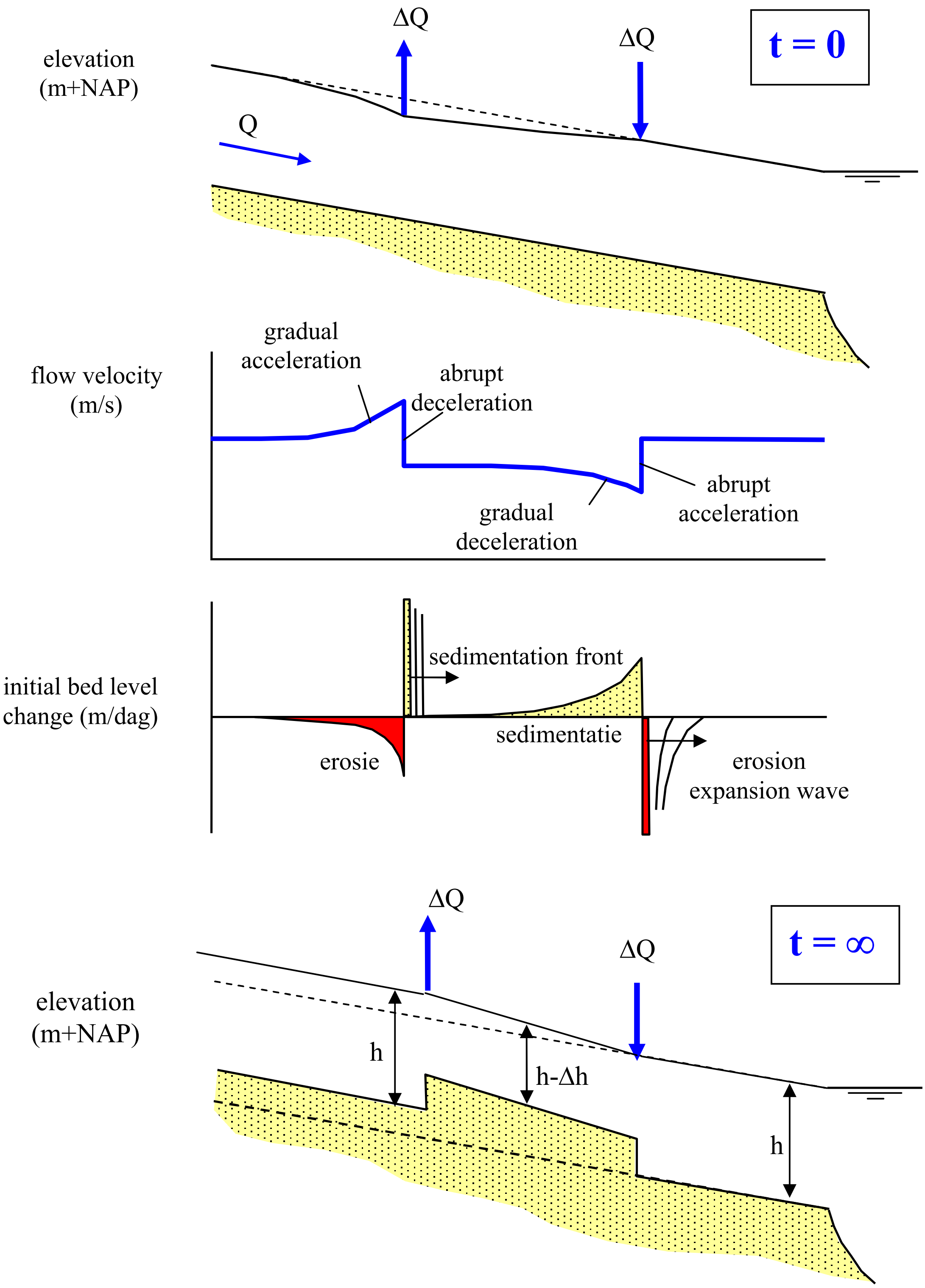

Figure #.19. Initial (t = 0) and long-term (t = ∞) river response to enlarged floodplain conveyance.

The design and implementation of the Room-for-the-River programme has originally been set up in a sectoral approach, attaching primary importance to key objectives regarding safety against flooding and spatial quality. Navigation and long-term sustainability are considered to be side aspects that can be dealt with using *a posteriori* mitigating measures. Nonetheless, the Programme Direction Room for the River has increased its attention to possible negative effects on navigation since 2007. The major problem for navigation is that most measures, except for the lowering of groynes, have a limited spatial extent and hence cause accentuated shoals during floods. Those shoals remain in the main channel for some time during low-flow periods after the floods. The following principles are used to minimise the adverse navigation effects of local Room-for-the-River measures:

1. Make sure that the shoals are formed outside the navigation profile in the cross-section. This can be below the navigation profile in zones where the channel has extra depth, or besides the navigation profile. The latter solution utilises the two-dimensional character of the shoal that is not evident from the simplified one-dimensional picture in Fig. #.19.
2. Decrease the inundation frequency of the floodplains, so that the adverse effect on navigation occurs less frequently. This can be achieved by raising summer levees or by raising weirs at the entrance of secondary channels or flood channels. For secondary channels, the solution is in conflict with the ecological requirement of creating permanent flows in secondary channels.

7. Future morphological changes due to climate change and other forms of global change

7.1 Introduction

The analysis of the effects of different climate scenarios on the water system in this report quantifies the consequences of low river discharges under the assumption that the waterway does not experience any morphological changes. However, morphological changes affect the navigability of the waterway too. Potential morphological changes as a result of climate change and other forms of global change consist of four components:

1. Morphological changes due to modification of annual discharge hydrographs;
2. Morphological changes due to developments in the supply and extraction of sediment as a result of changes in dredging, sediment nourishment and the sediment yield of the river basin;
3. Continued overall river bed degradation;
4. Formation of shoals due to implementation of the Room for the River programme.

These four components are addressed in more detail in the following sections.

7.2 Morphological changes due to modification of annual discharge hydrographs

The effects of modification of annual discharge hydrographs can be analysed using Equation (7). Integration over time yields an expression for the annual sediment transport capacity:

$$\overline{Q_S} = B^{1-n/3} m C^{2n/3} i_x^{n/3} \frac{1}{T} \int_T Q^{n/3} \mathrm{d}t \tag{15}$$

The ratio between future and present annual sediment transport capacity is hence given by

$$\frac{\overline{Q_{S1}}}{\overline{Q_{S0}}} = \frac{\int_T Q_1^{n/3} \mathrm{d}t}{\int_T Q_0^{n/3} \mathrm{d}t} \tag{16}$$

Figures #.20 and #.21 show the results of evaluating this ratio for the effects of different climate change scenarios on the monthly discharges for the rivers Rhine and Meuse. The G and W scenarios lead to increased annual sediment transport capacities on both the Rhine and the Meuse, and hence to enhanced erosion and aggravation of the ongoing overall bed degradation. A comparison with Figure #.11 shows, however, that the 8% to 13% increase under these scenarios is small compared to the changes up to 60% due to training of the river Waal in the 19th century. Moreover, the G+ and W+ scenarios have a smaller or even opposite effect. On the Meuse at Borgharen, they either increase or decrease the sediment transport capacity by values up to 3%. On the Rhine at Lobith, the G+ and W+ scenarios produce a 3-5% decrease in sediment transport capacity, which would help in arresting the trend of overall bed degradation. Here climate change might turn out to be a blessing in disguise.

Varying discharges affect river morphology not only through their frequencies of occurrence, but also through their rates of change. Shoals formed during a flood may be eroded away by the river itself if the flood recedes slowly, whereas they may remain obstacles for navigation if the flood falls rapidly. A more refined picture of the morphological changes due to varying discharges requires computations using calibrated models based on SOBEK or Delft3D.

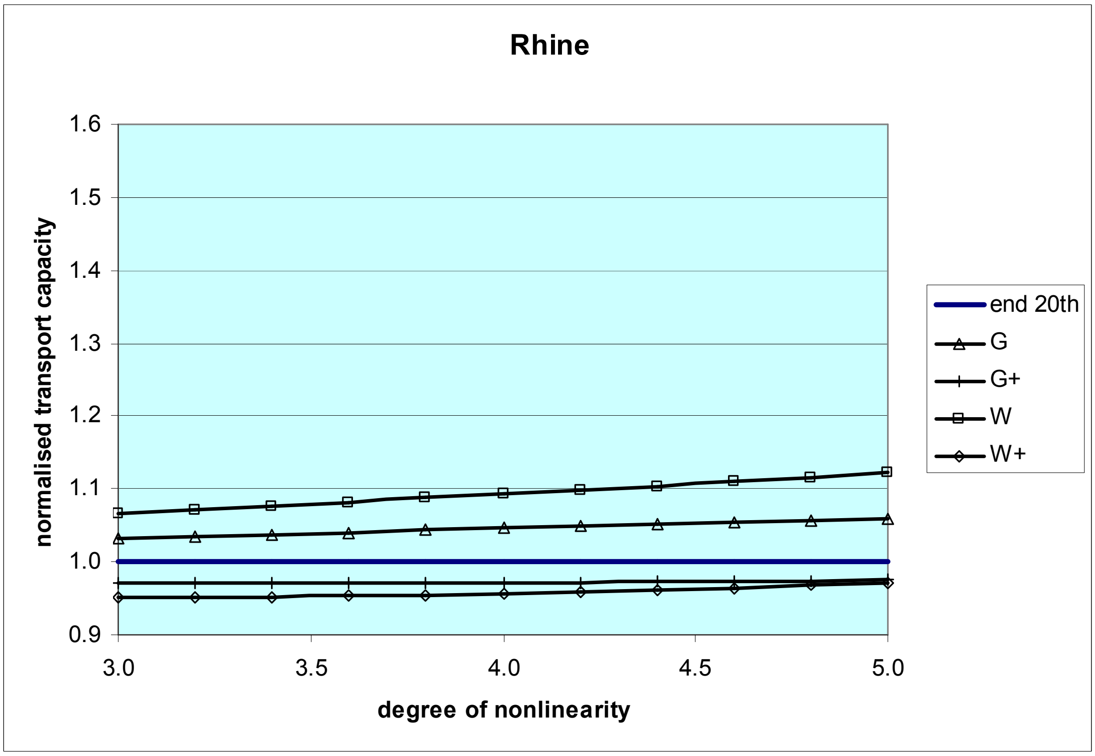

Figure #.20. Ratio of future to present annual sediment transport capacity as a function of the degree of nonlinearity, *n*, for the Rhine at Lobith.

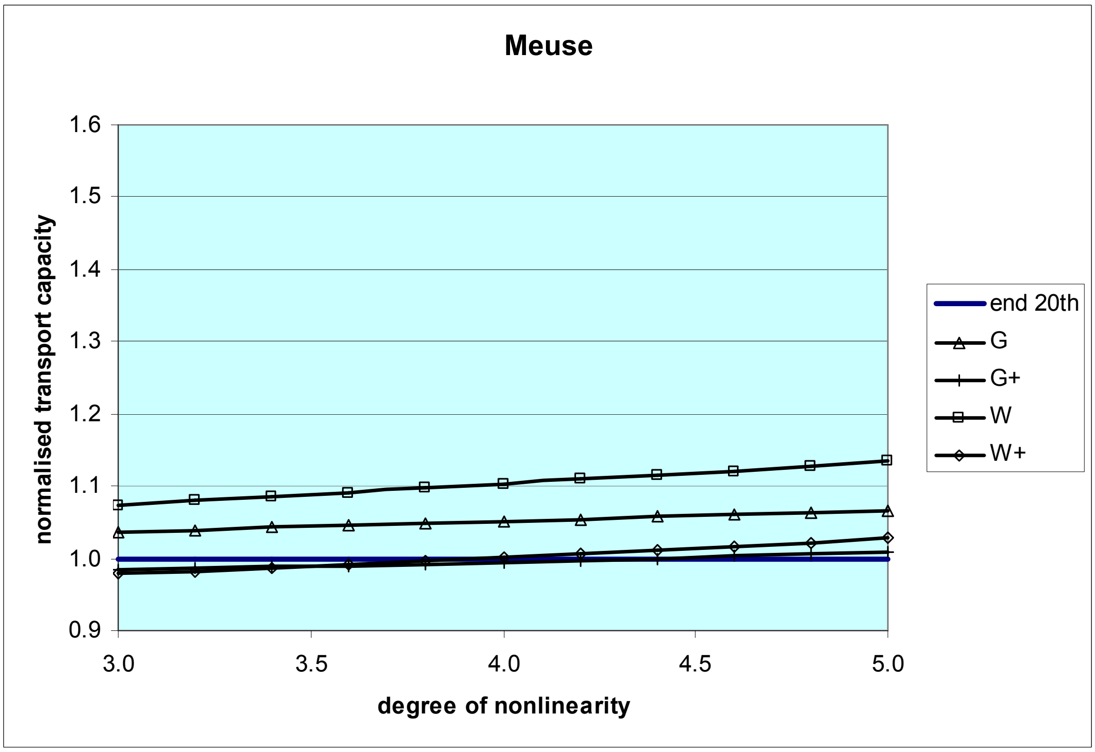

Figure #.21. Ratio of future to present annual sediment transport capacity as a function of the degree of nonlinearity, *n*, for the Meuse at Borgharen.

7.3 Morphological changes due to developments in the supply and extraction of sediment

Developments in the supply and extraction of sediment depend on dredging, sediment nourishment and river-basin sediment yield. Changes in these developments are essentially unknown. Future dredging and sediment nourishment will depend on future societal demands and financial constraints. Future sediment yield of the river basin depends on land use as well as on sediment management in tributary rivers. A relevant research project in this context is SEDRIVER which deals with the effects of climate change on mountain streams, carried out by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), although Swiss lakes will act as buffers before they transmit any effects of changes in Alpine streams to the Rhine downstream. Other relevant studies are those by Asselman (1997) and Erkens (2009).

7.4 Continued overall bed degradation

The overall river bed degradation has been discussed in Section 3 on the Waal Programme and the DVR project. It results from a deficit in the sediment supply from upstream, from excessive dredging in the past, from a retarded adaptation to river training works and from an inland shift of the erosion base (river mouth), but the relative contribution of each of these factors is still unknown. The causes are manifestations of global change, albeit with a negligible contribution from climate change.

7.5 Formation of shoals due to the Room for the River programme

The effects of the Room for the River programme has been explained in Section 6. Consultancy firms have assessed local short-term morphological effects for individual measures within the programme, but an overall long-term morphological impact assessment remains to be carried out. One of the sources of overall morphological change will be the resulting modification of discharge hydrographs in individual Rhine branches, caused by increased flows into the Waal at moderate floods due to the lowering of groynes under the programme. Shoals due to implementation of the Room for the River programme can be seen as an indirect result from climate change, as the programme is partly motivated from an expected future increase of the design flood discharge at Lobith to 18 000 m^3/s. The implementation is to be completed by 2015.

7.6 Interactions

Climate change, river training, sediment management and the Room for the River programme interact in a complex manner, as visualised in Figure #.22. Climate change affects discharge hydrographs and sediment yield in ways that either aggravate or mitigate the formation of navigation obstacles. It also incites further extension of Room for the River measures in order to provide safety at higher design discharges. Currently an increase from 16 000 m^3/s to 18 000 m^3/s is anticipated. Implementation of these measures may necessitate more river training and sediment management to mitigate the adverse effects on navigation. Replacing the current sectoral approach to river interventions by an integral approach would create optimum conditions for doing justice to these complex interactions.

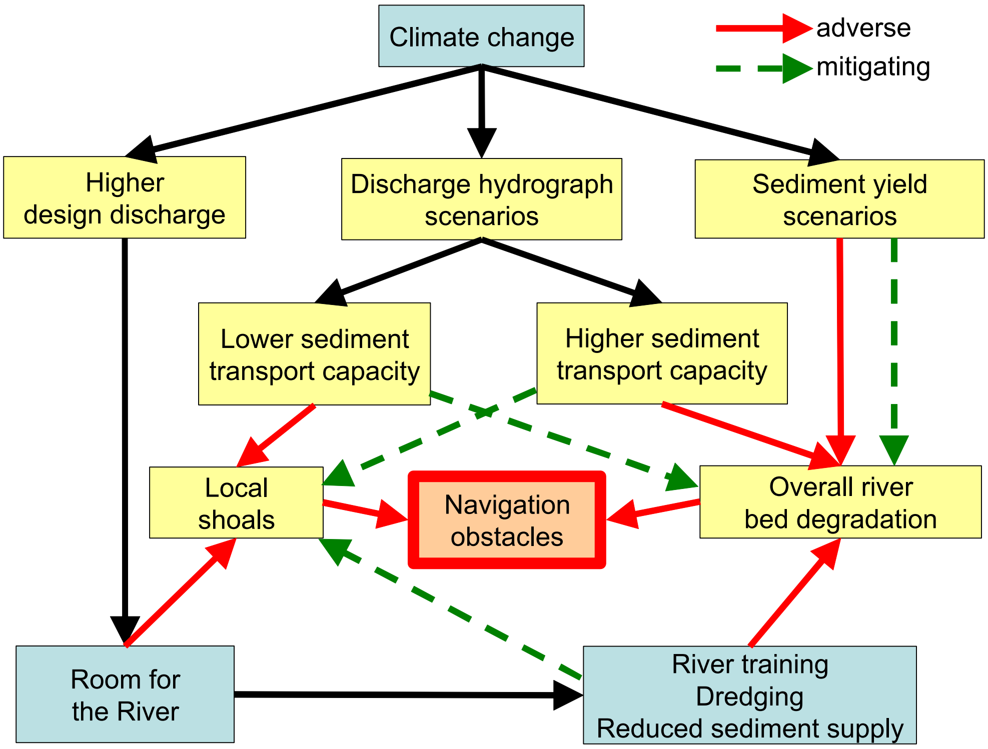

Figure #.22. Interactions between climate change, river training, sediment management and the Room for the River Programme.

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