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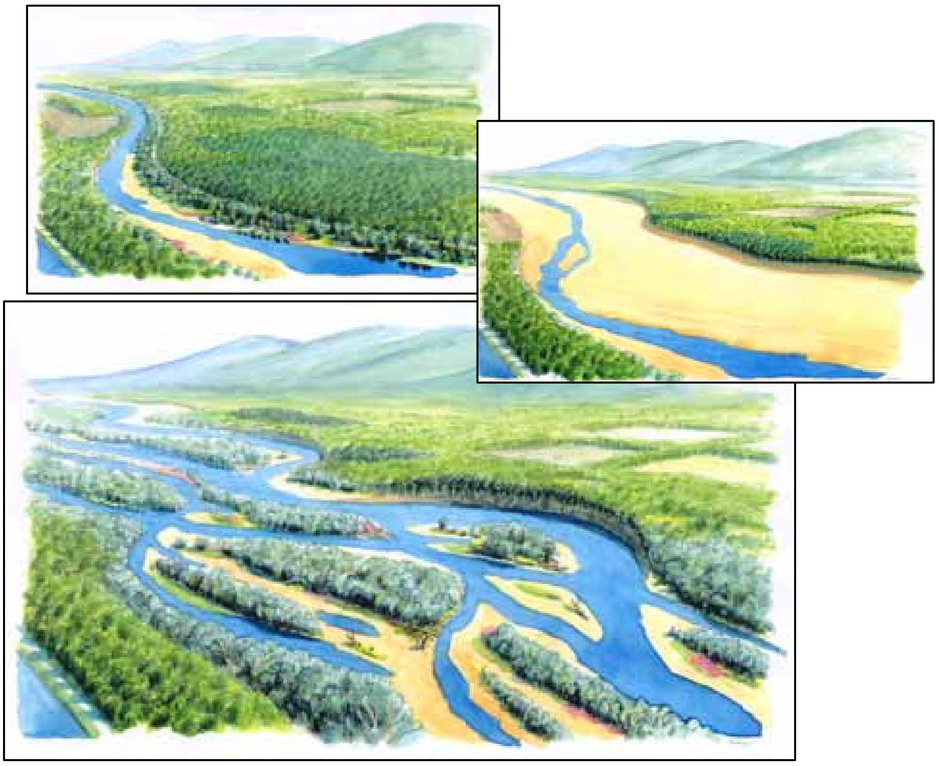
The Rest Rhine

New opportunities for nature rehabilitation and flood prevention



Bart Peters
Thorsten Stoesser

m.m.v. Andreas Dittrich, Toine Smits & Gertjan Geerling

December 2001

A preliminary study of possibilities to combine flood protection and nature rehabilitation objectives along the Rest Rhine. This study is part of the Irma-Sponge program "Cyclic Rejuvenation of Floodplains".

IRMA

NCR

Universität Karlsruhe

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Bart Peters & Thorsten Stoesser
m.m.v. Adreas Dittrich, Toine Smits & Gertjan Geerling
Illustrations: Jeroen Helmer, Ark Foundation
Photo's: Bart Peters

Content information:
Bart Peters, Bureau Drift
Nassaulaan 38, 6571 AD Berg en Dal
024 2502727, bartpeters@planet.nl

September 2001
Study in the framework of the Irma-Sponge project "Cyclic Rejuvenation of Floodplains"
University of Nijmegen, the Netherlands/University of Karlsruhe, Germany
Keywords: river rehabilitation, riverine nature, nature rehabilitation, flood prevention, gravel rivers, river Rhine, Integrated Rhine Program.

The Rest Rhine

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Contents

Abstract

Erosion and sedimentation are the major components that regularly reset the vegetation succession of floodplains (cyclic rejuvenation). As a result there is a wide spectrum of habitats present along the river axis, occurring in various development stages. In addition, large herbivores such as horses and cows but also little burrowing animals such as rabbits, moles and mice influence the vegetation succession and structure. Restoring the interaction between the river, the floodplain and the biota is the key to a successful rehabilitation of floodplains.

At present many river systems are regulated and have lost their rejuvenating character. After the flood events of 1993 and 1995 it was suggested to combine flood protection objectives with the nature rehabilitation objectives. In the river basin of he Border Meuse (The Netherlands) for example this was put into practice. Despite the fact that there are still some problems with the financial and legislative aspects of this project, both flood protection goals as well as nature rehabilitation objectives can be realised.

Within the context of the IRMA SPONGE program it was explored to which extent a related approach could be applied for the Rest Rhine. In co-operation with the University of Karlsruhe, the University of Nijmegen has made a design plan for a river section of the Rest Rhine. The nature rehabilitation approach and the available field experience of the Border Meuse project was combined with the history and available expert knowledge of the Rest Rhine to construct a design for a Rest Rhine river section which would both serve flood protection as well as nature rehabilitation objectives. Main features of the plan are: (1) restoring lateral movement of the Rest Rhine by lowering the existing river banks and removing the groin fields where possible and (2) spontaneous retrieval of gravel sediment from the steep banks by restoring lateral erosion. This way the spontaneous redevelopment of a more braided and constantly changing morphology seems, to a certain extent, within range. Furthermore measures for the management of the high, inundation-free (former) floodplains are being proposed.

The first indicative results of hydro-morphological calculations, using a 3D numerical model, are very promising. The desired retention volume of the Rest Rhine can be achieved by restoring the hydromorphodynamics of the Rest Rhine.

1. Introduction

1.1 IRMA-program

This study is part of the IRMA-SPONGE program on Cyclic Floodplain Rejuvenation and the Delft Cluster program on Biogeomorphological Developments of Floodplains.
IRMA stands for *Interreg Rhine-Meuse Activities*. The IRMA umbrella program was initiated after the rivers Rhine and Meuse flooded in 1993 and 1995. To reduce the risk of future flooding, a partnership for international flood control was created. The countries in the catchments of the rivers Rhine and Meuse - Belgium, France, Germany, Luxembourg, Switzerland and the Netherlands - submitted the IRMA umbrella program to the European Commission within the framework of the INTERREG-IIC initiative.
The IRMA-SPONGE Program includes 13 scientific projects, dealing with a wide range of flood management issues along the rivers Rhine and Meuse. It is one of the largest and most comprehensive flood management programs of its kind.
The overall aim is defined as:

"The development of methodologies and tools to assess the impact of flood risk reduction measures and scenarios. This to support the spatial planning process in establishing alternative strategies for an optimal realisation of the hydraulic, economical and ecological functions of the Rhine and Meuse River Basins."

The main objectives of IRMA-SPONGE are to (a) enhance the level of scientific input into flood management, and (b) promote trans-boundary co-operation. Specific areas of interest are:
- Efficiency of flood risk reduction measures;
- Flood risk assessment;
- Sustainable flood risk management;
- Public participation in flood management issues.

1.2 Cyclic Rejuvenation of Floodplains

Nature rehabilitation projects along the floodplains of the rivers Rhine and Meuse tend to result in an increased hydraulic roughness (more forest, deposition of sand, etc.) that may lead to higher water levels during flood periods. This is an undesirable side effect of nature rehabilitation. The project Cyclic Rejuvenation of Floodplains (CRF) aims at developing a creative management strategy that reconciles the goals of nature rehabilitation with those of flood management.

Cyclic rejuvenation is a recurring process of disturbance that triggers the development of new pioneer vegetation and succession. Rejuvenation processes are considered important driving forces behind ecological diversity. Nowadays, rejuvenation processes have largely been banned from the floodplain because of normalisation and canalisation. Reintroduction of rejuvenation processes, whether natural or artificial, will stimulate ecological diversity and increases the discharge and retention capacity of rivers.
The project Cyclic Rejuvenation of Floodplains includes two major case studies: the river Waal case study in the Netherlands and the Rest Rhine case study in Germany. For the Dutch situation, an artificial form of cyclic rejuvenation is proposed by human intervention that increases the discharge capacity and stimulates ecological diversity. However, this approach seems less suitable for the Rest Rhine. Along the Rest Rhine water retention seems more an appropriate measure than increasing the water discharge capacity. Creating a larger retention area provides unique chances to re-introduce the natural cyclic rejuvenation processes in this area.

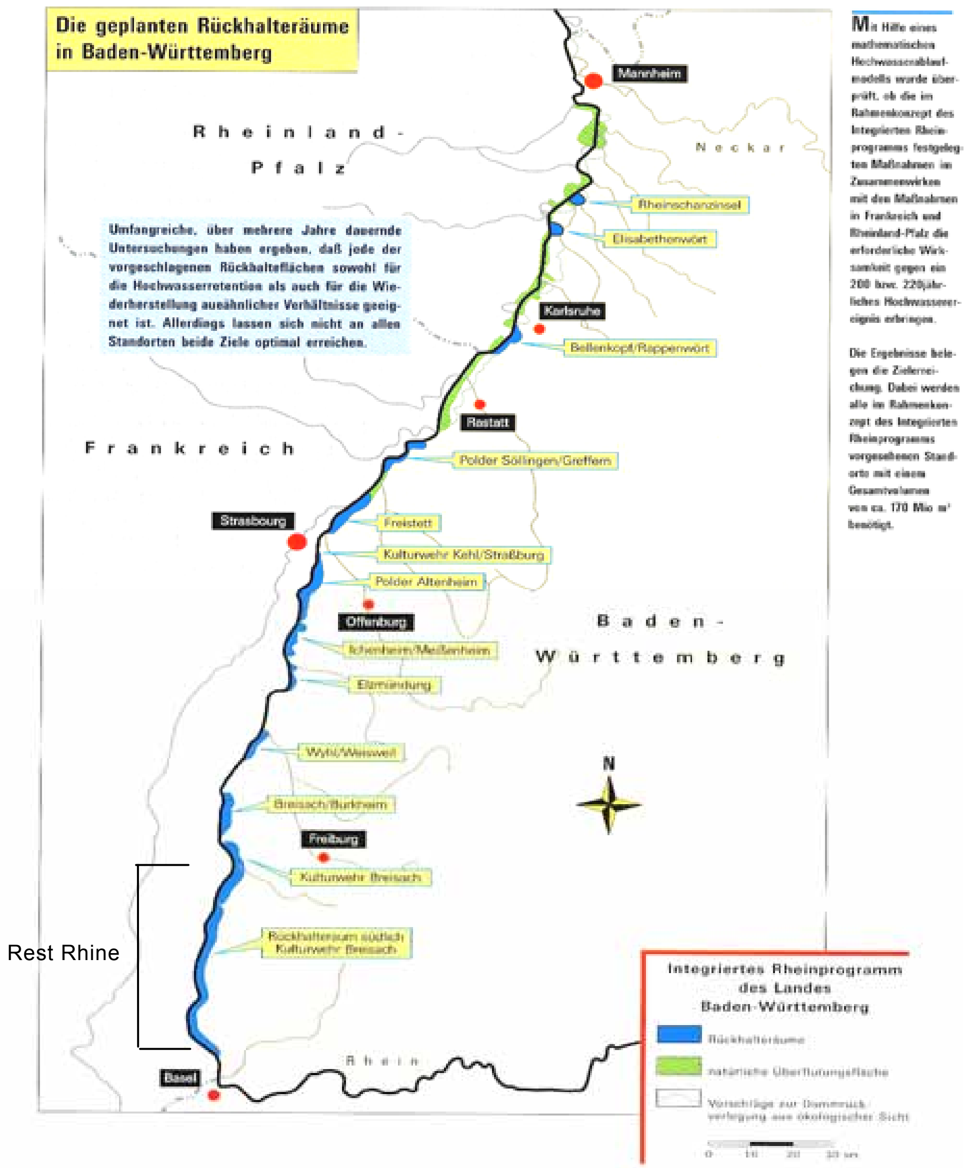


Figure 1: Planned retention areas in Baden-Württemberg and the location of the Rest Rhine. (source: Ministerium für Umwelt und Verkehr, Baden-Württemberg)

1.3 The Integrated Rhine Project

Corrections and canalisation of the Upper Rhine have increased flooding risks and damaged the unique and valuable riverine ecosystems (see Chapter 2). About 130 km^2 of floodplains were reclaimed from the Rhine after the construction of dams between Breisach and Iffezheim. Consequently, the flooding risk downstream from the last dam at Iffezheim increased considerably. In 1982, the Federal Republic of Germany and the French Republic agreed to restore the flood protection level to a level that existed before the construction of the dams. To this purpose, the Ministry of the Environment in Baden-Württemberg (1988) elaborated the Integrated Rhine Project (IRP). The main aims of the IRP are:

- Increase flood protection level;
- Maintenance and rehabilitation of the natural alluvial landscape of the Upper Rhine.

IRP studies have shown that retention capacity is not only needed in the section between the dams but also in the plains south of Breisach and north of the last dam at Iffezheim. According to current IRP insights, it is necessary to create a retention volume of 25 million m^3 between Basel and Breisach (Oberrheinagentur, 1996). In the last century, this part of the Rhine has been lowered about 5-10 m due to riverbed erosion, so that the former floodplain is no longer inundated.
Along the Rest Rhine there are, in principle, two options to create extra retention volume. The first option is to raise the water level to the level of the current floodplain, for example by construction of a weir or by artificial elevation of the present riverbed. This option would result in re-inundation of the floodplains. The second option is to lower parts of the current floodplains by the excavation of gravel. In case of high water levels, these lowered plains would contribute to natural flood retention. After a thorough examination of the options, Baden-Württemberg decided to lower a 90-meter wide strip of the current floodplains (GWD, 1997).
The current 90-meter plan combines flood protection with nature rehabilitation. The aim is to retain water in the Rest Rhine area by widening the riverbed, followed by a spontaneous development of riparian forest. The current plan, however, does not foresee in the reinstatement of natural cyclic rejuvenation processes. Consequently, continuous sand deposition in the relatively shallow groin fields and broadened areas will result in a succession of vegetation types. Because natural cyclic rejuvenation processes are absent in the current situation, this will ultimately lead to the disappearance of open gravel banks and other pioneer situations. On the long term, transition to hardwood forest is possible but regeneration of new softwood forest (on a larger scale) is less likely. This alternative is sub-optimal in terms of the restoration of the original biodiversity.
The current 90-meter plan could be strengthened if it includes measures that would restore at least partly the cyclic rejuvenation process. This report explores options to realise such measures, for example, by re-introducing

lateral riverbed movement in the Rest Rhine. In addition to the current 90-meter plan that focuses on the right (German) bank of the Rest Rhine; the present study considers both banks resulting in a trans-national approach. A project between France and Germany could be an important step forwards to a European Ecological Network as described in the Nature 2000 Concept and the EU Water Framework Directive. The Dutch/Belgium Border Meuse Project (see Chapter 4) was an important source of inspiration for this study.

1.5 Cooperation in CRF

Various Dutch and German organisations cooperate in the CRF project. The University of Nijmegen and Delft Hydraulics are the leading organisations, supervised by Rijkswaterstaat Directie Oost. The University of Nijmegen cooperates with the University of Karlsruhe, which participates in the IRP. The present report is the result of combined efforts of the University of Nijmegen and the University of Karlsruhe.

1.6 Readers guide

The present Chapter outlines the flood management and nature rehabilitation problems along the Rest Rhine and indicates opportunities for cyclic rejuvenation. Chapter 2 gives an impression of the natural state of the Rest Rhine and describes how it lost its natural hydro-morphodynamics because of historical corrections. Chapter 3 describes the morphodynamics and how they initiate the rejuvenation of floodplains and river banks. Chapter 4 summarises the plans that have been developed to restore lateral river movement and cyclic rejuvenation along the river Border Meuse on the Dutch/Belgium border. Similarities and differences with the Rest Rhine river are identified. In chapter 5, a reference situation is presented and compared with the current status of the Rest Rhine. Chapter 6 describes the principles of the "moving river variant" and presents measures that could be taken to restore natural dynamic processes (rejuvenation processes) along the Rest Rhine. The hydraulic consequences of the proposed measures are presented in Chapter 7.

2. Historical perspective

2.1 The braided Rest Rhine

Since about 500.000 years, the river Rhine connects the Alps with the North Sea. The current floodplain exists for approximately 8.000 years. It arose after the melting of the ice-aged Alps-glaciers. In the area of the Upper Rhine Valley, 3 types of river courses can be distinguished over a relatively short distance: the zone of furcation, the zone of transition and the meandering zone. The tectonic conditions of the Upper Rhine Valley have led to this diversity in river courses.
The zone of furcation reaches from Basel to approximately south of Altenheim (near Strasbourg) and shows a fall of about 1°/00 on average (compared with 0,3°/00 in the meandering zone). The Rest Rhine between Basel and Breisach is part of the furcation zone. Morphologically it is a flat plain leaning to the North, with a geological bottleneck near the rock massif of the "Isteiner Klotz" (near the village of Istein).
Comparison of today's appearance of the landscape of the Upper Rhine with old paintings (Figure 2) and descriptions gives an impression of the vast changes that took place, i.e. due to the Rhine corrections that were planned by Tulla (see § 2.2).

Figure 2: The historical Rest Rhine near Istein; painting by Birmann around 1840, today in the Museum of Art in Basel.

In former times, the gravel in the main riverbed was a suitable habitat for algae only. Nevertheless, water plants could develop abundantly in the wells and side channels. Examples are homogeneous stands of stoneworts (*Chara hispida)*, stocks of mare´s tail (*Hippuris vulgaris)*, red algae (*Hildenbrandia rivularis)* and the water parsnip (*Sium erectum)*. The soil type along the banks of Rhine branches and old channels, with little or mild currents, varied from silt to gravel. Typical vegetation developed in the transition and furcation zones that could not be found in the meandering zone. Part of this vegetation was a community of

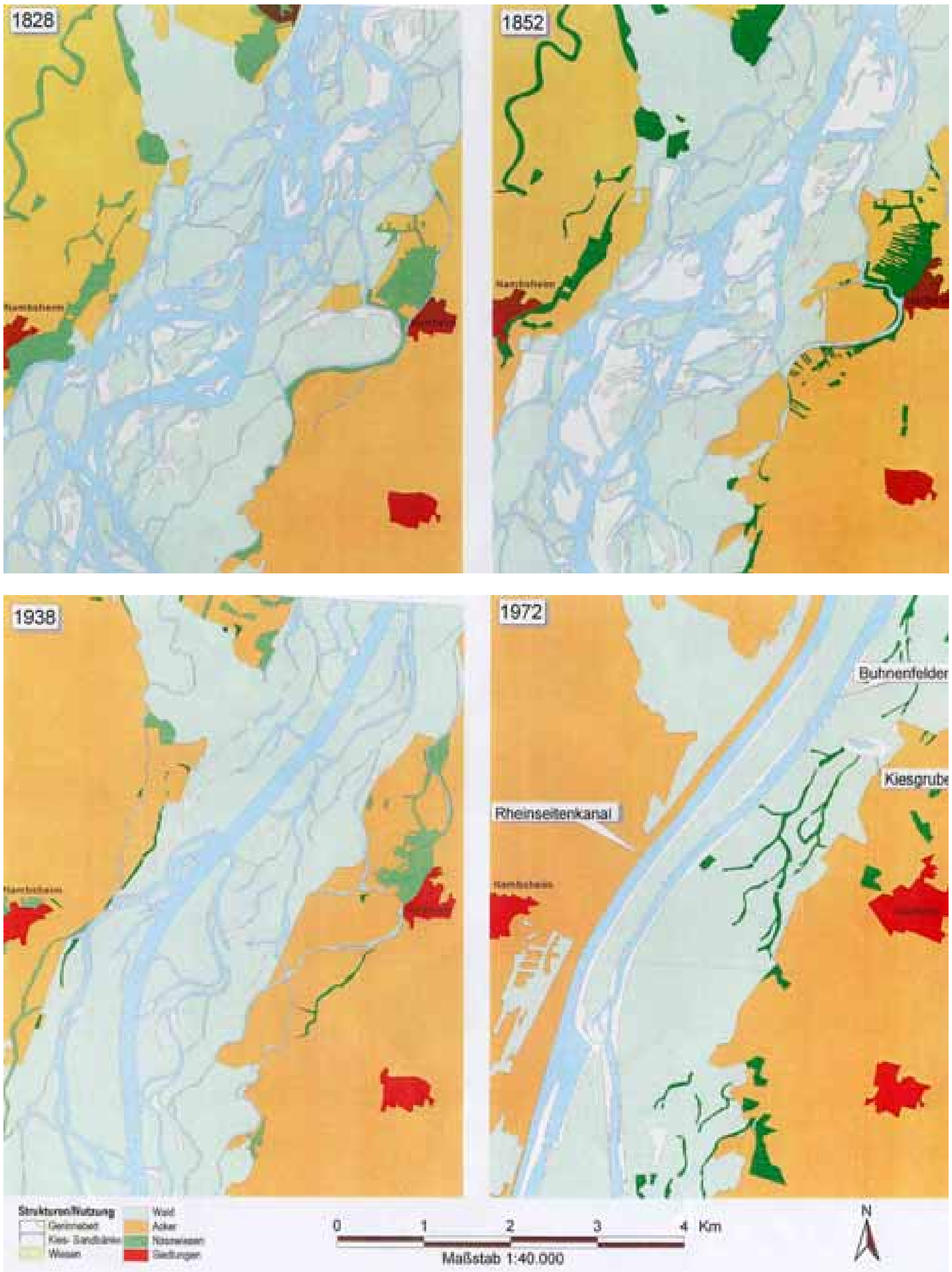


Figure 3: The historical development of the Rest Rhine bed as a result of the embankments and canalisation measures (Source: ILN-Bühl).

pioneer reeds with little bulrush (*Typha minima*), variegated horsetail (*Equisetum variegatum*), mountain rush (*Juncus alpinus*) and yellow wort (*Blackstonia perfoliata*). Gerken (1988) described the dynamics and the succession of gravel banks towards riparian hardwood forests as it possibly took place along the Upper Rhine:

"Some flotsam and jetsam start to sprout on the open gravel, sand, and alluvial clay areas. Willow branches and poplar roots that are washed ashore, sprout and start to take root in the loose substratum. Young alluvial shrubs emerge accompanied by thin pioneer herbs. This herb vegetation is composed of species that today mostly occur on substitute sites such as wasteland, land tips, waysides and fields. Examples are mild knotweed *(Polygonum mite)*, melanocarpous stick-tights *(Bidens frondosa),* poppy species *(Papaver div. spec .)* and wild carrot *(Daucus carota*). If the deposit dynamics of the river allows a further development of these pioneer fields towards forest, the herb and copse stands consolidate. Apart from the fully-grown driftwoods, thousands of sprouts of different willow species (e.g. white willow, lavender willow, basket willow and almond willow), of black poplar and grey alder take root in the raw ground. The stands of softwood are interspersed with tamarisks and sea buckthorn whose swimming seeds drifted in with one of the previous inundations. It mainly depends on the conditions of the substratum and the flood dynamics what kind of species will become dominant in the medium term. For example, the black poplar and lavender willow need light and juvenile soils to grow, so these species will find good conditions for settling on gravel and sand banks that are altered every flood. Both species can withstand disturbances caused by flood dynamics better than the white willow. So the latter species has to grow on less dynamical and finer grained substratum (Dister, 1988). The young forest reduces the speed of the current during floods, which increases the deposition of fine sand and silt. These young alluvial soils are well ventilated and provide the quickly growing trees with nutrients and water. Forests of 20-30 meters high willows and poplars can arise. The limited penetration of light permits a marshy herb vegetation of watercress, forget-me-not, yellow iris (flag) and stick-tights. Over decades, the stratum has grown by several decimetres because of the continuous sedimentation. For this reason, the softwood riparian forests that previously arose from the gravel and sand were raised / have formed a deposit of 1 to 2 metres. The higher level of the alluvial forest is flooded less frequently, so that many species of the hardwood floodplain forest find good possibilities to develop. Because their seeds travel by wind, fluttering elm, ash and traveller's joy colonize the plain. Birds transport seeds of plant species to this plain such as whitethorn, dogwood, wild fruit and common oak. Under the sparse umbrella of the white willows and poplars, the trees and bushes of the hardwood floodplain forest form the next stage of succession. A complex oak-elm-riparian forest arises, with only singular softwoods like flack and grey poplar as relics. Due to the high life expectancy of the hardwood species, persistent and species-rich plant and animal communities of the hardwood floodplain forest develop."

2.2 Historical correction

The Upper Rhine correction of Tulla (1817 to 1880) changed the appearance of the river rigorously. The wild stream, which diverted in numerous branches, was canalised in a single bed. The balance between land and water shifted in favour of the land, especially in the southern Upper Rhine where a major part of the alluvial waters silted up or was separated from the Rhine. The gravel banks and more than 2000 islands in the Upper Rhine disappeared almost completely. At the same time, measures for reclamation of land and drainage were carried out, banks were reinforced and a dike system was constructed. As a result, the potential flooding area decreased. The construction of dikes resulted in a loss of the flooding area of about 660 km² on the river section Märkt (near Basel) to Karlsruhe. Erosion of the Rhine bed resulted in an additional loss of about 80 km². Eventually, c. 74% of the total natural flood area (IKSR, 1989) was lost.
South of Breisach, a strong erosion of the Rhine bed occurred. The level of the riverbed dropped gradually which has led to the current situation that the river rarely floods its banks. Because of the diversion of 1.400 m³/s in the Canal d' Alsace (constructed between 1932-1959) the water level in the Rhine subsided even further.
At some locations, the riverbed has eroded approximately 7 metres. Even in the case of a 200-year flood event (equivalent of 4.500 m³/s), the river only floods its banks at a few locations.

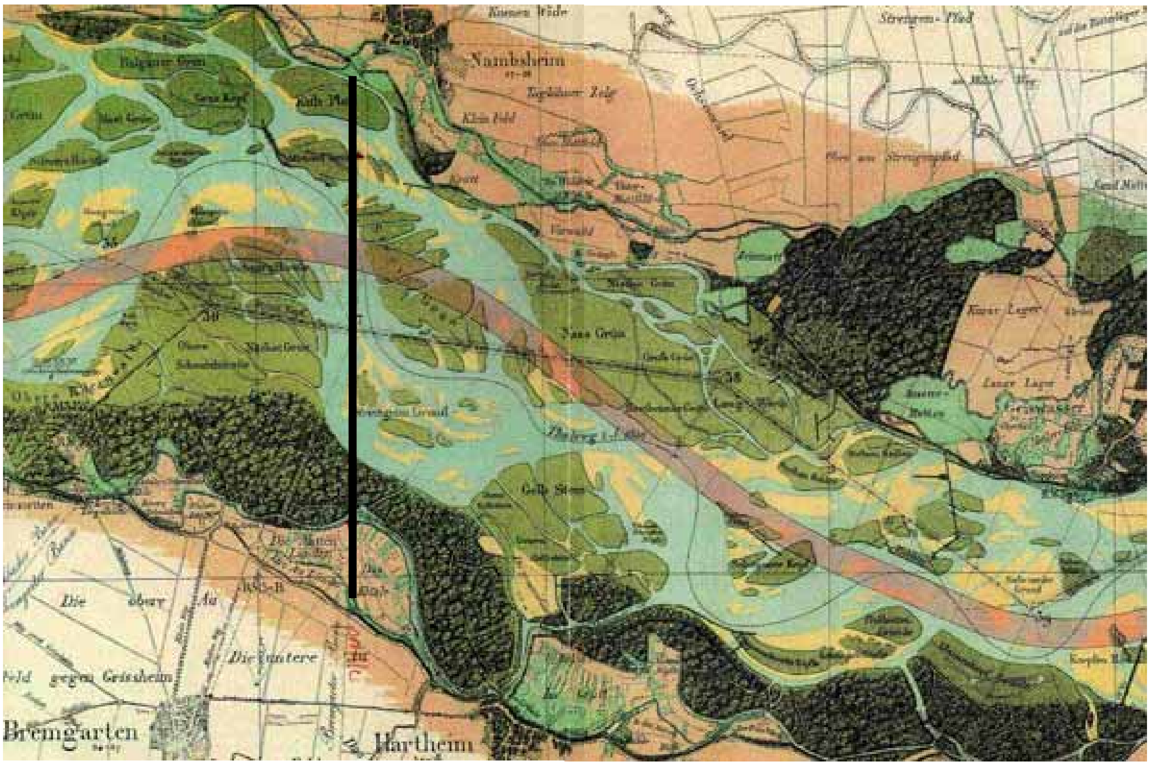


Figure 4: Rheingräntzkarte, 1938. ▬▬▬ = The cross-section shown in Figure 5

The groundwater in the floodplain has dropped and is no longer available for the vegetation. With the subsiding groundwater level, the abandoned side channels disappeared, the alluvial vegetation died off and the animals depending on this vegetation disappeared. Drought resistant species could expand or invade the new (dry) landscape. Today, the diversity in flora and fauna is considerable and the area has some valuable biotopes, i.e. for orchids and insects.

2.3 Consequences for the natural system and flooding behaviour

Figure 5 illustrates the transformations of the Rest Rhine after the so-called "Tulla" corrections. After the interventions were completed, the lateral migration of the river ceased, eliminating the natural resetting mechanism of the floodplain vegetation (natural cyclic rejuvenation). At first, there was still some gravel and sand deposition in the floodplain, partly filling the old river channels outside the Tulla bed. However, the incision of the riverbed proceeded at a fast pace so that deposition in the lateral direction of the main riverbed stopped. Softwood forest colonised the bare gravel banks. Because resetting of the vegetation succession by lateral migration did not occur any longer the habitats of open gravel banks and other pioneer situations disappeared from the river system.
Continuous erosion of the main riverbed and the construction of the Canal d'

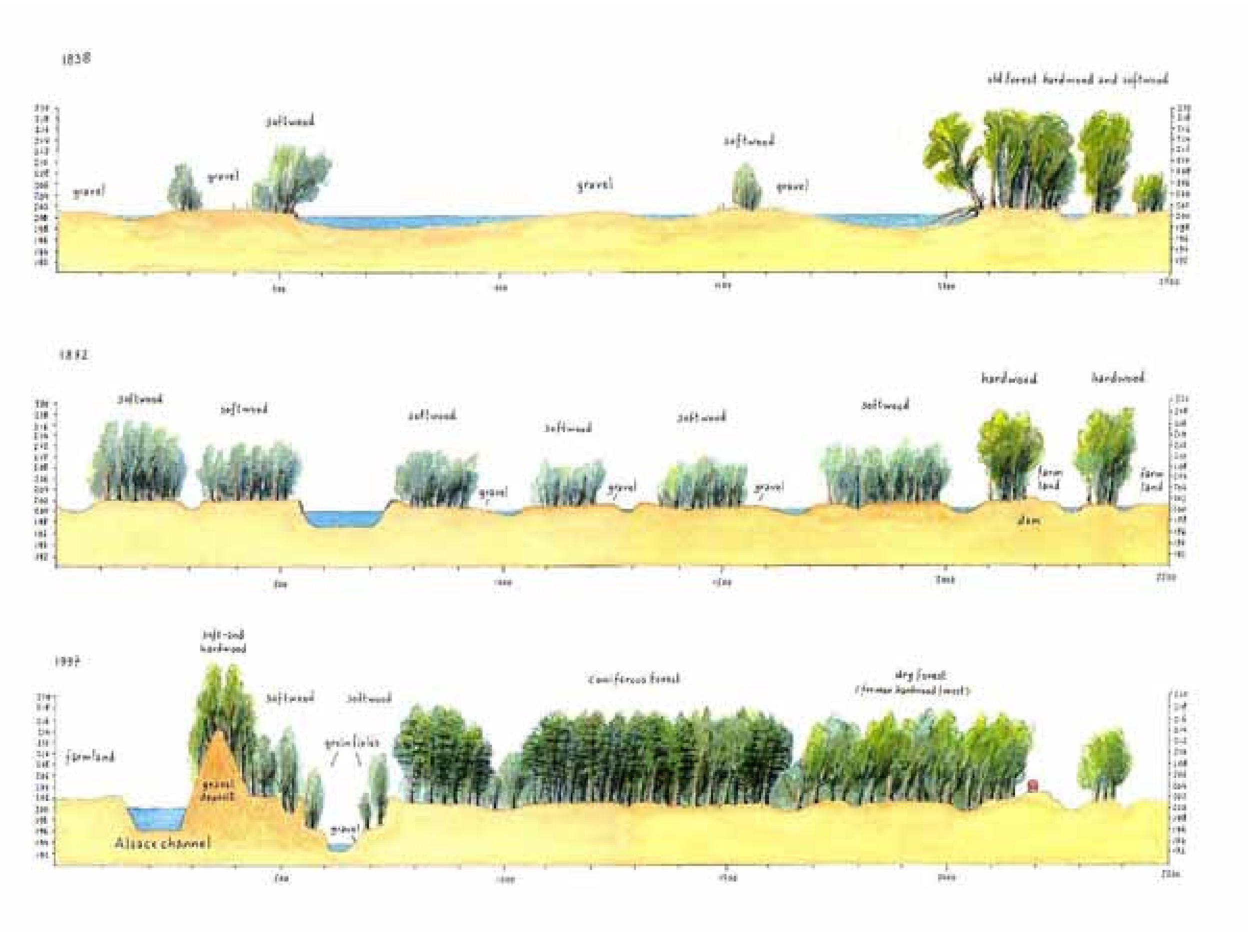


Figure 5: Cross-sections of the Rest Rhine in 1838, 1870 and 1997. Note the difference in forest area and gravel biotopes, caused by the disappearance of lateral erosion. Strong riverbed incision occurred and natural rejuvenation was banned from the floodplain.

Alsace in subsequent years further eliminated the interaction between the river and its floodplains.

Hydrological Consequences

Today, the riverbed of the Rest Rhine is approximately 7 m deeper than the original riverbed. About 300 days a year, the river has a flow of 20-30 m^3/s (the so-called "residual water volume"). This quantity increases only when the flow of the Upper Rhine exceeds 1.400 m^3/s. In that situation the water flows over the weir near Märkt into the Rest Rhine. This occurs on average of 65 days a year. Until now the highest water level measured was about 3.600 m^3/s (13 May 1999). At that time, the water level was circa 7 m higher than normal.

Figure 6: The narrow, incised riverbed of the Rest Rhine near Hartheim.

Figure 7: Aerial picture of the Rest Rhine with the Canal d'Alsace.

Morphological consequences

Relatively large open areas of gravel and sand banks without vegetation were typical for the natural state of the Rest Rhine (Figure 4). Generally, the soil consists out of silt or sandy sediments with a low nutrient content. The water permeability is high.

Due to the morphological effects of the hydraulic engineering measures (lowering of the Rhine, lowering of the groundwater level, etc.), the river-floodplain interaction does not occur any longer. The relatively high-located floodplains are called “Trockenaue”, indicating that desertification has changed its original character. As a consequence the vegetation has changed considerable and can no longer be referred to as “floodplain vegetation”. The sand or silt layer covering the gravel is less than 0,6 m thick. The “Trockenauen” have been subject to gravel excavation, agriculture but are usually natural floodplain forest or used for pine plantations.

At present, the morphodynamic processes are primarily confined to the 180 m wide “Tulla” bed. During periods of low water discharge dense willow stands develop in the riverbed. These stands enhance the sedimentation of sand and silt in the groin fields. The thickness of the deposited sand/silt layer in the groin fields varies strongly (Figure 8). At some places these sand and silt layers are 2 to 3 m thick, whereas in other places the gravel layer nearly covered.

Figure 8: Sand deposition in the groin fields along the Rest Rhine

Ecological consequences

Prior to Tulla’s intervention the lateral migration of the river and its gullies prevented an unbridled development of floodplain forest. natural Rest Rhine. Many pioneer plant species that are characteristic for the Alpine georegion could be found on the bare sand and gravel islands (German tamarisk, Sea buckthorn, Grey alder, Ripe willow, Dog figwort and Rosemary-willow herb; Lauterborn, 1917). After some years the vegetation succession was interrupted by the migrating river and started all over again (natural cyclic rejuvenation). After the river regulation works, the gravel banks disappeared due to the incision of the river bed and continuing alluvial depositions in the floodplain. The pioneer herb vegetations decreased dramatically. Some species of the former gravel banks have found alternative sites, for example on the banks of gravel pits, near weirs and in the “Trockenauen” south of Hartheim (e.g. Sea buckthorn, Dog figwort and Rosemary-willow herb).

Nowadays, natural rejuvenation is limited to the riverbed and the groin fields. Therefore, over the last 50 years, softwood riparian forests could expand

considerable and some hardwood forest species were successful in colonising gravel banks located only 2-4 m above the average low water discharge level. The human interventions in the basin of the Upper Rhine also affected the fauna. The migration routes and spawning grounds of the anadrome fish species were severely affected by the construction of weirs, dams and the diversion of water. Due to the incision of the main riverbed many of the former spawning grounds became disconnected and silted up.
Some of the breeding birds of the former gravel islands have survived in secondary biotopes. Before the correction of the Upper Rhine the little Ringed Plover was a common bird species and frequently breeding on the gravel islands and alluvial sand banks (Von Kettner, 1849). During the 19th century this population decreased drastically. The Little Tern, which was widespread in former days (Baldner, 1666; Von Kettner, 1849), became a rare species, and finally disappeared around 1930. Also the Common Sandpiper used to be a characteristic breeding bird for this part of the Rhine (Von Kettner, 1849).

3. Natural Rejuvenation

3.1 Natural processes

Gravel rivers have a very fast turnover in terms of succession rates and succession cycles. Strong lateral movement of the riverbed, erosion, high discharge dynamics and sedimentation of considerable amounts of gravel and sand are the ingredients of a continuously changing landscape. These hydro-morphological changes are the basis of natural cyclic rejuvenation. Besides from erosion and sedimentation other processes interact with the vegetation succession. The most important processes are described here briefly.

Figure 9: Bank erosion along the Allier river. Older grasslands and forests get "rejuvenated".

Erosion

Lateral erosion occurs during the process of meandering. During this process, the river moves laterally and takes away material from the steep banks of the outside bends. Riverbanks, floodplains and their vegetation disappear slowly into the waves. At the same time, sedimentation is deposited in the inside bends, creating point bars (Thorne, 1998; Knighton, 1998). Plants and animals quickly colonize these point bars.

Figure 11 illustrates the lateral movement of the Allier river, a typical gravel river in the middle of France. The river is known to move its course up to hundreds of meters over a period of hardly 10 years. It “resets” stream valley grasslands and older hardwood forests as it moves laterally. The steam transports seeds and the eroded trees end up as wooden debris in the riverbed and on the banks. Under water it provides habitats for many macrofauna

species (filterfeeders) and above the water level it offers a habitat for many specific insects species, birds and lizards.
In braided river systems, irregular and less predictable forms of bank erosion occur. Banks and islands shift randomly. Rivers like the Allier, the Durance (both France) and the former South-German Rhine have meandering as well as braided features.

Figure 10: Sedimentation plains along the Allier; the result of natural rejuvenation.

Sedimentation

The outside bends of a moving river erode and the inside bends form point bars. These point bars move in downstream direction, just like the meander itself. Hydraulic forces decline further from the waterline, resulting in sedimentation of gravel and considerable amounts of sand. This process is erratic because it depends on the frequency of high water events. As a consequence, bank sediments can be deposited in a "washboard” pattern, forming sandy levees or even sand dunes.

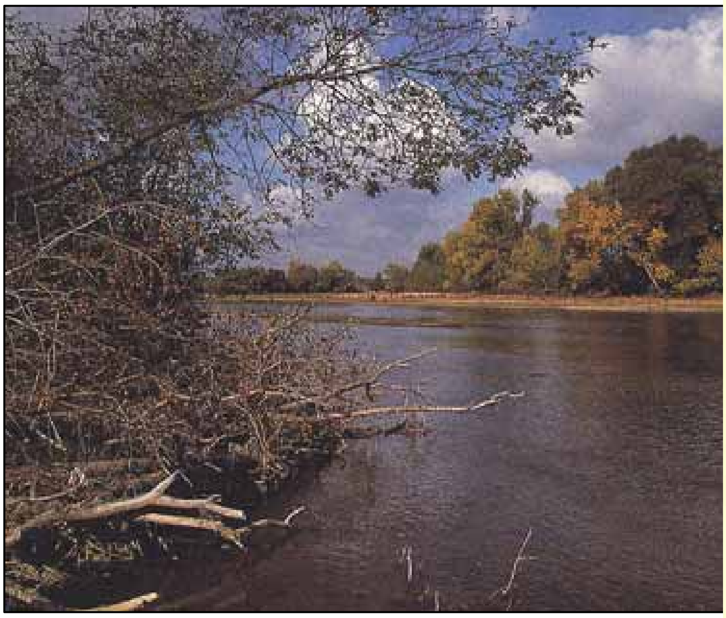


Figure 11: Changes in the riverbed of the Allier river south of Moulins (from: Van den Berg *et al.*, 2000).

In braided parts of the river, islands can develop because large quantities of gravel are deposited in the streambed. Severe erosion of outside bends during water spates can result in the deposition of large amounts of gravel and sand on relative high locations. This also happens when the river overflows a bank resulting in a sudden loss of hydraulic energy. Under these conditions, the river deposit several meters of gravel and sand. These sedimentation processes create new pioneer situations for plant and animal species. For the Allier River, for the most part an unregulated river, the total area of pioneer habitat has been estimated to approximately 32% of the floodplain area (Peters *et al.*, 2000).

Hydraulic effects of high water discharges

Apart from the morphological effects, high water levels result in mechanical stress on riparian vegetation. Especially, extreme flood events and floating ice can lead to large-scale resetting of the present vegetation, providing a new start for pioneers. The water can uproot trees and transport them downstream where they may result in extra mechanical stress on the bank vegetation.

Figure 12:
Groundwater-fed high water gully along the Allier River.

Groundwater level

Former stream gullies on the edge of the floodplain can fill up with groundwater from higher terraces. This process can result in valuable biotopes with a good water quality. The constant supply of groundwater slows down the development of forest, closed grassland and rough vegetation. The surface water level in the side gullies and secondary channels varies due to changes in groundwater level, rainfall intensity and river water levels. This results in a fluctuating water supply that contributes to the rejuvenation of vegetation.

Figure 13
Strom damage in riparian forest

Wind

Wind can have a devastating impact on floodplain forests. Especially the trees of old softwood forests (*Populus nigra, Salix alba*) can snap easily during storms and whirlwinds. This happened in 1999 when an extremely heavy storm occurred in parts of Southern Germany and France, destroying large parts of the floodplain forests between Basel and Karlsruhe.
The effects of heavy wind create new opportunities for the development of grassland and rough vegetation. Furthermore, hardwood trees get the opportunity to sprout and grow in the new open spaces, which stimulates the transition towards hardwood forest. On several locations in the Southern Rhine area we can now see rejuvenation effects caused by the storm of 1999.

Effect of grazing on the vegetation succession

The presence of large herbivores is a natural phenomenon in European river valleys. Animals like Red Deer, Roe Deer, Beaver, Auroch, European Bison, Tarpan and the omnivore Wild Bore all have a specific role that influences the riverine landscape. Relevant activities are cause grazing, trampling and perturbation of the soil. Smaller herbivores and burrowing animals like Rabbit, Badger, Fox and even mice have an effect on the vegetation succession (Butler, 1995). Experiences in Dutch nature rehabilitation areas support the idea that subtle forms of grazing and soil disturbing activities of large animals like wild cattle, horse, beaver and roe deer have a positive effect on biodiversity in floodplains (Ark Foundation, 1999).

Figure 14: Natural rejuvenation by large herbivores (Koniks disturbing the sandy top soil along the Meuse).

4. The Border Meuse Project

4.1 An integrated plan for nature rehabilitation, gravel excavation and flood prevention

The Border Meuse is the section of the river Meuse that flows between Maastricht and Maasbracht. It forms a natural border between the Netherlands and Belgium. In 1991 the "Border Meuse plan" was developed under the supervision of the Province of Limburg (Helmer *et al.*, 1991a). This plan aims at integration of nature rehabilitation, gravel excavation and flood prevention.

Figure 15: The Border Meuse: pleasure and menace.

Gravel excavation and nature development were the main triggers for the Border Meuse project. Before the plan, gravel excavation occurred in deep gravel pits, leaving uncharacteristic and ecologically uninteresting lakes in the

Present situation

After excavation

Future situation

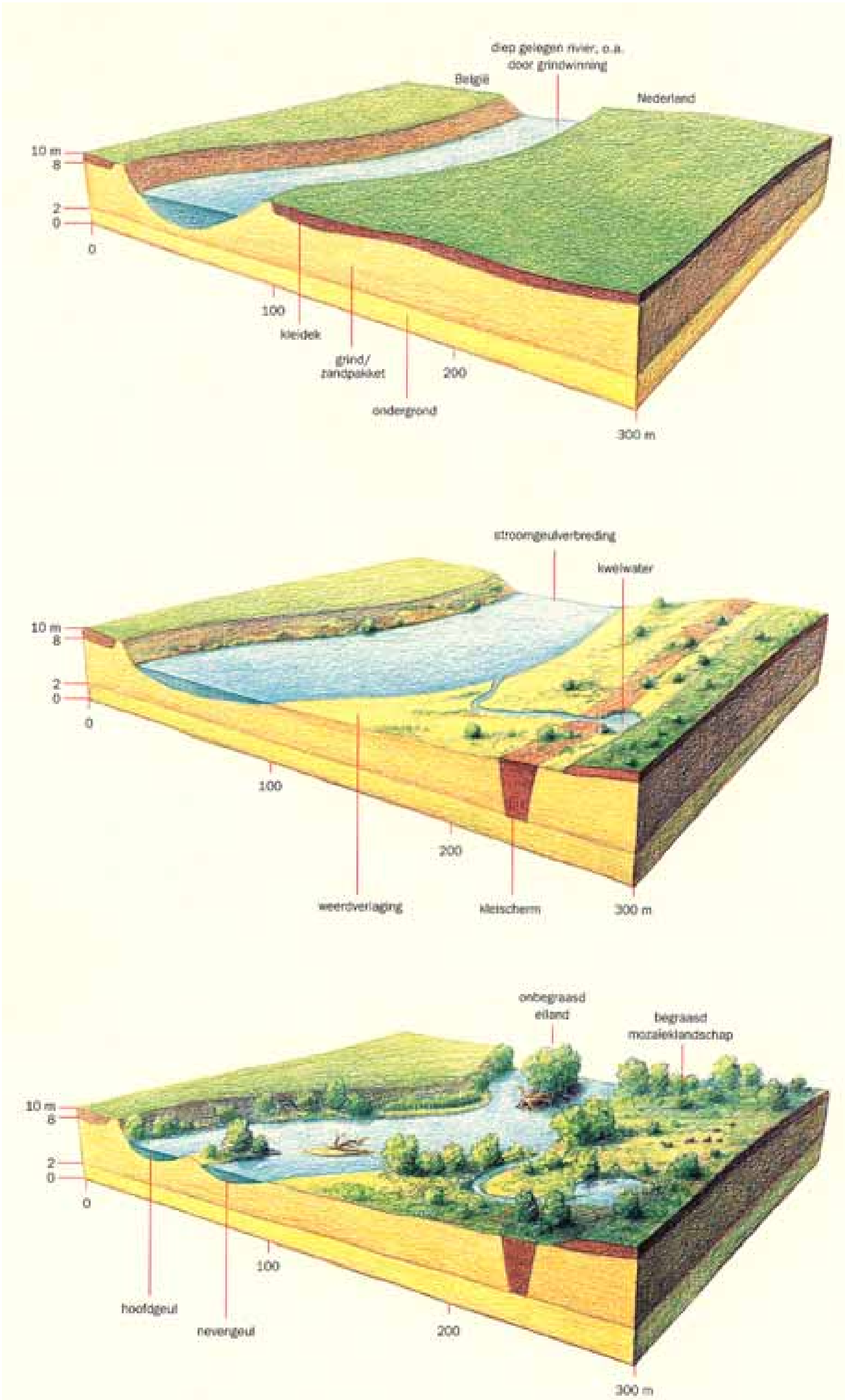


Figure 16: The Border Meuse Project (Projectbureau Border Meuse, 1994. Illustration Jeroen Helmer)

former floodplain areas. Ongoing protests in the region forced policy makers to review this gravel excavation approach, and to harmonise it with ecological rehabilitation and regional development (for example tourism and recreation). After the floods of 1993 and 1995, the positive impact of the plan on flood prevention became apparent. The initial plan had been elaborated further and impacts on morphology and water levels were extensively studied. The first pilot project started in 1999 near the village of Meers. Since then, the Flemish Government has also developed nature rehabilitation plans for the Belgium side. Gravel excavation is reduced, but the plan still relieves some Dutch bottleneck situations. The project is an example of trans-national cooperation in river management.

Like the Rest Rhine, the Border Meuse has an unnatural narrow, deep river bed caused by canalisation. Gravel excavation in the streambed has caused further deepening. The broad floodplain in which the river was able to move laterally has completely disappeared. Floodplain areas are nowadays dominated by intensive agricultural use. The current ecological values of the Border Meuse floodplain are limited. Like in the Rest Rhine, ships are led through a lateral channel; the Juliana Channel. This river section has no dams and sluices and the water is flowing freely. The floodplain of the Border Meuse is only inundated at high discharges (> 1200-1500 m^3/s). Because there is no lateral movement, silt and loam keep accumulating in the floodplain, heightening the difference between the riverbed and the floodplain.

4.2 The concept of the Border Meuse Project

The concept of the Border Meuse Project is to widen the river as much as possible by removing the top layer of the floodplain (Figure 16). The dimensions of widening vary, depending on the available space and the location of villages. In its broadened bed, the river can meander freely. New gravel islands, banks, sand levees and stream gullies are expected to develop. Spontaneous development of riparian forest can take place and natural grazing will occur over a new nature area of more than a 1000 ha. Due to low silt concentrations and high concentrations of heavy metals (mainly zinc), the top clay layer cannot be used for economic purposes. It has to be processed in the area itself. Some locations on the edge of the floodplain will therefore be used to build so-called "clay screens". On these locations, gravel will be excavated and the pits will be filled with the redundant clay. The groundwater level is expected to rise due to this impermeable clay layer resulting in wet headwater swamps.

In the Border Meuse Project, the future morphology is not pre-defined in the form of planned channels and islands. The river regains a broad floodplain valley and natural dynamics determine the morphology that will develop. It is expected that natural rejuvenation processes will become active again because erosion and sedimentation increase.

In total, the Border Meuse Project will yield more than 65 million tons of gravel. This is much more than the Province formally had to deliver in 1991 when the plan was presented (35 million tons). Furthermore, the occurrence of critical high water levels during floods is expected to drop well below the standard of 1/250 years. The bare landscape of gravel and sand offers ideal opportunities for the settlement of plants and animals. The open soil of the new floodplains also offers good colonization opportunities for riparian forests. Pilot projects for nature rehabilitation have shown that these riparian landscapes can develop towards rich nature areas in a matter of years.

Technical details

River section length	40 km
Area of gravel excavation	About 1000 ha (Dutch and Belgium side)
New nature area	About 1500 ha (Dutch and Belgium side)
Excavated gravel	About 65 million tons
Water lowering effect	Up to several decimetres (see IWACO/CSO/WL, 1998)
First Pilot project	Near the village of Meers

Figure 17: During the floods of 1995 large amounts of gravel were deposited in the nature area of Kerkeweerd; a floodplain of the Border Meuse. In 1997 a colourful bed of stream valley pioneer plants developed.
The area is currently under a low-density grazing regime and develops towards grassland and shrub land.

4.3 Comparison of the Rest Rhine with the Border Meuse

The Border Meuse Project is an appealing example of river widening. Comparison of the Border Meuse with the Rest Rhine may result in useful insights. Both similarities and differences are identified in this section.

Similarities

The following features of the Rest Rhine and the Border Meuse are comparable:

General features

- Originally, both gravel rivers braided in a much broader floodplain;
- Nowadays a narrow deep river bed is left, mainly because of canalisation;

- There is no shipping traffic on the rivers because of a lateral channel;
- Both areas have an active gravel mining industry;
- In both areas gravel mining and flood prevention can go hand in hand;
- Gravel mining tends to conflict with and other regional functions.

Hydraulic features

- Extreme streambed dynamics during high water;
- Lack of dynamics in the floodplain areas;
- Formation of an armoured layer in the streambed;
- Very low water levels during summer: Border Meuse 25-50 m^3/s; Rest Rhine 30-40 m^3/s;
- Both river systems have lowered groundwater levels;

Figure 18: Both the Rest Rhine and the Border Meuse have a layer of rocks and gravel boulders in their streambed. Here the Rest Rhine in one of its most dynamic sections near Istein.

Morphological features

- No lateral movement;
- Lack of small gravel and coarse sand because of bed erosion;
- Lack of sediment transport from upstream parts.

Ecological features

- Poor development of young, dynamic biotopes in the floodplain;
- Almost no natural cyclic rejuvenation and succession;
- Locally still a lot of reference species available;

Differences

The following features of the Rest Rhine and the Border Meuse clearly differ:

General features

- The Border Meuse Project aims at increasing discharge capacity, but retention is the goal for the Rest Rhine;
- In the Border Meuse area there is a flooding danger for villages in the valley; the Rest Rhine no longer inundates its former floodplains.

Hydraulic features

- Mean fall at low water: Border Meuse 0,5 m/km, Rest Rhine 1 m/km;
- Maximum velocity at high water: Border Meuse 3,5-5 m/s; Rest Rhine 4-5 m/s;
- Maximum discharge (1/200 years) of the Border Meuse is about 3000 m^3; in the current Rest Rhine it is about 3700 m^3 (excl. Canal d'Alsace);
- The original floodplain area along the Rest Rhine is nowadays completely free of inundation.
- The Canal d'Alsace has an average flow of 1400 m^3/s; the Juliana Canal has an average flow of only $10m^3/s$.

Morphological features

- In the Border Meuse floodplains, a thick clay/loam layer (2-4 meters) has formed on top of the gravel; the Rest Rhine floodplains lack this clay layer;
- Originally, the Rest Rhine probably had a more braided character than the Border Meuse;
- The Rest Rhine is able to spontaneously erode its banks laterally if bank protection fails, because the banks exist out of pure gravel and sand (no clay layer). This can still be observed at Istein. The Rest Rhine can recycle gravel material of its own banks and use it as "building material" in the riverbed. This means the Rest Rhine has a lesser problem with the continuity of upstream sediment influx.

Ecological features

- The higher floodplains of the Rest Rhine still have valuable nature (dry biotope); the Border Meuse floodplains are characterised by intensive agriculture;
- The Rest Rhine valley has much more riparian forest, also in the streambed area (between the groin fields).

4.4 Conclusions

Although there are clear differences between the Rest Rhine and the Border Meuse, both rivers also have many features in common. High discharges of the river cause extreme dynamics in the narrow riverbed. A homogeneous layer of rocks and gravel boulders (armoured layer) replaced the natural variety in bed sediment. The floodplain itself has been largely deprived of hydromorphodynamics, although the Border Meuse's floodplains are still inundated during peak levels. Most biotopes in the transition zone between the dynamic riverbed and the relatively calm higher parts (gravel banks, sand levees, open grasslands, pioneer situations and young forests) have disappeared, or are only locally present, often in a deteriorated form (e.g., in the groin fields). This implies that elements of the Border Meuse concept may be suitable for the Rest Rhine.
But there are also differences. The Rest Rhine still has valuable nature areas on the high floodplains. The Border Meuse has a thick clay layer on top of the gravel. The Rest Rhine has a higher fall and maximum discharge than the Border Meuse, etc. etc.. This means that specific measures may be necessary for the Rest Rhine, but the Rest Rhine also offers opportunities for revitalising natural processes that are not viable along the Border Meuse.

Figure 19: In 1999 gravel was excavated along the Border Meuse near Meers for the first pilot project of river widening.

Figure 20: Settlement of Willow (mainly *Salix viminalis* but also *Salix alba*) at Meers (end of 1999).

5. A reference image for the Rest Rhine

5.1 The reference image of the Integrated Rhine Program

The Integrated Rhine Program (IRP) defines a reference image for the Upper Rhine as follows (LFU Baden-Württemberg, 1994):

"An ecosystem that contains the whole spectrum of typical biotopes, symbiosis, species and functions of the Upper Rhine floodplains serves as reference image for the restoration of an ecologically intact and natural alluvial landscape."

Based on this general description of a reference image, a specific reference image for the Rest Rhine can be drafted.

5.2 Reference image for the Rest Rhine

A reference image for the Rest Rhine emerges when the present Rest Rhine is compared with other natural gravel rivers. For this comparison, information on the natural gravel rivers listed in Table 1 is used (SEPNMC, 1981; Gerken, 1988; Helmer, 1989; Schepers & Kerkhoffs, 1994; Helmer *et al.*, 1994; Van den Berg *et al.*, 2000; Peters *et al.*, 2000; Van Looy & Peters, 2000, Landesanstalt für Umweltschutz, 2000). Furthermore, Also the historical description of the former Rest Rhine as presented in chapter 2 gives an impression of the variety in landscape and species richness of natural gravel rivers. However, it has to be realised that the historical state of the furcation zone of the Rhine (before 1840) cannot be re-established under today's conditions, not even on the long-

Figure 21: The river Durance in South-Eastern France,: a reference image for the Rest Rhine.

term. For that reason, elements of historical situations can only partly be included (e.g., the presence of certain species, biotopes or complexes of habitats before 1870).

Table 1: List of important reference areas for natural gravel rivers in Western Europe.
• The rivers Allier, Middle-France; • The river Durance, South-East-France; • The German Isar; • Parts of the French Meuse; • Elements and historical data of the Dutch/Belgium Border Meuse; • Elements and historical data of the German Rest Rhine

A reference image is an idealised picture that, although it will probably never be fully accomplished, provides important guidelines for the restoration of the Rest Rhine. The following description of the reference image is based on the various ecological elements (ecotopes) of a natural floodplain. An impression of the characteristic species and communities is also given.

1. Riverbed

Natural characteristics

- Streaming water with variations in water depth and stream velocity;
- A broad streambed with different channels and islands;
- The riverbed contains gravel and sand of different sizes;
- Water levels fluctuate with river discharge and are influenced by rain and melting water;
- The variation in summer water levels is relatively small;
- Groundwater levels influence the shallow banks;
- There are sunny as well as shaded banks;
- Presence of dead trees and woody debris in the river bed;
- Local groundwater effects in particular parts of the banks.

Characteristic communities and species

- *Rheophilic fish species, e.g. Barbel (Barbes Barbus), Nose Carp (Chondrostroma nasus), Bullhead (Cottus gobio), Greyling (Thymallus thymallus) and Alburnoides bipuctatus;*
- *Filter feeders on woody debris and gravel;*
- *Fishing grounds for Terns, Black Kite and Kingfisher.*

2. Low gravel- and sand banks (up to 1 m above summer water level)

- River banks are inundated frequently, also in summer (365-50 days/year);
- Sediment types vary from large gravel to silt;
- Frequently changing sedimentation.

Characteristic species

- *Important foraging zone for herons, sandpipers and plovers;*
- *Foraging habitat of Beaver;*
- *Habitat of specific dragonflies (Gomphus spec);*
- *Pioneer plants, sometimes rejuvenation zone of Salix alba and Populus nigra.*

Figure 22: Undeep and often groundwater-fed gullies along the Allier (F).

3. High gravel and sand banks (> 1-4 m above summer water level)

- Broad, bare gravel banks and sand depositions, sometimes as islands in the river;
- Low inundation frequency (20-50 days/year), especially in summer;
- Variation between sand and gravel depositions;
- Local differences in height and sun exposition;
- Presence of dead trees that function as habitat for insects and reptiles;
- Sometimes existence of whirlpools and sand dunes.

Characteristic communities and species

- *Habitat for many stream valley plants, preliminary stage for stream valley grassland; species like Euphorbia cyperassias, Echium vulgare, Berteroa incana, Sedum alba, Sedum sexangulare, Saponaria officinalis, Gypsophila muralis, Petrorhagia prolifera, Cynoglossum officinale, Scrophularia canina, Epilobium dodonaei and Vulpia spec;*
- *Rejuvenation of softwood forest with Populus nigra and Salix purpuraea; also colonisation of first hardwood species possible;*
- *Special xerophylic insects (grasshoppers, tiger beetles, spiders);*
- *Breeding site for Terns, Stone-curlew (Burhinus oedicnemus), Little ringed plover (Charadrius dubius), especially on islands;*

- *(Winter)Habitat for Natterjack (Bufo calamita), Common Spadefoot Toad (Pelobates fuscus) and Wall Lizard (Podarcis muralis).*

4. Steep erosion banks

- Destruction zone of old forest, shrubs and grasslands;
- Source of woody debris and seeds in the river;
- Source of new river sediment;
- Steep banks offer breeding opportunities for birds and bees.

Characteristic communities and species

- *Breeding site (if loamy or compact sand) for Kingfisher, Sand Martin and on high banks even Bee-eater;*
- *Habitat for sand bees and wasps.*

5. Groundwater-fed, high water gullies

- Old stream channels, raised by deposited sand or gravel;
- Used for water discharge in winter;
- Seepage in summer;
- Constant wet zones or open water in summer.

Characteristic communities and species

- *Special pioneer plants, like Penny-Royal (Mentha pulegium), Brown Galingale (Cyperus fuscus) and Small Fleabane (Pulicaria vulgaris);*
- *Water plants and algae adapted to clear waters;*
- *Breeding spots for specific amphibians and dragonflies;*
- *Germination zone for willow forest.*

6. Scarcely inundated floodplain

- Scarcely inundated zone (0-20 days inundation/year);
- Low dynamics;
- Older succession stages with a (grazed) tessellation of woodland, shrubs and grassland;
- Warm en dry summer conditions.

Characteristic communities and species

- *Hardwood forest and shrubland with a.o. Quercus robur, Ulmus minor, Fraxinus excelsior, Crataegus monogyna, Rosa canina, Ligustrum vilgare, Prunus spinosaoften with well developed liana (Clematis vitalba, Cucubalis baccifer);*
- *Dry streamvalley grasslands and border vegetation with a.o. Euphorbia cyperassias, Potentilla verna, Potentilla argetea, Coronilla varia, Agrimonia eupatoria, Sherardia*

arvensis, Calamintha sylvatica, Origanum vulgaris, Echium vulgare, Sedum alba, Sedum sexangulare, Vincetoxicum hirundinaria, Dianthus cartusianorum and Anacamptis pyramidalis;

- *Winter habitat for Amphibians;*
- *Rich bird population with many species of older forest and dead trees (Several woodpecker species, Nightingale, Stockdove, Hoopoe and Flycatchers);*
- *Indicative insect species of older forest: many Long-horned beetles and other beetles;*
- *Shrub land and grasslands with rich Butterfly fauna and birds like Red-backed shrike, Nightingale and Whitethroats.*

Figure 23: The forests and grasslands in the (former) floodplain of the Rest Rhine are important habitat for many threatened species like Black-veined White (left, *Aporia crataegi*), Pyramidal orchid (right, *Anacamptis pyramidalis)* and Wall Lizard (below, *Podarcis muralis)*

7. Old, abandoned side channels

- Former main channel that is cut off;
- Low dynamics;
- Often further away from the mainstream;
- In contact with groundwater from the terraces.

Characteristic communities and species

- *Older softwood forest, flanked by hardwood on the higher parts;*
- *Abundant water plant vegetation;*
- *Fish habitat for species of stagnant environments;*
- *Many herpetofauna species like European Tree Frog (Hyla arborea), Grass Snake (Natrix natrix), Pool Frog (Rana lessonae), Edible Frog (Rana esculenta), Lake Frog (Rana ridibunda), several Newt species (Triturus spec.).*

8. Tributary deltas

- Exchange of aquatic species and sediment between tributaries and the main river;
- Formation of junction bars (x.x?);
- Water quality can differ from main river in terms of chemical quality as well as water temperature and oxygen content.

Characteristic communities and species

- *Habitat for young rheophilic fish species;*
- *Foraging spot for fishing birds like Kingfisher.*

9. Wells

- Groundwater emerging within the floodplain;
- Small ponds and undeep waters with constant water levels during summer;
- Very good water quality.

Characteristic communities and species

- *Community of typical groundwater and moist dependant plant species like Equisetum fluviailis, Chrysosplenum species, Veronica beccabunga, Cardamine amara, Caltha palustris, Carex remota and Cyperus fuscus;*
- *Foraging spot for fishing birds like Kingfisher.*

5.3 Status of the current Rest Rhine

What can still be recognised of the original ecotopes along the Rest Rhine today? Below follows a description of the current status of the various elements of the reference image.

1. Riverbed

- There still is a gravel bed situation with free flowing, undammed water;
- Water quality is still relatively good;
- Extreme flow velocity during high water (up to 3700 m^3/s);
- Large gravel is still present because of high river bed dynamics; smaller sediment fractions have been washed away;
- Changes in water levels only above 1400 m^3/s (discharge of the channel);
- Low summer discharges (down to 30 m^3/s);
- Lack of local, sheltered pools;
- Lack of woody debris in the riverbed;
- There still is a supply of sand and gravel, although less, from upstream parts of the river (Swiss).

2. Low gravel- and sand banks

- Low gravel banks are still present;
- Banks consist mainly of large gravel boulders; silt and sand have been washed away;

- Relatively high flow velocities;
- Relatively frequent fluctuations in summer water level;
- High gravel and sand banks (> 1 m above low water);
- There still is sand deposition in the groin fields, although on a very narrow part of the riverbed;
- Lateral erosion of sand banks is impossible;
- Occasional extremely high sand deposits, sometimes even silt deposition in a narrow zone;
- Extreme hydraulic forces during high water;
- High inundation frequency and height (up to 6 m), also in the summer season;
- Locally extreme relief, mainly in sand;
- No real islands left;
- No gradient from gravel via sand to silt;
- Forest development possible.

4. Steep erosion banks

- No longer present, only locally where embankments have been damaged.

5. Groundwater-fed, high water gullies

- Not well developed forms can only occasionally be found in the groin fields.

6. Scarcely inundated floodplain

- Still very well developed along the Rest Rhine;
- No river influence;
- Very deep groundwater level;
- Lack of rejuvenation processes because there is no river influence and scarce grazing activity of large animals;
- Still grassland rejuvenation by wild bore.

7. Old, abandoned side channels

- Do not exist due to incision of the riverbed.

8. Tributary deltas

- Present in very bridled states.

9. Wells

- Real wells are no longer present.

5.4 Limitations

The reference image describes an ideal situation. It can be used for ecological valuation and as a selection criterion for river management options. The reference image is not to be confused with a target image which also has to account for present conditions. These include:

- The “Canal d'Alsace” that has a flow of more than 1.400 m^3/s;
- The necessary retention capacity of 25 million m^3 that has been laid down in the Integrated Rhine Program;
- The lack of sediment influx from the “Hochrhein”;
- Infrastructure constructions and disposal sites;
- Valuable nature reserves and other protectorates.

Figure 24: Groin fields along the Rest Rhine with softwood forest, rough vegetation and stream gullies.

5.5 Conclusions

The current Rest Rhine valley still is a valuable nature area. A large range of flora and fauna species is present, among which internationally protected species. Ecology and nature values are extensively described in a publication of the Landesanstalt für Umwelstschutz (2000).
Only certain elements and zones of the system are well developed (Table 2). Inundation free forest and grassland areas contain most of the ecological values. The riverbed and groin fields offer habitat for riverine nature, but in a deteriorated form. Certain zones such as higher, open gravel banks (small gravel), erosion banks and groundwater influenced side channels are lacking completely. The ecological connection and exchange between the riverbed and the mostly dry floodplain is limited because the border is straight and steep. To achieve a situation that resembles the reference image of a natural gravel river the following measures are suggested;:

- Widening of the floodplain area by gravel excavation;
- Removal of embankments and groins at the widened sites;
- Allowing lateral erosion at specific sites;
- Allowing lateral movement and bank building in the riverbed;
- Development of natural vegetation within the floodplain;

- Improvement of the ecological links between the riverbed and the floodplain;
- Increase of the minimum water discharge.

Table 2: The status of the different zones (ecotopes) along the current Rest Rhine.

Poor	Poorly developed or completely disappeared
Moderate	Moderately developed or present in uncharacteristic form
Reasonable	Reasonably present
Good	Good preserved

Zone/Ecotope	Poorly	Moderate	Reasonable	Good
1. Riverbed			X	
2. Low Gravel- and sand banks		X		
3. High gravel and sand banks*	X*			
4. Steep erosion banks	X			
5. Groundwater-fed, high water gullies	X			
6. Scarcely inundated floodplain				X
7. Old, abandoned side channels	X			
8. Tributary delta's	X			
9. Wells	X			

* Sand is still deposited in the groin fields but there is no natural sandbank morphology and a dry, warm microclimate typical for higher sand and gravel deposits is also lacking.

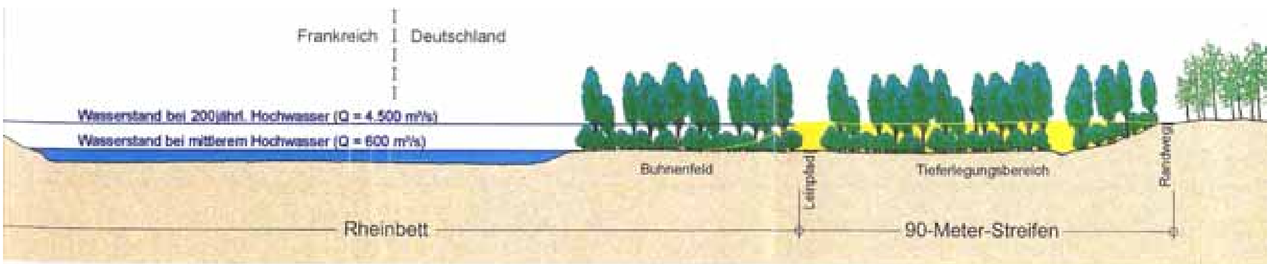
6. Nature rehabilitation and flood protection

6.1 The IRP retention plan

New strategies for nature rehabilitation and flood protection along the Rest Rhine must build upon the existing ideas as described in the current retention plan (GWD, 1998). Within the framework of the Integrated Rhine Program (IRP), a variety of possibilities for the retention of flood and its effects were examined. The results indicate that lowering of the right bank to the height of the groins from Märkt to south of Breisach is the most favourable option (90 meter stripe).

The widening of the Rest Rhine riverbed will be realised by lowering the floodplain by approximately 6 m to the upper edge of the current groins. This will result in a retention capacity of about 25 million m^3. As soon as the vegetation on the lowered grounds develops sufficiently, it will slow down the water in case of floods and realise the necessary retention volume. In this way, new forest vegetation impedes a rash discharge of water and increases the retention capacity. The current vegetation in the groin fields indicates the following opportunities for development of the lowered grounds:

Figure 25: Riverbed widening as proposed in the 90-meter plan that is part of the Integrated Rhine Program on flood protection (source: Gewässerdirection Südlicher Oberrhein/Hochrhein).



- A spontaneous forestation with white willows and black poplars is possible;
- The existing riparian forests of the groin fields provide the necessary airborne dispersal and enable spontaneous regeneration;
- The appearing riparian forests can develop towards ecologically valuable forests without extra management;

- Flooded areas 1,5-2 meters above low water level can produce hardwood floodplain forests with typical tree and bush species.

The lowered area is flooded at a flow levels that exceed 2.000 m^3/s in Basel (600 m^3/s in the Rest Rhine). This flow level occurs approximately 15 days/year.

Technical details

Retention volume	*approx. 25 million m³*
Gravel excavation area	*approx. 400 ha*
Area width	*on average 90 m*
Lowering of the plain	*approx. 6 m*
River stretch	*from Rh-km 174,3 to Rh-km 218,8*
Excavated gravel	*approx. 28 million m³*
Realisation period	*approx. 15 years*

The environmental impact assessment (UVS) and discussions with the local authorities and NGOs have resulted in a detailed demarcation of the area that is to be lowered. Valuable dry biotopes, nature protection areas (NSG) and important infrastructural facilities were largely excluded from this area. Realization of the project will probably take 15 years for two main reasons:

- The river stretch is divided into sections and developed gradually to reduce the annual intervention in nature and landscape;
- Gravel mining has to contribute to the local supply without disturbing the regional gravel market significantly.

Figure 26: The "Isteiner Schwelle" is an eddy that is caused by a geological formation of limestone in the riverbed.

6.2 A new approach: the living river

Immediate realisation of the current retention plan is necessary to guarantee safety and realise flood protection goals. In a next step, measures can be taken to optimise the combination between flood prevention and nature restoration. To this purpose, it is necessary to go one step further than the current retention plan. It is beyond the scope of this report to present a detailed location study. For now, it suffices to present an overview of the main principles of restoring lateral movement and natural rejuvenation.

Lateral movement

Besides widening of the river bed, the process of lateral movement has to be restored as well. Only under these conditions an active and more natural morphology will develop and rejuvenation processes be able to function again. As mentioned above, it is unfeasible to restore the Rest Rhine valley to its original dimensions (Chapter 5). However, there are still areas where there is ample space for riverbed widening by lowering the floodplains, both on the German as well as on the French side. At some places it is possible to broaden the floodplain up to 500 meters or even more. Figures 27 and 29 show the

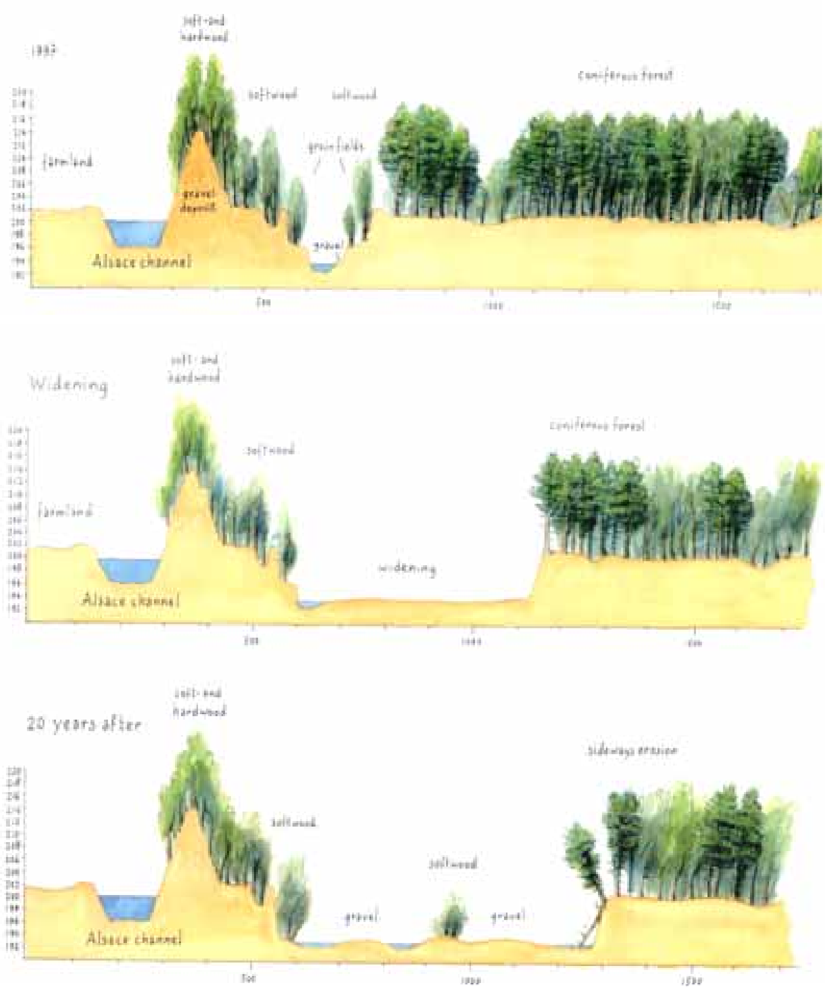


Figure 27: The principles of river widening along the Rest Rhine.

current situation of the Rest Rhine and give an impression of future developments if the river is allowed to flow freely in a widened riverbed.
The removal of the groin fields is necessary to restore lateral movement in the broadened areas. This gives the river the opportunity to move laterally over the newly obtained gravel plains. Floodplain lowering should cut down the floodplain by ca. 6-7 meters. This should result in a gravel plain about 1 to 2 meters above low water levels. Gravel material that deposited in these new plains can be used by the river to create a morphology with different streams, banks and even islands. As a result, different stream patterns, water depths and assorted sediment banks evolve. Pioneer species will be able to find habitats on the new gravel plains and forest will develop on the less dynamic parts of islands and river banks. The excessive streambed dynamics is expected to decrease, offering more space for the settlement of pioneer species and forest. Recurring set back of succession by flood events contribute to the sustainable appearance of pioneer habitats.

Retrieval of sediments

The formation of a heterogeneous morphology depends, among other things, on the availability of sediments, e.g. gravel and sand (Knighton, 1998). Part of this material originates from the broadened gravel plains, but in case of the Rest Rhine gravel can also be supplied by erosion of the steep banks of the floodplain. It provides a gradual but constant influx of new gravel into the river system.
Evidently, the use of gravel can be most effective if erosion occurs in the upstream parts, but also elsewhere steep eroding banks can provide gravel to the new floodplain. Just downstream from the weir near Märkt, the French side offers space for bank erosion. This process occurs already on sites where embankments have been damaged (Figure 28).

Flood protection

To protect downstream areas, it is desirable to slow down the water flow during floods by increasing the retention capacity of the Rest Rhine (GWD, 1997). In the Rest Rhine area itself there is no immediate flooding risk. Erosion of the streambed has deepened the river to a level where inundation of the former floodplains does not occur anymore. It seems plausible to increase water retention in this section of the Rhine Valley. In sustainable flood protection it is important to review river management measures in the perspective of ecological restoration. The Integrated Rhine Program already acknowledges this in its 90-meter plan. It also implicates the important role of riparian forests in reducing peak levels.
Willow and poplar forests have a limited life expectancy and after about 50 years (along the dynamic Rest Rhine probably faster) they start to degrade spontaneously. Although the 90-meter stripe will allow initial forest development, rejuvenation of softwood forest on the long term can expected to be limited. Without new bare soils they may not rejuvenate, leading to less water retention capacity. Apart from ecological and morphological advantages, the moving river-variant has the additional advantage that it allows for forest

renewal on the long term. Some dynamic form of hardwood forest will probably emerge.
Introduction of lateral river movement will lead to continuous development of new germinating grounds for softwood species. Although the location of the forests will vary, the total amount will not decline on the long term. No extra management is needed to maintain the retention effect of the forests.

Figure 28: Where embankments are damaged, the Rest Rhine immediately starts to erode the steep gravel banks, delivering new material to the streambed.

The 90 -meter plan does not allow lateral river movement because it is based upon an international contract between France and Germany, which prescribes that flood retention in this section should be restored within the borders of Baden-Württemberg. To realise a living river that moves laterally, more space is needed on both, the German and the French side. This requires the willingness of Germany and France to allocate more space for nature rehabilitation.

Spontaneous development
Nature rehabilitation by means of restoring the natural geomorphological and ecological processes has to consider the self-restoring capacity of river ecosystems. In the Netherlands, there is already extensive experience with the spontaneous rehabilitation of riverine nature. In these areas, the effects of flooding, groundwater restoration, spontaneous forest (vegetation) development, sedimentation, erosion and natural grazing have led to the return of varied landscapes with hundreds of new species. After river widening, it is not necessary to shape the morphology of the floodplain with machines, to plant trees or arrange other design measures. The idea is that natural processes create a landscape that fits the prevailing geomorphologic conditions.

A coalition with the gravel industry
Current policy in Baden-Württemberg aims at maximising the amount of gravel won per hectare (deep winning instead of superficial winning). Although gravel companies already posses large areas for future mining, nature organisations (NGOs) demand restrictions. They also recommend

Figure 29:
The living
river concept.

Current situation

After excavation

Future situation

measures to compensate the negative impacts of the 90-meter plan on nature. Gravel mining can be a serious threat to the original riverine landscape, leaving nothing but deep water bodies that are uncharacteristic to natural river systems. It is especially the deep winning of gravel that results in limited ecological values after excavation. However, superficial excavation of gravel within the floodplain area, can harmonise gravel excavation with nature rehabilitation and flood prevention in a sustainable way. Ideas for nature development become directional for the gravel excavation. Excavated areas will no longer be "lost areas", but part of a future nature area. This new concept offers the gravel industry a sustainable basis for gravel excavation.

Existing natural values

Widening of the floodplain can conflict with the present natural values of the dry floodplain areas. As described in former chapters, these floodplain areas are the domain of valuable hardwood forests and dry, shrubby grasslands. Many internationally protected species find habitat in these areas (Landesanstalt für Umweltschutz, 2000). It is therefore important to acknowledge where widening is feasible and where natural values demand restraint. Location-specific decisions are necessary regarding the feasibility and form of river widening.

Forestry and agriculture

The concept presented in this report offers a coalition between flood prevention, nature rehabilitation, gravel industry and other economic functions (e.g. recreation and eco-tourism). It makes a clear choice to ban commercial pine forestry and agriculture from the floodplain.
Forestry parcels are found scattered throughout the former floodplain. They are mainly composed of coniferous trees that are planted in straight formations. These forest types offer no serious ecological values. Instead, they prevent the development of a rich fluvial system. Forestry parcels are therefore the first locations that can yield to river widening.
Agriculture has a marginal role in the area. There is some arable land close to the river, mainly on the French side. These agricultural grounds can be transformed into nature areas. The area of natural grasslands and dry (hardwood) forest can be expanded. Gravel excavation can function as the financial motor behind the acquisition or exchanges of arable land. A policy of land purchase in cooperation with the gravel industry seems promising.

International cooperation

The widening of the Rest Rhine river should not only be seen as a concept to increase retention capacity and solve flooding problems along the German side. It primarily is a promising concept for nature rehabilitation and offers interesting opportunities to realise international cooperation between France and Germany.
Rivers are important ecological corridors and are therefore logical areas to include in national ecological structure and the European Ecological Network as described in the Nature 2000 Concept. The Rest Rhine and parts of the floodplain belong to the Nature 2000 area. The Rest Rhine is an important

south-north connection of the European Ecological Network. Cooperation between France and Germany is vital for the realisation and maintenance of this network.

Water distribution

Summer levels of the Rest Rhine are extremely low due to the high water demand of the hydropower plants in the Canal d'Alsace. This results in a retreat of the Rhine (also in its widened form) in one channel during summer. During higher water levels a more braided character is visible.
The extreme differences in water level and hydrodynamics can be harmful to aquatic and terrestrial ecosystems. It is therefore useful to continue efforts to realise a more natural distribution between the Rest Rhine and the Canal. The realisation of higher minimum water levels in summer should have priority in international cooperation.

6.3 Natural rejuvenation "on higher grounds"

The higher floodplains contain, as stated before, valuable areas of natural grassland and hardwood forest. Because the river does not erode and inundate these areas anymore, all hydraulic dynamics have disappeared from these areas. Vegetation succession continues, without any large-scale rejuvenation mechanisms. The living river concept offers ideas that protect the ecological values of the higher floodplains but also introduce rejuvenation dynamics

High-water channels

The presence of natural values in some parts of the higher floodplains precludes the lowering of these areas. However, a more subtle solution than large scale lowering may result in introduction of natural dynamics without endangering the current natural values.
In some parts of the floodplain, parcels of pine trees with a limited ecological value are situated in between hardwood forest and dry grasslands. These spots can be excavated to create side channels leading through the wooded floodplains (figure 29). Besides coniferous forest parcels, present gravel pits may also be included in these gravel channels. Water will use these channels during floods resulting in a meandering channel bed. The dynamics in these side channels will be high and forest development within the channels is expected to be limited. At low water levels, the channel bed will have an open gravel appearance. At high water levels, the water will erode the steep banks of the high-water channels, undermining trees and grasslands on a small scale. This will lead to local natural rejuvenation. Seeds of stream valley plants will fall into the water with the eroded turf layer, to be deposited on new gravel banks elsewhere. Locally, open grassland vegetations will emerge on the flanks of this periodic streambed. The high water channels will act as ecological corridors, connecting the higher dry floodplains with the alluvial zones.

Figure 29: River widening is not desirable because of valuable "Trockenauen", high water channels can be excavated, following the parcels of pine forest. Lateral erosion in de side channel will cause constant rejuvenation along the channel banks. Gravel pits can be integrated in the side channel.

Natural grazing

Grasslands can be preserved and managed by grazing animals or an artificial form of grazing (mowing). Large herbivores are important to keep spots open and throw back succession in less dynamic parts of the floodplain. Not only grazing activities are important. Animals like wild bore, cattle and small burrowing animals also have an impact on the topsoil. In the nature reserve near Griβheim, Wild Bore shrubs turbates the grasslands locally resulting in exposure of the underlying turf. Nonetheless, this turbation is not enough to preserve the grasslands from being overgrown by shrubs and forest on the long term. Rare grassland species are being threatened. Local nature organisations manually remove grass covers and bushes, exposing the open gravel soil (a clear form of artificial rejuvenation). On these locations, specific species can germinate again.

The Rest Rhine floodplains are ideal areas to reintroduce natural grazing on a larger scale. Natural grazing is an important step in slowing down succession and developing a variety of biotopes in riverine areas (Vera, 1997; Ark Foundation 1999). The primary goal of introducing small herds of free roaming herbivores (approximately 1 animal per 5 ha) is not management but re-

Figure 30: Artificial rejuvenation in the grasslands near Grißheim. The turf layer is removed by hand or machine, leading to new possibilities for plants to settle and for pioneer fauna to persist.

introduction of an important natural process. Experiences with wild cattle (resilient cattle races) and wild horse (Tarpan) are good. Red deer can also contribute significantly, but this may conflict with agricultural and forestry interests outside the nature reserve, because they cannot be kept inside normal seized fences. Wild bore, rabbits, foxes and badgers also have an important local impact on the vegetation.
Introduction of large herbivorous animals will also appeal to the general public. People will be able to visit the area, encountering free roaming herds and observe the spectacular impacts of high water levels. Dutch and Belgium experiences show that areas with these "wilderness experiences" rapidly gain status as important nature areas. They are popular and stimulate economic activities in the surrounding areas. If managed correctly, this must not be a threat but serve as a basis to expand the nature areas.

6.4 Recreation/tourism

Recreation and tourism are important for the region between Breisach and Basel. The surroundings of the roads that lead to the bank of the Rhine are used for barbecue, sunbathing and walking. The borderline between the forest and the river also is an important recreational area. The main activities are cycling, walking and camping. Swimming and canoeing along the Rhine bank are of secondary importance. The Rhine bank itself and some groin fields are used for recreation by some hundreds of people during the six months of the summer. The area is attractive because of the adventurous character (e.g. open gravel and sand fields, “wild stream aspects”, sparse willow bushes and riparian forests). The Rhine bank and the groin fields near Istein are an example.
The lowered and widened floodplain will add an extra dimension to nature tourism along the Rest Rhine. Instead of a fixed landscape, people will experience constant changes of gravel islands and stream gullies. Fly-fishing and other outdoor activities will profit from the new developments. The dynamic nature of the moving gravel river will not be particularly vulnerable to disturbance as long as natural processes are allowed. Extensive recreational use of the area is therefore well possible and important to gain support for nature rehabilitation projects in the Rest Rhine area.

6.5 Future plan design and pilot project

This report only offers the wider scope of a nature rehabilitation plan for the Rest Rhine. To realize these ideas a detailed location study has to be made, in which local details are imbedded in a more comprehensive design. Such a study could be financed by German as well as French organisations, supporting the idea of a trans-national project.
At short notice it is possible to start natural grazing with free roaming cattle and wild horses in the area near Griβheim, giving it the status of pilot project and ideal area to inform a broader public about the ideas.

7. Hydraulic calculations

7.1 Description of the hydraulic and morphological Situation

The Rest Rhine between Märkt (Rhine km 176.2) and Breisach (Rhine km 220.0) was severely impacted by the Rhine correction (see Chapter 2.2), leaving a stretched meander with originally trapezoidal cross-sections and an average slope of 0.1%. This was mainly done in order to enable river navigation. Groin fields on alternating sides of approximately 1 km length and 80 m in width were constructed in order to sustain the main channel. The topography and the vegetated banks and groin fields are shown in Annex 7.1.1 and Annex 7.1.2 for the reach between km 209.4 and km 214.4. Over the last decades, a well-developed riparian forest has grown as a consequence of natural succession and sedimentation processes.

The Rest Rhine is hydraulically predominated by the Grand Canal D'Alsace, providing low flow conditions ($Q \approx 30 - 50\ m^3/s$) for most of the hydrological year. The discharge in the Rest Rhine does not rise until the overall upstream discharge exceeds the capacity of the Grand Canal D'Alsace (1400 m^3/s). Under low flow conditions the Rest Rhine riverbed is characterised by an almost smooth gravel surface interrupted by small cascades whose hydraulic effects vanish quickly with rising water levels.

As shown in water level calculations and an accompanying sensitive analysis of the relevant parameters undertaken in the past (Dittrich *et al.*, 2000), the extent of the vegetated groin fields has a major influence on the water levels in the Rest Rhine and hence predominates the hydrodynamics in the river reach.

Due to the Grand Canal D'Alsace and the relatively few and short times of high flow, an armoured layer has formed in the main streambed, leaving bed load sediments. The sieve analysis data in Figure 7.1 show the shift and rise of the gradation curve between sub-layer (red line) and armoured layer (blue line). As was documented by Dittrich *et al.* (1998), the stability of the armoured layer is best estimated with the approaches of Günter (1971) for the case of maximum bed stability or Parker and Klingeman (1982) for an intermediate state of stability, and is approximately $\tau_{0c} \approx 70 - 80\ N/m^2$. The presence of vegetation on the groin fields extremely increases the stability of the natural floodplains, where dense vegetation decelerates the flow and acts as sediment trap for suspended sediments, forming sand and silt banks along and within the groin fields.

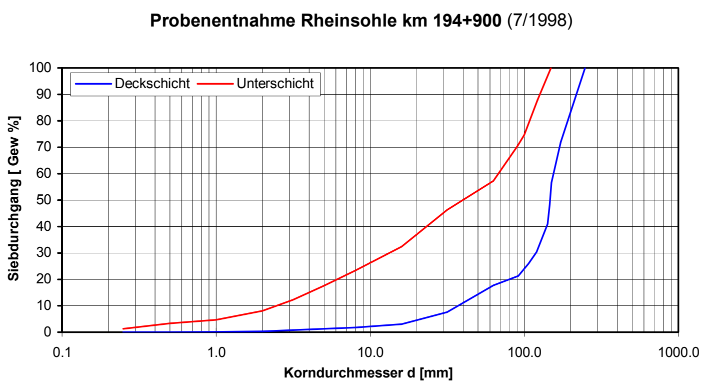


Figure 7.1: Sieve curves of bed material sample at km 194.9 of the Rest Rhine.

7.2 Numerical Modelling of Hydraulic Conditions

One and three-dimensional numerical methods can be applied to predict the flow properties in the relevant reaches of the Rest Rhine. The data generated are essential to evaluate both, flood protection and the hydrodynamic environment to ensure development of natural vegetation. One-dimensional methods can predict the water surface with a sufficient precision and the stage discharge data can be used in order to calculate the retention volume. Three-dimensional methods however, are necessary when the flow is expected to possess fully three-dimensional flow properties, e.g. for sudden expansions or contractions in cross-sectional areas or for channel curvature. Moreover, in this project the turbulent flow properties near the channel bed (velocities and bed shear stresses) are needed to predict the geomorphology in the channel and on the floodplains qualitatively and to enable ecologists to assess whether certain types of riparian forest vegetation are likely to survive and resist the hydrodynamic forces. In order to accomplish this, a robust and reliable turbulence model as well as a fully three dimensional vegetative flow resistance closure are essential.

In this study, a reach of approximately 5km in length between Rhine km 209.87 and Rhine km 214.6 was selected in order to predict the hydraulic and morphological consequences of the reference image as introduced previously (Chapter 6). The methodology applied is as follows:

1. Evaluation of the present situation and determination of flow resistance values from field investigations;
2. Calibration of the flow resistance values on the basis of two selected high flow events where water level data were available;
3. Transfer of the resistance values and modelling of the future situation following the reference image of the Rest Rhine outlined in Chapter 6.2;
4. Comparison and analysis of the results with respect to retention effects and dynamic river morphology and further morphologic developments.

7.2.1 Numerical Model and Boundary Conditions

The applied CFD code solves the discrete form of the basic equations of incompressible, Newtonian fluid flow for the conservation of mass and momentum i.e. the continuity and the Navier-Stokes equations. The discretisation in space is accomplished with the finite volume method, where the complex bathymetry is split into a finite number of control volumes with a curvilinear co-ordinate system. A second order implicit three-time-level scheme is employed for time discretisation. Convective and diffusive terms are modelled using second order upwind scheme or central differencing schemes, respectively.

For practical open channel flows, the conditions can be considered as turbulent. Turbulence is a property of the flow and tends to three-dimensional unsteady eddy-structures, which remove kinetic energy from the flow and split into infinitesimal small structures dissipating the kinetic energy into heat energy (Rodi, 1980). In order to account for turbulence it is best to average the fluctuations over a certain period of time and employ the k-ε model to compute the increased eddy viscosities (Stoesser, 2001).

For the simulation of a channel flow, four distinctive boundaries have to be considered: inflow, outflow, free surface and wall boundaries. Along impermeable walls the no-slip condition applies. Roughness of rain and bed represent the boundary roughness of natural riverbeds and are responsible for the boundary layer. The extension of the log-law including the sand grain roughness k_s to account for bed friction is included in the code (Stoesser, 2001). The hydraulic resistance effects of submerged aquatic vegetation is accounted for by usage of a drag force approach, which is included as sink terms into the Navier-Stokes equations (Fischer-Antze *et al.*, 2001). Since a subcritical flow situation is modelled, the inflow boundary conditions consist of prescription of the discharge; a fixed downstream water level comprises the outflow boundary condition. An interface tracking method is used to represent the free surface boundary (Stoesser, 2001).

7.2.2 Evaluation of Present Situation - Calibration

To discretise the topography of the existing situation, a fairly high-resolution mesh was chosen with the computational grid comprising of 13,392 finite volumes (Q=1450 m^3/s) and 16,740 (Q=3040 m^3/s) finite volumes, respectively. Details of the modelled reach and the numerical setup are given in Table 7.1.

Table 7.1: Channel geometry and simulation details.

Length of River Reach *[m]*	*≈5000*
Discharge *[m^3/s^{-1}]*	*1450/3040*

Average River Width *[m]*	*≈165/180*
Turbulence Closure	*k-ε model*
Roughness Closure	*Two-Layer no-slip+ Drag Force*

The sand grain roughness k_s was determined by using sieve analysis data. The average curve of the sampled bed material of the river Rhine is presented in Figure 7.2.

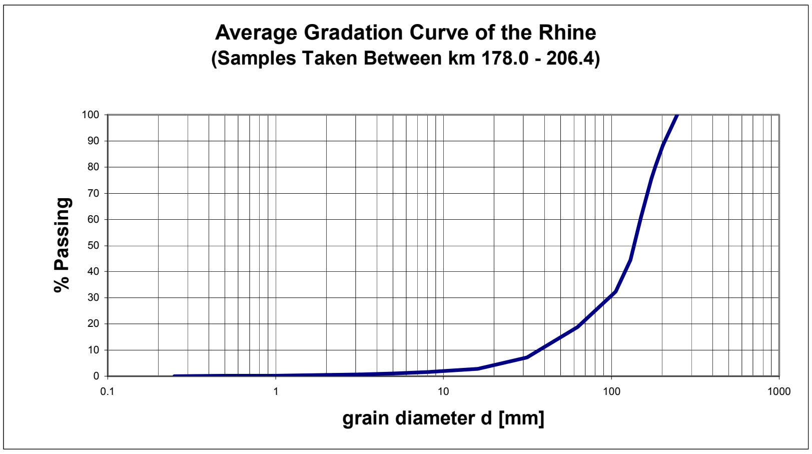


Figure 7.2: Average gradation curve of the Rhine south of Breisach (km 178 - 206).

The equivalent sand grain roughness varies between $k_s = 0.31$ and $k_s = 0.67$ depending on the employed conversion formula (Table 7.2).

Table 7.2: Sandgrain roughness and Strickler value of main channel as suggested by different authors.

	d [mm]	Author	k_s [m]	k_{st} [$m^{1/3}/s$]
d_{65}	*155*	Engelund / Hansen [1966]	*0,310*	*32*
d_{84}	*192*	Hey [1979]	*0,672*	*28*
d_{50}	*136*	Mertens [1997]	*0,340*	*31*
d_m	*129*	Dittrich [1998]	*0,451*	*30*

The vegetative resistance coefficient λ_P was determined, following the concept recommended by the German Association for Hydraulic Engineering (DVWK,

1990) with the help of Figures 7.3, Figure 7.4 and on the basis of the following formula:

$$\lambda_P = c_s \cdot \frac{A_P}{a_x \cdot a_y} \qquad \textbf{(7.1)}$$

where A_P is the momentum absorbing plant area of the vegetation (Figure 7.3) and a_x and a_y are two characteristic lengths (Figure 7.4):

- a_x := mean distance of vegetational elements in streamwise direction;
- a_y := mean distance of vegetational elements in cross-streamwise direction.

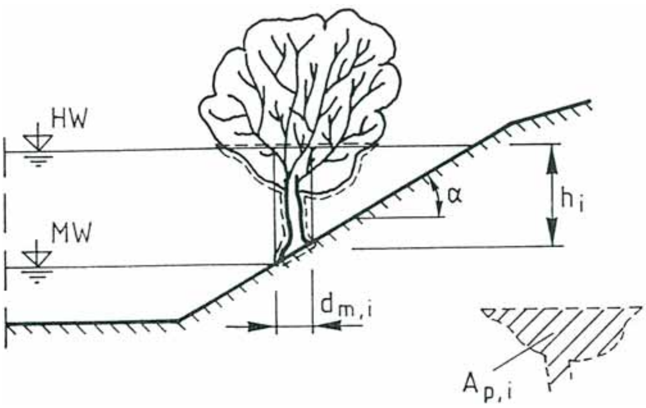


Figure 7.3: Definition of momentum absorbing area.

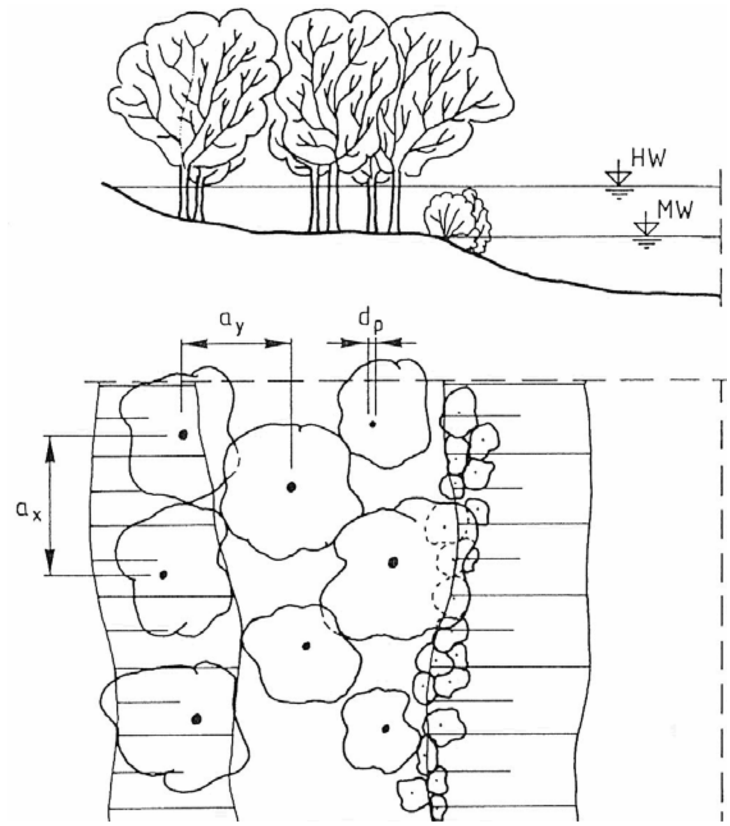


Figure 7.4: Relative location of vegetative elements in the flow domain.

Photo's 1 and 2 show the riparian vegetation prevailing in a representative groin field along the Rest Rhine.

(1)

(2)

Photo's 1 and 2: Floodplain riparian forest vegetation within the groin field near Bad Bellingen at km 191+300 (Dittrich *et al.*, 1998).

For several selected test sites along the Rest Rhine, 8 different types of riparian forest were identified and the typical values of momentum absorbing area of the different plant types and their relative locations were quantified (Dittrich *et al.*, 1998). Figure 7.5 shows an example of a monitored patch of *77 m* x *45 m*.

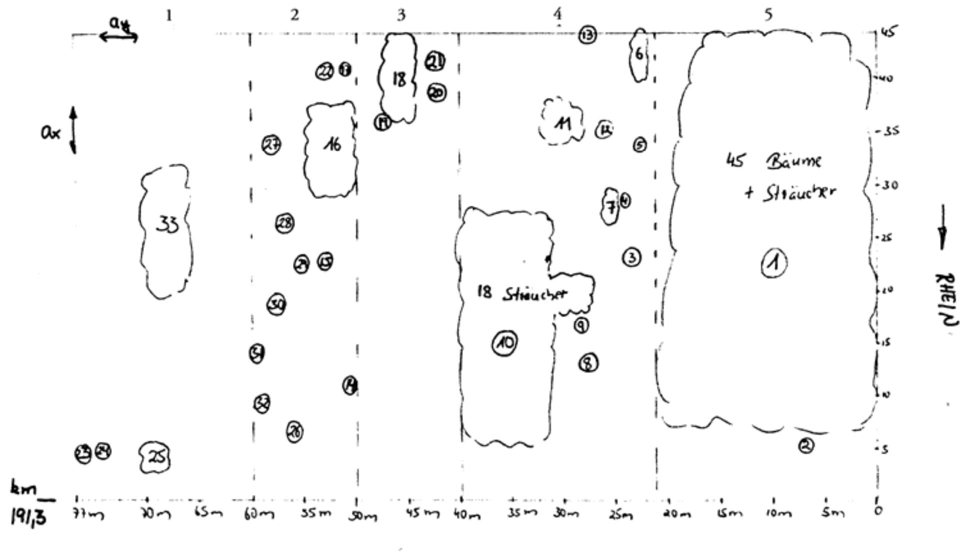


Figure 7.5: Quantification of riparian forest vegetation in the groin field near Bad Bellingen (Dittrich *et al.*, 1998).

Model Calibration

Field work and the resultant parameterisation of hydraulic resistance values can only provide estimates of bed and vegetative roughness. To ensure a reliable prognosis the flow resistance parameters have to be independently calibrated at two different scenarios for which water level observations are available. The two selected high flow scenarios to calibrate the CFD code are:

- HQ-Fixing (29.5.94) with Q = 3040 m³/s;
- HQ-Fixing (4.11.98) with Q = 1450 m³/s.

The bed roughness and vegetative roughness parameters are then modified in order to match observed water levels for both events. The equivalent grain roughness that represents the bed roughness has been determined to be k_s = 0.51 m for the discharge Q = 3040 m³/s and k_s = 0.34 m for Q = 1450 m³/s and is found to be in the area of those suggested in the literature (Table 7.2). The vegetative roughness coefficient λ_p is far more uncertain and hence it was decided to use a constant value for both discharges. A value of λ_p =0.024 was selected, which corresponds to Vegetation-Type 5 (i.e. "Durchforsteter Weiden-Pappelwald-Plenterphase=thin stand of willow and poplar with various stages" with a_x =5.2, a_y =9.5 and A_p =1.19) and which matches the riparian forest vegetation prevailing in the selected model-reach of the Rest Rhine. It has to be noted that the selected roughness value of λ_p =0.024 is significantly lower than that corresponding to Figure 7.5, which is classified as Vegetation Type 8 (Mischbewuchs) with λ_p =0.11. However, previous investigations (Stoesser, 2000; Dittrich *et al.* 2000a) showed that the dominating factor on the water levels and hence on the hydraulics is the extent of vegetated groin fields rather than the exact value of bed roughness and vegetative roughness.

As can be seen in Figures 7.6 and 7.7, a good match between observed and calculated water levels was achieved with the calibrated flow resistance values.

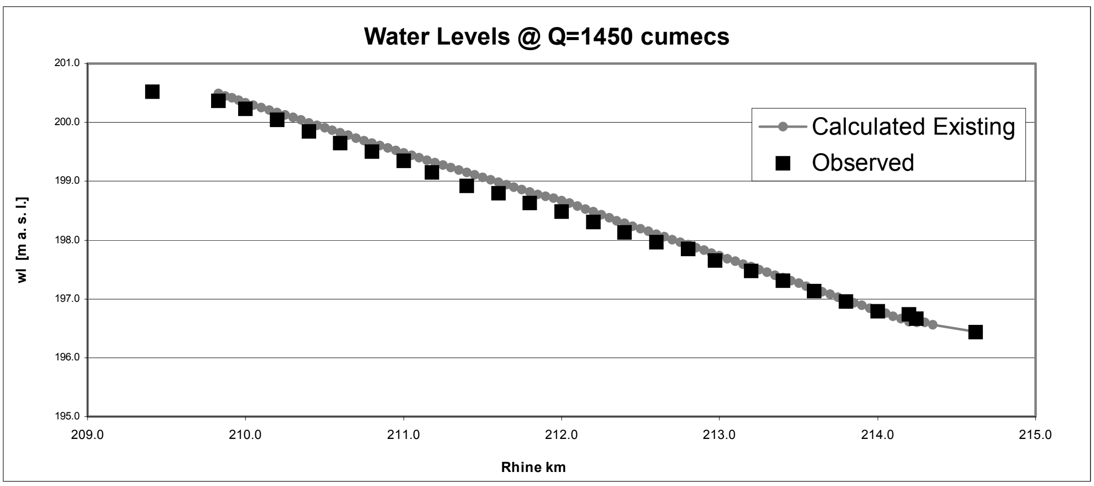


Figure 7.6: Calculated and observed water levels at Q=1450 m³/s.

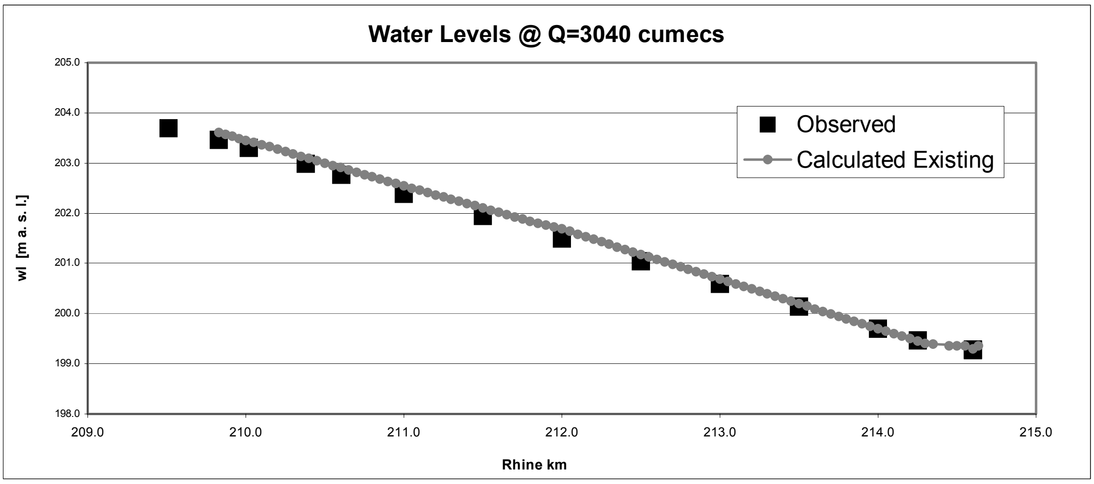


Figure 7.7: Calculated and observed water levels at Q=3040 m^3/s.

The calculations of the existing situation show similar near bed velocities for both discharges (Appendix 7.1.3 and 7.1.6). The presence of alternating vegetated groin fields accelerates the flow in the main channel. For the discharge of Q = 3040 m^3/s, near surface velocities above 4.0 m/s can be observed (Appendix 7.1.7). The bed shear stresses in the main channel are approximately $\tau_0 = 40 - 50$ N/m^2 at Q = 1450 m^3/s and $\tau_0 = 80 - 100$ N/m^2 at Q = 3040 m^3/s. Consequently the above mentioned critical value of $\tau_{0,crit}$ = 70 N/m^2 is exceeded at the higher discharge. It follows from the calculations that for discharges above Q = 3000 m^3/s the armoured layer will be destroyed and massive geomeorphological changes will take place. This, however, corresponds very well with observations after the 1999 flood, where a maximum discharge of Q = 3700 m^3/s was recorded. A field visit after the 1999 stormwater event in the Rest Rhine showed that morphodynamic changes occurred in the Rest Rhine reach as a consequence of that event (Dittrich *et al*, 2000b).

7.2.3 Assessment of Future Situation - Application

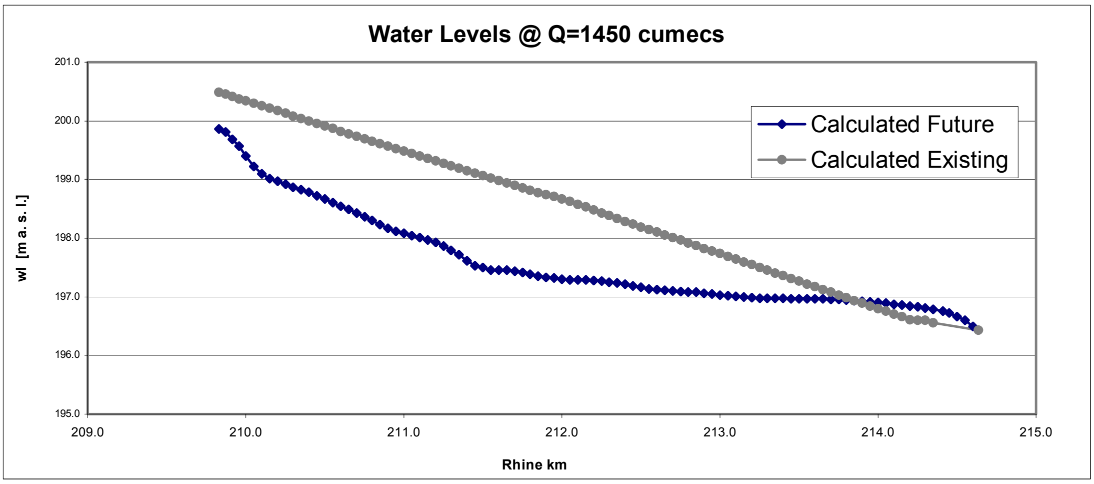
The topography of the future situation (Annex 7.2.1) and the matching vegetation zoning (Annex 7.2.2), which follow the reference image introduced above, are discretised in a finite volume mesh consisting of 39,285 finite volumes (Q=1450 m^3/s) and 42,777 (Q=3040 m^3/s) finite volumes, respectively. Details of the modelled reach and the numerical set-up are given in Table 7.3. The roughness parameters are the same as the calibrated ones, corresponding to a gravel bed river with riparian forest vegetation on gravel banks and floodplains.

Table 7.3: Channel geometry and simulation details.

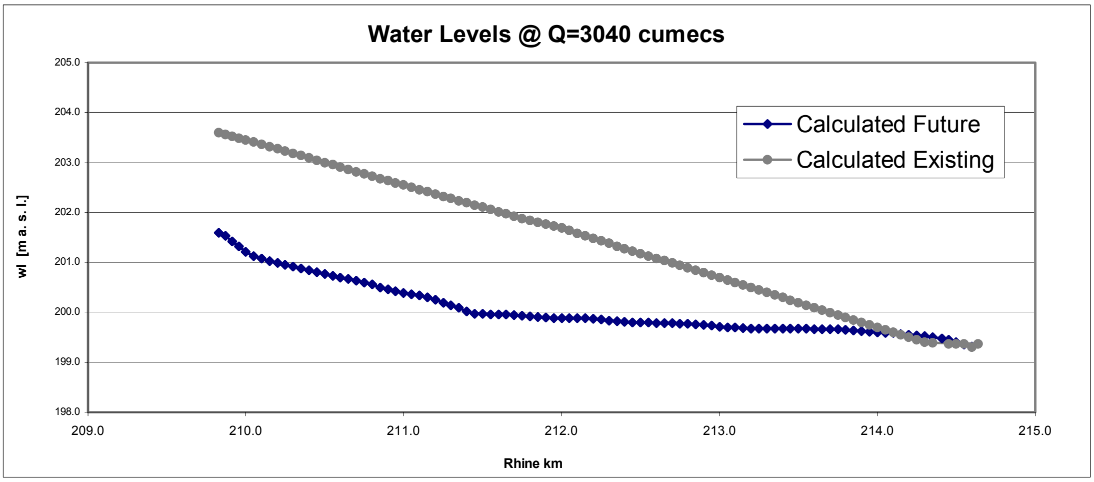
Length of River Reach *[m]*	*≈5000*
Discharge *[m^3/s^{-1}]*	*1450/3040*
Average River Width *[m]*	*≈460/480*
Turbulence Closure	*k-ε model*
Roughness Closure	*Two-Layer no-slip+ Drag Force*

Retention Effect

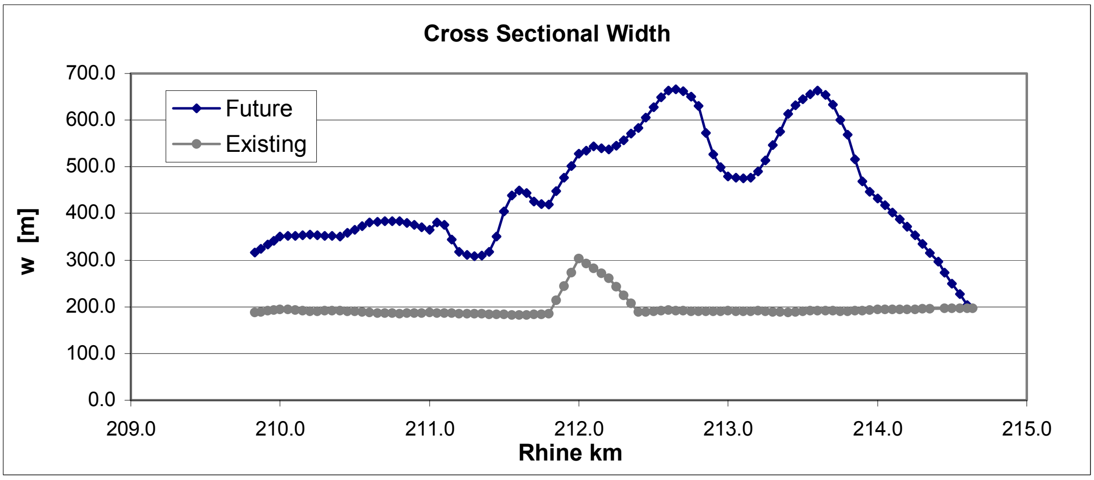
Figures 7.8 and 7.9 below show the comparison of water levels between existing and future situation at the selected discharges. It is evident that the increased cross-sectional width (see Figure 7.10) influences the water levels in the selected reach. The deceleration of the flow in the big widening between Rhine km 212.0 and Rhine km 214.0 results in an almost horizontal water level at both discharges and a decrease of water depth of maximal 2 m.



Figures 7.8: Calculated water levels for existing and future situation at Q=1450 m^3/s.

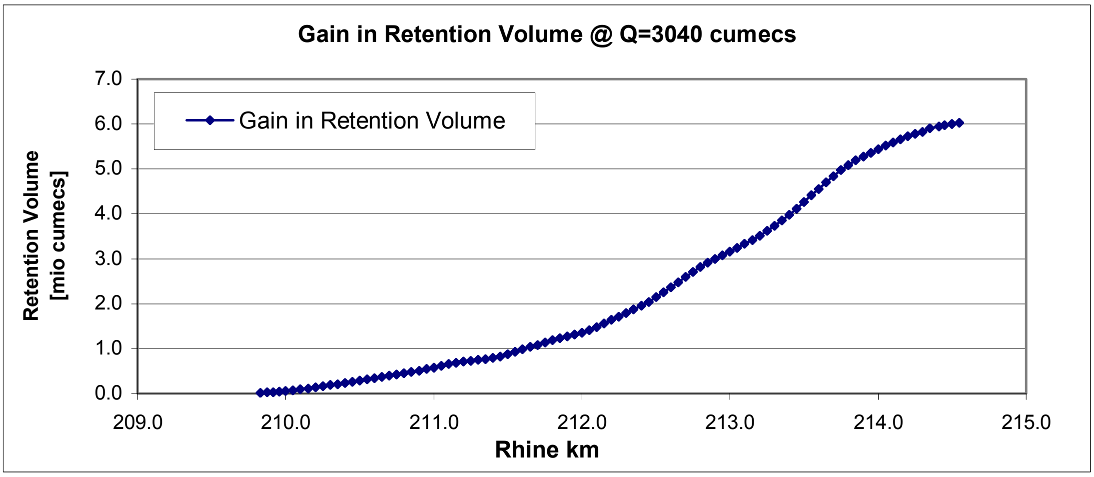


Figures 7.9: Calculated water levels for existing and future situation at Q=3040 m^3/s.



Figures 7.10: Cross sectional width for existing and future situation.

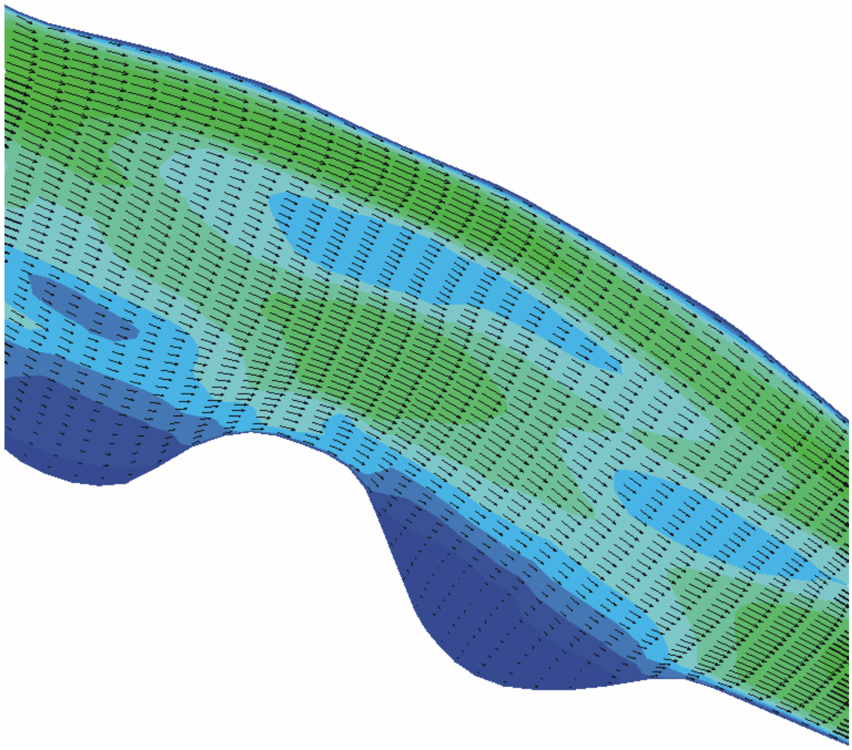
Figure 7.11 shows the effect of the high diversity in the topography and riparian forest vegetation on the retention volume at Q = 3040 m^3/s. A total of 6 million cubic meters of retention volume could be gained for the proposed variant. However, as can be seen from Figure 11 the bulk of retention growth (4 million cubic meters) can be achieved between Rhine km 212,0 and Rhine km 214,0, were the reach is characterized by the wide floodplains with a great extent of vegetation in the proposed areas.



Figures 7.11: Gain in retention volume at Q = 3040 m^3/s for the proposed variant.

Hydraulic Effect

Annexes 7.2.3 and 7.2.4 show the impact of the future topography and vegetation distribution on the hydrodynamics in the selected river reach at Q=1450 m^3/s. The near bed velocities and the near surface velocities in the main channel are reduced by approximately 40% in the section of the 90 m stripe and by approximately 60% in the section of the wide floodplain. The high flow scenario with Q=3040 m^3/s displays the effect of increased cross sections with a great vegetational extent accordingly (Annexes 7.2.6 and 7.2.7). However, the vegetated gravel banks in the stream and the vegetated floodplains ensure that the flow is relatively diverse across the channel, even with reduced flow velocities (Figure 7.12).

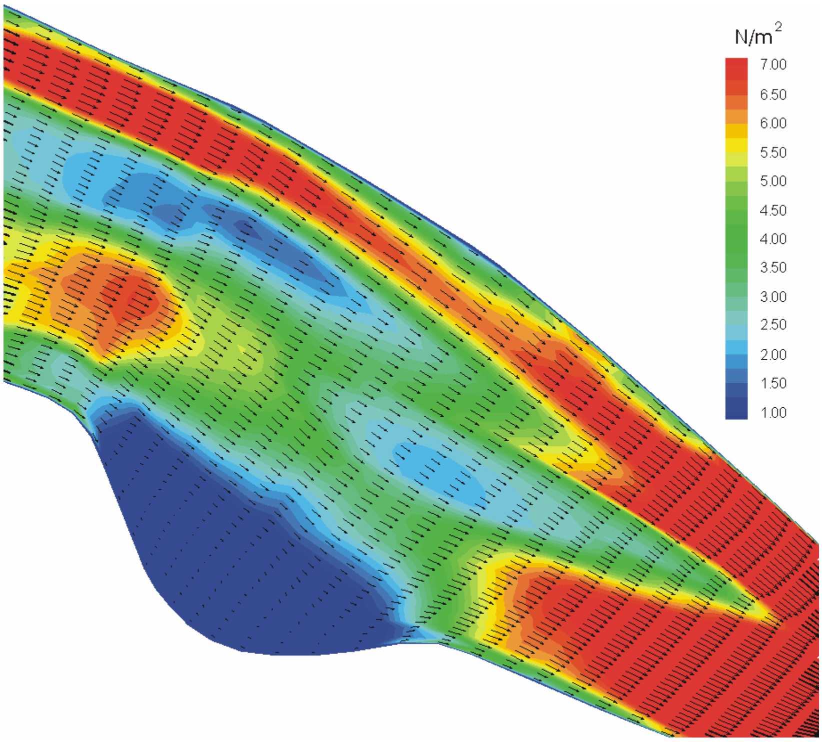


Figures 7.12: Near Surface vector distribution in the large channel widening at Q=3040 m^3/s.

Decreased river hydrodynamics yields to decreased shear stresses as shown in Annexes 7.2.4 and 7.2.8, where the distribution of shear stresses is depicted. As can be seen in Annex 7.2.4, the shear stresses in the main channel and in the side channel are approximately $\tau_0 = 6 – 8$ N/m² at Q = 1450 m³/s. Slightly increased shear stresses prevail for the higher discharge of Q = 3040 m³/s, being approximately $\tau_0 = 8 - 10$ N/m². The simulations also show that there is apparently no flow dynamics on gravel banks in wide cross sections, with shear stresses dropping below $\tau_0 = 1$ N/m².

Geomorphologic Effect

As mentioned above, the shear stresses are substantially decreased for the future situation. The geomorphological consequences are reduced transport capacity of the flow. As was reported by Dittrich *et al.* (1998), the critical shear stress of loose gravel in the Rest Rhine is $\tau_{0,crit} \approx 14$ N/m². Consequently, loose gravel is transported from upstream into the reach, as the shear stresses are $\tau_0 = 25 - 30$ N/m² for both discharges (Annex 7.2.5 and 7.2.8). However, in the wide floodplains (Rhine km 212 – 214) shear stresses are below that critical value of $\tau_{0,crit} \approx 14$ N/m² and the loose gravel will be deposited. Furthermore, the fine suspended sediments transported in the river will be trapped on the vegetated gravel banks and floodplains. Finer portions of the bed load material (fine gravel) can be deposited in the side channel and block the channel, as the flow dynamics reduce with increased cross-sectional width (Figure 7.13).



Figures 7.13: Near bed vector and shear stress distribution in the large channel widening at $Q=3040\ m^3/s$.

Thus the new armoured layer in the new main channel will consist of much finer material, as the shear stresses are reduced by a factor of 3.
As was shown previously by Stoesser (2000), the apex angle of the pockets on the new floodplains plays an important role on the horizontal secondary currents. A steeper apex angle yields to recirculation zones, where suspended sediments can settle and fill up these pockets with fine material. Here the apex angle of the first pocket is smaller than the apex angle of the second pocket. The recirculation pattern can be observed in Figures 7.14 and 7.15.

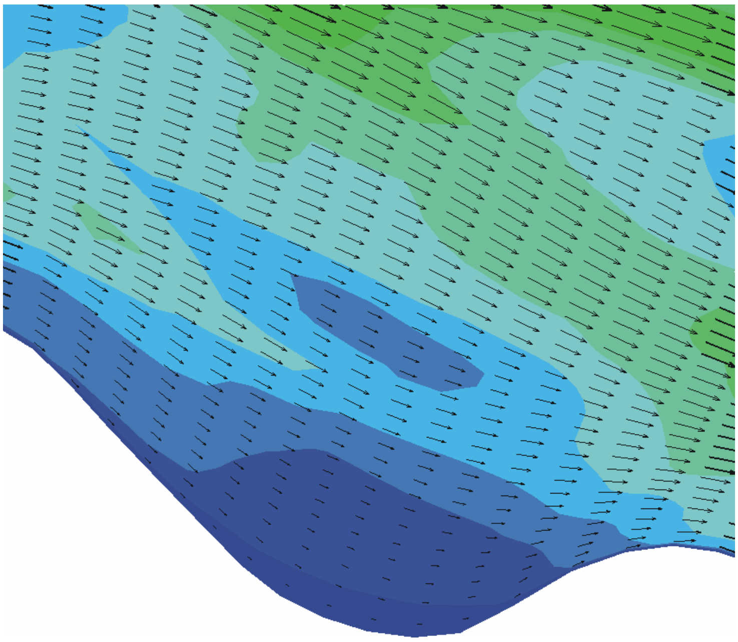


Figure 7.14: Near surface velocity and vector distribution of the first pocket.

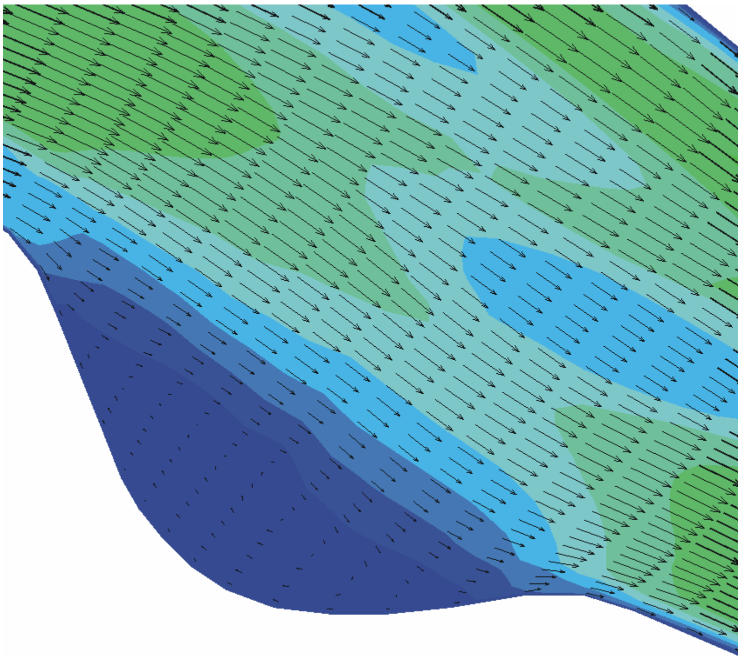


Figure 7.15: Near surface velocity and vector distribution of the second pocket.

8. Summary

8.1 Introduction

Both from a technical and socio-economic context the German, French and Swiss part of the Rhine differ significantly from the Dutch situation. This chapter therefore focuses on these upstream parts of the Rhine where flood prevention has to be designed differently from the downstream situation. Artificial forms of cyclic rejuvenation are not an appropriate strategy along these upstream parts, since here large areas of the river floodplain are already naturally covered with floodplain forest (often with high natural values). In these parts of the river retention appears the most sustainable flood prevention method. Here flood prevention and nature rehabilitation can be combined. This can be done through restoring natural rejuvenation processes along the Rest Rhine. In co-operation with the University of Karlsruhe the University of Nijmegen has developed a plan were widening of the Rest Rhine could lead to restoration of vital hydro-morphological processes and the characteristic habitats of a dynamic gravel river (see Peters *et al.*, 2001).

8.2 Historical Perspective

Nowadays the Rhine is the connecting river between the Alps and the North Sea. The Rhine in this form exists for about 500,000 years. The current floodplain is only 8000 years young and arose after the melting of the ice-aged Alps-glacier. Although the Rhine has in the area of the Upper Rhine Valley already gone through a long incline - and here in its centre-course meander conditions could be expected - he forms 3 different river course types on a relatively short running course: zone of furcation, zone of transition and a meandering zone. These circumstances are due to the tectonic feature of the Upper Rhine Valley. The zone of furcation reaches from Basel to approximately south of Altenheim (near Strasbourg) and shows a fall of about 1°/00 on average (compared with 0,3°/00 in the meandering zone). Consequently the former area of the "Rheinauen" between Basel and Breisach is part of the furcation. Morphologically it is a flat plain leaning to the North, with a geological bottleneck near the rock massif of the "Isteiner Klotz" (near the village of Istein).
Through the Upper Rhine correction of Tulla (1817 to 1880) the wild stream was, which was split in numerous branches, combined in a single bed. The balance between land and water changed in favour of the land. Especially the alluvial waters of the southern Upper Rhine were silted up or separated from the Rhine. The gravel banks and more than 2000 islands in the Upper Rhine almost completely disappeared. At the same time measures for reclamation of

land and drainage were carried out, banks were reinforced and a continuous dike system was constructed. As a result the area that potentially could be flooded became smaller. Due to the building of dikes about 660 km^2 got lost on the stretch from Märkt (near Basel) to Karlsruhe and another 80 km^2 because of depth erosion of the Rhine bed. This amounts to a total of 74% of the natural flood area (IKSR, 1989).
The Rhine bed south of Breisach strongly eroded. Leading to the present situation where the river, even in the case of a 200-year flood (equivalent of 4.500 m^3/s), only bursts its banks at some points. Because of the drainage of 1.400 m^3/s by the Canal d'Alsace, a canal running parallel to the Rest Rhine (build between 1932-1959), the water level in the Rhine fell even further. Today the water level is up to 7 metres deeper than originally.
As a consequence the groundwater level has dropped considerably and is not available for the former floodplain's vegetation. Together with the falling groundwater level the side channels disappeared, the alluvial vegetation died and the amount of animals depending on this vegetation decreased. Species resistant to this arid environment could expand and new species colonized the former floodplains. Today, due to its diversity in flora and fauna, the area holds a lot of valuable biotopes (e.g. orchids and insects).

The current Rest Rhine lacks any lateral movement. The river bed is excessively dynamic, allowing no normal development of vegetation. The elevated hardwood floodplain forest areas are not inundated any more and river dynamics only allow a "one-way succession". Therefore only certain elements and zones of the system are well developed. Inundation free forest and grassland areas contain most of the ecological values (Landesanstalt für Umweltschutz, 2000). Also, the river bed and groin fields offer habitat to riverine nature, but in a deteriorated form. Many zones, like higher open gravel banks (small gravel), erosion banks and groundwater influenced side channels are not present.

8.3 The Border Meuse Project as inspiration

The Border Meuse Project is a trans-boundary project (Netherlands/Belgium) that combines nature development, flood protection and gravel excavation along the river Meuse. The concept of the Border Meuse plan is to widen the river as much as possible by removal of the top layer of the floodplain sediment (Figure ..). Depending on the available room and the position of villages, the dimensions of widening can differ strongly per location. In this new broadened bed the river can move laterally again and is able to use the new sediments to rebuild its stream bed. Locally new gravel islands, banks, sand levees and stream gullies will be able to develop. Spontaneous development of riparian forest, pioneer habitat and stream valley grasslands will lead to a new nature area of more than a 1000 ha.

8.4 The moving-river variant

Based on experiences of the Border Meuse project and taking the specific characteristics of the Rest Rhine into account, the following measures are selected for restoration of the Rest Rhine:

1. Widening of the floodplain area by gravel excavation.
2. Allowing lateral movement and bank building in the river bed.
3. Allowing lateral erosion on specifically chosen sites.
4. Increase of minimum water discharge.
5. Natural vegetation development within the floodplain.
6. Removal of embankments and groins in the widened sites.

1. Widening of the floodplain area

Certain parts of the Rest Rhine have possibilities for widening, by lowering the floodplain. It is possible to broaden the floodplain locally up to 500 meters or even more.

2. Lateral movement

The process of lateral movement has to be restored as well. Lateral movement is essential to restore natural morphology and activate rejuvenation processes. In the widened areas the groin fields should be removed to restore lateral movement. Floodplain lowering should cut down the floodplain by ca. 6-7 meters. This should result in a gravel plain about 1 to 2 meters above low water levels. The gravel material in these new plains can be used by the river to build a morphology with different streams, banks and even islands. As a result different stream patterns, different water depths and river banks evolve. Pioneer species will be able to find habitats on the new gravel plains and forest will develop on the less dynamic parts of islands and river banks. In total this will result in a decrease of dynamics in the streambed, offering more space for the settlement of pioneer species and forest. Recurring set back of succession by flood events will maintain pioneer habitats.

3. Allowing lateral erosion: retrieval of sediments

The formation of a varied morphology depends, among other things on the availability of sediments(Knighton, 1998);the Rest Rhine's sediments consist of gravel and sand. Both the (broadened) gravel plains and the steep flanks of the floodplain supply these sediments ensuring a constant influx of new gravel into the river system. Evidently, the use of gravel can be most effective if erosion occurs in the upstream parts, but also elsewhere steep eroding banks can provide gravel to the new floodplain. Just downstream from the weir near Märkt, the French site offers room for erosion of the banks. At present side erosion already takes place on sites were embankments have been damaged.

4. Increase of minimum discharge

As a result of the hydropower plants in the Canal d'Alsace, summer levels of the Rest Rhine are extremely low. Therefore the Rhine may (also in its widened form) retreat in one channel during summer, although during higher discharge a more braided character is visible. The extreme differences in water level and hydrodynamics can be damaging for both the aquatic and terrestrial ecosystem. It is therefore useful to continue with efforts to arrange a more natural distribution between the Rest Rhine and the Canal. Especially a higher summer minimum should be the aim in international co-operation.

5. Natural vegetation development within the floodplain

Softwood forests only colonise open soils. If no bare soils are created softwood forests will collapse in time. On higher ground in the floodplain a transition to hardwood forest is possible but in the lower parts development will result in a more open forest type with a higher rate of rough vegetation. A free river (i.e. not fixed) guarantees continuous development of open gravel and sand banks. This allows a sustainable presence of forest and consequently ensures the retention in the long run.

6. Removal of embankments and groins in the widened sites

By removing the groins and allowing lateral movement as described above, not only sedimentation but also erosion will take place. Sedimentation banks will be cleared away in time. Therefore a certain equilibrium in the retention volume can be expected and technical maintenance measures will be reduced to a minimum.

Relation with flood protection

There is no flood risk in the Rest Rhine area itself, but to protect downstream populated areas it is desirable to slow down the water during floods by increasing the retention capacity of the Rest Rhine (GWD, 1997). The measures proposed above have the desired effect for downstream areas. Retention in the Rest Rhine is achieved by delaying the flood wave and accommodating the extra water volume in the area. Widening the floodplain of the Rest Rhine provides both the storage capacity and the extra hydraulic roughness needed for the retention. The roughness is caused by the development of natural vegetation. Numeric effects of the plan on the retention-capacity are described in § 4.6.

A coalition with the gravel industry

Up till now gravel mining was considered a serious threat to the original riverine landscape, leaving nothing but deep water bodies behind, alien to natural river system. Superficial excavation of gravel though, within the floodplain area may connect gravel excavation with flood prevention and nature rehabilitation in a more sustainable way. It offers both a financial base to obtain areas for river widening and the technical means to do so.

Forestry and agriculture

Flood prevention through nature rehabilitation, using the gravel industry and other economic values (recreation, eco-tourism and living) as starting points also excludes commercial forestry and agriculture from the floodplain. Agriculture has a marginal role in the area. There is some arable land mainly on the French side. Forestry parcels are found scattered throughout the former floodplain. They contain mainly coniferous trees, planted in straight formations. This kind of forests offer no serious ecological values. Instead, they prevent the development of a rich fluvial system. Therefore forestry parcels form good locations for river widening. Also agricultural grounds can be converted to nature areas. Gravel excavation can function as the financial motor behind the acquisition of land.

8.5 Calculated effects on water retention

In this study a reach of approximately 5km in length between Rhine km 209. 87 and Rhine km 214.6 has been selected in order to predict the hydraulic and morphological consequences of the reference image as introduced in chapter 6.2. The methodology applied is as follows:

5. Evaluation of the present situation, determination of flow resistance values from field investigations.
6. Calibration of the flow resistance values on the basis of two selected high flow events where water level data were available.
7. Transfer of the resistance values and modelling of the future situation following the reference image of the Rest Rhine introduced in Chapter 6.2.
8. Comparison and analysis of the results with respect to retention effects and dynamic river morphology and further morphologic developments.

To solve the task, a 3D numerical model (Stoesser 2001) was applied to the situation described previously.

The calculations clearly show the effect of the high diversity in the topography and riparian forest vegetation on the retention volume at $Q = 3040\ m^3/s$. A total of 6 million cubic meters of retention volume could be gained for the proposed variant. However, the bulk of retention growth (4 million cubic meters) can be achieved between Rhine km 212,0 and Rhine km 214,0 only, were the reach is characterized by the wide floodplains with a great extent of vegetation in the proposed areas. The near bed velocities and the near surface velocities in the main channel are reduced by approximately 60% in the section of the wide floodplain. However, the vegetated gravel banks in the stream and the vegetated floodplains ensure that the flow is relatively diverse across the channel, even though with reduced flow velocities.

Decreased river hydrodynamics yield to decreased shear stress. Thus, the shear stresses in the main channel and in the side channel are approximately $\tau_0 = 6 – 8\ N/m^2$ at $Q = 1450\ m^3/s$. Slightly increased shear stresses prevail for the higher discharge of $Q = 3040\ m^3/s$, being approximately $\tau_0 = 8 - 10\ N/m^2$. This is a tremendous reduction in the shear stress compared to the initial situation, where τ_0 – values of 90 N/m^2 and more were obtained for a discharge of $Q=3040\ m^3/s$. The high shear stresses result in high morphological changes of the river bed with critical τ_0 – values of 70 to 80 N/m^2 for the amour layer and $\tau_{0,\ crit} = 14\ N/m^2$ for the loose gravel material. Furthermore, the simulations also show that there is apparently no flow dynamics on the gravel banks in the wide cross sections, where the shear stresses drop below $\tau_0 = 1$ N/m².

The fine suspended sediments transported in the river will be trapped on the vegetated gravel banks and floodplains. Finer portions of the bed load material (fine gravel) can be deposited in the side channel and block the channel, as the flow dynamics reduce with increased cross-sectional width. As was shown previously by Stoesser (2000), the apex angle of the pockets on the new floodplains plays an important role on the horizontal secondary currents. A steeper apex angle yields to recirculation zones, where suspended sediments can settle and fill up these pockets with fine material. In contrast, the fine material (silt, sand) can possibly be transported through the upstream pocket with a smaller apex angle than the downstream one.

Literature

Ark Foundation, 1999. Natural grazing. Study by order of World Wildlife Fund. Ark Foundation, Laag Keppel.

Baldner, 1666. Fisch- und Tierbuch.- Herausgegeben von R. Lauterborn. Ludwigshafen, 1903.

Butler, D.R., 1995. Zoogeomorphology; animals as geomorphic agents. Cambridge University Press, Cambridge.

Dittrich, A., Hartmann, G. (1998). Untersuchungen zum Vorlandabtrag zwischen Maerkt und Karpfenhod. Sclussbericht. Institut für Wasserwirtschaft und Kulturtechnik. Universitaet Karlsruhe.

Dittrich, A., Hartmann, G. (1998). Untersuchungen zum Vorlandabtrag zwischen Maerkt und Karpfenhod. Sclussbericht. Institut für Wasserwirtschaft und Kulturtechnik. Universitaet Karlsruhe.

Dittrich, A., Hartmann, G., Traebing K. (2000a). Rückhalteraum Weil-Breisach Bewertung der morphologischen und hydraulischen Auswirkungen der Hochwasserereignisse 1999 im Rhein zwischen Maerkt und Breisach. Sclussbericht. Institut für Wasserwirtschaft und Kulturtechnik. Universitaet Karlsruhe.

Dittrich, A., Hartmann, G., Traebing K. (2000b). Rückhalteraum Weil-Breisach Bewertung der morphologischen und hydraulischen Auswirkungen der Hochwasserereignisse 1999 im Rhein zwischen Maerkt und Breisach. Teil B. Analyse und Dokumentation der morphologischen Veraenderungen infolge des Hochwassers Mai 1999. Sclussbericht. Institut für Wasserwirtschaft und Kulturtechnik. Universitaet Karlsruhe.

DVWK. (1991). Hydraulische Berechnung von Fließgewaessern. Merkblaetter. 220/1991. Verlag Paul Parey. Hamburg und Berlin.

Fischer Antze, T., Stoesser, T., Bates, P.B., Olsen, N.R. (2001). 3D Numerical Modeling of Open-Channel Flow with Submerged Vegetation. Journal of Hydraulic Research. Vol. 39. No. 3.

Gerken, 1988. Auen – verborgene Lebensadern.- Verlag Rombach Freiburg.

Günter, A. (1971): Die kritische mittlere Sohlenschubspannung bei Geschiebemischungen unter Berücksichtigung der Deckschichtbildung und der turbulenzbedingten Sohlenschubspannungsschwankungen. Diss. Nr. 4649, Inst. f. Hydromech. u. Wasserwirtschaft ETH Zürich, Zürich.

GWD, 1997. Rückhalteraum südlich des Kulturwehres Breisach – Tieferlegung des 90-Meter-Streifens.- Faltblatt der GWD Südlicher Oberrhein/Hochrhein

GWD, 1998. Rückhalteraum südlich des Kulturwehres Breisach – Tieferlegung des 90-Meter-Streifens.- Entwurf des voraussichtlichen Untersuchungsrahmens zum Raumordnungsverfahren.

Helmer et al., 1991a. Toekomst voor een grindrivier (Future of a gravel rivier). 10 volumes. Study by order of the Province of Limburg, Maastricht.

Helmer, W. Ecologisch toetsingskader voor de Border Meuse.
IKSR, 1989. Aktionsprgramm Rhein – Internationale Kommission zum Schutz des Rheins gegen Verunreinigung. Koblenz.
IWACO/CSO/WL, 1998. MER-Border Meuse; deelrapport 2: rivierkunde. Study by order of the Maaswerken (Province of Limburg), Maastricht.
Knighton, D., 1998. Fluvial forms and processes; a new perspective. Published by Arnold, London.
Landesanstalt für Umweltschutz, 2000. Vom Wildstrom zur Trockenaue; Natur und Geschichte der Flusslandschaft am südlichen Oberrhein. Published by Landesanstalt für Naturschutz Baden-Württemberg, Karlsruhe. Verlag Regionalkultur, Ubstadt-Weiher.
Lauterborn, 1917. Die geographische und biologische Gliederung des Rheinstromes II: Der Oberrhein.- Sitz. Ber. Heidelb. Akad. Wiss. Math.-nat. Kl. Band 5; S. 3-70.
Looy, K. & Peters, B., 2000. Bosontwikkeling en morfodynamiek langs de Border Meuse. Natuurhistorisch Maandblad, 89-7, pp. 137-142.
Ministerium für Umwelt Baden-Württemberg, 1988. Hochwasserschutz und Ökologie- Ein Integriertes Rheinprogramm schützt vor Hochwasser und erhält naturnahe Flussauen.
Oberrheinagentur, 1996. Rahmenkonzept des Landes Baden-Württemberg zur Umsetzung des Integrierten Rheinprogrammes. Materialien zum Integrierten Rheinprogramm, Band 7.
Parker, G., Klingeman, P.C. (1982): On why gravel bed streams are paved. Water Resources Research, Vol. 18, No. 5, S. 1409 –1423.
Peters, B, K. van Looy & G. Kurstjens, 2000. Pioniervegetaties langs grindrivieren: de Allier en de Border Meuse. Natuurhistorisch Maandblad, 89-7, pp. 123-136.
Rheingräntzkarte, 1838. Karte vom Lauf des Rheins – Oberdirektion 1951.
Rodi, W. (1980). Turbulence Models and their Applications in Hydraulics. IAHR Monograph Series. A.A. Balkema, Rotterdam, Brookfield.
Schepers, F. & M. Kerkhofs, 1994. De Allier, referentierivier voor de Border Meuse? Projectbureau Border Meuse/RIZA, Maastricht/Arnhem.
SEPNMC (Societe pour l'Etude et la Protection de la Nature dans le Massif Central), 1981. Riviere Allier. Nature Vivante, n° special.
Stoesser, T. (2000). Rückhalteraum Weil-Breisach. Validierung des Hydrodynamisch Numerischen Verfahrens an den Hochwasserereignissen 1999. Sclussbericht. HYDRO.
Stoesser, T. (2001). Development and Validation of a CFD Code for Open-Channel Flows. PhD Thesis. Department of Civil Engineering. Bristol University.
Thorn, C.R., 1998. Stream reconnaissance handbook; Geomorphological investigation and analysis of river cahnnels. John Wiley & Sons, Chichester.
Vera, F., 1997. Metaforen voor de wildernis: Eik, Hazelaar, Rund Paard. Ministry of agriculture, Nature Management and Fishery, The Hague.
Von Kettner, 1849. Darstellung der ornithologischen Verhältnisse des Großherzogtums Baden. Freiburg.

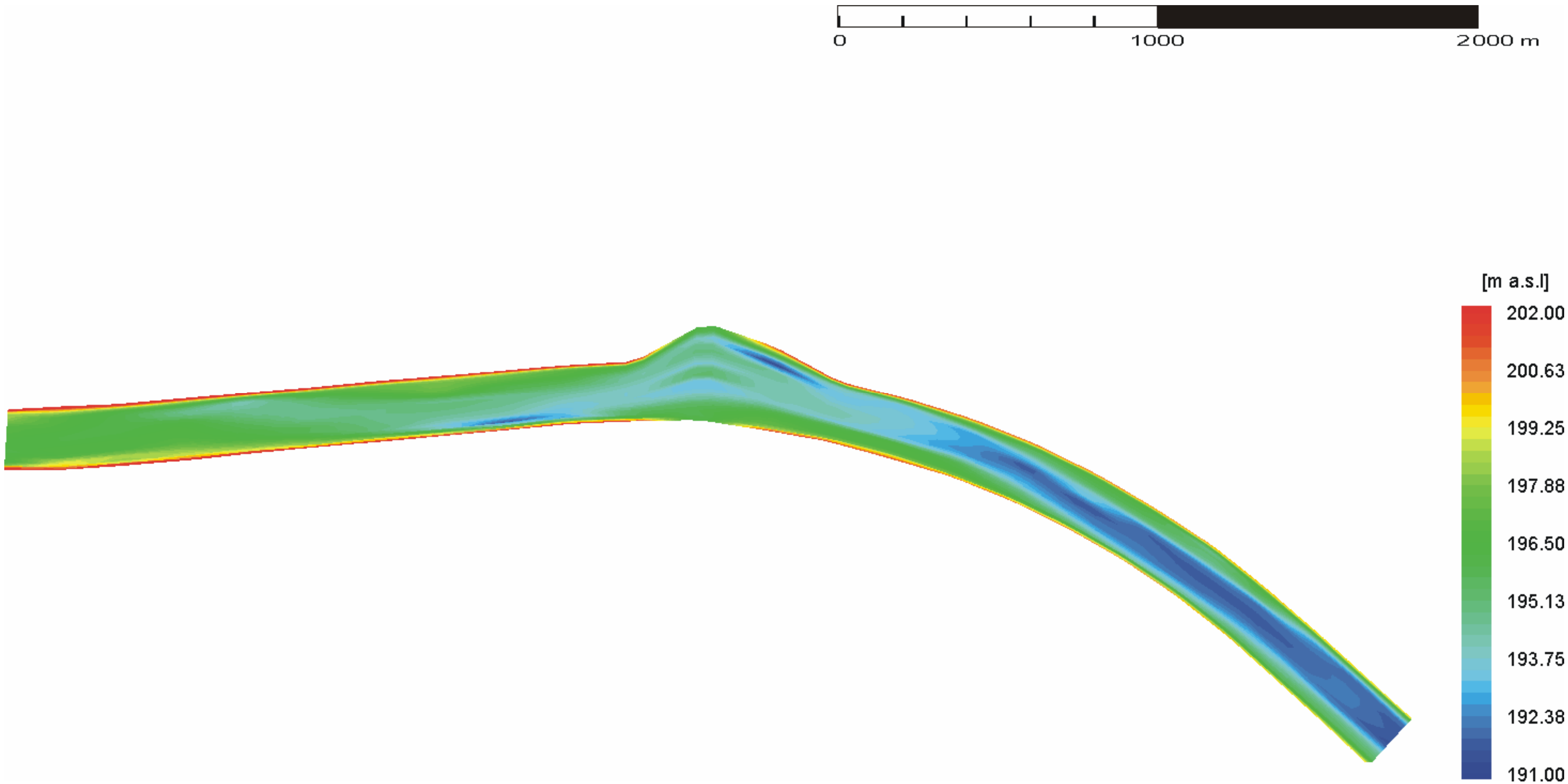
Appendix 1. Reports of the IRMA-SPONGE program CFR project

1. Duel, H., M.J. Baptist & W.E. Penning, 2001. Cyclic floodplain rejuvenation: a new strategy based on floodplain measures for both flood risk management and enhancement of the biodiversity of the river Rhine. IRMA-SPONGE program, CFR project main report, NCR-report 14-2001, Delft.
2. Duel, H., M.J. Baptist & W.E. Penning, 2001. Cyclic floodplain rejuvenation: a new strategy based on floodplain measures for both flood risk management and enhancement of the biodiversity of the river Rhine. IRMA-SPONGE program, CFR project executive summary, NCR, Delft.
3. Baptist, M.J., 2001. Review on biogeomorphology in rivers: processes and scales. IRMA-SPONGE program, CFR project report 3. Delft University of Technology.
4. Glasbergen, M.J., 2001a. Fish habitat requirements in the Dutch part of the river Rhine. IRMA-SPONGE program, CFR project report 4. WL | Delft Hydraulics.
5. Nijhof, B.S.J., 2001. Vegetation succession in floodplain flats. Inventarisation and modelling of measured data and expert judgement. IRMA-SPONGE program, CFR project report 5. Alterra, Wageningen.
6. Geerling, G.W., B. Peters & A.J.M. Smits, 2001. Development of floodplain ecotopes in the Netherlands (Rhine tributaries). IRMA-SPONGE program, CFR project report 6. University of Nijmegen.
7. Lee G.E.M. van der, H. Duel, W.E. Penning & B. Peters, 2001. Modelling of vegetation succession in floodplains. IRMA-SPONGE program, CFR project report 7. WL | Delft Hydraulics, University of Nijmegen.
8. Asselman, N.E.M., 2001. Sediment processess in floodplains. IRMA-SPONGE program, CFR project report 8. WL | Delft Hydraulics.
9. Mosselman, E., 2001. Morphological development of side channels. IRMA-SPONGE program, CFR project report 9. WL | Delft Hydraulics.
10. Stone, K., Baptist, M.J., 2001. Effects of hydraulic measures and nature development in the Gelderse Poort. IRMA-SPONGE program, CFR project report 10. WL | Delft Hydraulics.
11. Baptist, M.J., 2001. Numerical modelling of the biogeomorphological developments of secondary channels in the Waal river. IRMA-SPONGE program, CFR project report 11. Delft University of Technology.
12. Glasbergen, M.J., 2001b. Fish habitat modelling in the Gamerensche Waard. IRMA-SPONGE program, CFR project report 12. WL | Delft Hydraulics.
13. Kerle, F., F. Zöllner, B. Kappus, W. Marx & J. Giesecke, 2001. Fish habitat and vegetation modelling in floodplains with Casimir. IRMA-SPONGE program, CFR project report 13. IWS University of Stuttgart.

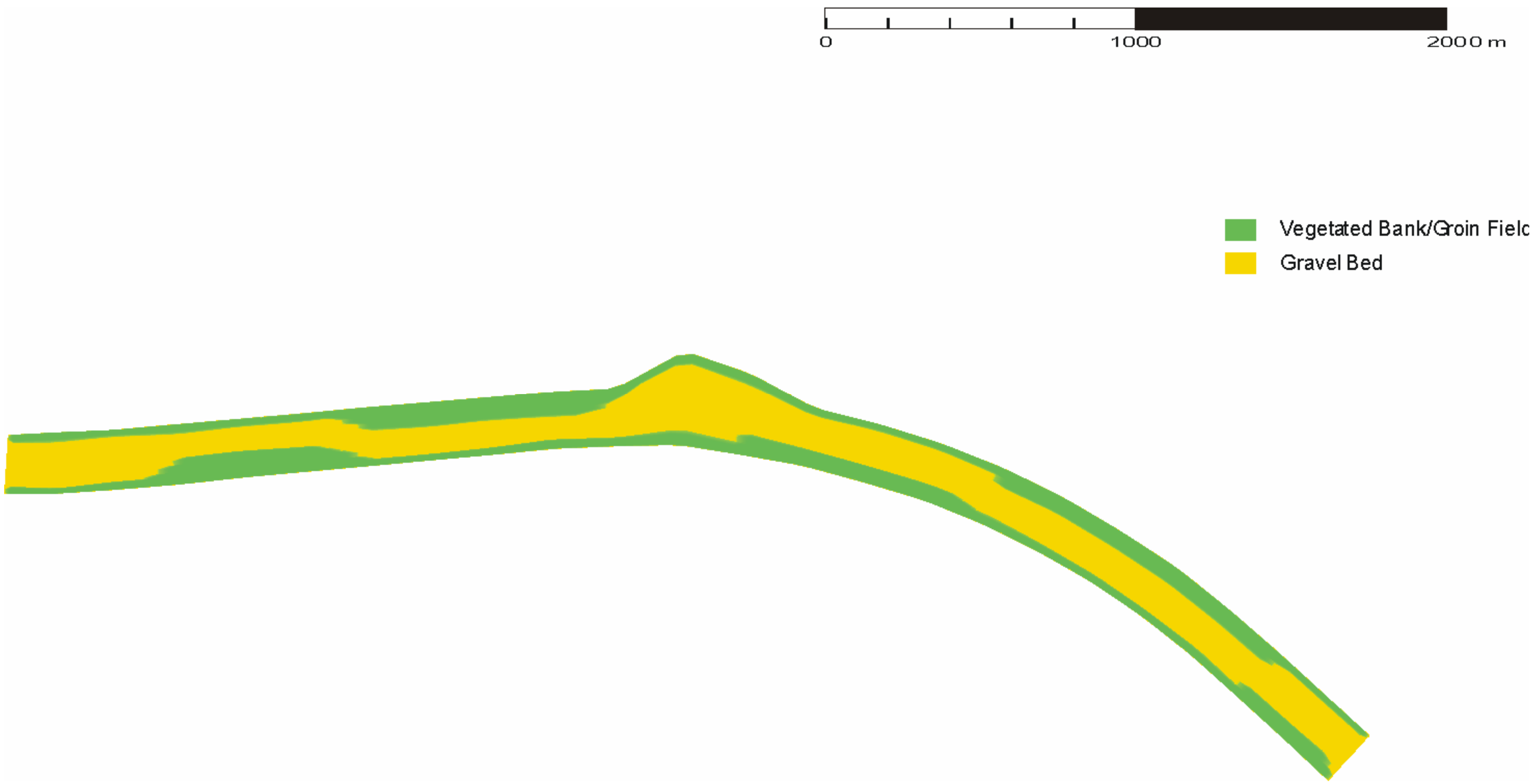
14. Peters, B., A. Dittrich, T. Stoesser, G.W. Geerling & A.J.M. Smits, 2001. The Rest Rhine: future chances for nature rehabilitation and flood prevention. IRMA-SPONGE program, CFR project report 14. University of Nijmegen, University of Karlsruhe.
15. Lee, G. van der, M.J. Baptist, M. Ververs & G.W. Geerling, 2001. Application of the cyclic floodplain rejuvenation strategy to the Waal river. IRMA-SPONGE program, CFR project report 15. WL | Delft Hydraulics, Delft University of Technology, University of Nijmegen.

Annexes

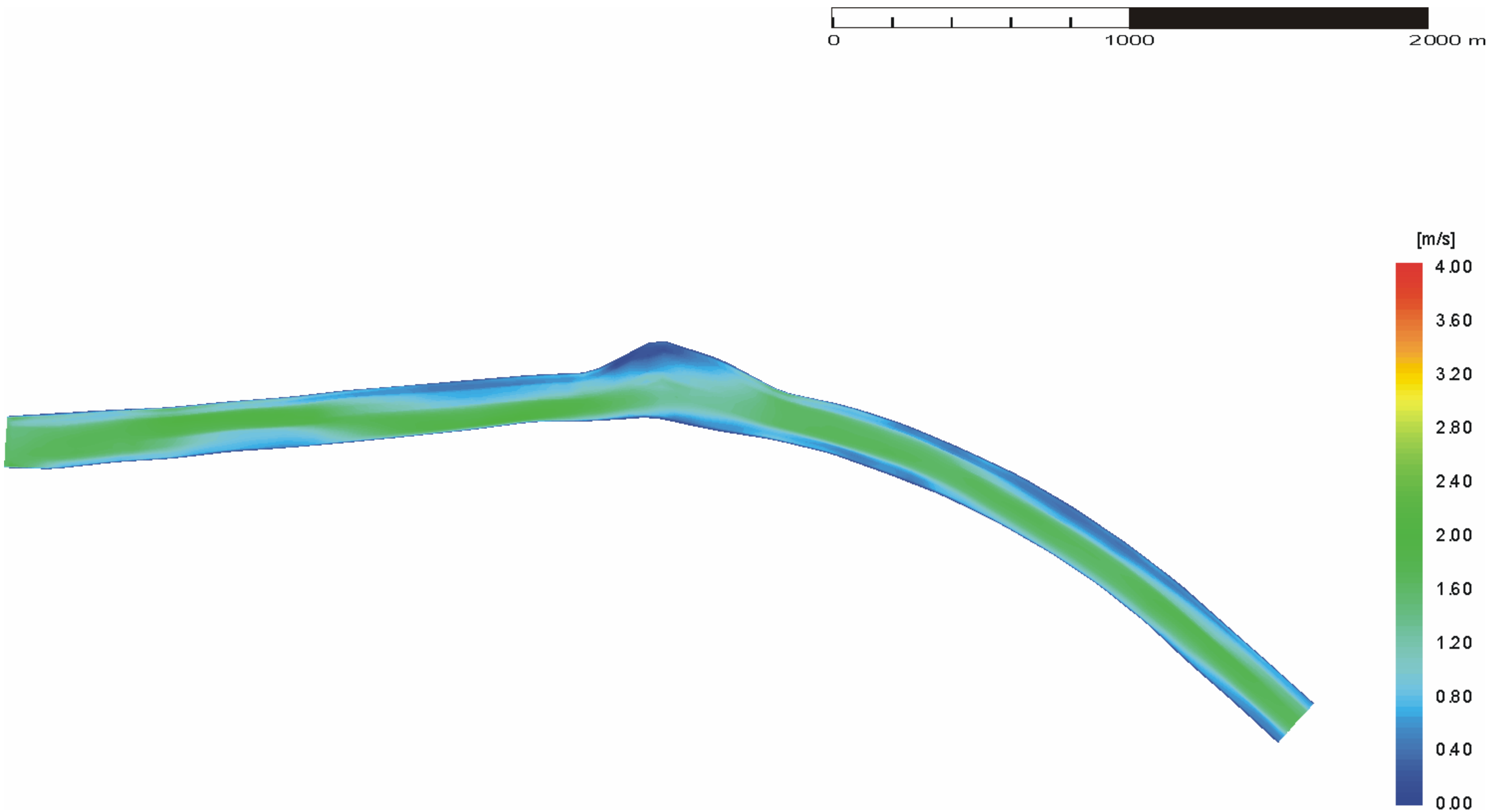
List of Annexes:



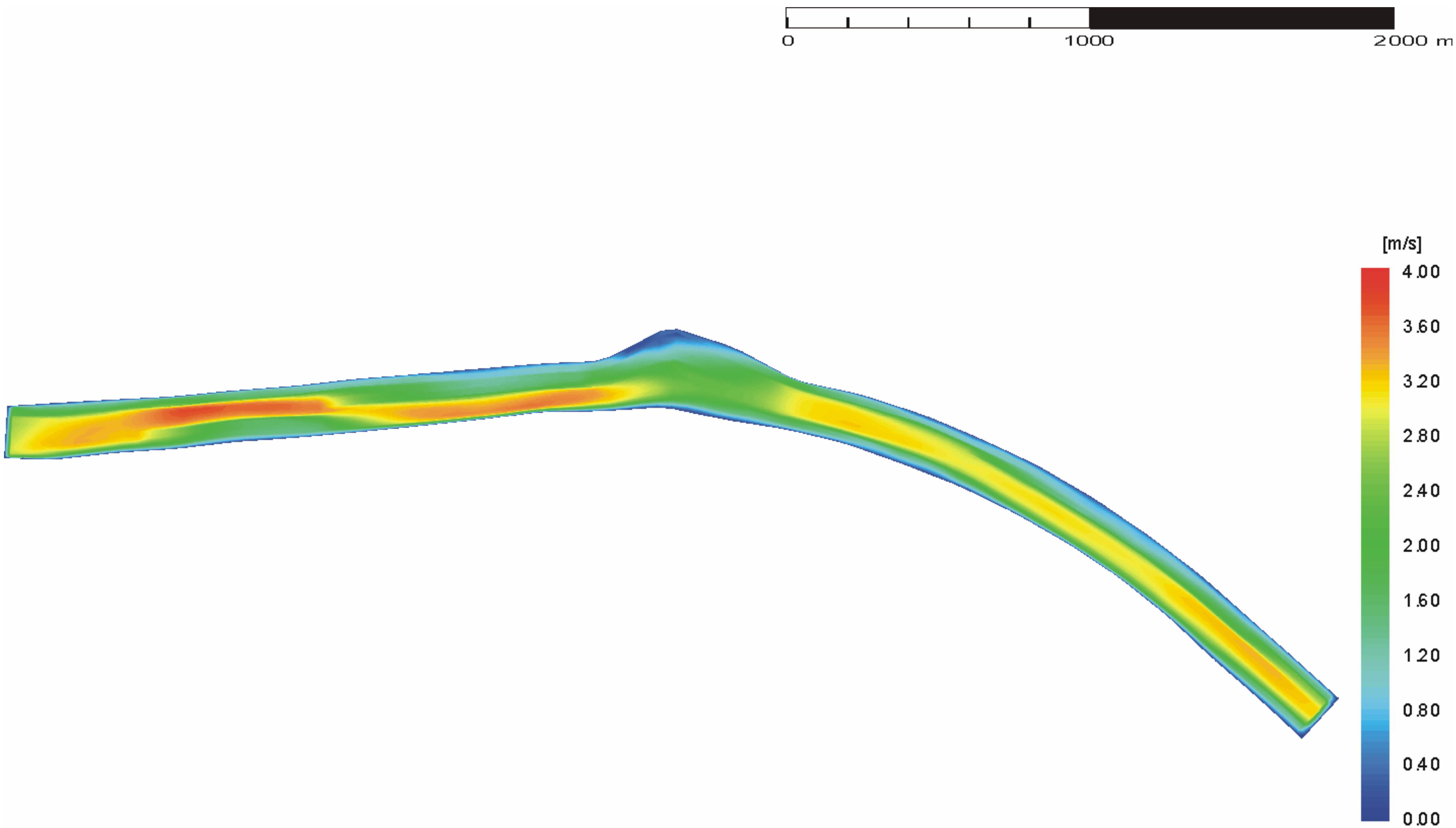
Annex 7.1.1: Topography: Existing Situation



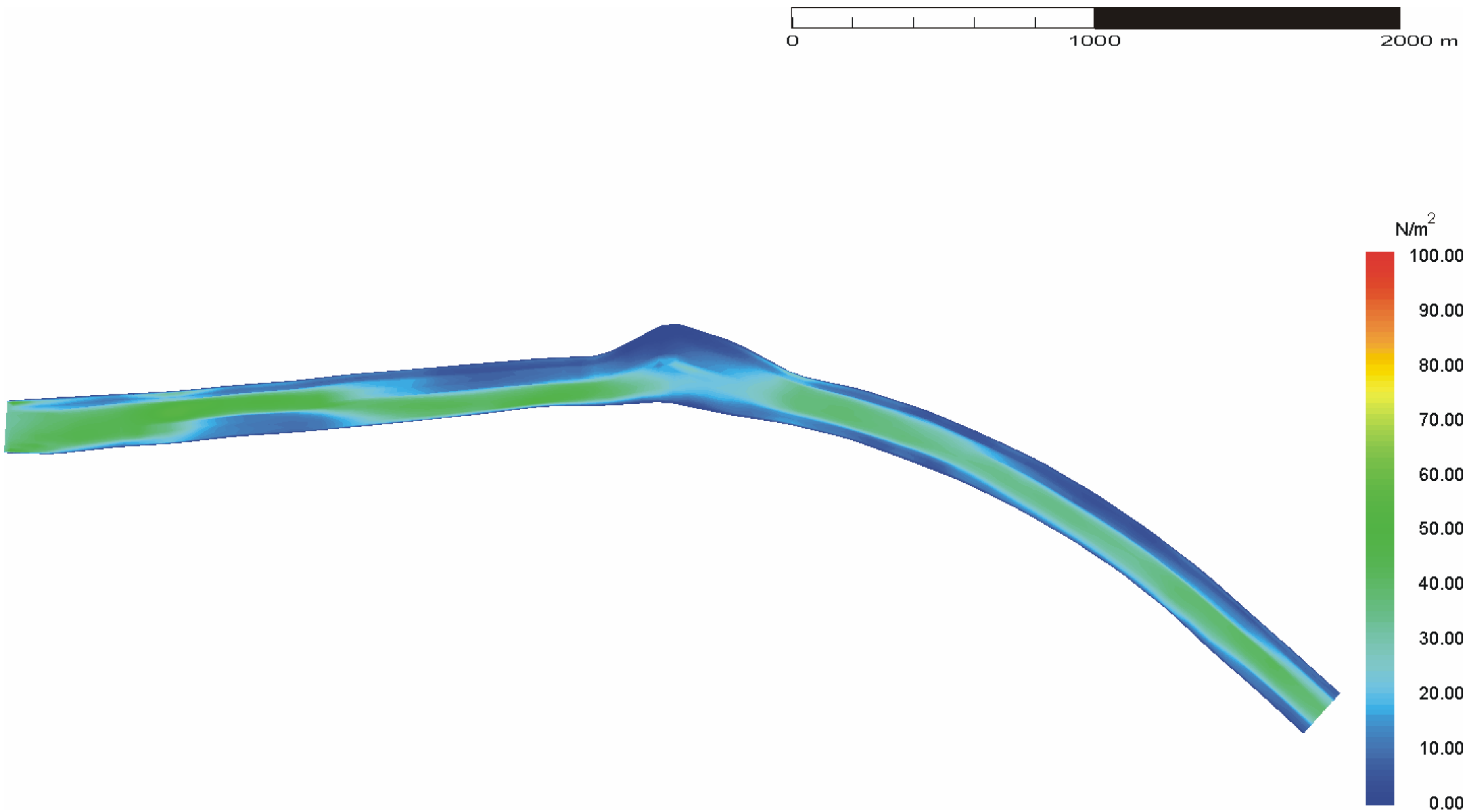
Annex 7.1.2: Distribution of Bank and Groinfield Vegetation: Existing Situation



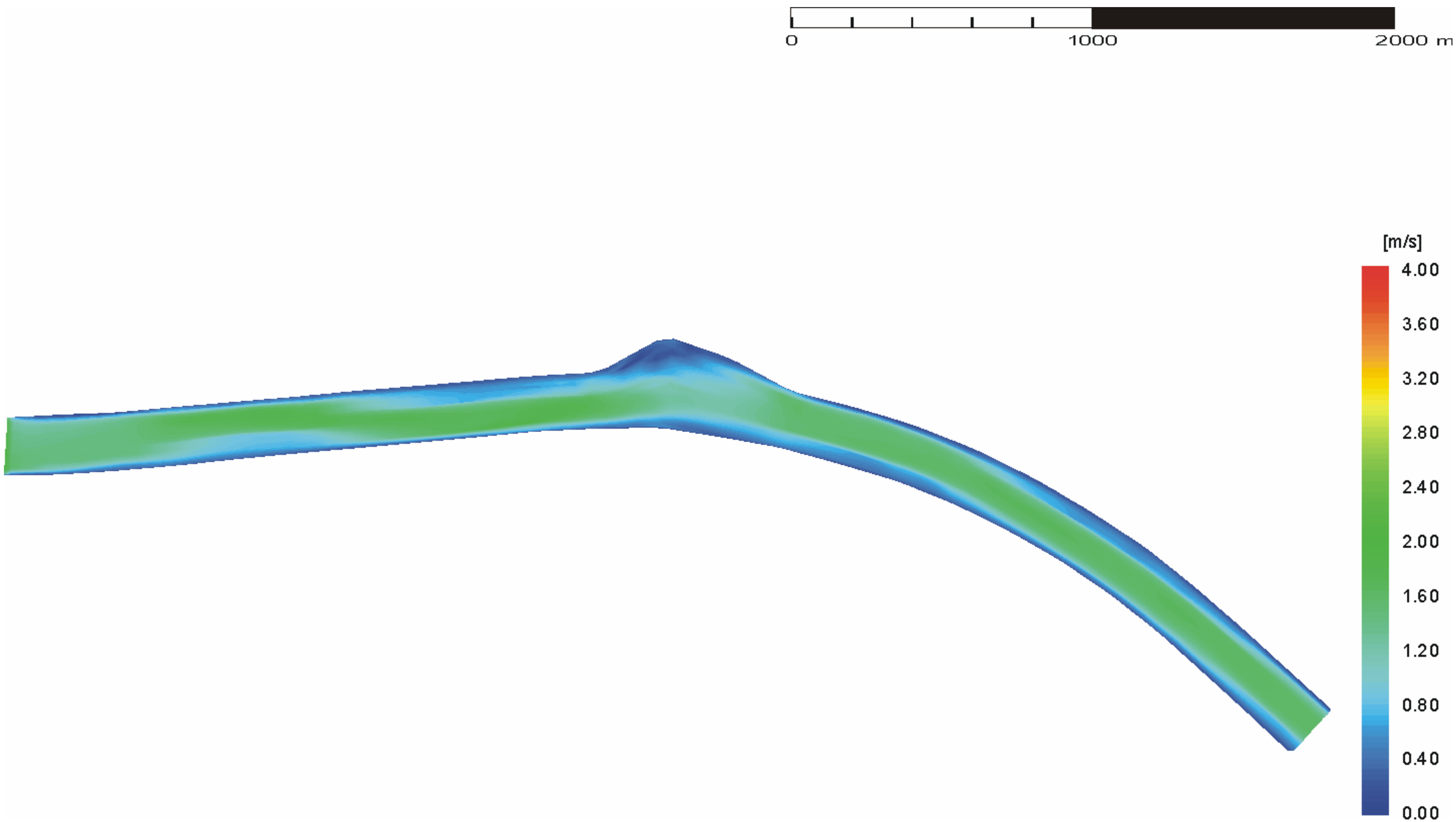
Annex 7.1.3: Near Bed Velocity Distribution: Existing Situation @ Q=1450 cumecs



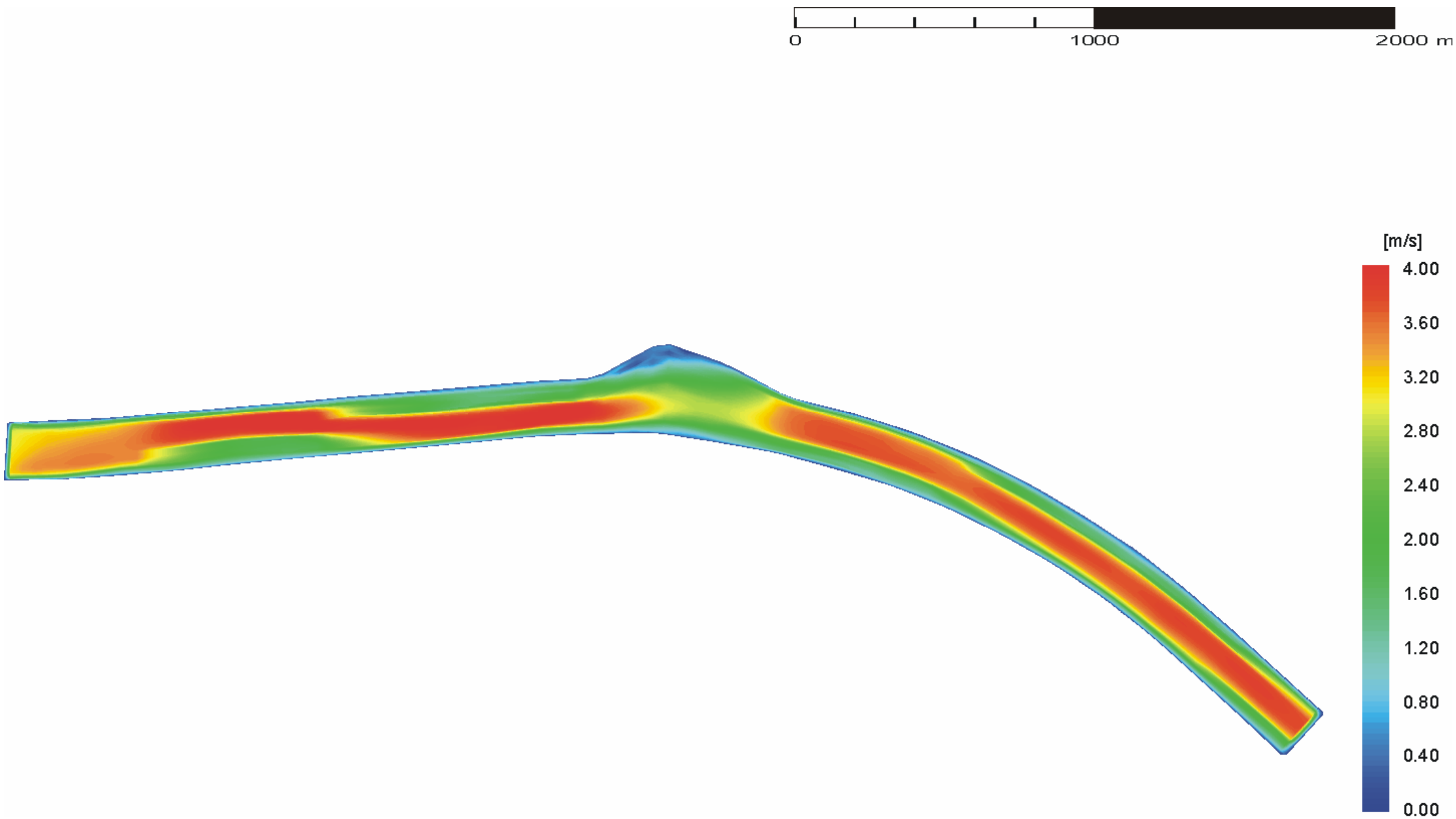
Annex 7.1.4: Near Surface Velocity Distribution: Existing Situation @ Q=1450 cumecs



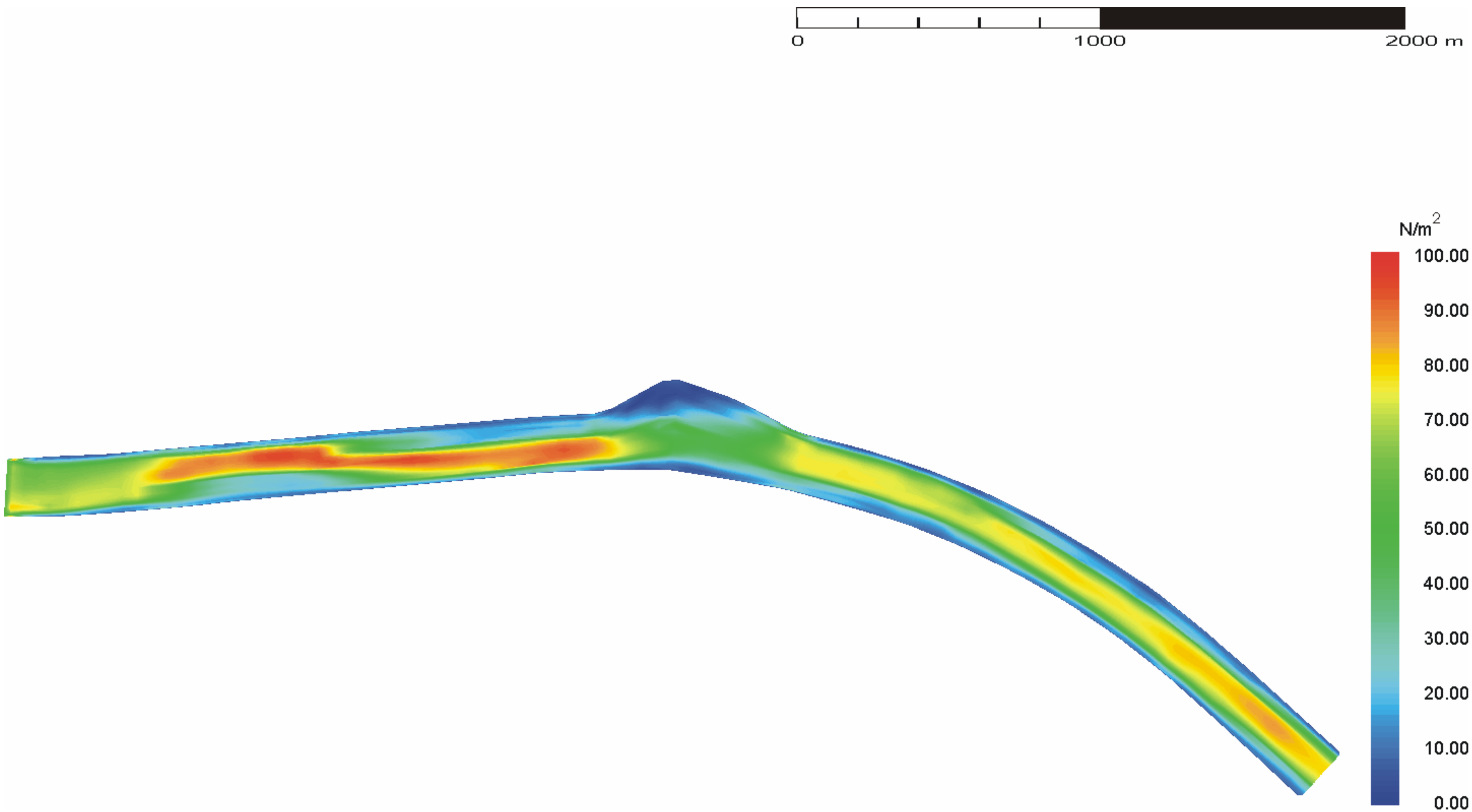
Annex 7.1.5: Shear Stress Distribution: Existing Situation @ Q=1450 cumecs



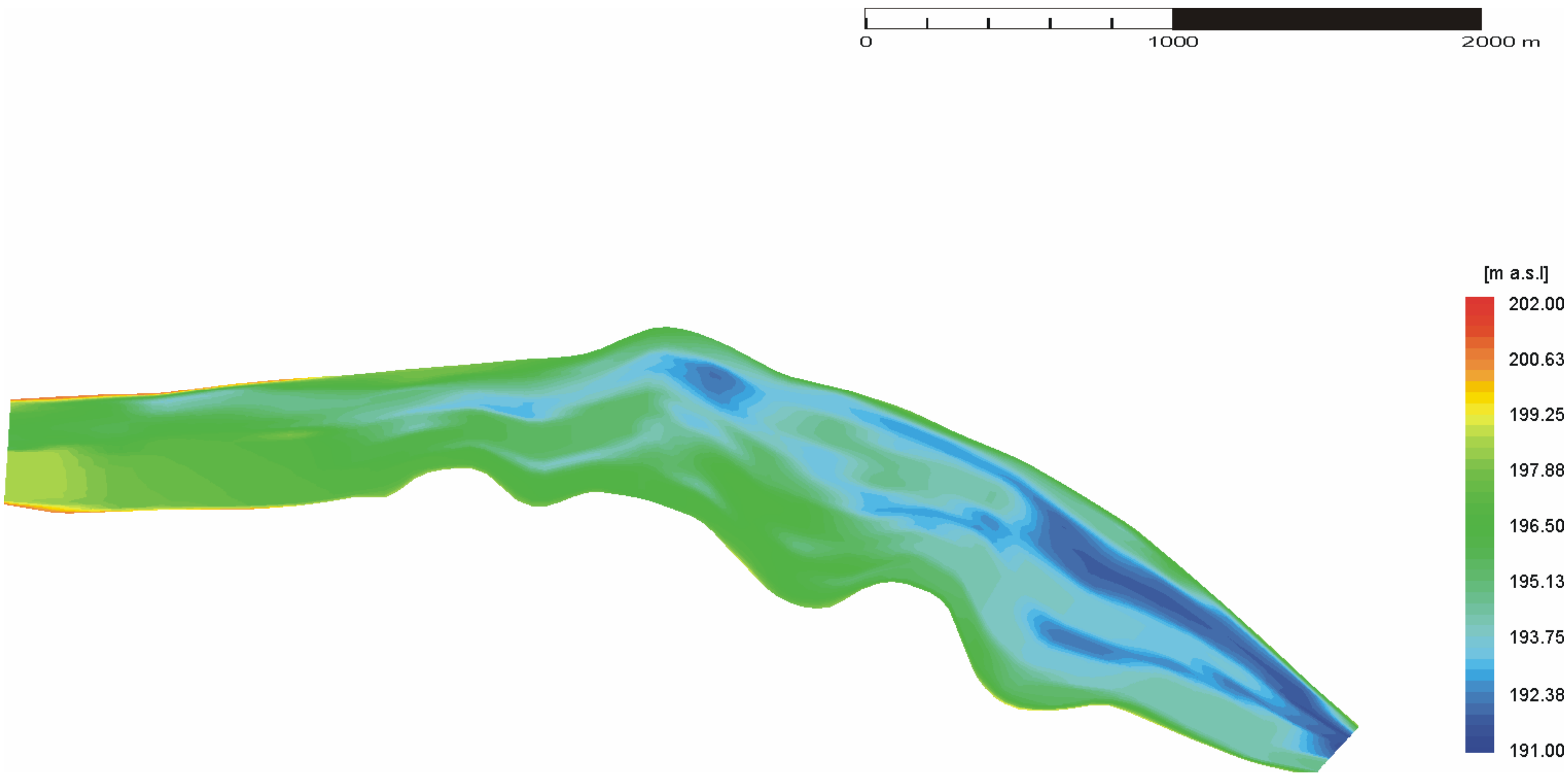
Annex 7.1.6: Near Bed Velocity Distribution: Existing Situation @ Q=3040 cumecs



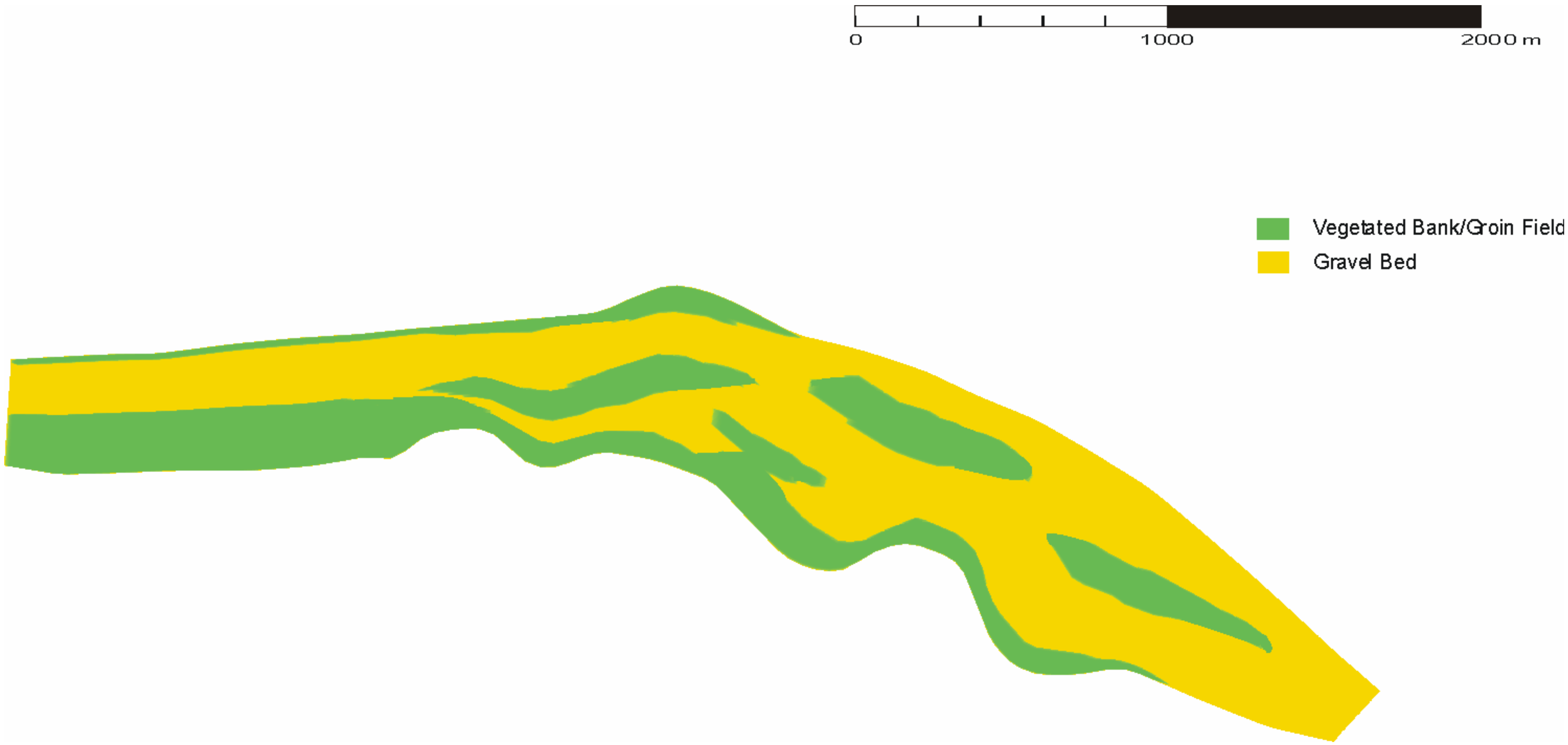
Annex 7.1.7: Near Surface Velocity Distribution: Existing Situation @ Q=3040 cumecs



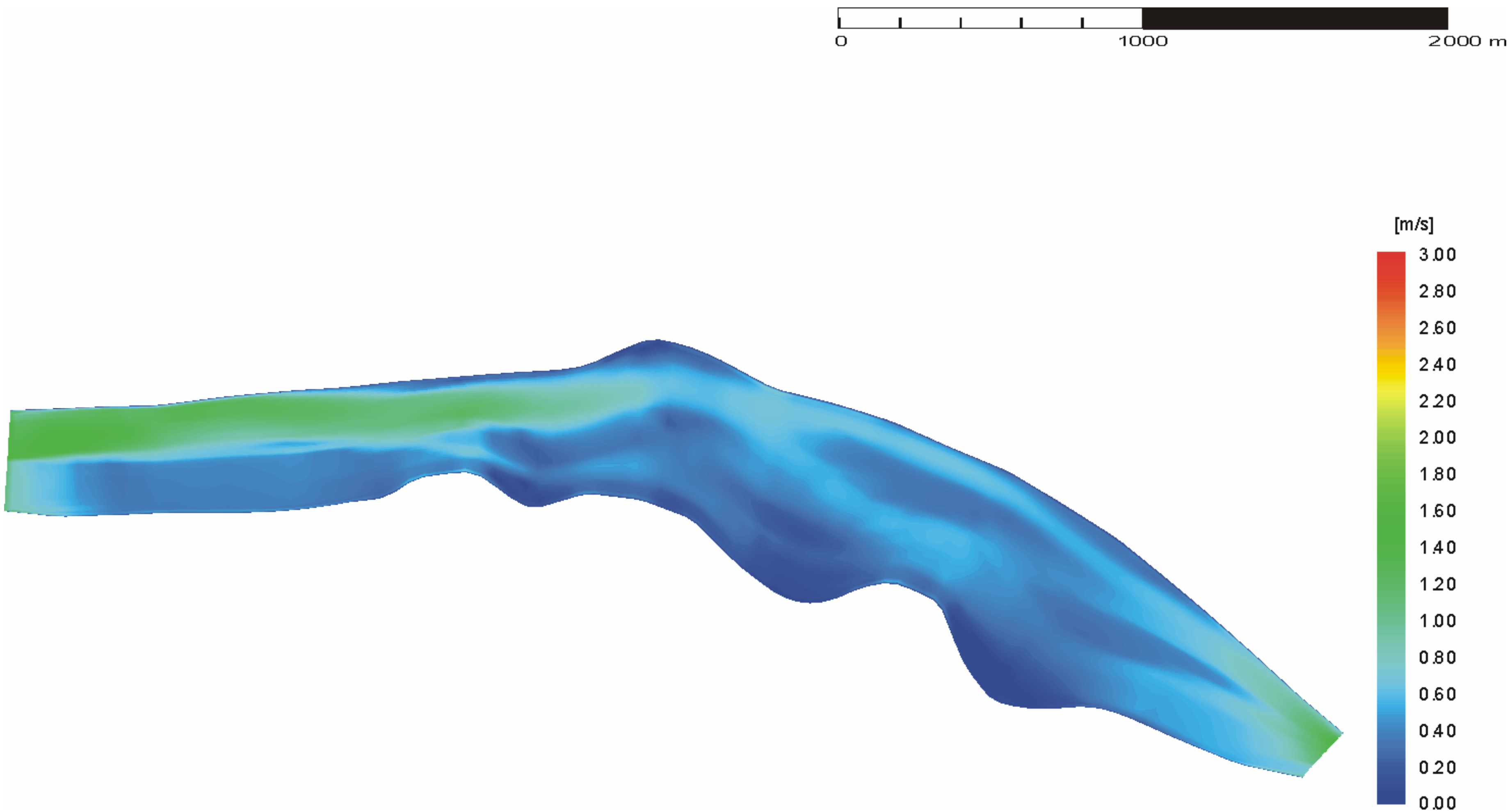
Annex 7.1.8: Shear Stress Distribution: Existing Situation @ Q=3040 cumecs



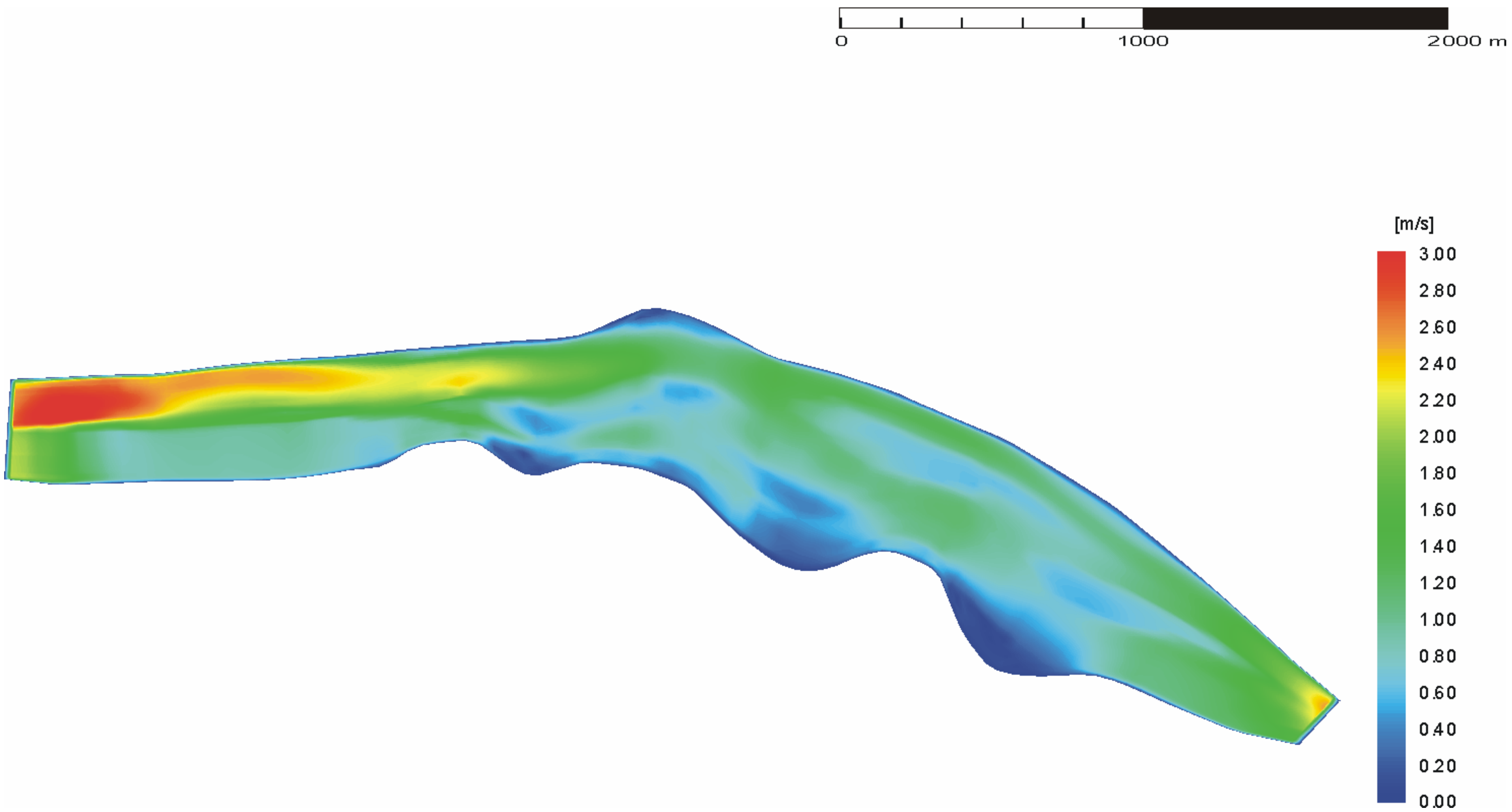
Annex 7.2.1: Topography: Future Situation



Annex 7.2.2: Distribution of Bank and Groinfield Vegetation:: Future Situation



Annex 7.2.3: Near Bed Velocity Distribution: Future Situation @ Q=1450 cumecs



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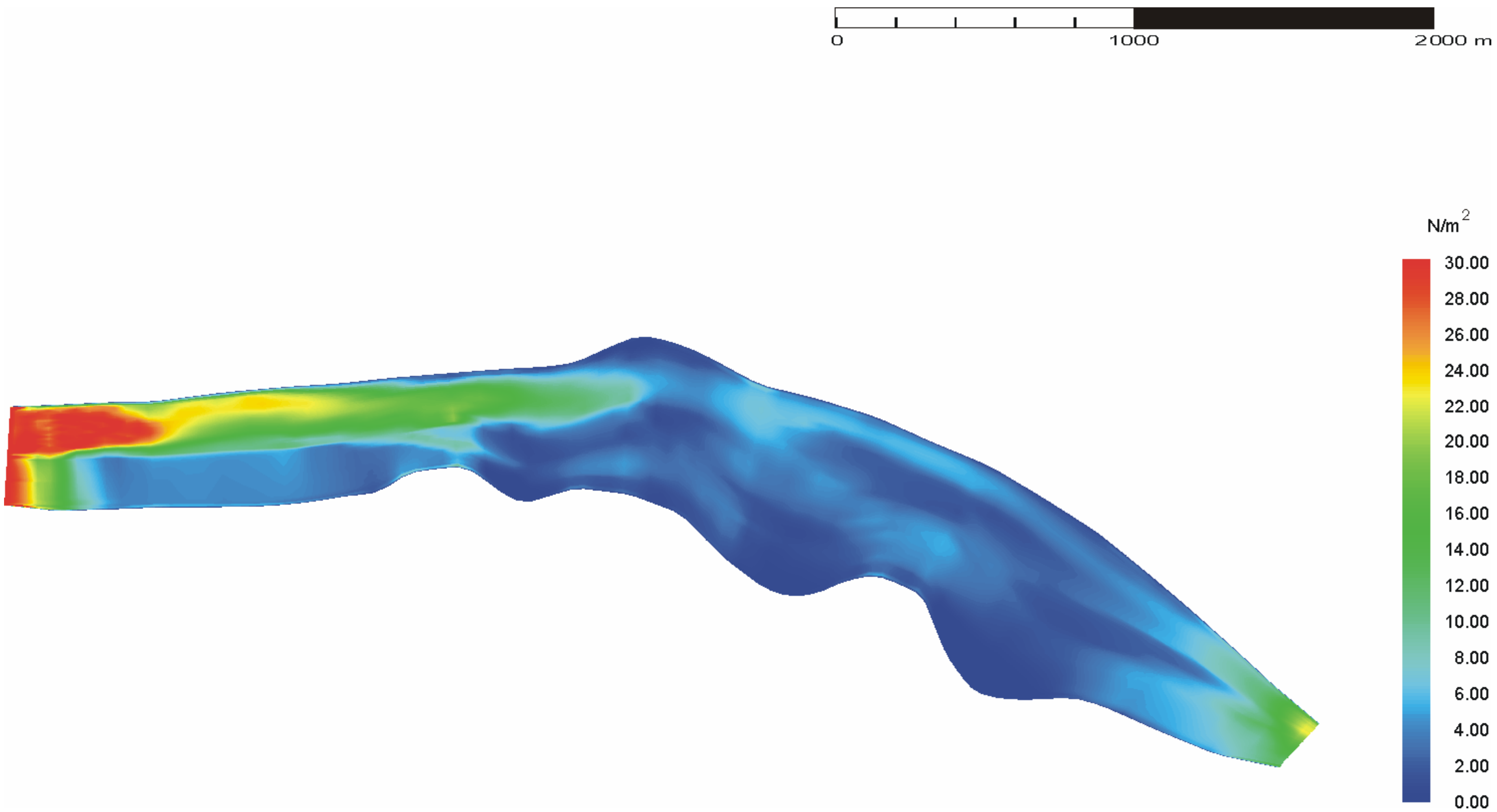
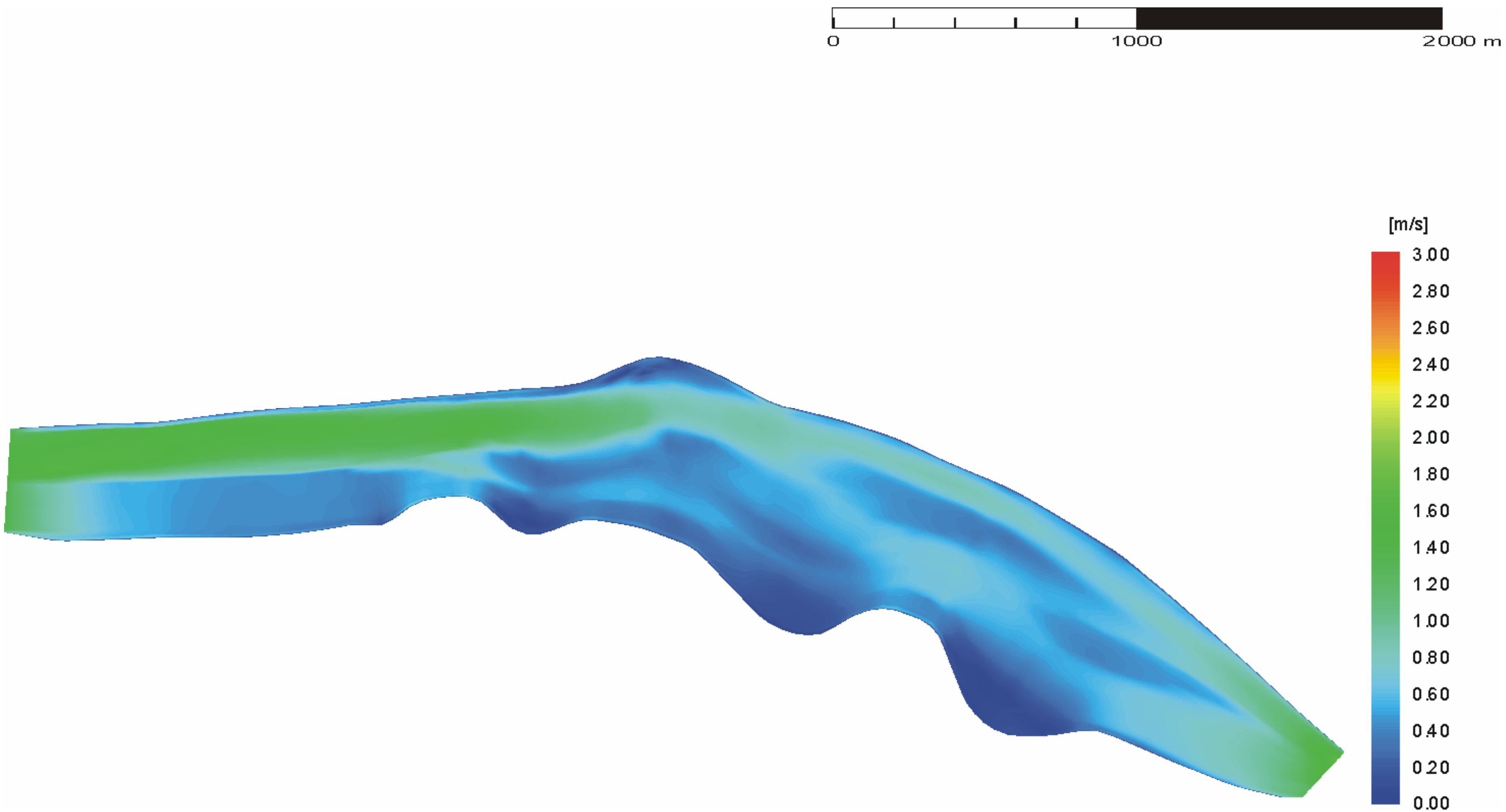
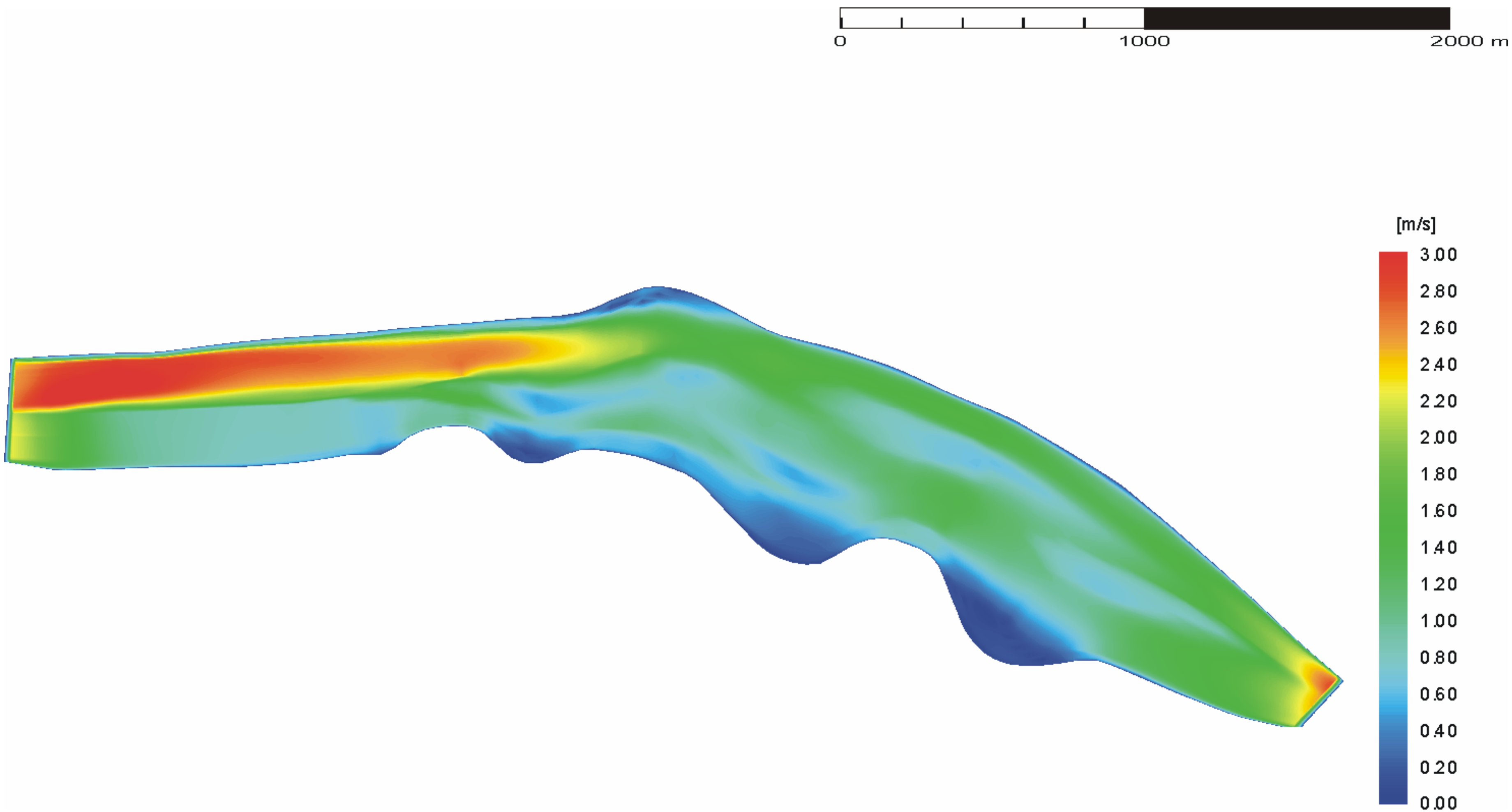


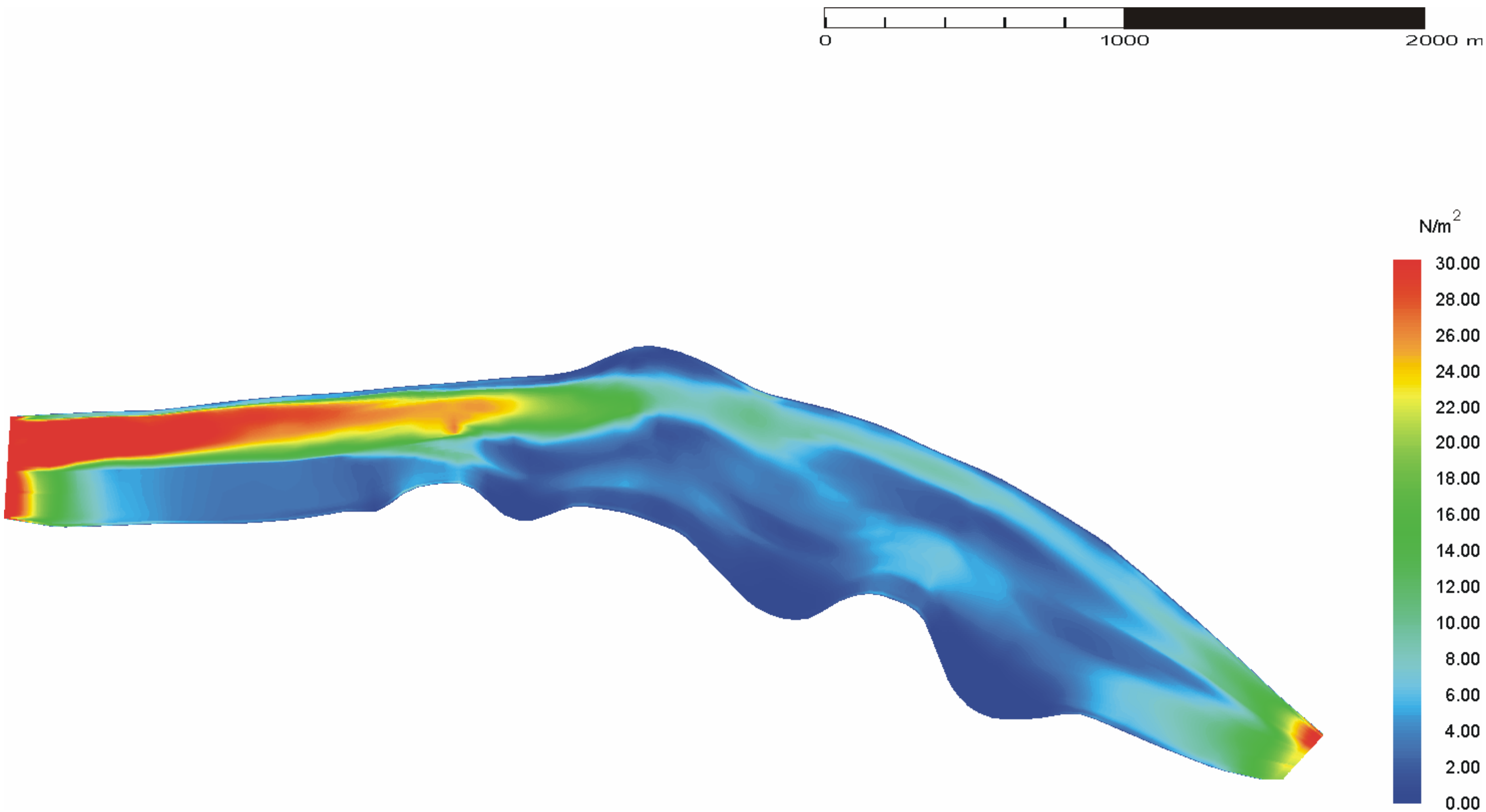
Annex 7.2.5: Shear Stress Distribution: Future Situation @ Q=1450 cumecs



Annex 7.2.6: Near Bed Velocity Distribution: Future Situation @ Q=3040 cumecs



Annex 7.2.7: Near Surface Velocity Distribution: Future Situation @ Q=3040 cumecs



Annex 7.2.8: Shear Stress Distribution: Future Situation @ Q=3040 cumecs