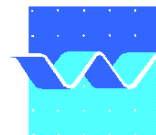


# CYCLIC FLOODPLAIN REJUVENATION

a new strategy based on floodplain measures  
for both flood risk management and  
enhancement of the biodiversity of the river Rhine

executive summary  
CFR project

H. Duel, M.J. Baptist, W.E. Penning



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## The river Rhine

The river Rhine is the largest river system in Western Europe. The total length of the river is 1,320 km and its catchment area comprises 185,000 km<sup>2</sup>. The Rhine basin extends over nine countries. The river Rhine flows from its source in Switzerland through France and Germany, and finally the Netherlands, where it discharges into the North Sea (figure 1). The German and Dutch part of the Rhine basin is a densely populated area in which all land is intensively used. Over the last centuries, the Rhine basin has undergone great changes in land use as a result of urbanisation, industrialisation and intensification of agriculture. To create optimal conditions for urbanisation, agriculture, inland water shipping and hydropower production, extensive hydrological measures and interventions of the river system have been introduced, which have had a large impact on the natural water system of the Rhine basin. The main river management objectives of the river Rhine have always been protection against flooding and maintaining the navigability of the river. To provide protection against flooding, dikes have been built. Large parts of the original floodplains were separated from the river by dikes and transformed into highly productive agricultural and urban areas. To facilitate shipping, the river has been changed into a regulated shipping channel with a uniform depth and width. Sand and gravel banks were removed and lateral channels were cut off from the river. These interventions in the river caused unexpected or underestimated hydro- and morphological responses by the river system, which in turn necessitated new management measures to mitigate the system's response. The interventions have resulted in unnatural fluctuations in the discharge of the river and therefore have reduced the hydrological resilience of the Rhine basin and river. Even moderate changes in rainfall intensity and frequency are nowadays reflected in extreme water levels in the Rhine.



**The Oberrhein at Mainz.**

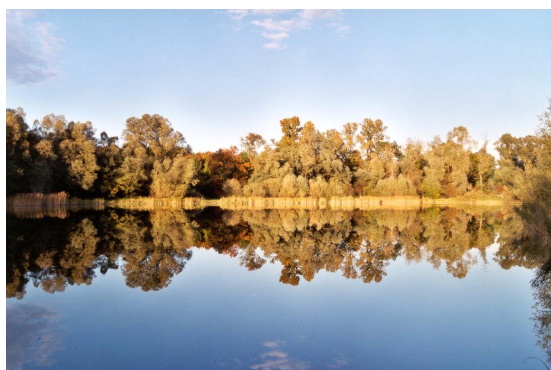


Figure 1. The Rhine river catchment.

## Ecological degradation

Due to river regulation and the utilisation of floodplains for agriculture, forestry, urbanisation and industry, characteristic riverine and floodplain habitats of the river Rhine were destroyed or fragmented and the quality of the remaining habitats was deteriorated. Water pollution added to the ecological degradation of the river Rhine as well. Especially after the Sandoz disaster, water pollution control and ecological rehabilitation of the river and its floodplains became important in river management. In 1987, the Rhine Action Programme was initiated





**Floodplain lake in Germany.**

to restore or create new habitats for characteristic species of the Rhine river (e.g. salmon) and to safeguard the water quality of the Rhine river for nature and drinking water production. This resulted, among other plans, in an Ecological Master Plan for the river Rhine with the following focus points: (i) restoration of the main stream, as the backbone of the complex Rhine ecosystem, together with its main tributaries as habitats for migratory fish and (ii) the protection,

preservation and improvement of ecologically important reaches of the river Rhine and the Rhine valley with the intention to increase the diversity of indigenous animals and plants. Substantial improvement of the ecological quality of rivers can be reached by (a) restoring habitat related to riverine marshes, oxbow lakes, floodplain forests and lateral channels, (b) improving the quality of the habitats and (c) connecting the habitats into an ecological network.

## **Flooding problems**

In the last decades of the 20<sup>th</sup> century, there have been problems with high river discharges along the river Rhine on several occasions. The high river discharges in the winter of 1994/1995 constituted a turning point in the history of water and river management in the Rhine basin. A general assembly of the riparian states of the river Rhine decided that further constriction of the floodplains of the river Rhine had to be counteracted and that the river needed to regain its hydrological resilience. This resulted in a Flood Action Plan to develop a new approach for river basin management.

In the Netherlands, the flooding problems of the nineties have also influenced the way in which river managers deal with flooding risks considerably. The decades-old plans for dike reinforcements were reviewed, revised and carried out. However, since the land is slowly subsiding and (global) climate change causes sea level rise and increases the peak discharges of the rivers, it is clear that however high the dikes are, they can only provide protection against flooding to a certain level. Current strategies for flood prevention attempt to prevent dike reinforcements, because these measures are very expensive and would result in a considerable loss of natural values and cultural heritage. The river management authorities emphasised on the need for a sustainable water management strategy based on dealing with the dynamics of the river systems in order to reduce the flooding risks on one hand and improve the quality of the physical environment, river ecosystems and landscape on the other hand.



**Flooding problems along the Waal river.**

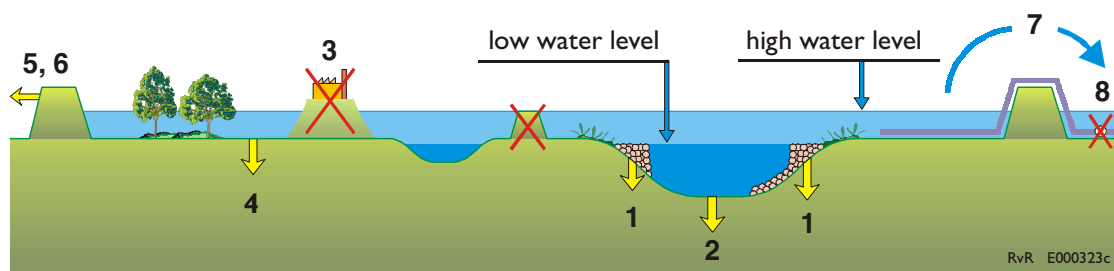


## Room for the river Rhine

In the Netherlands, the need for a new river management strategy for both flood protection and ecological rehabilitation resulted in a “room for the river” approach. In this concept of sustainable water management, a wide variety of measures is available:

- widening the main channel in combination with a reconstruction of the river banks, including removal of the groynes;
- excavating parts of the floodplain which are rarely or irregularly flooded;
- (re)constructing lateral channels and floodplain lakes;
- removing artificial levees in the floodplains;
- enlarging floodplains by relocating the existing dikes.

To answer the question whether it is possible to ensure the current safety level against flooding by taking measures based on room for river principles without subsequent dike reinforcement along the branches of the river Rhine, the “Room for the Rhine Branches” research project was initiated. In this project the most promising measures to reduce the flooding risks were analysed for the three Rhine branches in the Netherlands: the rivers Waal, Nederrijn-Lek and IJssel (figure 2). The first results of the Room for the Rhine research project showed that measures such as lowering of the floodplains and (re)constructing of secondary channels and riverbanks will result in an important reduction of the water levels at high river discharges. To reduce the flooding risks, large areas of floodplains need to be excavated. This creates large areas with opportunities for ecological rehabilitation of floodplains, especially for the floodplains that are currently used for agricultural production. However, there are still uncertainties regarding the sustainability of floodplain lowering and reconstruction of secondary channels, since the conditions will alter in time due to natural morphological and ecological processes. To ensure the safety levels at peak discharges, a strategy that includes cyclic lowering of the floodplains, (re)construction of secondary channels and setting back vegetation succession (e.g. development of floodplain forests) into juvenile vegetation stages may be a solution. This is the concept of Cyclic Floodplain Rejuvenation (CFR).



- |                                  |   |
|----------------------------------|---|
| 1 - lowering of groynes          | 5 - locally setting back dikes          |
| 2 - deepening low flow channel   | 6 - setting back dikes on a large scale |
| 3 - removing hydraulic obstacles | 7 - detention reservoir                 |
| 4 - lowering flood plains        | 8 - reduction lateral inflow            |

Figure 2. Room for the river: plenty of possibilities.

## Cyclic Floodplain Rejuvenation project

In this project the strategy of CFR was investigated. The CFR project is one of the projects from the research programme of the Room for the Rhine project. The main objective of the CFR project was:

*The development of a strategy for sustainable cyclic floodplain rejuvenation as flood risk management and nature restoration strategy.*

As mentioned before, “room for the river” measures create opportunities for ecological rehabilitation of the floodplains. However, rehabilitation of floodplains does not implicate restoring the ecological values which were present in more or less undisturbed floodplains many centuries ago. Due to societal and economical interests in the river catchments and due to climate changes, restoring the hydro- and morphodynamics of rivers to nearly pristine conditions is not possible as well as not desirable. Nevertheless, it is clear that the ecological quality of floodplains may be improved by restoring the river dynamics in floodplains to a certain extent and by allowing natural vegetation succession. However, there are limitations to ecological and morphological developments of the floodplain because of flood protection reasons. Due to climate changes, which will probably result in an increase of the river discharge, those limitations will be stronger in the near future. Therefore, the main purpose of the CFR project was to investigate the opportunities for ecological and morphological development of floodplains with respect to the constraints related to flood protection.



**River dune along the river Waal**

Floodplain rejuvenation comprises a number of components and processes, related to marshes, floodplain forests, secondary channels and natural levees. These rejuvenation components can be defined by a number of more specific research questions that have a relation with flood management strategies:

- What is the influence of periodic inundation on the development of floodplain vegetation?
- What is the morphological development of floodplains and what consequences does this have for the development of floodplain wetlands and vegetation and how does this affect the hydraulic roughness?
- How is the development of floodplain forests in time, taking different initial conditions into account and what does this mean for the hydraulic roughness of the vegetation cover and its developments in time and space?
- What is the sedimentation or erosion rate of secondary channels and what consequences does this have for the availability and suitability of habitats?

To answer the research questions, the CFR project consisted of three main research activities:

- Generation of knowledge on the ecological and morphological processes that are essential for analysing the sustainability of floodplain rejuvenation processes. This is based on

available data from literature and from existing monitoring programmes, field surveys and other research projects. Special attention was paid to:

- vegetation succession (rate, direction), especially the impact of changes in hydro- and morphodynamics on vegetation succession and the impact of rejuvenation measures on initial vegetation development;
  - fish habitat requirements of characteristic fish species in the Delta Rhine stretch;
  - morphological developments of secondary channels (sedimentation and erosion rates);
  - morphological developments of floodplains, especially the impact of floodplain lowering on the sedimentation rate.
- Translation of the knowledge on ecological and morphological processes that are associated with floodplain rejuvenation into expert rules and implementation of expert rules into hydromorphological and ecological models.
  - Analysis of the Cyclic Floodplain Rejuvenation strategy in several case studies using the Decision Support System Large Rivers, geographic information systems (GIS-tools), hydraulic models (1D, 2D, 3D), morphological models, vegetation succession models and fish habitat models.

The study areas of the CFR project were the floodplains of the river Rhine, from the upstream parts in Germany to the downstream parts in the Netherlands. Floodplains in this project were defined from a hydrological point of view: a landform subject to periodic flooding by the parent stream or the area between the main dikes. Case studies in this project were the Restrhein in Germany and the river Waal in the Netherlands. In the river Waal case, special attention was paid to the Gameren floodplain and to the floodplains upstream from Nijmegen (Gelderse Poort area).

The CFR project has many links and relations with a number of other research programs and projects. Besides a part of the research program of the Room for the Rhine project, the CFR project is also a part of the IRMA-SPONGE research program and has important links with other projects in this program, especially with the following projects: DSS Large Rivers, Living with Floods, Biosafe and Guidelines for Ecological Rehabilitation Measures. The CFR project has also a linkage with the Biogeomorphological Developments of Floodplains project of the Delft Cluster research program.

## **The concept of CFR**

To ensure the safety levels for flood protection, room for the river has to be created to cope with extreme high discharges. Without relocation or heightening of the existing dikes, room for the river can be only created by widening or deepening the main channel, reconstructing the river banks including removal of groynes, floodplain lowering, (re)constructing lateral channels and floodplain lakes and removing artificial levees. The room for the river measures in the floodplains create room for hydrodynamic and morphodynamic processes in the floodplains, which also create favourable conditions for nature development and ecological succession processes. As a consequence, the diversity of vegetation and habitats will increase and therefore the biodiversity will be enhanced.





**Construction of a secondary channel in the Klompenwaard, the Netherlands.**

landscape heterogeneity, similar to river dynamic processes (inundation, erosion, sedimentation).



**Black poplar**

The first step of the CFR strategy is to implement floodplain measures to create room for the river and to set initial conditions for ecological development of the floodplains. After that, river dynamic processes (especially erosion and sedimentation) and ecological processes (vegetation succession) will take place and will determine the ecological development of the floodplain. The potential of ecological rehabilitation of floodplains is best fulfilled by spontaneous return of flora and fauna species that will fill the newly created niches (created by the initial conditions). The rate and the direction of vegetation succession should be controlled by both nature and river dynamics. In this respect grazing by large herbivores is seen as a natural process, on the condition that the density of herbivores is comparable to natural circumstances. Grazing by large herbivores creates niches by favouring certain plant species above others and thereby influencing

Vegetation succession leads to an increase in hydraulic roughness of the floodplains. After a period of time, the hydraulic roughness may have increased to such an extent that, in combination with floodplain elevation due to sedimentation, the water levels during high floods will reach the safety level. This means that a further roughening of, and sedimentation in, the floodplains will cause unsafe situations. In a natural river system “room for the river” is created by its own dynamics. The ecological succession is occasionally set back into juvenile stages due to river dynamics. These resetting mechanisms do not occur in the middle and lower reach of the river Rhine anymore, because the river is fixed into one channel. This implies that river managers need to rejuvenate the floodplains themselves, artificially, to re-establish enough room for the river.

The next step in the CFR strategy is therefore to take management measures in floodplains that both enhance the floodplain diversity (creating new pioneer stages) and increase the discharge capacity. The scale and frequency of these management activities is related to the succession rate and the required decrease of the water levels for both flood protection and ecological development. This ranges from taking relatively small measures at higher frequencies towards large scale activities less often. Four theoretical concepts can be distinguished to apply CFR, each of them differ in their approach towards ecological diversity.

**Concept 1: Ecological reference condition**

The ecological reference condition or the ecological potential of a river stretch can be used as a measure for biodiversity. Once management activities are required to ensure the safety levels, the ecological reference condition is used to test if there is a surplus of, for example, floodplain forest, which can be removed to decrease the hydraulic roughness of the floodplain. The ecological reference condition has to be defined for each river section, because each section has its own hydrological, morphological and ecological characteristics. Furthermore, it has to contain information on the diversity of natural elements: floodplain forests, such as hardwood (Oak, Ash, Elm) and softwood (Willow, Poplar) floodplain forests, grasslands, species rich ruderal vegetation, floodplain marshes, secondary channels, oxbow lakes, natural levees and sand dunes. In a dynamic situation each of these elements is in a specific state of succession, most easily expressed as the age of the element. Therefore, the ecological reference condition should also include the different stages of succession (initial/juvenile, mature, degradation/transition phase). For each river stretch, ideally the occurring areas or at least minimum areas of each element should be defined. Table 1 summarises the ecological reference condition for the river Waal based on ecotopes, these are spatial ecological units determined by the hydrodynamic and morphodynamic processes of the river and by vegetation management options.

**Table 1. Ecological reference condition on the basis of ecotopes for the floodplains of the river Waal (floodplain area is in total 10,300 ha).**

Ecotopes	ecological reference condition (in ha)	ecotopes distribution in 1995 (ha)
natural river banks	>500	260
softwood forests	>500	290
hardwood forests	>750	10
dry ruderal vegetation	>150	60
wet ruderal vegetation	>500	340
dry grasslands	>100	60
wet grasslands	>1000	30
agricultural areas	0	6400
marshes and oxbow lakes	>300	290
secondary channels	>1000	600
other (sand pits, built-up areas)	0	1960

**Concept 2: Rejuvenation frequency of vegetation**

In the concept of CFR, diversity of ecotopes and habitats is not fixed per river stretch, but is a consequence of river dynamics, morphological development, vegetation succession and



**Ruderal floodplain vegetation**

management interventions. The rejuvenation frequency of vegetation is dependent on the succession rate and development time of vegetation to reach the mature phase. For example, it takes at least 30-50 years for softwood floodplain forests to establish and to develop into climax stage. After that, the softwood floodplain forests will be in

degeneration or transition phase. Therefore, softwood floodplain forests are preferably rejuvenated after 30-50 years. However, it is not recommended to remove all of the softwood floodplain forests after 30-50 years of development time, because softwood floodplain forests in degradation or transition phase provide characteristic habitats for a numerous number of fauna species. Nevertheless, it can be decided that softwood floodplain forests will be removed for safety reasons. Table 2 gives an overview of the estimated time for establishment and development into climax/mature stage for different types of vegetation based on expert knowledge and scarce field data. The development time is considered to be the minimum number of years required for development before it can be allowed to artificially rejuvenate.

**Table 2. Minimum number of years required for development of vegetation types and secondary channels**

ecotopes	recommended minimum development time (years)
softwood forests	30 -50
hardwood forests	>100
dry ruderal vegetation	5 - 10
wet ruderal vegetation	5 - 10
dry grasslands	10 - 25
wet grasslands	10 - 25
marshes	10 -25
secondary channels	15 - 30



**Pioneer floodplain vegetation**

morphological modelling. The rejuvenation frequency of floodplain areas depends on the sedimentation rate. When the sedimentation rate is high, the rejuvenation frequency of the floodplains is high as well.

### ***Concept 3: Morphological rejuvenation***

In natural meandering rivers, the main stream rejuvenates the adjacent floodplains by shifting into these floodplains and creating pioneer stages. In the fixed Rhine system, only secondary channels can shift in dynamic parts of the floodplain. In view of CFR measures, when hydraulic resistance becomes too high, a new side channel can be created. This has two effects. Firstly, the hydraulic resistance on the location of the new channel has decreased, and secondly, new pioneer stages are created.

The floodplains can be divided into different types of morphological units with distinct morphological behaviour. Table 3 shows the aggradation rates for each morphological unit for the river Waal. The aggradation rates expressed in millimetres per day of inundation imply that the rates of aggradation decrease as bed elevation increases. The figures presented are based on field measurements and



**Table 3. Estimated sedimentation rates in the floodplains and in secondary channels along the Waal river.**

Morphological unit	Deposit composition	Aggradation rate	
		(mm per day of inundation)	(m/year)
Inflow area	sand	1.0	
Point bar extension	sand	1.0	
River dune	sand		0.15
Entrance section of slowly aggrading secondary channel	-	0.2	
Entrance section of moderately aggrading secondary channel	sand	1.0	
Entrance section of fast aggrading secondary channel	sand	2.0	
Other sections of secondary channel	silt, clay	0.13	
Rest of floodplain	silt, clay	0.13	

**Concept 4: Rejuvenation of parts of floodplains**

In the floodplain areas where low flow velocities occur during high discharges, an increase of the hydraulic roughness, due to vegetation succession, may have a relatively small effect on the water levels. These areas are therefore suitable for development of vegetation types that need a lot of time to reach the mature stage of succession. For example, the development of a hardwood forest takes approximately 100 years. In those parts of a floodplain where high flow velocities occur during high discharges, the rejuvenation frequency needs to be higher. This is similar to the situation in natural rivers.

**Bank erosion along the river Allier, France.**

For CFR measures related to vegetation development, floodplains can be divided in three categories:

- relatively high parts, irregularly flooded, low flow velocities during high discharges;
- relatively low parts, regularly flooded, however the flow velocity is low;
- relatively low parts, regularly flooded, with fast flowing water.

The first category is the most suitable for floodplain lowering, since removing these areas is effective in reducing the water levels. The latter category is the most interesting for rejuvenation of vegetation in case these areas are covered with forest, because this will decrease the hydraulic resistance.

## CFR case study: Restrhein

The Restrhein is the remaining river stretch of the southern part of the Upper Rhine from Basel to Breisach after the Tulla corrections and the construction of the Grand Canal d'Alsace. Due to these interventions, the Restrhein was transformed into a fixed channel with small floodplains and an unnatural hydrological regime. Not surprisingly, the loss of most of its former floodplains increased the water levels during floods enormously and so decreased the protection against flooding downstream. In order to create more water retention for flood control, the local water authority of the federal state Baden-Württemberg developed the retention basin Weil-Breisach plan.



**Floodplain lowering along the river Grensmaas, the Netherlands.**

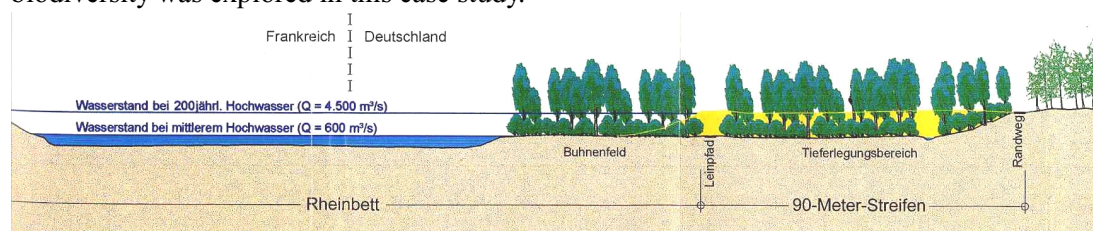
In this plan excavating and lowering the floodplains is the main measure to increase the storage capacity of the river with 25 million m<sup>3</sup>. At the same time this creates opportunities for re-establishment of characteristic floodplain vegetation. To protect downstream population areas it is desirable to lower the water levels during floods by increasing the retention capacity of the Restrhein.



**The Restrhein in its present state**

In the Restrhein area itself there is no immediate flood risk. Erosion of the stream bed has deepened the river to a level where inundation of the former floodplain does not occur anymore. Therefore the Restrhein area is extra-ordinarily suitable to increase the water retention capacity of the river. In sustainable flood protection it is important to review measures in the perspective of ecological restoration. The Flood

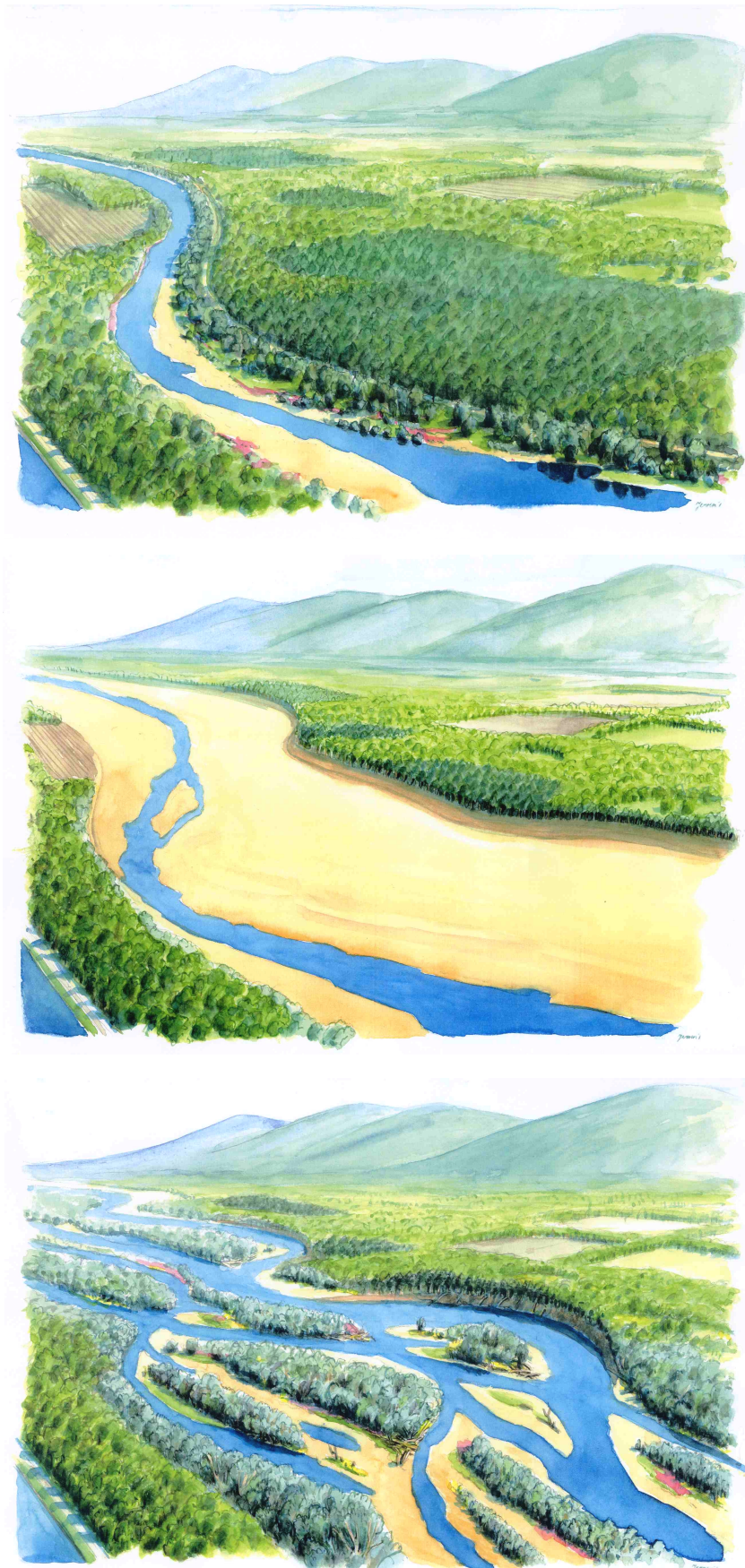
Action programme already acknowledges the existing water retention plan (figure 3). It also acknowledges the important role of riparian forests in lowering of the peak levels. The retention effect is a combination of more room and a higher hydraulic resistance, to prolong the storage of water in the Restrhein. In addition to this water retention plan the role of cyclic rejuvenation for both flood protection (additional storage capacity) and enhancement of biodiversity was explored in this case study.



**Figure 3. Water Retention Basin Weil-Breisach Plan**

To identify additional measures for increasing both the water retention capacity and diversity of river and floodplain habitats, the Grensmaas project was used as reference situation. The Grensmaas project is a transboundary project (Netherlands/Belgium) that combines nature development, flood protection and gravel excavation along the river Meuse. The concept of the Grensmaas Project is to widen the river as much as possible by removal of the top layer of the floodplain. Depending on the width of the floodplains 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 use the new sediments to rebuild its stream bed. Locally new gravel islands, banks, sand levees and secondary channels could develop. Spontaneous development of riparian forest, pioneer habitat and stream valley grasslands will lead to a new nature area of more than 1000 ha (figure 4).



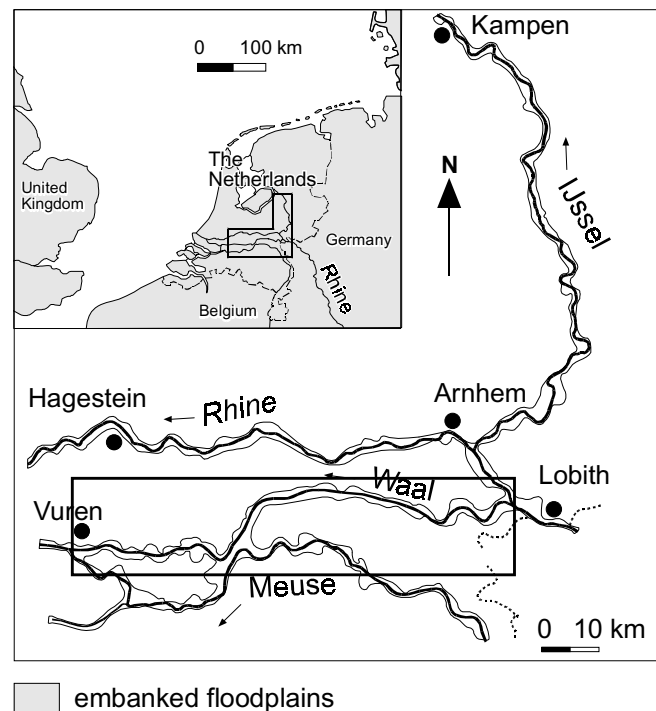


**Figure 4. Impression of the ecological development of the Restrhein after applying CFR, top: current situation, middle: after excavation, bottom: future situation.**

For a 6 km stretch of the Restrhein (rkm 209-215), additional measures were developed and analysed with regard to the hydraulic and morphological consequences using a 3D numerical model, based on the specific characteristics of the Restrhein and on the experiences from the Grensmaas project. The additional measures comprise widening the main channel by lowering the floodplains, removal of groynes and embankments and allowing lateral erosion and natural vegetation development within the floodplain. Model results showed that a total of 6 million  $\text{m}^3$  meters of retention volume can be gained additionally by the proposed measures. However, a major part of the retention capacity (4 million  $\text{m}^3$  meters) can only be achieved where the reach is characterised by the lowered floodplains with a large extent of floodplain forest development. The flow velocities in the main channel will be significantly reduced in the section with the lowered floodplains. 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. The question remains whether and to what extent the morphodynamic processes (with respect to gravel) of the Restrhein can be revitalised. It is assumed that erosion, transport and sedimentation of gravel in the main channel will be low because of the armoured river bed and the relatively low flow velocities even during extreme high floods. The fine suspended sediments transported in the river will be trapped on the vegetated gravel banks and floodplains. Finer portions of the bedload material (fine gravel) can be deposited in the secondary channels and block the channel, as the flow dynamics reduce with increased cross-sectional width.

### **CFR case study: Waal**

The river Waal is the largest branch of the river Rhine in the Netherlands (figure 5), carrying about 2/3 of the total discharge of the river Rhine. The river Waal is embanked and the floodplains are 500 - 1,000 metres wide. Most of these floodplains are used as pasture land for grazing cattle, with local tree stands and a few fields of arable land. With respect to flood protection, the critical water levels are associated with a river discharge in terms of its 1/1250 year probability of entering the Netherlands at Lobith. This discharge is currently 15,000  $\text{m}^3/\text{s}$ . The actual dimensions of the river embankments are based on this discharge. As a result of the floodings in the last decade, statistics have shown that the flood event with a 1/1250 year probability will be 16,000  $\text{m}^3/\text{s}$ . Without the implementation of measures, the water levels will exceed the critical water levels with 20-30 cm. Since reinforcement of the dikes is no option anymore, there has to be searched for room for the river by measures such as floodplain lowering, widening the main channel, reconstruction of the river banks and reconstruction of secondary channels. Since the floodplains of the river Rhine are also a part of the Main Ecological Structure of the Netherlands, it is important to create opportunities for ecological rehabilitation as well.



**Figure 5. The river Waal, the Netherlands.**

In the first phase of the Room for the Rhine project an inventory was made of possible measures to create room for the river. The impact of these measures on lowering the water levels was analysed (Table 4). Subsequently, the effects of floodplain lowering and nature development were assessed for four alternatives which were put together on basis of existing flood protection and ecological rehabilitation plans:

- alternative 1: nature development without floodplain lowering;
- alternative 2: nature development with limited lowering of the floodplains;
- alternative 3: nature development with additional lowering of the floodplains: resulting in large areas with marshes and shallow floodplain lakes;
- alternative 4: nature development with limited lowering of the floodplains and without forest development.

For the river Waal, nature development plans without floodplain lowering, alternative 1, lead to an increase of the water levels with a maximum of 10 cm. In alternative 2 the water levels decrease with a maximum of 30 cm and alternative 3 leads to an additional decrease of the water levels with 10-20 cm. Alternative 4 leads to a decrease of the water levels with 45 cm at most.



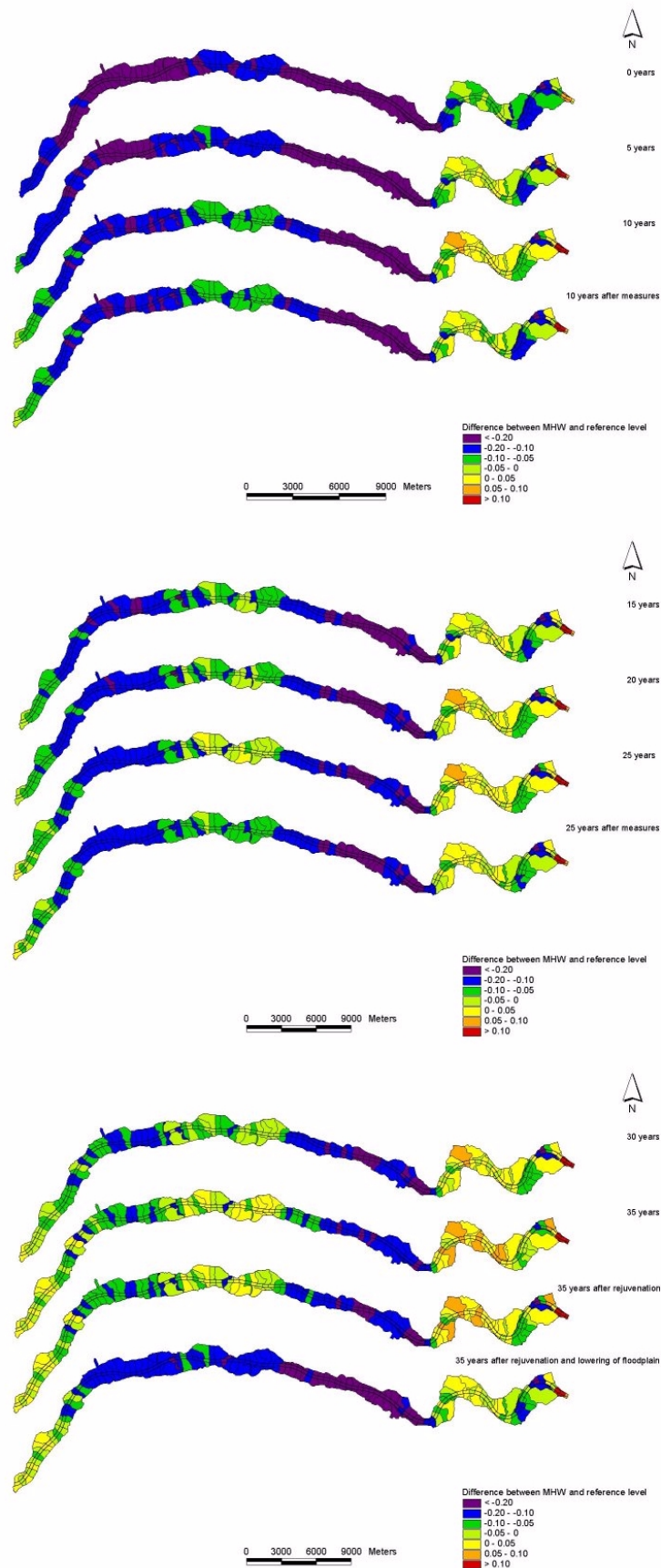
**Table 4. Impact of hydraulic measures on the water level of the Waal at extreme discharge**

hydraulic measure	lowering of the water level (cm)
lowering of floodplains (1m)	20 - 30
lowering of floodplains (2m)	40 - 50
lowering low flow channel (1m)	20 - 30
groyne lowering (1-2m)	5 - 15
removing summer embankments	15
removing small hydraulic bottlenecks	20
removing urban bottleneck of Nijmegen	max. 50
enlargement of floodplains (relocation of dikes: 300-500m)	60
(re)construction of secondary channels	5
deforestation of floodplains	15

The management concept of cyclic floodplain rejuvenation was applied on the entire Waal river in a large-scale analysis with DSS Large Rivers in combination with expert models on vegetation succession and sedimentation rates dependent on estimated inundation times. The study starts with the floodplain lowering measures as were defined in alternative 3 of the Room for the Rhine study, because this alternative creates the best opportunities for ecological rehabilitation of the floodplains. In deviance to this alternative, dike relocation Nijmegen was added as additional measure and the vegetation development of the lowered parts of the floodplains was set to a starting situation of bare substrate and pioneer vegetation. Subsequently, the morphological development and vegetation succession were analysed for time steps of 5 years using a morphological model and a vegetation succession model. After that, hydrodynamic computations were performed with DSS Large Rivers. The hydraulic effects were evaluated for a discharge of 16,000 m<sup>3</sup>/s at Lobith and the water levels were compared with the critical water levels (with respect to the dimensions of the embankments). When the increase of the water levels results in exceeding the critical water levels, CFR measures are necessary. The type of CFR measures that were implemented were:

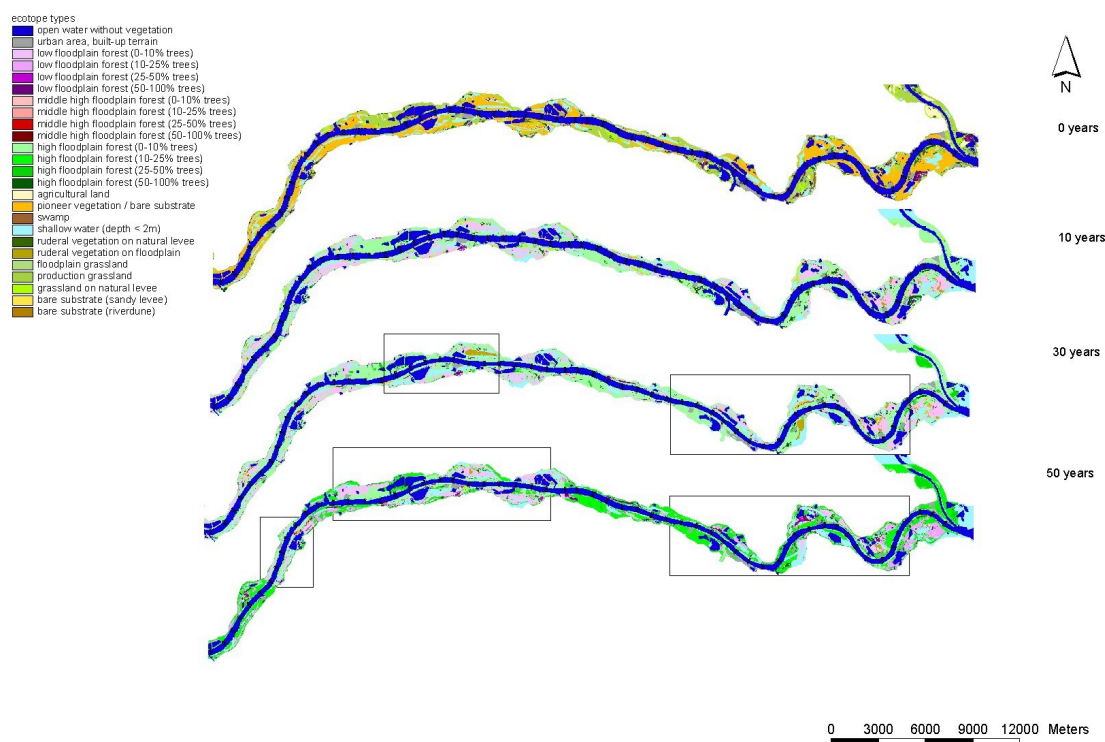
- (re)construction of secondary channels;
- lowering of the floodplain;
- rejuvenation of the vegetation succession into pioneer stages.

The initial measures resulted in a decrease of the water levels of 35 cm, except for several locations with hydraulic bottlenecks: for those locations the reduction of the water levels was 5-15 cm. Since water levels increased due to vegetation development and sedimentation in the order of 1 cm per year, the development time for vegetation is limited for locations with hydraulic bottlenecks. This was the case for the Gelderse Poort area, the floodplains along the river stretch upstream from Nijmegen. CFR measures had to be taken each 10-15 years, which is not favourable for nature development (figure 6).



**Figure 6. The changes in water level as a result of CFR measures and morphological and ecological development.**

The increase in water levels in the first ten years after the river restoration is relatively large, because floodplain forest quickly develops from the bare substrate. Furthermore, the sedimentation rates are also relatively large, because the floodplains respond to the lowered state they were put in after the river restoration works. The rise in water levels for subsequent years gradually decreased because the sedimentation rate decreased and because the increase in hydraulic roughness due to the vegetation succession was not that pronounced anymore as in the first five years. In the middle stretch of the river Waal CFR measures have to be taken after 25-35 years of development.



**Figure 7. Ecotope development over a period of 50 years. Boxes indicate areas where CFR measures were applied.**

In this case study agricultural production grasslands and fields in the floodplains along the river Waal were transformed into nature development areas. Since grazing by large herbivores in low densities is a common practice in nature management in the Netherlands, this was also the case in this project. The areas of agricultural production grassland mainly develop into vegetation mosaics with a hardwood floodplain forest cover of less than 10% during the first decades after the initial measures (figure 7). After 50 years of development, the forest cover in these areas is 10-25%. Areas with a forest cover of more than 50% are scarce. In the considered period of 50 years, such vegetation mosaics only develop locally along the river and the secondary channel banks. The lowered floodplains develop into vegetation mosaics with a softwood forest cover of less than 10% during the first decades. Large parts appeared to be the areas where CFR measures needed to be reapplied. After implementation of these CFR measures vegetation mosaics with softwood forest regenerate, with an intermediate stage of wet ruderal vegetation. After 50 years of development, the total area of forest increased significantly, despite CFR measures in which forest was removed. With respect to the ecological reference the increase of forested areas is sufficient (table 5). The fact that the forest cover gradually increases over time has important implications for the CFR management strategy. Deforestation as CFR measure will have only a significant impact on

the water levels when the forest cover is high. From the hydraulic point of view, this type of CFR measure is therefore best applied after at least 50 years of undisturbed development when the forest cover is more than 25%.

**Table 5. Applying CFR measures for the floodplains of the river Waal: ecotope development over 50 years.**

ecotopes	ecological reference (ha)	initial situation (ha)	10-years ecological development after "room for the river" measures (ha)				
			10 y	20 y	30 y	40 y	50 y
floodplain hardwood forest	>750	300	700	700	800	1200	1300
floodplain softwood forest	>500	300	300	300	300	400	500
floodplain marshland	>300	200	<100	<100	<100	<100	<100
dry grasslands	>100	400	3100	3900	3600	3100	3200
wet grasslands	>1000	400	1400	1300	1200	1200	1100
dry ruderal vegetation	>150	200	400	400	500	400	500
wet ruderal vegetation	>500	100	300	200	300	200	200
shallow water including channels	>1000	1300	1400	900	1600	1700	1600



**Large grazers in the floodplains of the river Waal.**

Due to the large scale of floodplain lowering and the construction of secondary channels, the sedimentation rates during the first 5 years were high. After the application of the CFR measures, a significant, although smaller, increase of sedimentation rates was also noted. Sedimentation rates in the relatively high parts of the floodplains were about 2-7 cm per 5 years. Although these areas covered nearly 90% of the floodplain area, they were responsible for not more than 50-70% of the total sediment volume that was added to the

floodplains over time. In the lowered floodplains sedimentation rates varied locally up to 1 m per 5 years and up to 2 m in 5 years in the channel entrance sections.

The total volume of sediment added to the floodplains decreased from about  $6 \cdot 10^6 \text{ m}^3$  per 5 years after the initial measures to less than  $4 \cdot 10^6 \text{ m}^3$  per 5 years at the end of the 50 year period. This sediment volume corresponds to an average increase of floodplain height of nearly 1 cm per year. To maintain water levels below the reference levels, parts of the floodplain have to be lowered periodically. At each intervention period therefore, a volume of sediment should be removed, corresponding to the amount of sediment deposited during the preceding period, which is also expected to be in the order of  $4 \cdot 10^6 \text{ m}^3$  per 5 years. Removing this volume in an intervention area, would correspond to a lowering of 1 m over an area of 400 ha. This is about 4 % of the total area of the floodplains along the Waal river.

The changes in morphodynamics of the secondary channels and the consequences for availability and suitability of habitats for fish species was studied in detail using a



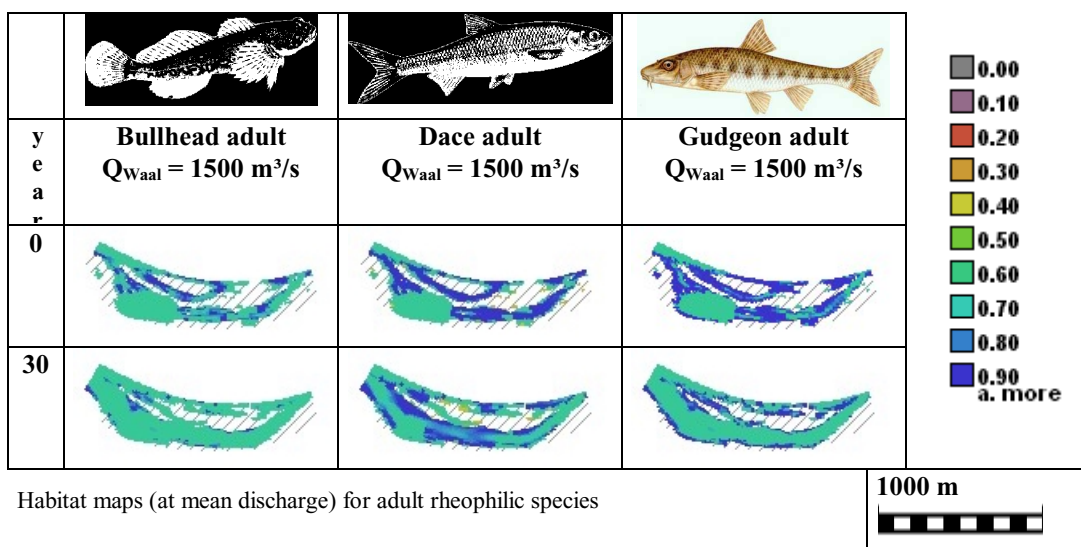


**One of the secondary channels in the Gamerensche Waard, a floodplain along the river Waal.**

hydromorphological model (2D application of a Delft3D), a vegetation model and fish habitat models. The study area was the Gamerensche Waard floodplain along the river Waal. In this floodplain three man-made secondary channels are located. The largest one is connected with a sand-mining pit. The model results indicate that a sand-mining pit in a secondary channel not only acts as a sediment trap, but will also increase the stream flow and erosion of the

channel. In the two smaller channels there was a overall sedimentation rate of 2-5 cm per year. After 30 years the inflow opening of these channels was filled up to such a level that floodplain vegetation can develop.

Secondary channels are important fish habitat areas, especially the shallow areas that are important habitats for fish reproduction. The morphodynamic development changes the habitat suitability over time (figure 8). For rheophilic fish species (adapted to flowing water) the habitat availability and quality will gradually decrease over the years when secondary channels are silting up. On the other hand, for fish species with a strong dependency in rivers on oxbow lakes and backwaters, the habitat availability and quality will gradually increase, until the water depth in the secondary channels becomes too shallow (due to sedimentation).



**Figure 8. Habitat suitability for fish species in the secondary channels of the Gamerensche Waard.**

## CFR as river management strategy



**Construction of a secondary channel in the Klompenwaard, the Netherlands.**

In natural river systems, rejuvenation of islands, river banks, secondary channels and floodplain forests occur from time to time due to erosion. However, the current large river systems in Western Europe are fixed into one channel. Natural rejuvenation no longer occurs. Due to the urbanisation and economic developments along the river Rhine large areas of floodplains were cut off from the river in the past centuries and as a consequence the current room for the rivers is very limited

(between the dikes). To ensure the safety levels for flood protection now and in the future, there is a need for creating room for rivers. Since the river Rhine and its floodplains have been recognised as the backbone of the ecological main infrastructure in Northwest Europe, flood protection measures ought to be sustainable and improve the ecological quality as well. Fortunately, the room for river measures also create room for ecological development. However, to ensure the safety levels, the ecological development will now and then have to be set back into juvenile stages. Since rejuvenation processes no longer occur naturally, the river managers have to apply artificial rejuvenation. CFR may be a good strategy to do so, since it enhances both flood protection and the ecological quality of the river system.

The first step in the CFR strategy is to create room for the river for both flood protection and ecological development. After that hydrological, morphological and ecological processes will give direction to the natural developments of the river and floodplain ecosystems. As a consequence, morphological developments and ecological succession will result in a gradual increase of the water levels. When the increase of the water levels result in unsafe conditions, CFR measures are necessary. Roughly, there are two possibilities:

- (1) decreasing the hydraulic roughness of the floodplains by rejuvenating or removing vegetation types that have a high hydraulic roughness (such as forests);
- (2) creating room for rivers by floodplain lowering and (re)construction of secondary channels; as a consequence of floodplain lowering the existing vegetation will be removed and therefore the hydraulic roughness of the floodplain will decrease.

With respect to biodiversity, several important criteria for selecting CFR measures are indicated:

- the ecological reference condition or the ecological potential is setting the boundary conditions for changes in diversity of vegetation, habitats and landscape elements;
- rejuvenation of vegetation is dependent on the development time of the vegetation;
- morphological rejuvenation is dependent on the sedimentation rate of the morphological elements in the floodplains;
- rejuvenate those parts of the floodplains that are most effective in lowering the water levels: the more effective, the less floodplain area need to be rejuvenated. The relatively low parts of the floodplain which are regularly flooded with fast flowing water are most

interesting for rejuvenation of vegetation (deforestation) and the irregularly flooded parts of the floodplain for morphological rejuvenation (floodplain lowering).

CFR is in fact rejuvenation of both morphological elements and vegetation, to meet the safety levels on one hand and to achieve the ecological reference condition on the other hand. Given the actual characteristics of the floodplains and the potential for ecological development, CFR is creating a balance between safety and biodiversity. The case studies in this project showed that the role of CFR for flood control and ecological development can differ for individual stretches of a river. In the Restrhein case, CFR is aiming to increase the storage capacity of the river and to restore river habitats by enhancing morphological processes in the river. In the river Waal case, CFR measures are focusing on enlarging the discharge capacity of the river and restoring morphological and ecological processes in the floodplains. The two case studies emphasised the importance of CFR for both the lower and middle section of the river Rhine.

### CFR tool box

The application of CFR will result in dynamic river management, but should not lead to an increased flood risk: thus, ensuring the safety level must be the main focus of river management and within this safety restriction river dynamics and nature development will be given maximum freedom in the floodplains. In order to assess the consequences of sedimentation and vegetation development on the safety levels, two factors are essential: (i) monitoring the changes in vegetation structure and morphological changes within the floodplains and (ii) predicting future developments. This implies that proper river management tools are necessary that can assess and predict the present and future developments of the floodplains based on monitoring results. Therefore, it is necessary to monitor the morphological developments and changes in vegetation structure of the complete floodplain system at least every five years. Remote sensing techniques (e.g. satellite images, laseraltimetry) seem to be very promising for collecting detailed monitoring data at large scale (figure 9). Furthermore, to evaluate the monitoring results and subsequently to predict the future occurrence of unacceptable risks (5-10 years ahead) a modelling framework such as DSS Large Rivers is indispensable. If flood risks are expected, plans for CFR measures need to be made. After assessing these plans for flood risks and biodiversity, they can be implemented.

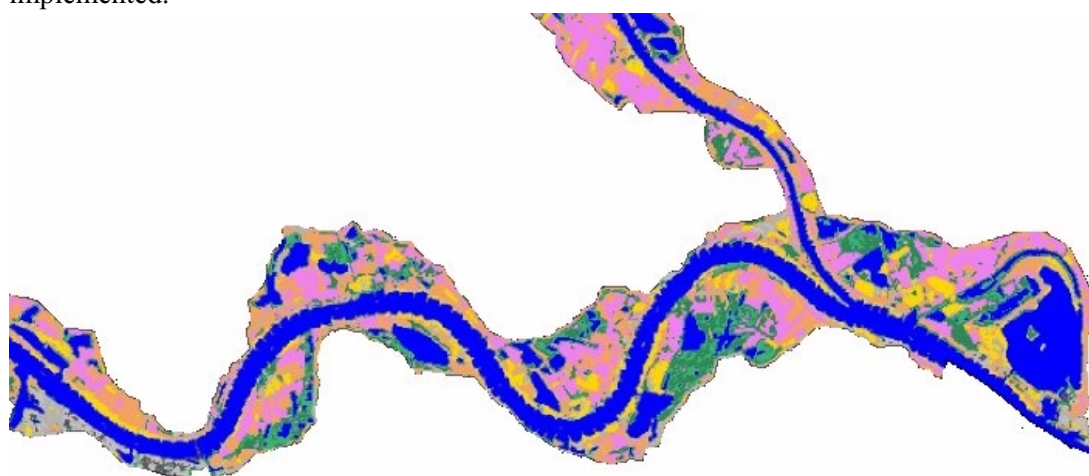


Figure 9. Ecotope classification of the upper stretch of the river Waal based on Landsat images.

## Guidelines for application of CFR

To apply CFR measures successfully for the Waal river, the following guidelines are developed:

- CFR measures should be applied on the river stretch scale (>25 km).
- CFR measures should be taken on the level of one or more floodplains (>250 ha).
- Do not underestimate the impact of morphological developments on the water levels, especially when the required time for ecological developments is more than 30 years.
- The rejuvenation frequency is dependent on the development time of vegetation types and morphological elements (such as secondary channels).
- To be very effective in lowering the water levels, deforestation should take place at large scale (>200 ha).
- Rejuvenate those parts of the floodplains that are most effective in lowering the water levels: the more effective, the less floodplain area need to be rejuvenated.
- Floodplain lowering at large scale (>200 ha) will lower the water levels considerably and as a result it creates many opportunities for ecological succession from pioneer stages. Unfortunately, this will be at the expense of existing ecological values.
- When changes in hydraulic roughness of floodplains are not acceptable because of safety reasons and the impact of CFR measures on lowering the water levels is limited (in many cases there are hydraulic bottlenecks present in the river stretch), the opportunities for increase of forest cover in the floodplains are restricted.
- CFR measures should be based on the existing characteristics and the ecological potential of the floodplains.
- To enhance and maintain the diversity of ecotopes, vegetation types (including different succession stages) and habitats, a description of the ecological reference condition or ecological potential at the scale of a river stretch is essential.
- Rejuvenate those parts of the floodplain that are most effective in lowering water levels; boundary conditions are, however, the ecological reference condition and the development time of characteristic floodplain vegetation and morphological elements.

## Recommendations for further research

This study is the first to assess the Cyclic Floodplain Rejuvenation strategy to link flood protection and nature development in the floodplains of rivers. The results of this study are promising, but there are still many questions and uncertainties. Before this new strategy can be applied in river management, more aspects of CFR need to be investigated. The most



**Hardwood floodplain forest along the Resthrein.**

important issues are mentioned here:

- the development of a cost effective method for monitoring vegetation development and morphological changes in the floodplains at river stretch scale;
- the analysis of effectiveness of local CFR measures using 2D hydrological models;



- the assessment of the applicability of CFR measures for other stretches of the river Rhine;
- the generation of knowledge on the interactions between vegetation and erosion and sedimentation within the floodplains, and subsequent incorporation of this knowledge in existing morphological models is essential;
- the impact of floodplain measures on river bed morphology needs to be investigated;
- the uncertainties in modelling need to be quantified;
- the socio-economic and environmental aspects of CFR need to be addressed;
- the definition of the ecological reference condition or maximum ecological potential of the river Rhine and its floodplains;
- the assessment of the effectiveness of the combination of ecological based strategies for both flood protection and enhancement of biodiversity;
- the legislation with respect to the application of CFR needs to be examined.

## Conclusions

The river management strategy of Cyclic Floodplain Rejuvenation is a promising strategy for nature rehabilitation and flood protection, both in the lowland river Waal and in the upper river Restrhein. In the Restrhein, river restoration in combination with the CFR strategy leads to an increase of the retention volume needed for flood peak lowering. At the same time the strategy leads to restoration of the former river dynamics and enhancement of the biodiversity. In the river Waal, the CFR strategy leads to an increase in the discharge capacity that results in a reduction of water levels during floods. Simultaneously, the strategy leads to more diverse floodplain nature in several states of succession and an increase in biodiversity.



**Floodplain lake.**

In the Restrhein case study it was demonstrated that superficial excavation of gravel within the floodplain area may connect gravel excavation with flood prevention and nature rehabilitation in a more sustainable way. Natural rejuvenation processes in braided channels can be restored, leading to a more diverse and dynamic river nature that belongs to a gravel bed river.

In the Waal case study it was shown that river restoration measures in combination with the dynamic river management of CFR can synergistically lower the water levels and increase the natural value of floodplain nature. It was also demonstrated that natural processes of sedimentation and vegetation succession can partly diminish the effects of hydraulic measures in rivers. The study results show that the increase in water levels due to both sedimentation of floodplains and growth and succession of vegetation is in the order of 1 cm per year. Each 5 years, the increase in forest area is about 50-300 ha and the increase in floodplain sediment volume about  $4 \cdot 10^6 \text{ m}^3$ . In order to prevent water levels from increasing on the long term, CFR measures need to be taken that are in the same order of magnitude. The study results further show that the CFR strategy is optimally applicable in river stretches where a relatively large rise (more than 25 cm) in water level can be accepted before the critical water level is reached. Furthermore, CFR is best applicable when there are no hydraulic bottlenecks in the

river stretch. The Waal case study has further demonstrated the consequences for biodiversity and fish habitats resulting from morphological and vegetation developments in and around secondary channels.

The objectives of this study were to assess several components of floodplain rejuvenation in relation to flood management strategies. A number of research questions have been formulated and subsequently answered.

- What is the influence of periodic inundation on the development of floodplain vegetation?
- What is the morphological development of floodplains and what consequences does this have for the development of floodplain wetlands and vegetation and how does this affect the hydraulic roughness?
- How is the development of floodplain forests in time, taking different initial conditions into account and what does this mean for the hydraulic roughness of the vegetation cover and its developments in time and space?

A floodplain sedimentation model has been developed that describes the sedimentation rates for various morphological features in floodplains. A floodplain vegetation model for the Waal river has been developed that describes the succession of vegetation types dependent on the inundation frequency and initial situation of nature development. The combined models were used to simulate the natural developments in floodplains. The changing vegetation composition led to a changing hydraulic roughness of the floodplains that was successively used to assess the water levels for a flood discharge. It was demonstrated that the CFR strategy can reduce water levels and increase biodiversity.

- What is the sedimentation or erosion rate of secondary channels and what consequences does this have for the availability and suitability of habitats?

A numerical model for hydrodynamic and morphodynamic processes has been applied on the secondary channels of the Gamerensche Waard in combination with a simulation of the vegetation developments and its effects on hydraulic roughness. The resulting developments in floodplain topography, flow characteristics and vegetation composition were subsequently used to assess biodiversity and habitat quality for fish. The results showed that secondary channels can either show erosion or sedimentation depending on the characteristics of the channel. Channels with sedimentation are overgrown with vegetation after about 30 years. The fish habitats change considerably over time and the biodiversity reaches a maximum after 15 years.

This study is the first to assess the CFR strategy to link flood protection and nature development in the floodplains of rivers. Before this new strategy can be applied in river management, more aspects of CFR need to be investigated. A combination of modelling and monitoring of the river is a prerequisite for the CFR strategy. Instruments need to be developed that aid the river manager in the implementation of river restoration plans to keep an eye on what is actually happening and what can be expected. In particular, the hydrological consequences of natural changes in morphology and vegetation need to be surveyed and model uncertainties need to be quantified. Furthermore, the socio-economic implications of the application of the CFR strategy need to be assessed. Finally, the combination of flood protection strategies both in floodplains and protected areas is a topic of further research.

CFR is one of the strategies for sustainable river management. It is recommended to explore the possibilities for combining CFR with other strategies for both flood protection and nature development. For example, the Sponge strategy in the upper reaches of the river basin and in the subbasins, the Retention Polder strategy in the middle and lower reaches and the Spillway strategy in the lower reach.