IRMA-SPONGE Project 8

Evaluation of floodplain management strategies: the added value of wetlands

Draft Executive Summary for discussion, 14 January 2002

Contents

Abstract

The objective of this project was to evaluate the beneficial effects of wetlands on flood risk reduction and water quality improvement in the Rhine.

The analysis of wetland effects on flood risk reduction aimed at evaluating whether the position of a wetland in the basin – upstream or downstream – will influence the added value of the wetlands in terms of reduced flooding damage. It was found that storing one cubic metre of water in an upstream wetland is generally more beneficial than storing a cubic metre of water in a downstream wetland, because the beneficial effects of upstream wetlands are felt throughout the basin and the effects of downstream wetlands are only felt downstream. However, upstream wetlands can not be used as a means for flood mitigation during extreme discharge conditions. Under such conditions, upstream wetlands will be completely saturated and directly discharge additional water. Extreme flood events in the Netherlands can thus only be mitigated by downstream detention areas.

The analysis of wetland effects on water quality improvement aimed with evaluating (i) whether increased areas of active downstream floodplains may increase nutrient retention in rivers, and (ii) whether rehabilitation of natural floodplain wetlands from agricultural grasslands may increase nutrient retention. This study showed that both an increase in the area of active floodplains in the Rhine delta, as well as rehabilitation of natural wetlands within floodplains will likely significantly improve water quality with respect to phosphorus, but will hardly affect water quality with respect to nitrogen. Moreover, nature restoration from agricultural grasslands towards reedbeds and ponds will be more beneficial for river water quality, than restoration towards woodlands or semi-natural grasslands.

Keywords: flooding, water retention, nutrient retention, value of water, denitrification, floodplain wetlands, river Rhine, sedimentation.

1. Background and objective of the study

The recent flood events in the Rhine basin have contributed to a growing awareness that the issue of flood risk management has to be considered in an integrated and international context, in which hydraulic, ecological and socio-economic functions of the river system are taken into account from the perspective of sustainable development. Flood risks are inherent to the dynamic nature of the water system, where wet and dry periods alternate. It are the peak discharges caused by excessive precipitation and snowmelt that constitute the risk of flooding. Therefore one can understand that much attention is paid to the question how to 'smoothen' the effect of excessive precipitation and snowmelt through temporary retention and storage of water. Retention of water naturally takes place in the soil and in pools, ponds, lakes, wetlands, small streams and rivers. The intensification of land use in the Rhine basin – which took place over a period of centuries – has probably led to a reduced water storage capacity in the basin. Particularly the area of wetlands has been reduced, due to 'canalisation' of both small and large streams. This has led to accelerated runoff and the preservation of peak flows. The question arises whether the creation of new wetlands, by allowing water to enter areas that are currently being protected against flooding, can contribute to the lowering of peak discharges and thus in reducing flood risks. This is however not the only reason why an increasing number of people plea for considering the possibilities of creating new wetland areas. Floodplains with well-developed wetlands may retain nutrients and reduce sediment loads; hence they may improve downstream water quality. In addition, natural wetlands have high ecological and biological values and can form essential connections in ecological networks (e.g. river corridors).

The discussion about the benefit of wetlands is quite complex, because many uncertainties remain: to which extent can wetlands actually contribute to the reduction of peak flows and the retention of nutrients, and can we evaluate the effect of different management strategies in terms of their net value added? Few efforts have been made to assess the overall net value added of wetlands, which is not just equal to the economic benefits of reduced flood risks minus the costs of creating the wetland (e.g. costs of land, construction costs). The net value added should also include ecological benefits such as the positive contribution of wetlands to water quality, biodiversity, and environmental quality. This study contributes to the debate on the value of wetlands by considering two particular questions:

1. At which location in the basin – in the upstream or the downstream parts of the basin – it is most beneficial to retain water in order to reduce flood risks?
2. What is the additional benefit of floodplain wetlands in terms of improved water quality?

The objective of the project was to evaluate the beneficial effect of wetlands on flood risk reduction and water quality improvement. In the analysis of the beneficial effect of wetlands on flood risk reduction, the major aim was to analyse to which extent the position of a wetland in the basin – upstream along the small streams or more downstream along the main river – influences the added value of the wetlands in terms of expected reduced flooding damage. The major aims of the study on water quality improvement were: (i) to evaluate whether an increase of the 'active' floodplain area may increase nutrient retention in the river, and (ii) to evaluate whether rehabilitation of natural floodplain wetlands (i.e. transformation of agricultural grasslands into semi-natural grasslands, reedbeds, woodlands or ponds) may increase nutrient retention.

The study consisted of two main parts: the part in which the value of water retention by wetlands was studied and the part in which the nutrient retention by wetlands was analysed.

2. The value of water retention by wetlands

Today water flows are often strongly regulated – the Rhine being a proper example – so that one would expect water to be allocated such that the net socio-economic and ecological benefits are optimised. However, nothing is less true. The actual situation is that the overall performance of the water system is not properly evaluated when making decisions with respect to water allocation, spatial planning and infrastructure. A precondition for such evaluation is that we put a proper (positive) value on water if it is scarce, but also that we put a proper (negative) value to water if it constitutes a risk factor. The latter means that water has a negative economic value in case of a harmful flooding event. A proper valuation of water would enable us to make more rational decisions on all kinds of activities that change the river regime, including the creation of wetlands.

The value of a water particle at a certain place and a certain point in time depends on its value in situ and on its value in a later stage (downstream). This means that the positive or negative value of water in a certain place can be translated into a value of the water upstream. As a first activity in this study, a method was developed for the calculation of the value of water as a function of its downstream benefits and costs (e.g. in case of flooding). In a second step, the method of water valuation was formalised in the form of a computer model and applied to the case of water excess and flooding damage in the Rhine basin. To test the genericity of the method, it was also applied to the case of economic benefits from water under conditions of water scarcity in the Zambezi region, which is however not reported here.

A water valuation method was developed that can be used to assess the economic values of different types of water stocks and flows, linking economic valuation to the physical nature of water flow dynamics. The valuation method was formalised in the form of a computer tool. The valuation methodology was applied and tested for the two case studies mentioned. Per case study, it was explored how people can manage water in a sustainable way. In practical terms, this means that it should be avoided that people use high-value water for purposes with a relatively low benefit. Groundwater recharge and standing or slowly flowing water in wetlands in the upstream parts of the Rhine basin for instance is high-value water, which should be prevented from turning into rapid surface runoff, forming peak discharges downstream (low-value water). The water valuation tool developed was operationalised and applied in the two case studies. In each case study, the valuation model was linked to an existing and validated water resources model, so that interventions in the water system could directly be translated into a net value added for the river basin as a whole. In the Rhine case study the RHINEFLOW model was used.

2.1. The water value-flow concept

The value of water is a key issue in managing water resources in an efficient, equitable and sustainable way. Efforts to assess the value of water are often not linked to the properties of the natural water system, which makes it difficult to analyse upstream-downstream dependency. In order to account for the cyclic nature of water in the assessment of water value, we introduce the 'value-flow concept'. This concept aims to provide the missing link between water valuation and hydrology. The hypothesis is that the full value of a water particle depends on the path it follows within the hydrological cycle and the values generated along this path. The full value of a water particle in a certain spot at a certain point in time is supposed to be the sum of its in situ value and all values that will be generated along its path later. It follows that all values generated by water can ultimately be attributed to rain. This simple concept implies that there is a direct analogy between the flow of water and the flow of values, but there is one big difference. Water values flow backwards in time and in a direction opposite to that of the water. In other words, the value-flow attributes local water values to the upstream water flows within the natural system. The aim of this paper is to put the value-flow concept in a proper mathematical model that is able to attribute the value of water produced in a certain place and at a certain time to the source of that water. Three models are considered in a progressive manner, to arrive at a generic form of the value-flow concept. The first two models were developed and used in an earlier study. In the current study a third model is introduced, in order to properly account for the dynamic nature of the hydrological cycle. This third model draws a parallel between the dynamics of water flows and the dynamics of value flows (Table 1). This study shows that the newly proposed model is the most generic one, able to correctly describe the flow of values in a dynamic water system. The parameterisation of the model is based on the hydrological characteristics of the water system. Further analysis of the value-flow concept addresses the way in which return flows generate a multiplier effect on the value of water.

Table 1. *Comparison of water flow and value-flow processes.*

Flow process	Balance components	Balance equation	Residence time
Water Flow		$\frac{dS(t)}{dt} = \sum_{i=1}^{m} Q_{in,\,i}(t) - \sum_{j=1}^{n} Q_{out,j}(t)$	$k_w(t) = \frac{S(t)}{\sum_{j=1}^{n} Q_{out,\,j}(t)}$
Value Flow		$\frac{dFVS(t)}{dt} = \sum_{j=1}^{n} FVQ_{out,j}(t) - \sum_{i=1}^{m} IVQ_{in,\,i}(t)$	$k_v(t) = \frac{S(t)}{\sum_{i=1}^{m} Q_{in,\,i}(t)}$

2.2. Application of the value-flow concept for conditions of water excess in the Rhine basin

The value-flow concept was originally developed within the context of water scarcity. In the current study the concept is applied to flooding conditions. When water causes damage or constitutes the risk of damage, a *negative* value should be attributed to the water. The value-flow concept is used to estimate the negative value of water that results from the risk of flooding within a river basin perspective. The value-flow concept assumes that the total value of a water volume passing a certain point consists of two components: a 'direct value' and an 'indirect value'. The direct value refers to the value of the water in situ, meaning the economical benefits or costs that are experienced due to the presence of the water at that location. The indirect value of water refers to the downstream benefits or costs of the water. The indirect value can be calculated from the discharge in the river and the total value by:

*Indirect value (i) = Total value (i+1) * Discharge (i) / Discharge (i+1)*

where (i) refers to the actual location and (i+1) to the downstream location.

The application of the value-flow concept for a river basin is illustrated in Figure 1. Suppose a small river basin is being studied, schematised into three grid cells with a precipitation excess of for instance 1 mm/day. Suppose further that the discharge from each grid cell equals 1 m^3/s and the discharge of the entire river basin is 3 m^3/s. If the direct value of the water in the most downstream grid cell is estimated at 100 Euro/day, the indirect values of the 2 upstream grid cells are calculated 67 and 33 Euro/day respectively.

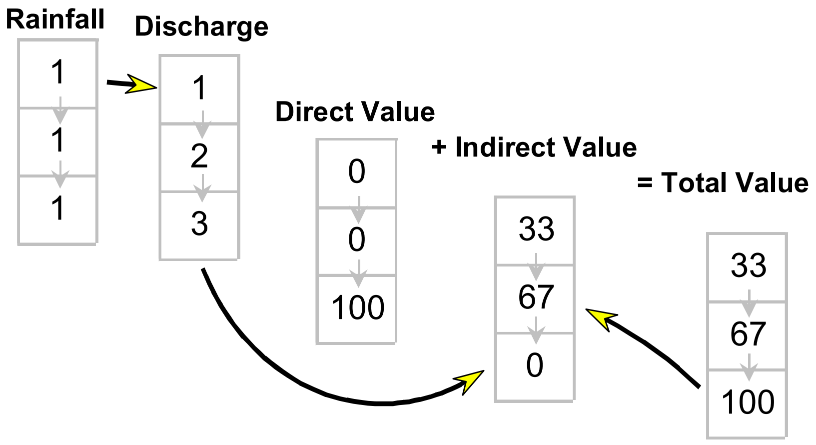

Figure 1. *Illustration of the value-flow concept for grid cells in a river basin.*

To apply the value-flow concept for the Rhine basin (see Figure 2), the basin is schematised into grid cells of 3×3 (km)^2. The RHINEFLOW model is used for simulating the water flow dynamics within the basin. The value-flow model is linked to this water-flow model in order to study the dissemination of values through the river basin. The negative direct values due to flooding in the Netherlands and Nord-Rhein Westphalen are estimated based on data in literature. The results of the calculations are presented in Figure 2.

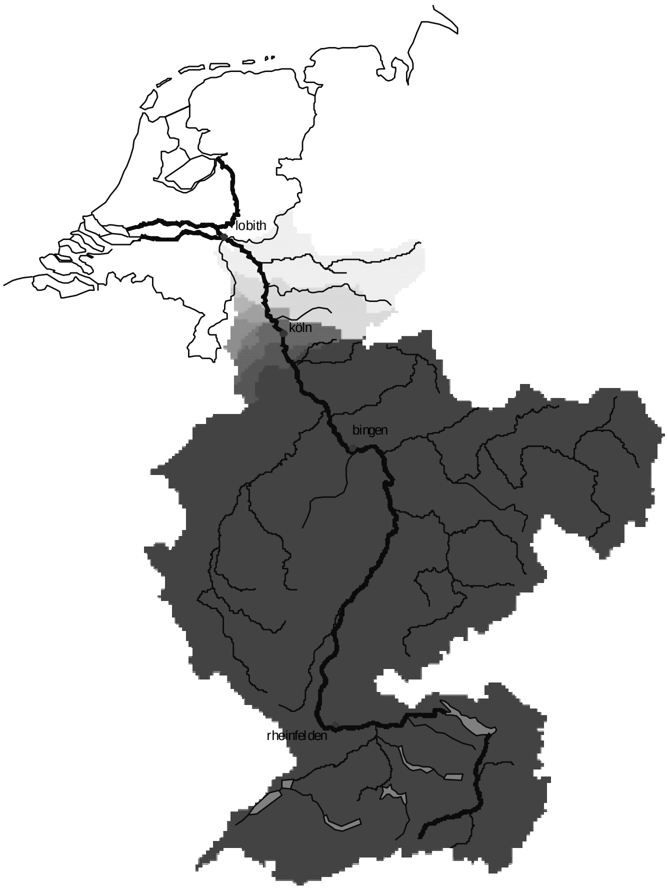

Figure 2. *Calculated unit values of water due to flooding of the Netherlands and Nordrhein Westphalen.*

The application of the value-flow concept for the Rhine basin revealed that the concept can be used to study flooding conditions (in addition to water scarcity conditions). The application indicates that measures aiming at the reduction of the discharge are equally benefit-effective anywhere upstream of the flooded areas. This is represented by the constant (negative) *unit* value of water upstream of the flooded areas (Figure 2). The costs of measures are not included in the present study. The study also indicated that the dissemination of the *total* negative values through the river basin depends on the discharge distribution of the various tributaries.

The application of the value-flow concept for the Rhine River Basin was also used to evaluate the effect of flood mitigation measures in upstream and downstream sections of the river basin. The risks for flooding of the Rhine River in the Netherlands might be reduced by (temporarily) storage of water either in upstream or downstream sections in the river basin. The upstream storage could be implemented by improving infiltration to groundwater and by reducing surface runoff, or by improvement of the retention in the floodplains. This should be achieved by re-naturalisation of the first-order streams. The downstream storage may the realised by the construction of detention areas along the main river. Upstream water retention and downstream water detention fundamentally differ in the way they buffer peak discharges (Figure 3). The two options are evaluated for the Rhine basin using the value-flow concept, and various characteristic values as described below and summarised in Table 2.

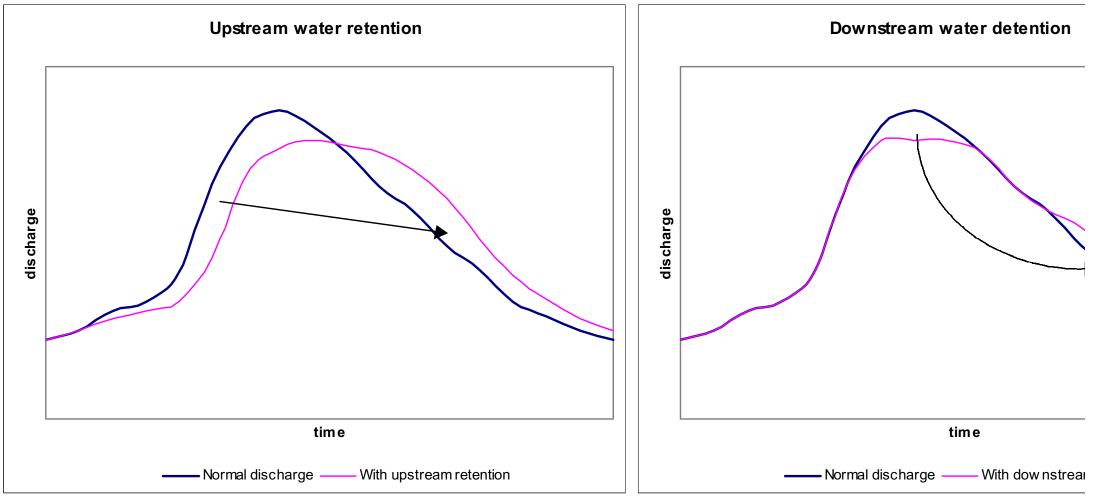

Figure 3. *Theoretical change in hydrographs due to upstream water retention and downstream water detention, assuming enough storage space available.*

The total volume of water that has to be stored to prevent flooding depends on the time span and the magnitude of the peak discharge, exceeding 15.000 m^3/s. For instance, to cope with a peak discharge of 16.000 m^3/s during a period of 24 hours, 1.000 $m^3/s \times 24 \times 3.600$ seconds = 86.400.000 m^3 should be stored. In the present analysis a water volume of 200.000.000 m^3 is used, representing the volume of water to be stored to cope with a discharge of 17.000 m^3/s during 27,8 hours or 16.000 m^3/s during 55,6 hours.

Assuming an average shallow water depth of 0,25 m in the floodplains, the additional retention in the upstream part of the river basin of this volume of water might require a surface area of 80.000 ha. In detention areas in the downstream part of the river basin the average water depth might be some 4 meters and consequently the required surface area amounts to 5.000 ha.

To implement the retention of water in the upstream floodplains, a number of relatively small structures are required. As the floodplain in the upstream part of the river basin will be flooded on a regular basis, the area should be assigned to the storage of water only and other economic functions are hardly possible. This implies that the area should be purchased. As the costs of the required (small) structures are assumed to be limited, the costs for the construction of these retention areas are merely related to the costs of the purchase of the land.

The detention areas in the downstream part of the river basin will be used only during discharge of more than 15.000 m^3/s. The detention areas can be used for agricultural purposes without any problems during normal discharge conditions. As agricultural land-use remains possible, the costs of the land are smaller than the costs of the land in the upstream part of the river basin. In this study it is assumed that the costs to assign the land as detention area in the downstream part of the river basin amounts to 50% of the costs to purchase the land in the upstream part of the river basin.

The costs for the construction of the detention areas are merely related to the construction of the dikes surrounding the detention areas and the structures for water intake (during peak discharge conditions) and water release. Depending on the type of dike and the necessary preparation, the costs for 1 km dike varies from 1 to 8 million Euro (Baan *et al*., 2001); in the present study 5 million Euro/km dike is assumed, including the required structures.

Various hydrological studies (for instance Van Deursen *et al*, 2001) indicate that a change in land-use will not contribute to the reduction in river discharge during flooding conditions. The main reason is that the soil is expected to be completely saturated with water, or even frozen, during these exceptional conditions and all excess precipitation will contribute directly to the discharge of the river.

The construction of wetlands in the floodplains of the upstream section of the river basin will result in retention of water during normal discharge conditions. These wetlands are localised in the lowest part of the upstream river valleys and will contribute to nutrient retention and local ecological conditions. However, as these wetlands will be filled with water already during normal discharge conditions, the additional retention of water during flooding conditions is practically zero.

The downstream detention areas will only decrease the damage due to flooding in the further downstream part of the river basin. Assuming that the detention areas will be constructed near the German-Dutch border, only the damage in the Netherlands will be reduced and flooding in Nordrhein Westphalen will persist.

Table 2. *Upstream water retention versus downstream water detention in the Rhine basin.*

	Upstream water retention by improved infiltration, reduced surface runoff and retention in floodplains	**Downstream water detention in constructed detention areas**
Total necessary area (ha)	80.000 ha (0,25 m depth)	5000 ha (4 m depth)
Estimated costs		
- land purchase	80.000 ha × 20.000 Euro/ha	5.000 ha × 10.000 Euro/ha
- construction structures	p.m.	50 km × 5.000.000 Euro/km
- maintenance cost	p.m.	p.m.
Estimated total costs	1.600 million Euro	300 million Euro
Area of influence	Downstream part of the river basin	Only the most downstream section (the Netherlands)
Reduced potential flooding damage	0 Euro	10 billion Euro
Additional benefits	- nutrient retention upstream during normal discharge - local ecological conditions	none

Considering the benefits of upstream water retention and downstream water detention for flood mitigation in the Netherlands only, the effects of both measures seem to be equal as both measures can reduce the peak discharge. In addition, upstream water retention can also reduce the risk for flooding upstream of the Netherlands, and contribute to additional benefits like increased biodiversity and nutrient removal (Table 2). However, implementation of upstream water retention during extreme discharge conditions (> 15.000 m^3/s) is hardly possible as the soil is likely to be completely saturated after prolonged rainfall. Notwithstanding the benefits of upstream water retention during less extreme discharge conditions, it will not be able to use this option for flood mitigation during extreme discharge conditions, so that downstream water detention remains necessary to prevent flooding in the Netherlands.

The results of the Rhine case study show that the value-flow concept offers the possibility of accounting for the cyclic nature of water when estimating its value. The other case study that was carried out, for the Zambezi basin, supports this and shows that the concept is not only useful in circumstances of water excess, but also in the case of water scarcity. It is stressed, however, that in both case studies many crude assumptions had to be made, so that the exact numbers presented should be regarded with extreme caution. Further research is necessary to provide more precise and validated estimates.

3. Nutrient retention by floodplain wetlands

Recreation of active floodplains along rivers, or restoration of natural wetlands within the floodplains, may not only enhance the value of rivers for flood protection or biodiversity, but may additionally increase the rivers natural capacity to remove nutrients from the water. This removal of nutrients from the water—generally called nutrient retention—is performed through processes as sedimentation and denitrification. Notwithstanding that these processes may occur in the main channel of rivers, it is likely that they particularly occur in the floodplains along the rivers, considering that the conditions for these processes are more favourable in the floodplains than in the main channel. Moreover, within floodplains, site conditions affecting sedimentation (e.g. vegetation structure, soil elevation) or denitrification (e.g. soil wetness, periphyton production) are likely more favourable in natural floodplain wetlands as reedbeds, woodlands or ponds than in agricultural grasslands. Large areas of floodplains along European rivers are, however, no longer 'active', in a sense that canalisation and construction of dikes have prevented the floodplains from flooding. Additionally, large areas within the floodplains have been cultivated into agricultural grasslands. Hence, these changes in the river morphology and floodplain land-use may have reduced the rivers natural capacity for nutrient retention, and may have contributed to eutrophication of rivers and coastal marine waters. Recently however, floodplain areas of large European rivers are expanded again to reduce the hazard of dike breaks during high water events, and natural floodplain wetlands are rehabilitated in order to increase biodiversity.

The two main objectives of this part of the study were (i) to evaluate whether an increase of the 'active' floodplain area may increase nutrient retention in the river, and (ii) to evaluate whether rehabilitation of natural floodplain wetlands (i.e. transformation of agricultural grasslands into semi-natural grasslands, reedbeds, woodlands or ponds) may increase nutrient retention. We used two approaches to quantify nutrient retention. By the first approach, nutrient retention was determined by measuring the decrease in N and P concentrations in river water during its downstream transportation in the rivers Waal and IJssel. By the second approach, nutrient retention was assessed through measuring retention mechanisms as denitrification and sedimentation in five types of floodplain wetlands along the rivers Waal and IJssel. Subsequently, nutrient retention was assessed by summation of the various nutrient output flows, and up-scaling to entire river stretches of the Waal and the IJssel.

3.1. Importance of active floodplain area for nutrient retention

We studied the importance of floodplains for nutrient retention by measuring the decreases in N and P concentrations in bodies of water which we followed during their downstream transport in the rivers Waal and IJssel. Water samples were taken from subsequent bridges over the rivers Waal and IJssel in February, March and July 2001. Because the percentages of the rivers discharge that flew through floodplains (Q_F) varied in time, as well as between the two rivers (cf. Figure 4), we were able to evaluate whether N and P retention increased with an increasing percentage of the rivers discharge running through floodplains.

Total-N concentrations did not significantly decrease during downstream transport in both rivers. In contrast, 20-45% of total-P disappeared during transport, but only in the river IJssel. As sedimentation is the major retention mechanism for nutrients in these rivers (see below), the difference between N and P retention is caused by differences in percentages of these nutrients adsorbed to particles in river water (2-3% of N vs. 50-70% of P). In an absolute sense, P-retention (g P s^{-1} km^{-1}) increased with increasing Q_F in the IJssel, but the percentage P-retention (% of P load) decreased with increasing Q_F (Figure 5). The high percentage P retention (45%) at low discharge was due to P retention in the channel and low total-P concentrations in the water. As a consequence, the percentage P-retention increased with decreasing stream depth, as was also found in streams and rivers of the Mississippi catchment. Apparently, the highest percentage P retention can be achieved in shallow rivers with a maximum contact between water and soil surface of the channel or floodplain; such conditions are indeed favourable for sedimentation.

Figure 4. *Cross sections of the rivers Waal and IJssel showing discharges (Q), as well as percentages of the discharge flowing through floodplains (Q_F), during the three sampling events. Arrows indicate sampling locations.*

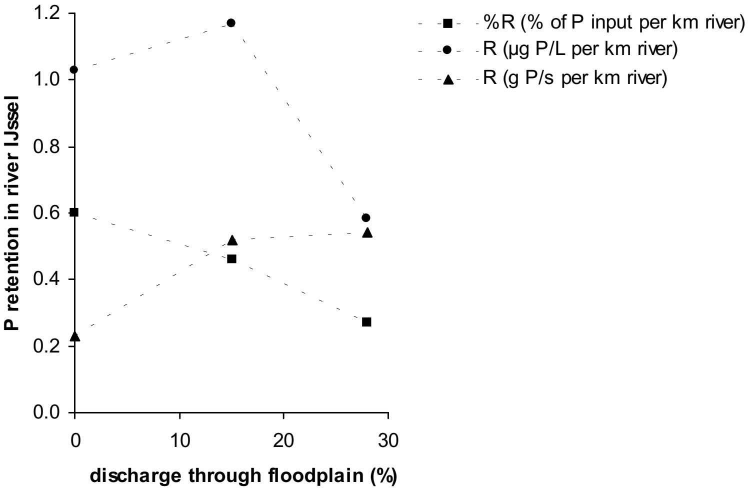

Figure 5. *Nitrogen en phosphorus retention vs. the percentage of river discharge flowing through floodplains, in distributaries of the river Rhine.*

The importance of floodplains for nutrient retention in rivers was also evaluated by comparing sedimentation and denitrification rates between floodplains along the rivers Waal and IJssel. As a much larger part of the rivers discharge had been in contact with floodplains in the river IJssel than in the river Waal (Figure 4), floodplains along the IJssel were more 'active' than floodplains along the Waal. In accordance with our expectations, we also found that sedimentation of nitrogen and phosphorus, as well as denitrification rates in the soil, were on average higher in floodplains along the IJssel than in floodplains along the Waal (Figures 6 and 7). Up-scaling of these measurements to the entire rivers Waal and IJssel showed consistent results with the retention rates as determined from decreased nutrient concentrations in river water. Retention of nitrogen was negligible in both rivers (< 3% of annual N-load) and P retention was only 4.6% of the annual P load in the Waal, but reached 18% in the river IJssel (Table 3). Sedimentation was the major retention mechanism. We note that these retention percentages of the total annual loads were achieved during a relatively short period of flooding in winter/spring., and that P-retention in the main channel at low discharge was not included in the assessments.

Figure 6. *Average sedimentation rates of nitrogen and phosphorus during one flood event (February 2001) in floodplains along the rivers IJssel and Waal. Average values of agricultural grasslands, semi-natural grasslands, reedbeds, and woodlands of Figure 10 are shown. Significant differences between IJssel and Waal are indicated as: ** p<0.01 1-way ANOVA, and p<0.001 by 2-way ANOVA.*

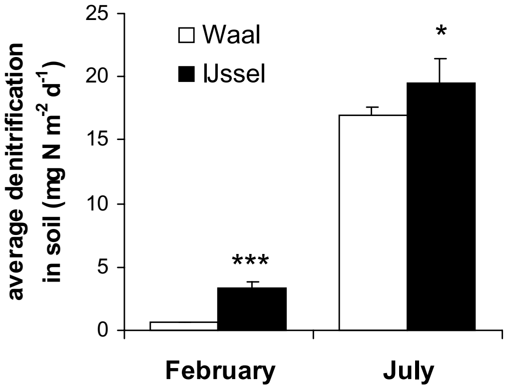

Figure 7. *Average denitrification rates in floodplain soils along the rivers IJssel and Waal, in February and July 2001. Average values of agricultural grasslands, semi-natural grasslands, reedbeds, woodlands, and ponds of Figure 11 are shown. Significant differences between IJssel and Waal are indicated as: *** p<0.001 1-way ANOVA and 2-way ANOVA; * p<0.05 2-way ANOVA only.*

Table 3. *Total retention of nitrogen and phosphorus in floodplain stretches of the rivers IJssel and Waal in comparison to the total annual river loads of nitrogen and phosphorus.*

River	Annual N-load river (10^3 kg N)	N retention Floodplains (10^3 kg N)	N retention %	Annual P-load river (10^3 kg P)	P retention Floodplains (10^3 kg P)	P retention %
Waal	182000	1240	0.7	9330	430	4.6
IJssel	30330	810	2.7	1560	290	18

We conclude that rehabilitation of active floodplains along the river Rhine—particularly when containing water at low and intermediate discharges—will decrease downstream P-concentrations, but will hardly affect N-concentrations. Hence, such rehabilitations may reduce the hazard of eutrophication in P-limited waters as the coastal area of the North Sea.

3.2. Importance of the type floodplain wetlands for nutrient retention

To evaluate whether nutrient retention may be increased by transforming agricultural grasslands into more natural types of floodplain ecosystems we performed a series of experiments. We measured retention mechanisms as denitrification and sedimentation in agricultural grasslands, as well as in natural types of floodplain wetlands as semi-natural grasslands, reedbeds, woodlands, and ponds.

A laboratory experiment was carried out to assess denitrification rates in flooded agricultural grasslands and reedbeds, by means of bacteria in flood water, sediment and periphyton (bateria-layer attached to plants). Preceding the experiment, we measured oxygen conditions in a floodplain along the Waal to evaluate whether denitrification could take place in floodplains flooded with nitrate-rich but also oxygen-rich river water. Because oxygen levels in flood water dropped to very low levels during the night, denitrification could indeed takes place in floodplains inundated with oxygen-rich river water (cf. Table 4).

Table 4. *Day-night fluctuations in oxygen contents in the river Waal and its floodplain, during spring. Mean (S.E.) values of three replicate sites are shown.*

	oxygen concentration (mg/L)		oxygen saturation (%)	
	day	Night	day	night
river	11.1 (0.2)	10.3 (0.1)	103 (1)	93 (1)
reedbed 1	15.7 (1.8)	0.4 (0.0)	145 (10)	3 (0)
reedbed 2	18.5 (0.3)	0.5 (0.0)	169 (1)	5 (0)
woodland	14.4 (0.9)	0.8 (0.1)	138 (6)	6 (1)

day = 26 April 2001 at 4 p.m.; night = 27 April 2001 at 6 a.m.

In the laboratory experiment, light and oxygen conditions were simulated which occurred during day, evening and night in the investigated floodplain along the Waal. Denitrification rates were measured in water, in water + sediment, in water + periphyton, and in water + sediment + periphyton. The sediment was collected from a reedbed and an agricultural grassland along the Waal; periphyton was attached to reed stems or grass, respectively. Denitrification rates were rather low at day and evening conditions, increased significantly during night conditions, but only when sediment or periphyton was added to the water (Figure 8). Calculations of denitrification rates per square meter showed that denitrification in periphyton was low compared to denitrification in sediment, due to the limited surface area for periphyton on reed stems. Overall denitrification rates were therefore rather similar in reedbeds and agricultural grasslands (Figure 9). So, rehabilitation of agricultural grasslands into reedbeds will likely not affect nutrient retention through denitrification, but rehabilitation towards wetlands with larger surface areas for periphyton (e.g. ponds with a well developed submerged macrophyte vegetation) may increase N loss by denitrification.

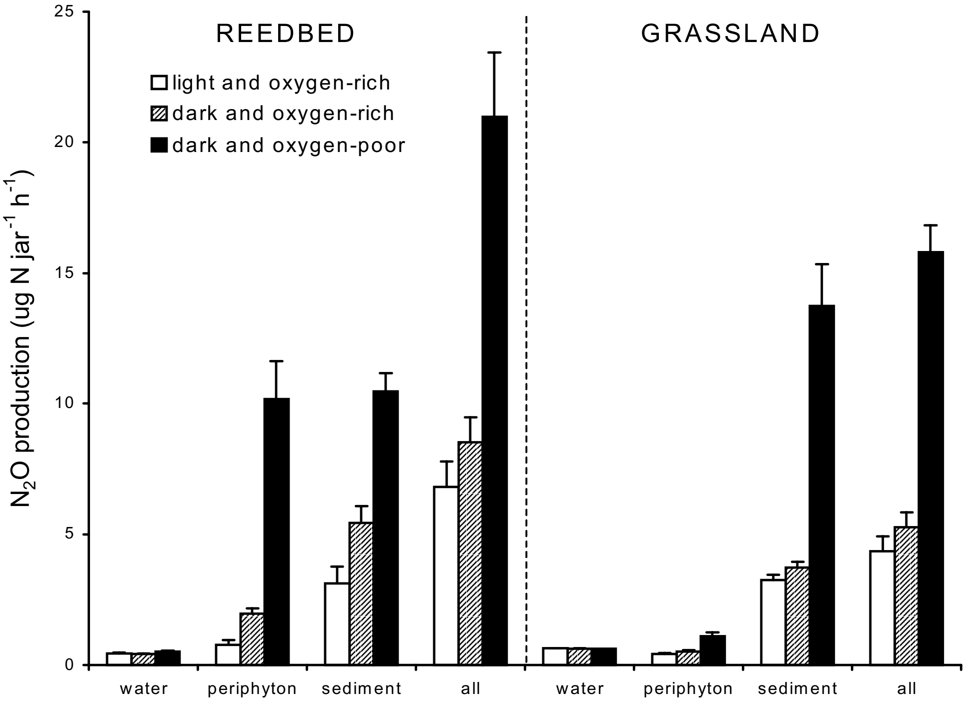

Figure 8. *Importance of bacteria in water, sediment and periphyton on denitrification rates (measured as N_2O production) in river water above flooded grasslands and reedbeds, at different light and oxygen conditions.*

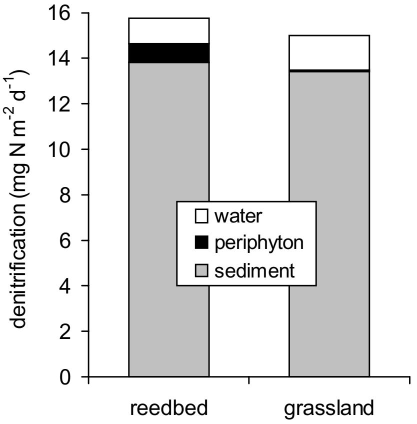

Figure 9. *Estimated daily denitrification rates in floodwater in agricultural grasslands and reedbeds. Daily rates were calculated from rates in Fig. 8; assuming 6 hours light and oxygen-rich, 12 hours dark and oxygen-rich, and 6 hours dark and oxygen-poor per day. A flood depth of 30-cm was assumed. Water = water treatment; Periphyon = periphyton treatment minus water treatment; Sediment = sediment treatment minus water treatment.*

In another series of experiments and measurements, we assessed the contributions of sedimentation and denitrification in floodplain soil to annual nitrogen and phosphorus balances in agricultural grasslands, semi-natural grasslands, reedbeds, woodlands and ponds.

Sedimentation rates of nitrogen and phosphorus were measured during a flood event in February 2001, by means of sediment traps (mats) placed in the five types of floodplain wetlands along the rivers Waal and IJssel. Apart from very high sedimentation rates of nitrogen and phosphorus in a pond along the Waal (see Figure 10), sedimentation rates were also significantly higher in reedbeds than in the other floodplain types ($p<0.05$; two-way ANOVA).

Figure 10. *Sedimentation of nitrogen (A) and phosphorus (B) during one flood event (February 2001) in five types of floodplain wetlands, along the rivers Waal and IJssel. Significant differences are indicated by different letters ($p < 0.05$; one-way ANOVA).*

Denitrification rates in the top soil of the five types of floodplain types were measured in February and July 2001, by measuring N_2O-production after soil incubation with acetylene. Denitrification rates in the soil were rather low in February but were higher in July; the highest rates were found in agricultural grasslands (Figure 11). The source of nitrate for dentrification seemed to be different in March and July; i.e. 'free' nitrate in March versus coupled nitrification-denitrification in July. Inhibition of nitrification by acetylene may explain the drop in N_2O production after 1 hour of incubation (Figure 11).

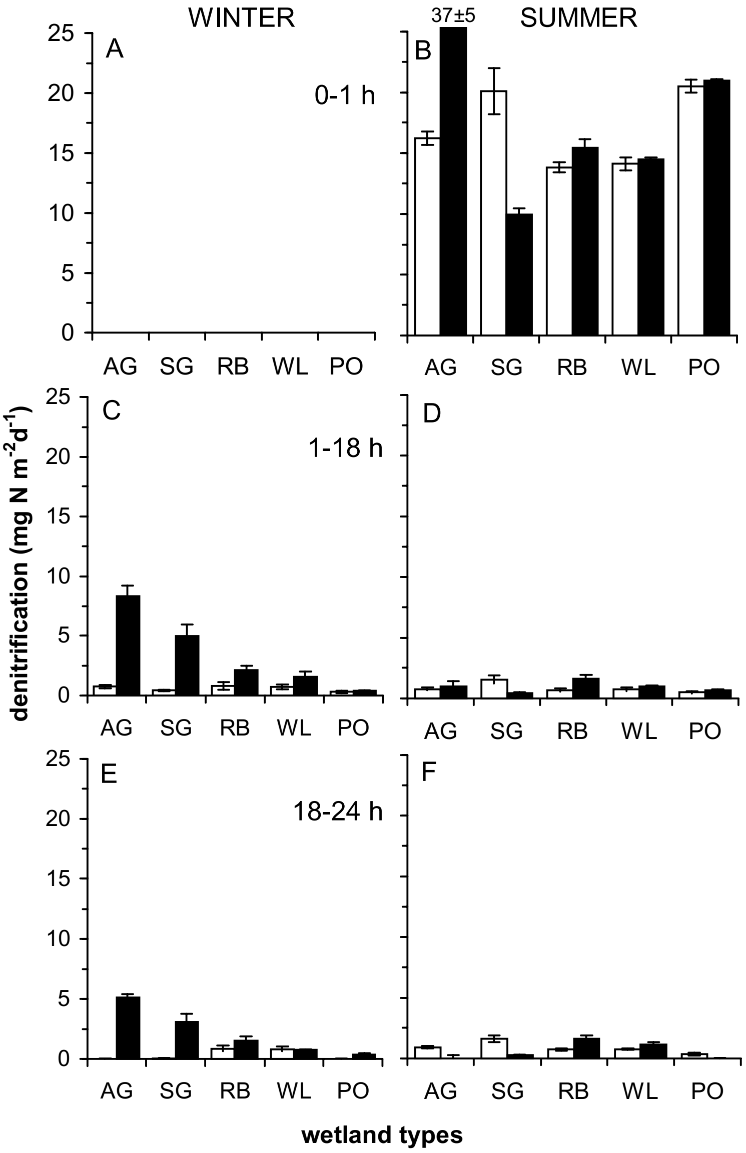

Figure 11. Average denitrification rates in top 5 cm soil from various floodplain wetlands along the rivers Waal (white bars) and IJssel (black bars). Cores taken in winter (27 February-1 March 2001) were incubated at 5 °C, and cores taken in summer (10-12 July 2001) were incubated at 18 °C. A-B, C-D, and E-F show N_2O-accumulation rates between 0-1, 1-18, and 18-24 hours of incubation

with acetylene. In winter, denitrification rates during the first hour of incubation were all too low to be measured. Error bars represent the standard error of eight replicates. AG agricultural grasslands, SG semi-natural grasslands, RB reedbeds, WL woodlands, PO ponds.

A compilation of our measurements and data from literature resulted in annual input-output balances for nitrogen and phosphorus for the five types of floodplain wetlands (Table 5). Due to high levels of fertilisation, agricultural grasslands could be a sink or a source for nutrients in river water. The natural floodplain wetlands were all sinks for nutrients. Based on the nutrient balances, we concluded that nutrient retention in the rivers Waal and IJssel (or similar European rivers) may considerably increase when agricultural grasslands are transformed into reedbeds or ponds. Transformations into woodlands or semi-natural grasslands seemed to have a much smaller effect on nutrient retention, or no effect at all.

Table 5. *Annual balances of N and P in five types of floodplain wetlands along two Rhine-distributaries in The Netherlands. All nutrient fluxes are in kg N ha^{-1} y^{-1} or kg P ha^{-1} y^{-1}.*

	agricultural grasslands		semi-natural grasslands		reedbeds		woodlands		ponds	
	N	P	N	P	N	P	N	P	N	P
Input										
sedimentation[1]	31-33	11-17	25-73	12-38	126-144	53-61	26-67	9-32	341	156
atmos. deposition[2]	34-46	< 1	34-46	< 1	34-46	< 1	34-46	< 1	34-46	< 1
N fixation[3]	< 1	-	< 1	-	< 1	-	< 1	-	< 1	-
Fertilization[4]	> 211	> 34	-	-	-	-	-	-	-	-
Output										
denitrification										
calc. March[5]	3-29	-	1-17	-	3-8	-	3-5	-	1	-
calc. July[5]	59-134	-	36-73	-	50-56	-	51-53	-	75-76	-
average	56	-	32	-	29	-	28	-	38	-
hay harvest[6]	88-92	17-17	42-61	10-15	-	-	-	-	-	-
input – output[7]	> 137	> 31	6	13	146	57	59	21	343	156
input – output (excl. hay)	227	48	56	25	146	57	59	21	343	156
plant productivity[8]	77-79	15-16	16-39	6-11	194-265	25-28	0-22	0-2	61-68	13-17
productivity/net input %	34	32	49	34	158	46	19	5	19	10

1 calculated from Fig. 10, assuming three flood events per year
2 unpublished data from RIVM
3 symbiotic fixation is negligible because N-fixing species hardly or not occurred
4 see chapter 8; artificial fertilizer is not included in values but is applied, therefore '>'
5 calculations based on measurements in March or July (Fig. 11)
6 hay-making in grasslands during summer; data from chapter 8
7 calculated from average values
8 productivity in 133 days; data from chapter 8

A scenario study, in which all agricultural grasslands along the rivers Waal and IJssel were transformed into reedbeds or ponds, indeed showed that the annual amounts of N and P deposited in floodplains through sedimentation, would increase 1.5-5.4 fold (Table 6). These values were however overestimated, because the annual amounts of deposited nutrients in floodplains can not exceed the total amounts of nutrients attached to sediment in the annual floodplain discharge. Since sediment trapping efficiency in the Dutch distributaries was already 50-70% of the total sediment load in the present situation, increases in nutrient retention in these river stretches will not be more than 1.5- to 2-fold (100/70 or 100/50). Moreover, the effects of these increased floodplain sedimentation rates on nutrient retention in the rivers will be much more significant for phosphorus than for nitrogen, because a large fraction of phosphorus in river water is adsorbed to sediment (50-70%) whereas only 2-3% of the nitrogen is adsorbed to sediment.

Table 6. *Assessed increase in sedimentation of nitrogen and phosphorus along the rivers Waal and IJssel for increased areas of reedbeds or ponds in floodplains along the rivers. For present sedimentation rates in agricultural grasslands, reedbeds and ponds, see Table 5.*

River	fraction agricultural grassland area	present sedimentation (10^3 kg N or P)		factor of increase scenario reedbeds[1]		factor of increase scenario ponds[2]		average trapping efficieny
		N	P	N	P	N	P	
Waal	0.17	1136	429	1.5	1.5	2.6	2.7	0.5
IJssel	0.43	757	286	2.4	2.3	5.2	5.4	0.7

[1] factor = 1 - fraction agr. grasland + fraction agr. grassland * ($\text{sedimentation}_{\text{reedbeds}}/\text{sedimentation}_{\text{agr. grasslands}}$)

[2] factor = 1 - fraction agr. grasland + fraction agr. grassland * ($\text{sedimentation}_{\text{ponds}}/\text{sedimentation}_{\text{agr. grasslands}}$)

4. Discussion, conclusions and recommendations

4.1. The added value of wetlands on flood risk reduction

- In years without exceptionally wet periods, wetlands in the upstream parts of the Rhine basin are more beneficial (in terms of reduction of peak discharges and in terms of additional benefits per cubic metre of water stored) than wetlands in the downstream parts of the basin.
- However, during an exceptionally wet period – with extreme discharge conditions (> 15.000 m^3/s) – wetlands in the upstream parts of the basin will not be functional in lowering downstream flood risks, because under such extreme conditions wetlands will no longer be able to further store water. Soils and wetlands will be completely saturated after prolonged rainfall and directly discharge additional water. Thus, implementation of natural retention areas in the upstream parts of the basin will reduce non-extreme peak discharges but have insignificant effects on *extreme* peak discharges.
- Besides, creating a large number of (relatively small) wetlands in the upstream parts of the basin with a sufficient accumulative storage capacity is expected to be more costly than creating a limited number of larger wetlands downstream, because a larger area will be required.
- The final conclusion is that extreme flood events in the Netherlands can only be mitigated by downstream detention areas.

4.2. The added value of wetlands on water quality improvement

- Floodplain wetlands contribute significantly to the retention of phosphorus in the river Rhine, but have a negligible effect on N retention. Based on measured sedimentation and denitrification in floodplains, P retention is assessed at 5% and 18% of the annual P load in the rivers Waal and IJssel respectively, whereas N retention is assessed at 0.7-3% of the annual N load in these rivers. In general, these estimates are consistent with measured changes in N and P concentrations in river water during downstream transport in these rivers (i.e. P concentrations decreased significantly in the river IJssel, whereas changes in P concentrations in the Waal as well as N concentration in both rivers were too small to be detected significantly). Measured P retention rates in the IJssel (20-45%) are somewhat higher than the assessed 18%, because particularly at low discharge P retention also takes place in the main channel.
- Increased areas of active floodplains along the Rhine and other large rivers—particularly those that contain water at low and intermediate discharges—will decrease downstream P-concentrations, but will hardly affect N-concentrations. Hence, rehabilitation of active floodplains may reduce the hazard of eutrophication in P-limited waters as the North Sea.
- Both for phosphorus and nitrogen, sedimentation is the major mechanism of nutrient retention. High retention rates are therefore only found for P, as N is hardly adsorbed to sediment in river water.

- Phosphorus retention is highest in shallow rivers with a maximum contact between water and soil surface of the channel or its floodplain, as such conditions are favourable for sedimentation.
- Highest sedimentation rates are found in wetlands were water velocity is reduced by vegetation structure (reedbeds) or by a drop in surface elevation (pond). Sedimentation is, however, not higher in woodlands than in agricultural or semi-natural grasslands, probably because woodlands receive less water.
- Denitrification rates in floodplain soils are rather low in winter but can be substantially higher in summer through coupled nitrification-denitrification, although the latter may not contribute to N retention in river water. Therefore, denitrification contributes less to N retention in rivers than sedimentation. Highest denitrification rates in soils can be found in agricultural grasslands (winter and summer) and in ponds (summer).
- During the night, denitrification takes places in nitrate-rich flood water, resulting in daily denitrification rates comparable to rates for wetland soils. Denitrification rates in flood water are similar in reedbeds and agricultural grasslands, because denitrification in the sediment/water zone is more important than in periphyton/water zone in these two floodplain types. Denitrification rates in flood water are likely higher in floodplain wetlands with larger surface areas for periphyton, as ponds.
- Floodplain rehabilitation from agricultural grasslands towards natural types of floodplain wetlands will reduce the hazard of eutrophication of rivers and coastal waters as agricultural grasslands may act as sources for nutrients, whereas natural floodplain wetlands are nutrient sinks. Moreover, rehabilitation towards ponds or reedbeds will be more beneficial for downstream water quality than towards woodlands or semi-natural grasslands.

4.3. Synthesis

- Notwithstanding the benefits of upstream water retention during less extreme discharge conditions, it will be impossible to use upstream water retention as a means for flood mitigation during extreme discharge conditions. Extreme flood events in the Netherlands can only be mitigated by downstream detention areas.
- In principle, increasing the area of floodplain wetlands in the Rhine delta can effectively reduce the risk of flooding. An additional benefit of more floodplain wetlands will be the increased retention of phosphorus.
- However, effective P removal and effective reduction of extreme peak flows are conflicting aims. Effective nutrient retention requires a high inundation frequency. Flood risk reduction requires sufficient water storage capacity at the beginning of a peak discharge, which means that detention areas should preferably be used in a controlled way and only when necessary.