Hydrobiologia (2006) 565:243–257
R.S.E.W. Leuven, A.M.J. Ragas, A.J.M. Smits & G. van der Velde (eds), Living Rivers: Trends and Challenges in Science and Management
DOI 10.1007/s10750-005-1917-3

Flood detention, nature development and water quality along the lowland river Sava, Croatia

M.J. Baptist[1,2,*], M. Haasnoot[1], P. Cornelissen[3], J. Icke[1], G. van der Wedden[4], H.J. de Vriend[4] & G. Gugić[5]
[1]*WL|Delft Hydraulics, P.O. Box 177, 2600 MH Delft, The Netherlands*
[2]*Faculty of Civil Engineering and Geosciences, Water Resources Section, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands*
[3]*Rijkswaterstaat, RIZA, Zuiderwagenplein 2, 8284 AD Lelystad, The Netherlands*
[4]*Faculty of Civil Engineering and Geosciences, Hydraulic Engineering Section, Delft University of Technology, Stevinweg 1, 2628 CN, Delft, The Netherlands*
[5]*Lonjsko Polje Nature Park, HR-44324, Jasenovac, Croatia*
*(*Author for correspondence: E-mail: m.j.baptist@citg.tudelft.nl)*

Key words: ecohydrology, hydrologic modelling, nature management, phosphorus storage, sediment storage, vegetation succession

Abstract

The construction or designation of detention areas along lowland rivers is considered along many European rivers. Since Croatia accommodates large detention areas, both natural (e.g., Mokro Polje) and controlled (Lonjsko Polje), it serves as an excellent example for planned detention areas elsewhere in Europe. This modelling study focuses on the controlled detention area of Lonjsko Polje. The flooding characteristics of the area are assessed in combination with the vegetation development and the transport and storage of sediment and phosphorus. Results of the modelling show that it is not so much the intake capacity that determines the flood duration time of a detention area, but the drainage capacity. A too long inundation duration following a flood event is shown to lead to major shifts in the vegetation composition. The results further indicate that about 30% of the sediment and adsorbed phosphorus that enters the detention area during an extreme (1:100 years) flood is retained within the area; this is about 10% of the total sediment and adsorbed phosphorus load of the Sava. Results of this study can be used to properly design and manage detention areas along lowland rivers.

Introduction

Detention areas serve as a temporary storage of water that is diverted from the river channel. This lowers the peak level of the flood and thus alleviates the flood risk for downstream areas. The construction or designation of detention areas along lowland rivers forms part of strategies to reduce flood water levels and is considered along many European rivers (Van Stokkom et al., 2005).

Detention areas need to be large enough to be effective, while inlet and outlet structures and embankments may allow managing the timing of the flood alleviation. Flood detention may involve large areas and will also affect the ecological functioning of such areas.

The Lonjsko Polje detention area in Croatia (Fig. 1) is probably the best example in Europe to study the hydrology, ecology and water quality of a large, controlled flood detention area. Besides its role in flood control, it has very important ecological values, on a regional, national, and even global scale.

The objective of this study is to evaluate different flood control strategies for the Lonjsko Polje detention area and to assess their implications for

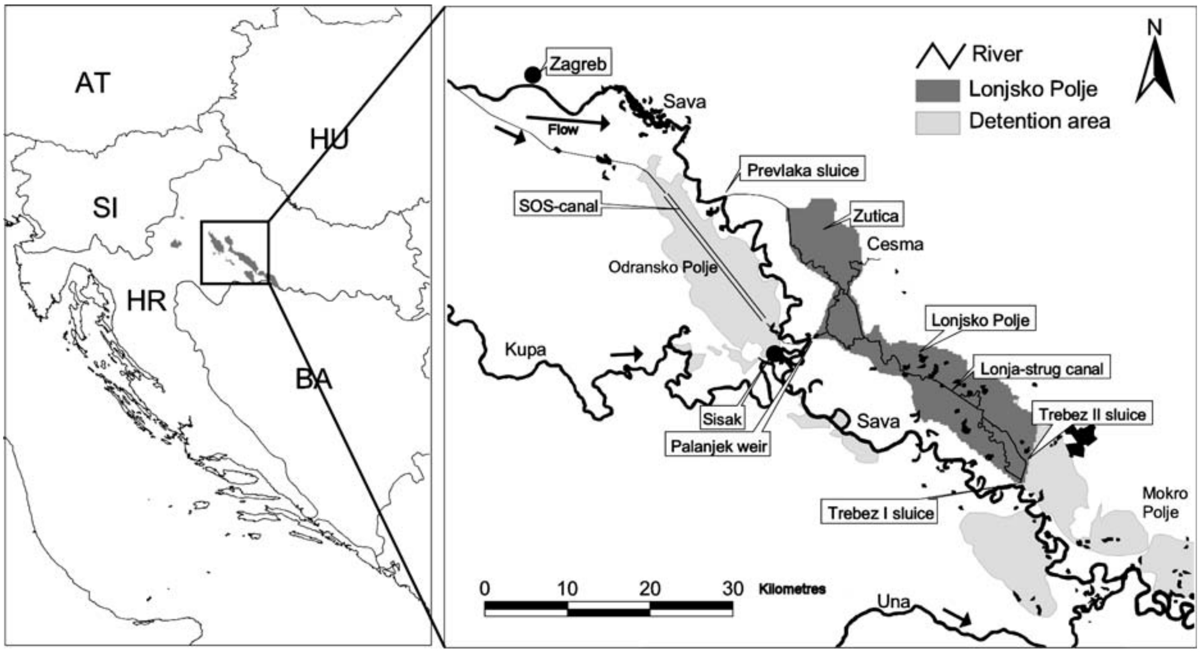

Figure 1. The Lonjsko Polje detention area and flood protection works in the Central Sava Basin, the towns of Zagreb and Sisak, and the rivers Sava, Kupa, Una and Česma. AT is Austria, HU is Hungary, SI is Slovenia, HR is Croatia and BA is Bosnia–Herzegovina.

flood safety, ecosystem development and phosphorus storage. Flood control strategies were evaluated using an overland flow model for the flooding of Lonjsko Polje. Subsequently, the effect on vegetation development was evaluated on the basis of knowledge rules describing ecohydrological relationships for vegetation. Finally, water quality modelling shows the sediment and phosphorus deposition in Lonjsko Polje.

Material and methods

Study area

Flood control in the Central Sava Basin (CSB) is accomplished through controlled flooding of (semi-)natural detention areas, transforming the flood wave of the river Sava and its tributaries. The flood control system includes artificial canals, dams and sluices for controlled distribution of the water, and detention areas for flood water storage. An overview of the various flood control works in the CSB and their history is given by Petričec et al. (2004).

The Lonjsko Polje *detention area* is the largest detention area in the CSB. It measures 237 Mm^2 and has an estimated maximum detention capacity of 634 Mm^3 (Brundić et al., 2001). It forms part of the Lonjsko Polje *Nature Park*, which has an area of 510 Mm^2 and consists of various detention areas and floodplains downstream of Zagreb.

The Lonjsko Polje Nature Park is a protected wetland under the Ramsar treaty and is an important bird area (Heath & Evans, 2000). The present vegetation distribution and composition is the result of the hydrological conditions and the land use of the past. In the past decades the vegetation composition has changed from a predominantly open landscape with pastures to a landscape with a mosaic of riparian forests and herbaceous vegetation. Due to economic and demographic reasons, the traditional grazing with indigenous breeds of cows, horses and pigs has declined. In addition, the hydrology is affected by the construction of embankments and sluices around the Lonjsko Polje detention area in the 1970s (Gugić & Ćosić-Flajsig, 2004).

Figure 1 presents an overview of Lonjsko Polje. In this paper, the name Lonjsko Polje refers to the detention area, not the Nature Park. A Sava flood wave enters Lonjsko Polje through the Prevlaka sluice, which has a maximum capacity of 600 m^3 s^{-1}. It then flows through the Lonja-Trebež river to the Žutica area in the northwest. In Žutica more water may be added from the smaller streams Lonja and Česma. From Žutica onwards, the flood wave progresses overland and via the Lonja river. The flood wave subsequently leaves Lonjsko Polje via the Trebež I sluice, draining into the Sava River, with a maximum capacity of 500 m^3 s^{-1}.

Flood management plans

Since the Lonjsko Polje detention area is located *downstream* of Zagreb it cannot directly serve as a flood protection system for Zagreb. However, as part of a large flood management study completed in 1972 by a consortium of local and foreign specialists under the auspices of the United Nations Development Office (UNDO, 1972), the Sava-Odra-Sava (SOS) canal was designed. This canal takes in water *upstream* of Zagreb and transports part of the flood wave back into the Sava River, just upstream of Sisak. On the opposite side of the river, a planned sluice at Palanjek then fills the Lonjsko Polje detention area, thus providing flood safety for Zagreb. In this plan, the size of the Lonjsko Polje detention area is increased by 8% to 256 Mm^2, and the maximum detention capacity is supposed to increase to 915 Mm^3 (Brundić et al., 2000). This plan will be further referred to as the 1972-plan.

The execution of the 1972-plan ceased in the beginning of the 1980s (Petričec et al., 2004). The SOS-canal is in its current state partly finished and now fills the Odransko Polje during floods. The Palanjek sluice has never been built and neither has the planned Trebež II sluice that connects Lonjsko Polje with the downstream Mokro Polje detention area.

More recently, an Environmental Impact Assessment for the World Bank, executed by Croatian Waters (the water management authority of Croatia), the Hydrological Project Bureau of Croatia and Euronatur, proposed an alternative flood management plan (CW, 2001). In this plan, Odransko Polje will be transformed into a detention area, which will be filled by the SOS-canal in its present, unfinished state. In Palanjek a weir is proposed, instead of a sluice, providing capacity to fill Lonjsko Polje. Furthermore, it is proposed to build the Trebež II sluice, to connect Lonjsko Polje with Mokro Polje. In this plan, the maximum detention capacity is supposed to increase to 733 Mm^3 (Brundić et al., 2001). This plan will be further referred to as the WB-plan.

Case definition

Three planning alternatives were evaluated:

1. The current situation;
2. The 1972-plan;
3. The WB-plan.

It must be noted here that the expansion of the detention area from 237 to 256 Mm^2 in the 1972-plan is not taken into account in our model, since we do not know where exactly the additional area is planned.

The hydrology of floods in the CSB is complicated. Different origins of floods for different seasons bring different flood events. Consequently, Croatian Waters has defined three different flood types, characterised by an extremely high Sava, Kupa or Una discharge, respectively. One of these flood types is applied, i.e. the SL1 event, which is the 1:100 years event for an extremely high Sava discharge at the border between Slovenia and Croatia, combined with flood hydrographs from the other major tributaries to the Sava. This event yields the highest flood levels.

In this study the three planning alternatives were considered in combination with two hydrological scenarios, the SL1 event and the year 1997 as an average hydrological year, yielding six cases in total.

Hydrological model

The numerical model Sobek is applied in this study to investigate the flow and quality of water. Moreover, it serves as a base model for flood management evaluation and for assessing the ecohydrological developments. Sobek is a flow and transport model that solves the momentum and continuity equations for surface flow, as well as the advection diffusion equation for transport, in one and two dimensions, to model shallow overland flow in, for example, floodplains, polders or detention areas (Verwey, 2001; Postma et al., 2003). The model application for this study builds upon the existing one-dimensional (1-D) model of the Sava, which has been developed for the International Commission for the Protection of the Danube River (Van Gils & Bendow, 2000).

The model application simulates the flow of water in the Sava. It has an upstream boundary in Slovenia and a downstream boundary in Belgrade at the confluence of the Sava and Danube. One-dimensional modelling elements include the Sava itself, the SOS-canal near Zagreb, as well as canals and (former) streams in the Lonjsko Polje detention area, the Česma, the Lonja and the Lonja-Strug canal. Cross sections and stage–discharge relationships were obtained from Croatian Waters and the Hydrological Project Bureau (VPB) of Croatia.

Various sluices and weirs that affect the flooding of Lonjsko Polje were included in the model. These were the existing Jankomir weir at the entrance of the SOS-canal, and the Prevlaka inlet sluice and the Trebež I outlet sluice, connecting Lonjsko Polje with the Sava. Two planned water control devices were included in the model as well, to be able to simulate the consequences of the 1972-plan and the WB-plan. These were the Palanjek inlet weir into Lonjsko Polje and the Trebež II outlet sluice, which drains into Mokro Polje. Detailed specifications were obtained from Croatian Waters.

Tributaries to the Sava, such as the Kupa and Una, were modelled as lateral inflow locations, using a stage–discharge relationship. The SOS-canal was included in the model in two different ways. In the present situation and in the World Bank-plan, the SOS-canal ends in the Odransko Polje region, thus filling this area in case of a flood. In the 1972-plan, the SOS-canal is connected to the Sava, upstream of Sisak.

The Lonjsko Polje detention area is schematised on a two-dimensional (2-D) rectilinear grid, with grid cells of 250×250 m. A Digital Elevation Model made available by the Nature Park Service describes the main part of the topography. For the remaining part (viz. the Žutica area), the topography was derived from topographic maps. The water balance in the model for Lonjsko Polje is determined by the inflow and outflow discharges through the sluices, the inflow from the Česma and Lonja, the precipitation, evaporation and infiltration rates, the drainage through small ditches, and the hydraulic resistance of the canals and the land. The inflow and outflow discharges through the sluices are dependent on the Sava water levels and their operating regime. In the model, operating rules have been defined that open and close the sluices depending on required water levels in the downstream region. The discharge of the Česma can be significant (835 $m^3 s^{-1}$ for the 1:100 year event) and is included in the scenario analysis. The discharge of the Lonja is insignificant and was defined at a constant value of 10 $m^3 s^{-1}$. Monthly precipitation and evaporation rates in Lonjsko Polje were obtained from the VPB. The infiltration rate to groundwater aquifers was estimated at 1 mm per day. The flow through small ditches plays a significant role in the drainage of Lonjsko Polje. For this purpose, additional 1-D elements, representing small canals, were added to the model schematisation. Finally, the hydraulic resistance of the canals and the land affects the flow rates and water levels. A larger hydraulic resistance results in slowing down the celerity of the flood wave and increasing water levels. Since the hydraulic resistance is not exactly known, this quantity is used as a calibration parameter.

The model was calibrated with water level data from a flood event in November 1998, obtained from Croatian Waters. The calibration aimed at simulating the flood levels and the flood wave propagation in both the Sava and Lonjsko Polje as good as possible. After calibrating the bed roughness of the Sava, the modelled results for water depth in the Sava did not differ more than 5% from the measurements which stretched over 10 days. The calibration of roughness values in the Lonjsko Polje resulted in less than 10% error between measured and modelled water levels, for three locations. However, measurements of flooding were available over a 3.5 day period only, whereas the flood duration lasted for weeks. In addition, a sensitivity analysis was carried out on the flood duration, taking into account the discharges in and out of Lonjsko Polje, the bed roughness and the evaporation. It showed that the most sensitive and also uncertain parameter is the operating regime of the sluices that determines the discharges in and out of Lonjsko Polje.

The model was validated with an independent set of data from a small flood event in the spring of 2004. The calibration coefficients for the hydraulic resistance remained unchanged and the modelled results were compared with measurements. Measurements for the Sava consisted of time-series of hourly water levels at Prevlaka and Trebež, obtained from Croatian Waters. Measurements for Lonjsko Polje consisted of recorded maximum water level at the embankment near the village of Mužilovčica, and measurements of water depths at 11 locations, conducted on May 6th 2004, by WL|Delft Hydraulics. The comparison of modelled with measured water levels in the Sava resulted in a maximum difference of 14% in water depth. The comparison of water depths in Lonjsko Polje was rather ambiguous. The maximum recorded water level at Mužilovčica was underestimated by 0.50–0.75 m by the model. On the other hand, the correspondence between our own measurements and the model results yielded an accuracy of 0.15 m in water depth.

Vegetation succession model

The vegetation succession model describes the effects of flooding and land use on the distribution of vegetation over time. Site factors influencing the presence of vegetation are flood duration, spring groundwater level, soil texture and land use. The most discriminating factor for the distribution of plant species along rivers is the flood duration (Dister, 1980; Crawford, 1992; Rademakers & Wolfert, 1994; Gurnell, 1997; Vartapetian & Jackson, 1997; Pollock et al., 1998; Van de Steeg & Blom, 1998; Vervuren et al., 2003; Van Geest, 2005). Moreover, summer floods or floods in the growing season, have a large impact on the zonation of riparian plant species (Brock et al., 1987; Van den Brink et al., 1991; Vervuren et al., 2003; Van Eck et al., 2004).

Ecohydrological relationships between vegetation types of riverine wetlands and floodplains were based on a classification for the average inundation duration, with class boundaries of 2, 20, 50, 150 and >360 days per year (Van der Meijden, 1996; Van Splunder, 1998; Löffl, 1999; Peters, 2002; Klijn et al., 2004). Table 1 presents the vegetation types, their corresponding flooding durations (in days per year) and some examples of typical species found. Knowledge rules for the succession of vegetation types were defined, dependent on the inundation duration and the land use, for mean hydrological years, based on experiences of Lonjsko Polje park managers and on data from floodplains in The Netherlands

Table 1. Vegetation types, corresponding flooding duration and typical species

Vegetation type	Flooding (days year^{-1})	Typical species
Dry hardwood forest	< 20	*Quercus robur, Carpinus betulus*
Hardwood forest	20–50	*Quercus robur, Fraxinus excelsior, Ulmus minor*
Aspen plantation	< 150	*Populus tremula*
Softwood forest	20–150	*Salix alba*
Wet hardwood forest	50–150	*Fraxinus excelsior, Alnus glutinosa*
Marsh forest	> 150	*Alnus glutinosa, Carex* spp.
Hardwood shrub	< 50	*Crataegus monogyna, Rosa canina, Prunus spinosa*
Softwood shrub	50–150	*Salix alba*
Dry herbaceous	< 20	*Bromopsis inermis, Arctium lappa, Brassica nigra*
Wet herbaceous	20–150	*Phalaris arundinacea, Epilobium hirsutum, Cirsium arvense*
Helophytes	> 150	*Scirpus* spp., *Carex* spp., *Phragmites australis*
Floodplain hayfield	< 50	*Arrhenatherum elatius, Pimpinella major, Pastinaca sativa*
Wet hayfield	50–150	*Alopecurus pratensis, Rumex* spp., *Agrostis stolonifera*
Dry meadow	< 20	*Bromopsis inermis, Cynosurus cristatus, Ranunculus repens*
Wet meadow	20–150	*Agrostis stolonifera, Potentilla anserina, Trifolium* spp.
Arable floodplain	< 20	
Lake	365	

(Peters, 2002; Van Velzen et al., 2003; Baptist et al., 2004). The stage of vegetation succession after 2, 10, 20, 50 and 100 years was predicted based on these knowledge values (Table 2, left panel).

In addition to vegetation succession under mean hydrological conditions, lethal threshold values for inundation duration under extreme conditions were defined. The most important constraint that plants have to deal with during flooding is oxygen deficiency (Crawford & Brändle, 1996; Vartapetian & Jackson, 1997). Van den Brink et al. (1995) demonstrated that this effect is strongest with respect to soil with a high organic matter content and least on mineral soil. A lethal threshold value gives the number of days a certain vegetation type can survive while flooded. If the threshold is exceeded, the vegetation type is assumed to be set back to herbaceous vegetation in our model. Most major floods occur in autumn or winter, but the inundation duration can extend into spring. Since vegetation is more vulnerable to flooding in the growing season, lethal thresholds for both winter and growing season were defined (Blom et al., 1990; Van Eck et al., 2004). The threshold values were based on expert knowledge and the experience of the Lonjsko Polje park managers.

Three types of land use management affect the vegetation composition and succession in Lonjsko Polje, i.e., forestry (replanting of forest), grazing by a low density of herbivores and mowing. Table 2 presents the knowledge rules for vegetation succession for a mean hydrological year and for an extreme flood event, without land management (no grazing, no mowing, no planting of hardwood forest), and with land management consisting of grazing, mowing and planting of hardwood forest. The latter type of land use resembles the current land use the most.

Table 2. Vegetation succession rules for mean hydrological years and following a 1:100 years flood event

Vegetation succession for mean hydrological years							Vegetation succession following a flood event threshold (days)						
Vegetation type	Code	Year					Nov–Mar	Apr–Jun	Year				
		2	10	20	50	100			2	10	20	50	100
Dry hardwood forest	11	./.	./.	./.	./.	./.	20	10	31/31	21/21	21/.	./.	./.
Hardwood forest	12	./.	./.	./.	./.	./.	50	20	31/31	21/21	21/.	./.	./.
Aspen plantation	13	./.	./.	./.	./.	15/13	100	20	31/31	21/.	21/.	12/.	12/.
Softwood forest	14	./.	./.	./.	./.	15/15	150	90	32/42	22/42	./42	./42	15/42
Wet hardwood forest	15	./.	./.	./.	./.	./.	150	90	32/32	22/22	14/14	14/14	./.
Marsh forest	16	./.	./.	./.	./.	./.	150	90	33/42	33/42	./42	./42	./42
Hardwood shrub	21	./.	./.	./.	12/12	12/12	50	20	31/41	./41	./41	12/41	12/41
Softwood shrub	22	14/14	14/14	14/14	14/14	15/15	150	90	32/42	./42	14/42	14/42	15/42
Dry herbaceous	31	./51	21/51	21/51	11/51	11/51	20	10	./51	21/51	21/51	11/51	11/51
Wet herbaceous	32	./42	22/42	14/42	14/42	15/42	150	50	./41	22/41	14/41	14/41	15/41
Helophytes	33	./.	./.	./.	16/16	16/16	150	50	./.	./.	./.	16/16	16/16
Floodplain hayfield	41	./.	./.	21/.	21/.	12/.	50	20	31/.	21/.	21/.	12/.	12/.
Wet hayfield	42	./.	32/.	32/.	22/.	14/.	150	50	31/.	22/.	14/.	14/.	15/.
Dry meadow	51	./.	./.	31/.	21/.	11/.	20	10	31/.	21/.	21/.	11/.	11/.
Wet meadow	52	./42	32/42	32/42	22/42	14/42	50	20	32/42	22/42	14/42	14/42	15/42
Arable floodplain	61	31/41	21/41	21/41	11/41	11/41	50	20	31/41	21/41	21/41	12/41	12/41
Lake	71	./.	./.	./.	./.	./.	n.a.	n.a.	./.	./.	./.	./.	./.

Each vegetation type has its code listed in the code-column. Vegetation succession is depicted by codes for successive years. Left of the slash the codes are given for succession without land management, right of the slash the codes are given for succession with land management consisting of grazing in low density, mowing and planting of hardwood forest. When the vegetation equals the initial vegetation type, a dot is used, indicating no change.

An actual vegetation map made up in the mid-nineties was compared with the result from the ecohydrological knowledge rules applied on mean hydrological years and with land management. The result differed from the observed vegetation map in that it has a different classification methodology and there were some discrepancies, possibly caused by erroneous ecohydrological model rules, hydrological model results, or the presence of vegetation that has not adapted to new flood durations. For further analysis the ecotope map that results from the application of our knowledge rules was applied.

Three planning alternatives were distinguished: the current situation, the 1972-plan and the WB-plan. For each of these alternatives, the mean hydrological conditions differ. For these reasons, adjusted maps were made up that do not correspond exactly to the observed situation, but contained the theoretical vegetation composition as it has adapted itself to the flood durations resulting from our hydrological modelling. This means that it was assumed that vegetation development would follow our model rules. This is a necessary step for further vegetation succession modelling based on the current level of knowledge. The analysis of the results can be described as follows: if the 1972-plan would have been implemented, what would then be the spatial and temporal distribution of the vegetation for mean hydrological years and following a 1:100 year flood event.

For each of the three physical planning alternatives, the inundation duration (days per year) in each grid cell was calculated by the hydrological model, for average hydrological years and for the 1:100 years flood event. These data were used to calculate the vegetation succession, based on the knowledge rules from Table 2. The extreme flood was simulated as a single event, affecting the present day vegetation and commencing on January 1st.

Water quality model

The Sobek 1-D–2-D water quality module, which is coupled to the Sobek 1-D–2-D flow module was applied in this study to assess the sediment and phosphorus balance of Lonjsko Polje. The water quality model applies the advection diffusion equation in two horizontal directions to simulate the transport, mixing, loads and processes of sediment and phosphorus. The modelling of sediment deposition is carried out in 2-D, thus differing from the approach by Asselman & Van Wijngaarden (2002), who applied Sobek in 1-D mode.

The accumulation of fine sediment in Lonjsko Polje is due to the sedimentation of suspended matter, which is transported from the Sava river. The balance between sedimentation and resuspension depends on the flow velocities inside Lonjsko Polje and is based on the Partheniades–Krone formulae (Krone, 1962; Partheniades, 1962). At low flow velocities, net sedimentation occurs, whereas at high flow velocities, net resuspension occurs. The spatial distribution of sediments in Lonjsko Polje will, therefore, be determined by the inflow of sediments and the flow patterns of the water. Together with the sediment, phosphorus is brought into Lonjsko Polje.

The fate and transport of phosphorus is highly dependent on that of the sediment. Phosphorus occurs in different forms in the environment, but the majority is adsorbed to mineral particles, such as silt and clay. During a flood event, high suspended sediment loads enter Lonjsko Polje, yielding a high load of adsorbed phosphorus. The most important loss route for adsorbed phosphorus from the water to the soil is through sedimentation (Behrendt & Opitz, 1999). Phosphorus can also be released from the soil into the water column, and it can be transformed to organic phosphorus via plant uptake.

Since little data on nitrogen is available, and the removal rate in the detention area is expected to be insignificant (Pérez et al., 1999; Van der Lee et al., 2004), nitrogen was omitted in our analysis.

The input to the water quality model is the concentration of suspended sediment and phosphorus in the Sava at the border between Croatia and Slovenia. A power function with an additive constant term gives a good estimate for a sediment rating curve (Asselman, 2000). Alternatively a non-linear deterministic approach can be applied (Sivakumar & Wallender, 2005). However, there is not enough data available to fit a reliable rating curve or other function for high discharges in the Sava. Instead, it is assumed in this study that the suspended sediment concentration is simply proportional to discharge, reaching a maximum of about 2000 g m^{-3} at the peak discharge. The total phosphorus concentration is proportional to discharge as well, reaching a maximum of about 2 g m^{-3} at the peak discharge. These values were estimated on the basis of available measurements in the Danube near Vienna during a major flood event in August 2002 (Danubs, 2004). Effects of retardation and exhaustion were disregarded. At base flow conditions, the water quality monitoring data for the Sava was applied.

Unfortunately, there is no data on sediment and phosphorus available from inside the detention area, making calibration of the water quality model impossible. The results of the water quality modelling should, therefore, be considered merely indicative.

Results

Flood protection by Lonjsko Polje

Table 3 presents the maximum discharge at Sisak, upstream of the confluence with the Kupa, following from the model simulations for the 1:100 years event. The results show that the 1972-plan does not provide enough safety for Sisak, since the discharge here should be kept below 2200 m^3 s^{-1}. Upstream of Sisak, the flow from the SOS-canal adds up to the flow in the Sava. Part of the flow is redirected to Lonjsko Polje via the Palanjek weir. Although the maximum capacity is 2370 m^3 s^{-1}, the computations show that only 600 m^3 s^{-1} flows through the Palanjek weir. The remaining discharge on the Sava is well above the desired discharge. Both in the current situation and the WB-plan, flood protection is more effective than in the 1972-plan.

Flooding of Lonjsko Polje

About four days after the flood wave has passed the border between Slovenia and Croatia, the upstream part of Lonjsko Polje area starts to fill. Two to three weeks later, the Lonjsko Polje area is completely filled up, with an average depth of 3.3–4.2 m, depending on the planning alternative. Maximum water depths of more than 6 m will occur. Table 3 presents the maximum water depth and detention capacity that result from the model simulations. As compared with the planned capacity (Brundić et al., 2001), our results suggest a much higher capacity in the current situation, a higher capacity for the WB-plan, and a slightly higher capacity for the 1972-plan. Note that in the latter case, an extension of the area by 8% was originally planned, but was not taken into account in our computations.

Rather surprisingly, the detention capacity in the current situation is the largest. This is due to the fact that the drainage rates of the Lonjsko Polje area differ significantly between cases. For both the 1972-plan and the WB-plan, the outlet capacity of the additional Trebež II sluice drains the area faster. In addition, the flow direction in the Palanjek weir reverses once the flood wave has passed, yielding additional drainage capacity. In the current situation, the water is trapped inside Lonjsko Polje. In case of a high Sava discharge, the area keeps filling for a longer period compared with the other plans. The peak levels in Lonjsko Polje will be reached 8 days sooner for the 1972-plan, compared with the current situation, i.e. 19 days after the onset upstream of Zagreb, instead of 27 days. For the WB-plan the peak is reached after 21 days.

Furthermore, the propagation speed of the inundation of Lonjsko Polje differs between the planning alternatives. In case of the 1972-plan, the propagation speed is highest. The low-lying middle regions of Lonjsko Polje will be flooded slightly more than 2 days sooner, compared with the current situation and the WB-plan (5.9 days after the onset upstream of Zagreb, instead of

Table 3. Computed maximum Sava discharge at Sisak, computed maximum water depth in Lonjsko Polje, computed maximum and planned maximum detention capacity for the 1:100 SL1 flood event

Alternative	Max. discharge (m^3 s^{-1})	Max. depth (m)	Max. capacity (Mm^3)	Planned capacity (Mm^3)
Current	1900	7.45	1005	634
1972-plan	2400	7.13	932	915
WB-plan	2000	6.65	790	733

8 days, or 7.8 days respectively). The difference is due to the presence of the SOS-canal, which carries the flood wave swiftly to Lonjsko Polje via Palanjek. The 1972-plan thus gives less time for evacuation than the other two alternatives.

The relative inundation areas, expressed in hectares of inundation, are presented in Figure 2. In the current situation, for a mean hydrological year, almost 60% of the area is inundated for more than 20 days per year. With the implementation of the 1972-plan or the WB-plan, Lonjsko Polje becomes dryer, especially in the low-lying southern part, with a difference from the current situation between 20 and 40 days. Around 50% of the total area will be flooded more than 20 days per year.

In case of a 1:100 years event, the whole area is inundated for more than 20 days per year, and there are locations that are inundated continuously in the first year after the event, such as near the Palanjek sluice and in the lower southern part. If a flood event occurs, the 1972-plan results in the lowest flood duration times.

Vegetation development

Figure 3 presents the results of the computations for vegetation development. To limit the number of vegetation types presented in Figure 3, some have been aggregated, for example *hardwood forest* consists of the sum of dry hardwood forest, hardwood forest and aspen plantation, *herbaceous* consists of the sum of dry and wet herbaceous vegetation. The category herbaceous swamp consists of helophytes. Note that the percentage cover differs between the physical alternatives already at $t = 0$. This is due to the model methodology in which it was assumed that the vegetation has been adapted to the mean hydrological situation of the corresponding physical alternative. Since the 1972-plan shows the driest situation, the vegetation composition has been adapted accordingly. A methodological problem, however, is that the adaptation period differs between vegetation types. In the case of hardwood forest, for example, the adaptation to drier conditions is slow.

For mean hydrological years, the model rules imply that, in the current situation, the open parts of Lonjsko Polje will be gradually covered by more shrubs and, after 100 years, will change into a climax stage with hardwood forests, totalling 93% cover, in case no land use management is implemented. Typical wet types, such as helophytes (6% cover) will gradually be replaced by a higher successional stage. In the moist low-lying parts, a mixture of wet hardwood, softwood and marsh forest will be found. If land use of mowing and grazing at low animal densities is implemented, the growth of shrubs, rough herbaceous vegetation and softwood shrubs will be delayed and, therefore, a more open landscape will be maintained at

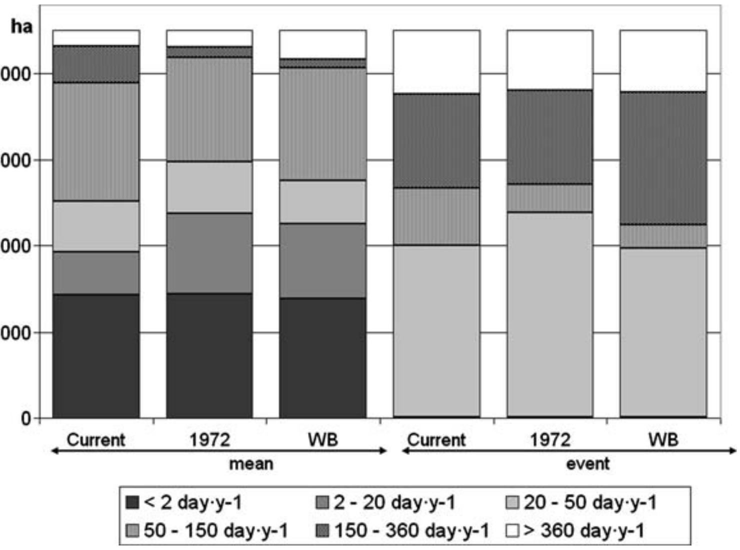

Figure 2. Relative share of areas (ha) with various flood duration times (day year^{-1}) for various cases (for mean hydrological years or the 1:100 years flood event, the current situation, the 1972-plan and the WB-plan).

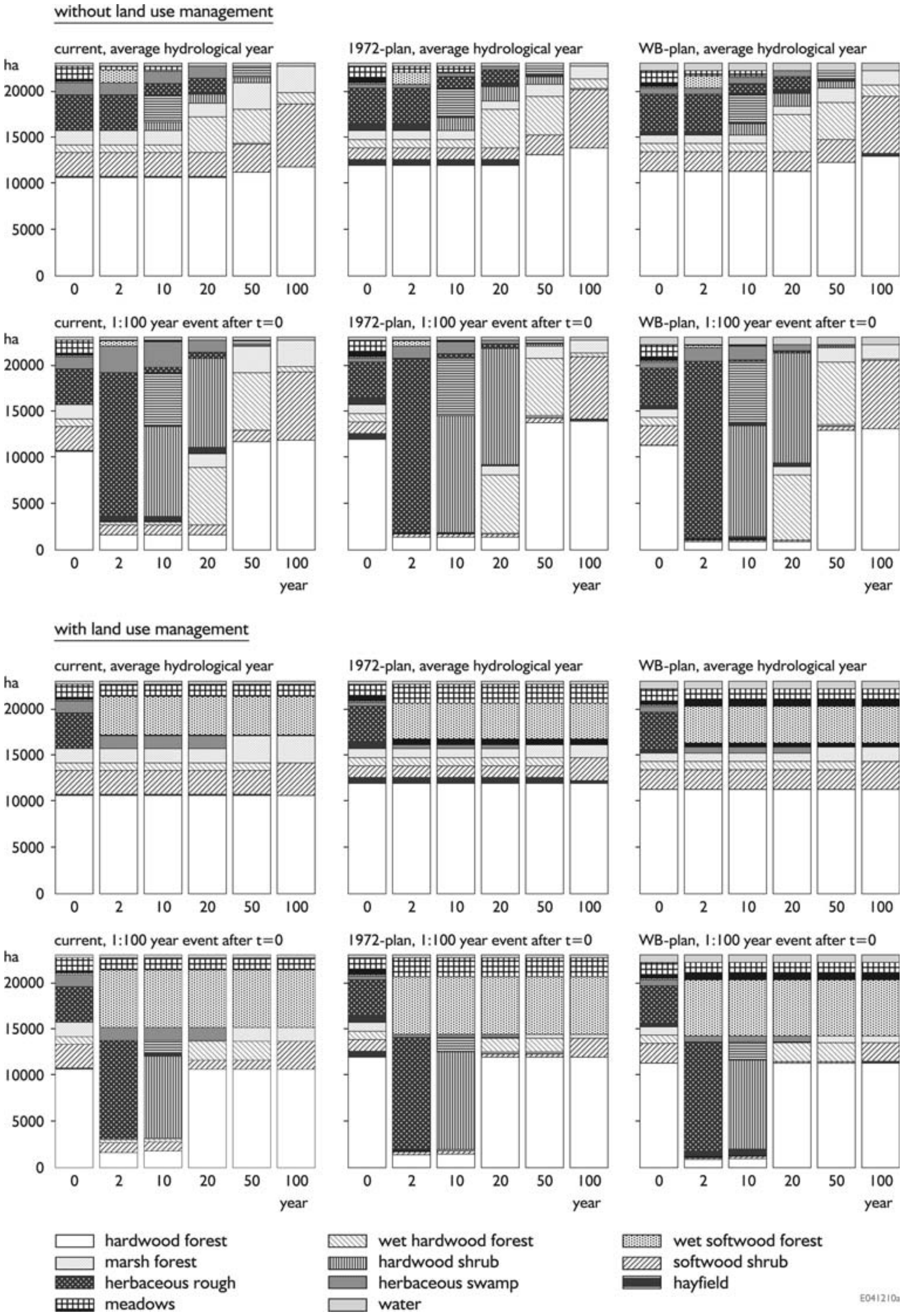

Figure 3. Results of the computations for vegetation development (ha) for the current situation, after implementation of the 1972-plan and after implementation of the WB-plan, without land use management and with land use management consisting of grazing, mowing and replanting of forest.

the cost of hardwood forest (74% cover instead of 93%). Furthermore, herbaceous vegetation will be managed and changed into hayfields to be used for the cattle.

If the 1972-plan would have been implemented, the northern part (Žutica) will not differ much from the current situation, being dominated by hardwood forest. In the remaining part of Lonjsko Polje, the dryer situation results in an increase of hardwood forest area with 6% at the cost of softwood and marsh forest. Especially in the low-lying southern part, there would be more hardwood forest compared with the current situation. Typical wet vegetation types will diminish. Part of the area covered by helophytes will change into herbaceous vegetation, initially diminishing the helophyte cover from 6 to 2%, and finally resulting in the absence of helophytes as a result of succession. The cover of marsh forest will decrease from 12.5 to 6%. Under conditions of land use with grazing and mowing the result differs from the 1972-plan without management, in that it has more hayfields and meadows (+4%) and much less wet hardwood forest (−15%).

If the WB-plan would have been implemented, the vegetation composition will be in between the current situation and the 1972-plan. There is a net increase of dry vegetation types, such as hardwood forest (+3%), at the cost of wet vegetation types, such as helophytes and marsh forest (both −3%), compared with the case for the current alternative. However, the WB-plan results in wetter conditions at specific locations; the total area permanently under water increases by 2%. The results for the land use scenario show 3% more hayfields and meadows, and a 15% decrease in wet hardwood forest compared to the WB-plan without management.

In case of a 1:100 year event, in the current situation, 2 years after an event, large areas of herbaceous vegetation appear (an increase from 17 to 70% cover) at the cost of hardwood and softwood forest. Ten years later, this will be followed by a large cover of shrubs, replaced by softwood and ultimately by hardwood forest. The area of marsh forest will be initially replaced by helophytes and subsequently succeeded by marsh forest again. Overall, the vegetation is less diverse, compared to the vegetation composition that would have been present without the event. As a result of land use management (grazing, mowing and replanting of forest), part of the herbaceous vegetation will be replaced by meadows, arable land and hayfields and ten years later, there will be much less shrubs (46% instead of 70% cover). As a result of the replanting of hardwood forest, this vegetation type is recovering faster than in the case without replanting.

If the 1972-plan would have been implemented, the hardwood forest will consist of relatively more cover of dryer types at the cost of wet hardwood forest and marsh forest, in comparison with the current situation. Whereas the cover of helophytes could reach 12% in the current situation, it is limited to only 6% in the 1972-plan. Would the 1972-plan be implemented, the vegetation composition would adapt to the corresponding flood durations. Since the flood duration for mean hydrological years is less for the 1972-plan, the vegetation consists of types that favour dryer conditions. The result of land use is comparable to that for the current situation, be it that there are less wet vegetation types.

In the case of implementation of the WB-plan, the results resemble those for the 1972-plan, with slightly less effect on the wet vegetation types.

Water quality

In the 1:100 year events, about 30% of the sediment and the adsorbed phosphorus that enters the Lonjsko Polje area deposits. This equals to 8–12% of the sediment and phosphorus loads that flow through the river Sava during this event (Table 4). In the current situation, more sediment and phosphorus is deposited than with the 1972-plan or the World Bank-plan implemented. The 1972-plan and the World Bank-plan are quite alike with respect to sediment and phosphorus entrapment.

One simulation has been made for a representative winter (1996–1997) in the current situation. It showed that 64% of the suspended sediment and 68% of the particulate phosphorus that enters Lonjsko Polje is deposited there. As compared with the sediment and phosphorus that is transported by the Sava, however, this is no more than 4 and 3%, respectively.

After a 1:100 event, for the current situation, the thickness of the freshly deposited sediment

Table 4. Deposition of sediment and phosphorus in Lonjsko Polje (LP), and storage of sediment and phosphorus, expressed as percentage of total input to LP and as percentage of total load of the Sava, for events and for a mean winter

Alternative	Sed. dep. (10^6 kg)	P dep. (10^3 kg)	Sed. trap. (% LP)	Sed. trap. (% Sava)	P trap. (%LP)	P trap. (% Sava)
Current, event	634	737	33	12	36	13
1972-plan, event	444	462	29	8	30	8
WB-plan, event	479	468	28	9	27	9
Current, mean ('96–'97)	7	14	64	4	68	3

layer is approximately 1 cm at maximum, assuming a porosity of 0.80 in the new sediment layer. The sediment layer is not evenly distributed over the Lonjsko Polje area. Most sediment settles in the deeper parts, downstream from the locations where the water enters the detention area. No accurate measurements have been made, but the Park Service confirms the presence of a layer of a few millimetres of fine sediment after a flood event.

Discussion

In retrospect, the flood control system in the CSB was ahead of its time. The plan that was made up in 1972 (UNDO, 1972) sought for a solution not only in river channel regulation and dike construction, but also in the storage of flood waters in natural inundation areas. On the other hand, the plan did have a very technocratic character. The economic and ecological values of lowland forests were ignored and the 1972-plan lacks any assessment of the biodiversity in the catchment of the Sava river and the impacts upon it from the planned construction works (CW, 2001). The latter is a major shortcoming, since the CSB is of unique ecological importance within Europe. The World Bank-plan, therefore, considered the natural values of the CSB and proposed some important changes to the original 1972-plan.

In this study a combination of a 1-D model for rivers and canals with a 2-D model for overland flow was applied, which has major advantages over existing models for the Sava (Filipovic et al., 2000). The flow model is coupled to a water quality model, making modelling of sediment deposition possible.

The knowledge rules for the vegetation model stem partly from Dutch floodplain studies and partly from expert knowledge of the Lonjsko Polje park managers. A demerit of our model approach is that we assume that the vegetation adapted itself to the corresponding new hydrological situation before we apply vegetation succession modelling. Furthermore, the knowledge rules given in Table 2 describe only the development of the dominating vegetation type. This means that not-dominating vegetation types (theoretically up to 49% cover) were not mentioned in the tables, but may form a substantial part of the vegetation of the area. Finally, we have assumed one type of land use to be executed in the entire area, whereas in reality, there is more differentiation in land use practise. For this study it was not possible to determine detailed land-use practise.

A following step would be to apply probabilistic modelling for the vegetation development. The existing vegetation composition then is the result of a spectrum of hydrological conditions and events. It might be possible to apply the hydrological model to simulate the inundation durations for a wider variety of hydrological events (1:90 years event, 1:80 years event, etc.). Subsequently, a number of discharge scenarios can be drawn, for example a series of dryer years, or wetter climate conditions, etc. For each of these scenarios the vegetation succession can be calculated yielding a probabilistic view of vegetation development. At this moment in time, however, detailed enough knowledge on the vegetation response to hydrological changes is lacking.

Another future step would be to use these model instruments to find an optimised scenario for both flood safety and ecology. It is then necessary to have a multi-criteria evaluation method. The models can quantify the parameters needed for evaluation of different scenarios. For ecological evaluation, the parameters should be extended with faunal species. The project results have proven that the models can help to find ecologically sound flood management strategies. An interesting follow-up of this project would therefore be the exploration of an ecological flood management strategy for the whole CSB.

We limited ourselves to suspended sediment and adsorbed phosphorus modelling. Suspended sediment sampling carried out by Wattendorf (2000) indicated that these suspended sediments may contain heavy metals and polycyclic aromatic hydrocarbons, responding to floodplain sedimentation as well (Walling & Owens, 2003). These substances have not been modelled in this study, but require attention in future research. The results for the removal percentages for suspended sediments and adsorbed phosphorus are of almost equal value in the 1:100 event simulations. This is partly due to the artificial boundary conditions in the model, which have been defined under the assumption that the concentrations of suspended sediments and adsorbed phosphate increase with the same ratio during a 1:100 event. The storage percentage of sediment found in our study (4% of the Sava load, for mean hydrological conditions, or maximum 12% for a 1:100 years flood event) is rather low. It is lower than that found by Walling et al. (1998), who measured 39 and 49%, or Middelkoop & Asselman (1998), who found 19% for a 1:40 years flood or Sweet et al. (2003), who determined 50–60%. The hydrological circumstances, however, differ a lot. The Lonjsko Polje area is not an active floodplain any longer and only fills via sluices under moderate flood conditions. Our results thus indicate that this controlled detention area is less efficient in storing sediment than natural floodplains. Finally, it is highly recommended to perform monitoring during flood events, to improve upon model simulations.

Conclusion

With respect to the effects of a 1:100 year flood event in Lonjsko Polje, some important general conclusions can be drawn. First, it is not so much the intake capacity that determines the flood duration time, but the drainage capacity. Second, the long inundation duration following a 1:100 flood event leads to major setbacks in the vegetation composition, even when the detention area is regularly flooded in mean hydrological years. However, the effect is less severe if the vegetation has been able to adapt itself to (small) regular flooding. Third, the vegetation distribution can be largely determined by land use management. Land use management can even be considered a prerequisite to get a wider variety in vegetation types, yielding more habitats for fauna. And fourth, about 30% of the sediment and adsorbed phosphorus that enters the detention area during an extreme flood is retained within the area. In terms of the purifying capacity of this detention area for the Sava, however, its effect is limited to maximum 10%, since the majority of the nutrients flows past the detention area through the main channel.

The evaluation of different flood control strategies for Lonjsko Polje showed that the current situation offers the highest flood safety for downstream regions, it has the highest cover of the important wet vegetation types and it has the highest nutrient storage.

An important lesson for the planning and construction of controlled detention areas is to take care of a large enough drainage capacity. The longer the inundation duration, the larger the effects of anoxia to vegetation will be. Shortening the flood duration is, therefore, advantageous to vegetation. Usually, full attention is given to the size of the intake structures, but the fast drainage of such areas can pose a problem and deserves attention, especially in low-lying regions, such as in the Netherlands. On the other hand, a shorter flood duration leads to lower sediment and nutrient storage rates. Major effects of inundation on vegetation development might be mitigated when the water management of a detention area is such that the vegetation composition is already adjusted to wet conditions. This can be achieved by regular flooding of the detention area, which also results in hydrological connectivity between the river and floodplain, enabling exchange processes and favouring migration of aquatic organisms (Hohensinner et al., 2004).

Acknowledgements

The authors wish to thank Croatian Waters, especially D. Biondić, G. Ćosić-Flajsig and

L. Kratofil, for their support and co-operation. Furthermore, a special word of thanks goes to D. Kovačić of the Lonjsko Polje Nature Park, for sharing his insights with us. This study has been carried out for the Dutch Partners for Water Programme 'Integrated Transboundary River Basin Management of the Sava' which is carried out by a consortium of Dutch institutes, consisting of the IAC, Ecorys, Alterra, RIZA and WL|Delft Hydraulics in co-operation with the Lonjsko Polje Nature Park Public Service (Javna ustanova Park prirode Lonjsko polje) and Croatian Waters (Hrvatske vode).

References

Asselman, N. E. M., 2000. Fitting and interpretation of sediment rating curves. Journal of Hydrology 234: 228–248.

Asselman, N. E. M. & M. van Wijngaarden, 2002. Development and application of a 1D floodplain sedimentation model for the River Rhine in The Netherlands. Journal of Hydrology 268: 127–142.

Baptist, M. J., W. E. Penning, H. Duel, A. J. M. Smits, G. W. Geerling, G. E. M. van der Lee & J. S. L. van Alphen, 2004. Assessment of cyclic floodplain rejuvenation on flood levels and biodiversity in the Rhine River. River Research and Applications 20: 285–297.

Blom, C. W. P. M., G. M. Bögemann & P. Laan, 1990. Adaptations to flooding in plants from river areas. Aquatic Botany 38: 29–47.

Brock, T. C. M., G. van der Velde & H. M. van de Steeg, 1987. The effects of extreme water level fluctuations on the wetland vegetation of a nymphaeid-dominated oxbow lake in the Netherlands. Archiv für Hydrobiologie Beihefte, Ergebnisse der Limnologie 27: 57–73.

Brundić, D., D. Barbalic, V. Omerbegović, M. Schneider-Jacoby & Z. Tusić, 2001. Alluvial wetlands preservation in Croatia; the experience of the Central Sava Basin flood control system. In Nijland, H. J. & M. J. R. Cals (eds), River Restoration in Europe; Practical approaches. Proceedings from the conference on River Restoration, Wageningen, The Netherlands, 2000. RIZA report 2001.023, Lelystad: 109–118.

Crawford, R. M. M., 1992. Oxygen availability as an ecological limit to plant distribution. Advances in Ecological Research 23: 93–185.

Crawford, R. M. M. & R. Brändle, 1996. Oxygen deprivation stress in a changing environment. Journal of Experimental Botany 47: 145–159.

CW, 2001. Environmental impact assessment of the Sava River flood control project. Croatian Waters, Zagreb.

Danubs, 2004. Nutrient management in the Danube Basin and its impact on the Black Sea. Vienna, University of Technology, Institute for Water Quality and Waste Management. daNUbs, Deliverable D1.2 "Data set of results of additional sampling", contract EVK1-CT-2000-00051, EU-EESD Programme.

Dister, E., 1980. Geobotanische Untersuchungen in der Hessischen Rheinaue als Grundlage für die Naturschutzarbeit. Ph.D. Dissertation, University of Göttingen.

Filipovic, M., D. Geres, M. Vranjes & V. Jovic, 2000. Flood control planning for the Sava river basin in Croatia. Proceedings of the Hydroinformatics 2000 Symposium, Cedar Rapids, Iowa, USA, CD-ROM.

Gugić, G. & G. Ćosić-Flajsig, 2004. A development plan for Lonjsko Polje Nature Park; Ways towards integrated river basin management. Third European Conference on River Restoration, Zagreb, Croatia, 17–21 May 2004. Croatian Waters, Zagreb: 149–154.

Gurnell, A. M., 1997. The hydrological and geomorphological significance of forested floodplains. Global Ecology and Biogeography Letters 6: 219–229.

Heath, M. F. & M. I. Evans (eds), 2000. Important Bird Areas in Europe: Priority sites for conservation. Cambridge, UK, Birdlife International. Birdlife Conservation Series 8: 137–145.

Hohensinner, S., H. Habersack, M. Jungwirth & G. Zauner, 2004. Reconstruction of the characteristics of natural alluvial river-floodplain system and hydromorphological changes following human modification: The Danube River (1812–1991). River Research and Applications 20: 24–41.

Klijn, F., J. Karsemeijer & S. van Rooij, 2004. How much natural development does a room-for-rivers policy allow for? Landscape 21: 29–44 (in Dutch).

Krone, R. B., 1962. Flume studies of the transport of sediments in estuarial shoaling processes. Final report. Hydraulic Engineering Laboratory and Sanitary Engineering Research Laboratory, University of California, Berkeley.

Löffl, C., 1999. Multitemporäre Satellitenbild-Auswertung zur Ermittlung von Vegetationseinheiten in den Save-Auen (Kroatien) und Ableitung von landschafts-ökologischen Veränderungen mit Hilfe eines Geographischen Informationssystems (GIS). Diplomarbeit Philosophische Fakultät der Universität Regensburg.

Middelkoop, H. & N. E. M. Asselman, 1998. Spatial variability of floodplain sedimentation at the event scale in the Rhine-Meuse delta, The Netherlands. Earth Surface Processes and Landforms 23: 561–573.

Partheniades, E., 1962. A study of erosion and deposition of cohesive soils in salt water. Ph.D. thesis, University of California, Berkeley.

Pérez, J. M. S., M. Trémolières, N. Takatert, P. Ackerer, A. Eichhorn & G. Maire, 1999. Quantification of nitrate removal by a flooded alluvial zone in the Ill floodplain (Eastern France). Hydrobiologia 410: 185–193.

Peters, B., 2002. Successie van natuurlijke uiterwaardlandschappen. Nijmegen University, Bureau Drift, Nijmegen (in Dutch).

Petriĉec, M., M. Filipović, L. Kratofil, S. Šurlan & Z. Tusić, 2004. Toward integrated water management in the Middle Sava Basin. Third European Conference on River Restoration, Zagreb, Croatia, 17–21 May 2004. Croatian Waters, Zagreb: 279–287.

Pollock, M. M., R. J. Naiman & T. Hanley, 1998. Plant species richness in riparian wetlands – a test of the biodiversity theory. Ecology 79: 94–105.

Postma, L., P. M. A. Boderie, J. A. G. van Gils & J. K. L. van Beek, 2003. Component software systems for surface water simulation. International conference on Computational Science 2003, June 2–4, Melbourne, Australia & St. Petersburg, Russian Federation, Springer-Verlag GmbH: 649–658.

Rademakers, J. G. M. & H. P. Wolfert, 1994. The River-Ecotope-System: a classification of ecologically relevant spatial units for planning and policy studies in river floodplains. RIZA, Lelystad (in Dutch).

Sivakumar, B. & W. W. Wallender, 2005. Predictability of river flow and suspended sediment transport in the Mississippi River basin: a non-linear deterministic approach. Earth Surface Processes and Landforms 30: 665–677.

Sweet, R. J., A. P. Nicholas, D. E. Walling & X. Fang, 2003. Morphological controls on medium-term sedimentation rates on British lowland river floodplains. Hydrobiologia 494: 177–183.

UNDO, 1972. Study for regulation and management of the Sava River in Yugoslavia. United Nations Development Office, Consortium Polytechna-Hydroprojekt-Carlo Lotti & C. Prag-Roma.

Van der Lee, G. E. M., H. Olde Venterink & N. E. M. Asselman, 2004. Nutrient retention in floodplains of the Rhine distributaries in The Netherlands. River Research and Applications 20: 315–325.

Van der Meijden, R., 1996. Heukels' Flora Van Nederland, Wolters-Noordhoff, Groningen.

Van den Brink, F. W. B., M. M. J. Maenen, G. van der Velde & A. bij de Vaate, 1991. The (semi-)aquatic vegetation of still waters within the floodplains of the rivers Rhine and Meuse in The Netherlands: historical changes and the role of inundation. Verhandlungen der Internationalen Vereinigung für theoretische und angewandte Limnologie 24: 2693–2699.

Van den Brink, F. W. B., G. van der Velde, W. W. Bosman & H. Coops, 1995. Effects of substrate parameters on growth responses of eight helophyte species in relation to flooding. Aquatic Botany 50: 79–97.

Van de Steeg, H. M. & C. W. P. M. Blom, 1998. Impact of hydrology on floodplain vegetation in the Lower Rhine system: implication for nature conservation and nature development. In Nienhuis, P. H., R. S. E. W. Leuven & A. M. J. Ragas (eds), New concepts for sustainable management of river basins. Backhuys Publishers, Leiden: 131–144.

Van Eck, W. H. J. M., H. M. van de Steeg, C. W. P. M. Blom & H. de Kroon, 2004. Is tolerance to summer flooding correlated with distribution patterns in river floodplains? A comparative study of 20 terrestrial grassland species. Oikos 107: 393–405.

Van Geest, G., 2005. Macrophyte succession in floodplain lakes. Spatio-temporal patterns in relation to hydrology, lake morphology and management. Ph.D. thesis, Wageningen University, Wageningen.

Van Gils, J. A. G. & J. Bendow, 2000. The Danube water quality model and its role in the Danube River basin pollution reduction programme. XX-th Conference of the Danubian Countries on Hydrological Forecasting and the Hydrological Basis of Water Management. Slovak Committee for Hydrology and Slovak Hydrometeorological Institute, Bratislava, CD-ROM.

Van Splunder, I., 1998. Floodplain forest recovery: softwoord forest development in relation to hydrology, riverbank morphology and management. Ph.D. thesis, University of Nijmegen, Nijmegen.

Van Stokkom, H. T. C., A. J. M. Smits & R. S. E. W. Leuven, 2005. Flood defense in The Netherlands; a new era, a new approach. Water International 30: 76–87.

Van Velzen, E. H., P. Jesse, P. Cornelissen & H. Coops, 2003. Hydraulic resistance of floodplain vegetation, Part 2 background document. Rijkswaterstaat RIZA, RIZA document 2002.141x. RIZA, Lelystad (in Dutch).

Vartapetian, B. B. & M. B. Jackson, 1997. Plant adaptation to anaerobic stress. Annals of Botany 9(Suppl. A): 3–20.

Vervuren, P. J. A., C. W. P. M. Blom & H. D. de Kroon, 2003. Extreme flooding events on the Rhine and the survival and distribution of riparian plant species. Journal of Ecology 91: 135–146.

Verwey A., 2001. Latest developments in floodplain modelling – 1D/2D integration. Proceedings of the 6th Conference on Hydraulics in Civil Engineering. Hobart, Tasmania.

Walling, D. E. & P. N. Owens, 2003. The role of overbank floodplain sedimentation in catchment contaminant budgets. Hydrobiologia 494: 83–91.

Walling, D. E., P. N. Owens & G. J. L. Leeks, 1998. The role of channel and floodplain storage in the suspended sediment budget of the River Ouse, Yorkshire, UK. Geomorphology 22: 225–242.

Wattendorf, P., K. Blauth-Baehr & O. Ehrmann, 2000. Gehalte von Schwermetallen und Polycyclischen aromatischen Kohlenwasserstoffen in Böden des Naturparks Lonjsko Polje (Kroatien) in Abhängigkeit von Überflutungen durch die Sava. International Association for Danube Research 33: 395–402.