Biogeochemistry **19**: 103—128, 1993

Impact of hydrology on the chemistry and phytoplankton development in floodplain lakes along the Lower Rhine and Meuse

F. W. B. VAN DEN BRINK, J. P. H. M. DE LEEUW, G. VAN DER VELDE & G. M. VERHEGGEN
Laboratory of Aquatic Ecology, Faculty of Sciences, Catholic University of Nijmegen, Toernooiveld, 6525 ED Nijmegen, The Netherlands

Received 7 June 1992; accepted 12 February 1993

Key words: chemistry, eutrophication, floodplain lakes, inundation, large rivers, phytoplankton, seepage

Abstract. The impact of hydrology (floods, seepage) on the chemistry of water and sediment in floodplain lakes was studied by a multivariate analysis (PCA) of physico-chemical parameters in 100 lakes within the floodplains in the lower reaches of the rivers Rhine and Meuse. In addition, seasonal fluctuations in water chemistry and chlorophyll-a development in the main channel of the Lower Rhine and five floodplain lakes along a flooding gradient were monitored. The species composition of the summer phytoplankton in these lakes was studied as well.

At present very high levels of chloride, sodium, sulphate, phosphate and nitrate are found in the main channels of the rivers Rhine and Meuse, resulting from industrial, agricultural and domestic sewage. Together with the actual concentrations of major ions and nutrients in the main channel, the annual flood duration determines the physico-chemistry of the floodplain lakes. The river water influences the water chemistry of these lakes not only via inundations, but also via seepage. A comparison of recent and historical chemical data shows an increase over the years in the levels of chloride both in the main channel of the Lower Rhine and in seepage lakes along this river. Levels of alkalinity in floodplain lakes showed an inverse relationship with annual flood duration, because sulphur retention and alkalinization occurred in seepage waters and rarely-flooded lakes. The input of large quantities of nutrients (N, P) from the main channel has resulted, especially in frequently flooded lakes, in an increase in algal biomass and a shift in phytoplankton composition from a diatom dominated community towards a community dominated by chlorophytes and cyanobacteria.

Introduction

The large rivers Rhine and Meuse are major European waterways which connect the Dutch sea ports with a highly industrialized hinterland. Most European rivers and their floodplains have been subjected to geomorphological changes since Roman times and probably even earlier (Petts 1989). In the Netherlands the large floodplain areas of the rivers Rhine and Meuse have been dramatically reduced by means of embankment and river engineering since the Middle Ages. The water quality of these rivers has deteriorated since that time, although major changes in water chemistry did not take place until the present century. The rivers Rhine and Meuse have been severely polluted with salts, fertilizers, heavy metals and organic micropollutants as a result of high population densities, extensive agriculture, and a high level of industrialization in their drainage basins. Water quality became very bad during the sixties and seventies. Since that time improvements have been made with respect to levels of oxygen, ammonium, heavy metals and some organic toxicants. By contrast, the concentrations of sodium, chloride, sulphate, phosphate and nitrate have not been improved at all and are still extremely high (Anonymous 1989). It should be realized that the rivers Rhine and Meuse are nowadays among the most eutrophic rivers in the world (Admiraal & Botermans 1989). Salinity is also very high, due to mining activities in the drainage basins. Mining effluents have shifted the ionic composition of the lower reaches of the rivers Rhine and Meuse from a calcium bicarbonate dominance, which is the normal situation in most rivers, towards a sodium chloride dominance (Kempe et al. 1991; Van der Velde et al. 1991). During periods of low river discharge the water of the Lower Rhine can no longer be considered 'fresh'. As a consequence of all these changes, the riverine vegetation, zoobenthos and fish communities in the main channels became improverished, especially in the lower reaches (Van den Brink et al. 1990, 1991a, 1991b; Van der Velde et al. 1990).

The importance of river-floodplain interactions for the functioning of large river ecosystems has been recognized relatively recently (e.g. Minshall et al. 1985; Amoros et al. 1987; Amoros et al. 1987; Amoros & Roux 1988; Junk et al. 1989). During floods, there is an exchange of water, sediment, chemicals and biota between the main channel and the floodplain lakes. Information on the influence of flooding on the water chemistry of floodplain lakes is poor and concerns mainly some pristine tropical rivers (e.g. Hamilton & Lewis 1987; Forsberg et al. 1988; Junk et al. 1989; Pedrozo et al. 1992). Studies on the impact of inundations on the water chemistry of floodplain lakes in highly eutrophic river ecosystems, which are mostly found in temperate zones (Peierls et al. 1991), are very sparse. Such studies, however, are extremely relevant for an understanding of the ecological functioning and hence for an ecological management of these river ecosystems (Bravard et al. 1986).

Although some influence of flooding on the water chemistry of floodplain lakes along the highly eutrophic rivers Rhine and Meuse might be expected (Van den Brink & Van der Velde 1991), it was not clear which parameters are most affected by the hydrology. Furthermore, it was unknown to what extent the inundation regime affects the water chemistry. In the present study the impact of hydrology on the chemistry (major ions, nutrients, heavy metals) of the ambient and interstitial water of floodplain lakes was examined by (1) a multivariate analysis of physico-chemical parameters of 100 floodplain lakes within the lowland reaches of the rivers Rhine and Meuse, and (2) an analysis of seasonal fluctuations in the water chemistry of the main channel and five floodplain lakes along an inundation gradient in the basin of the Lower Rhine. As phytoplankton development has a pronounced effect on physico-chemical parameters of the water and sediment, and vice versa (e.g. Admiraal et al. 1990), the impact of hydrology on phytoplankton biomass and species composition in floodplain lakes was studied as well.

Sites and methods

Study sites

Within the floodplains of the rivers Rhine and Meuse lentic water bodies can be categorized according to their geomorphology and hydrology. Sites were selected within the floodplains of the lowland reaches of the rivers Rhine and Meuse in the Netherlands, outside tidal influence (Fig. 1). During July—August of 1987 and 1988 the water, sediment and phytoplankton of 28 oxbow lakes, 22 break-through lakes, 23 clay-pits and 27 sand-pits were each sampled once.

In order to study the impact of hydrology on the water chemistry in more detail, five floodplain lakes along the Lower Rhine were selected on the basis of inundation regime, depths and river distance (Table 1; Fig. 2). During 1990—1991 seasonal fluctuations in physico-chemical parameters and chlorophyll-a were monitored by monthly sampling of the water of the main channel and three shallow (2—5 m) and two deep (8—15 m) floodplain lakes along an inundation gradient. The studied lakes were Lake Ewijk (shallow) and Lake Waaienstein (deep), which are not protected against flooding by dykes or levees and which are frequently inundated; Lake Oude Waal (shallow), which is protected by a small summer dyke and hence is rarely inundated; and Lake Duivelswaai (deep) and Pond G (shallow), which both receive seepage water if there are high water levels in the main channel and which are protected against inundation by the main dyke (Table 1; Fig. 2).

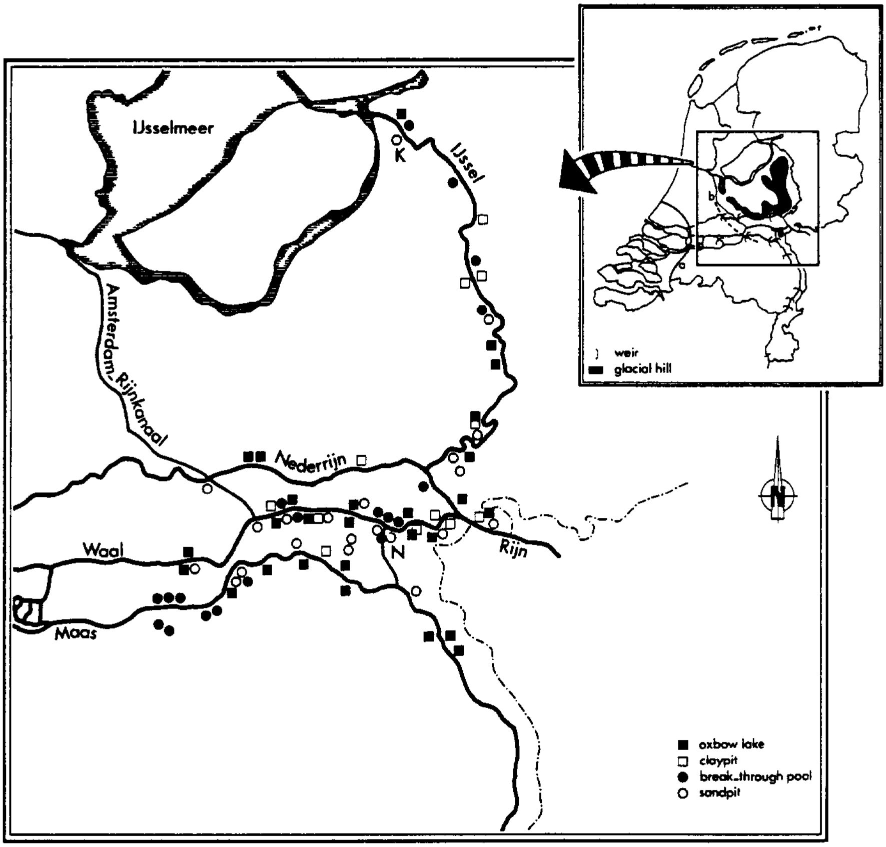

Fig. 1. Map of the sampling sites. Insert: a = 0.3% Cl^- isohaline, b = limit of tidal influence.

Hydrology

A hydrological characterization of the main channels of the rivers Rhine and Meuse has been presented in Van den Brink et al. (1991b). Major differences in hydrology between these river systems are the drainage areas and discharge characteristics. The total drainage area of the River Rhine measures 185,000 km^2, while the total drainage area of the River Meuse is 33,000 km^2. According to long-term measurements (1901–1985) the discharge of the R. Rhine at the Dutch-German border averages 2,200 $m^3 s^{-1}$, while the discharge of the R. Meuse at the Dutch-Belgian border averages 250 $m^3 s^{-1}$. Water-level fluctuations in the main channels of these rivers vary from 2 to 6 m in the sections under study.

Normally, the Dutch floodplain lakes are inundated during winter and spring, i.e. outside the vegetation growth season. Most lakes become

Table 1. Topographical, geomorphological, hydrological, and vegetational characteristics of five floodplain waters along the Lower Rhine where the water chemistry was monitored monthly. Location in km's from the source of the river. Flood duration: the calculated long-term average annual flood duration in days per year (1901—1985). Floods/seepage: periods of inundation and/or seepage during 1990/1991.

	Lake Ewijk	Lake Waaienstein	Lake Oude Waal	Lake Duivelswaai	Pond G
Coordinates	N 51°53′ E 5°45′	N 51°53′ E 5°51′	N 51°51′ E 5°55′	N 51°52′ E 5°48′	N 51°52′ E 5°54′
Location (km)	893	887	882	888	882
Surface area (ha)	10	9.5	16	6	0.6
Maximum depth (m)	3	15	5	8	2
Distance from river (m)	10	100	500	650	1150
Flood duration	67	23	3	0	0
Floods	Feb/Nov—Jan	Feb/Jan	Feb/Jan	—	—
Seepage	idem	idem	idem	Feb/Jan	Feb/Jan
Submerged vegetation	absent	absent	sparse	dominant	dominant
Nymphaeid vegetation	sparse	absent	dominant	dominant	dominant

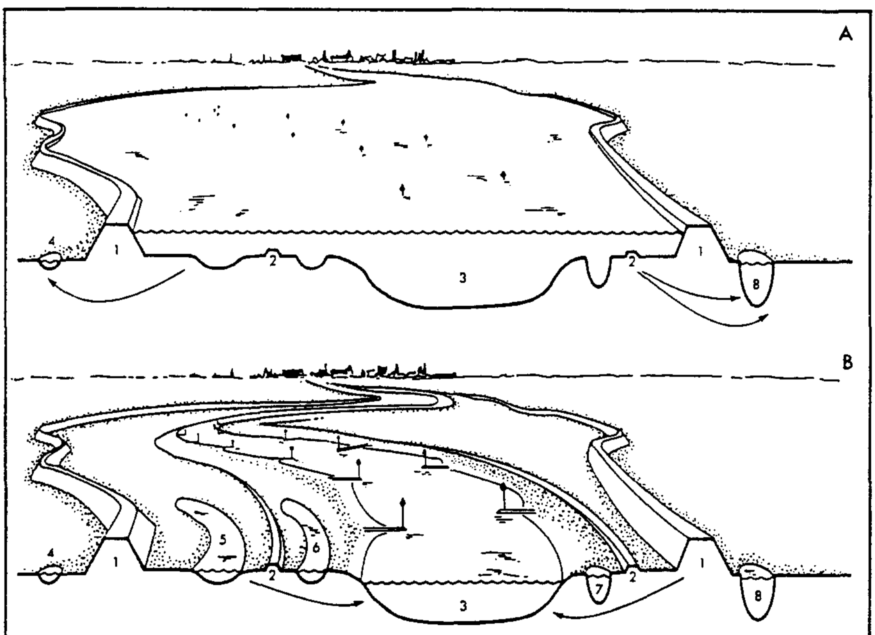

Fig. 2. Schematic view of hydrology of floodplain lakes, during A. high river discharges and B. normal river discharges. 1 = main dykes, 2 = summer dykes, 3 = river bed, 4, 8 = seepage lakes, 5 = infrequently flooded lakes, 6, 7 = frequently flooded lakes, 4—6 shallow lakes, 7, 8 = deep lakes. Arrows indicate directions of ground water fluxes.

isolated from the river during the rest of the year, except for water bodies which have a permanent open connection with the main channel. The duration and frequency of inundation of the lakes is largely dependent on the presence and height of summer dykes and natural levees, together with actual water-level fluctuations in the main channel. In general, the flood duration and flood frequency of the lakes decreases with increasing distance from the main channel. The water bodies behind the main dykes are never flooded, except during the very rare catastrophes, and are normally influenced by river water via seepage only (Fig. 2).

In order to quantify the hydrological situation of the floodplain lakes, the annual flood duration was calculated as follows. Firstly, river maps were used to estimate the inundation level for each site, i.e. the lowest water level of the river at which the part of the floodplain which includes the specific site is inundated. Next, the long-term (1901—1985) annual mean number of days on which the water level in the main channel reached this level of inundation was calculated (= annual flood duration). Hydrological data were obtained from the Institute of Inland Water Management and Waste Water Treatment (RIZA, The Netherlands).

Sampling, measurements and physico-chemical analyses

At each site a mixed sample (2 liter) of the ambient water was taken, at a depth of 20 cm below the water surface in the open water compartment, i.e. outside the vegetation belt. Three samples of 100 ml each were taken out of this mixed sample. One sample was used immediately for measurements of pH, alkalinity and acidity. The other two samples were passed through a Whatman GF/C filter (1.2 μm), and after addition of 0.5 ml of a 200 mg l^{-1} $HgCl_2$ solution, stored in iodated polyethylene bottles and frozen at -27 °C until further analysis. In one of the latter samples a few grains of citric acid were added in order to prevent precipitation of metals. pH was measured with a Radiometer Combined pH electrode, connected to a PHM82 Standard pH meter. Alkalinity was determined by titration of a subsample of 50 ml with 0.01 N HCl down to pH 4.2, while acidity was determined by titration by another subsample of 50 ml by adding 0.01 N NaOH up to 8.2 (modified from Stumm & Morgan 1981). The fractions of carbon dioxide and bicarbonate were calculated from equations for the inorganic carbon equilibria and pH, derived from Stumm & Morgan (1981). Conductivity was measured with an YSI model 33 SCT meter, turbidity with a Dentan model FN5 turbidity meter. Both measurements were carried out in the field. Chlorophyll-a determination was based on an ethanol extraction method according to Roijackers (1985).

Sediments were collected from below the water layer in the littoral zone, by means of a metal tube with a diameter of 7 cm. The upper 10 cm layer of sediment was sampled. Because of the inhomogeneity of the sediment, eight samples were collected and mixed. Sediment-water extracts were made for the assessment of the chemical composition of the interstitial water. 70 g wet sediment was thoroughly mixed with 200 ml twice distilled demineralized water for one hour at room temperature. The supernatant was separated from the extract by centrifugation (20′, 12,000 rpm). Further treatment of the supernatant was similar to that of the water samples. Subsamples of the wet sediment were dried at 105 °C for 24 hours. The percentage organic matter in the sediment was calculated from the weight loss of 50 g dried sediment after 4 hours heating at 550 °C (= loss on ignition).

Chemical analyses of the water and sediment extracts were carried out according to Technicon Auto-analyzer Methodology (1981). Na and K were determined by flame-photometry. Colorimetrical measurements were used for chloride (with ferri-ammonium sulphate according to O'Brien 1962), sulphate (with barium chloride), phosphate (with ammonium molybdate and ascorbic acid, according to Hendrikson 1965), nitrate/nitrite (with hydrazine sulphate, according to Kamphake et al. 1967) and total ammonia (with salicylate and hypochloride, according to Kempers & Zweers 1986). Fe, Ca, Mg, Zn, Al and Si were analyzed using an Inductively Coupled Plasma Spectrophotometer type IL Plasma 200. Climatological data on daily solar radiation and monthly precipitation were obtained from the Dutch Meterological Institute (KNMI, De Bilt, The Netherlands).

In order to study the species composition of the summer phytoplankton, three major samples per water body were taken by drawing a net (diameter of net opening: 20 cm, mesh width: 60 μm) over a distance of 10 m through the water in a horizontal direction towards the shore about 50 cm below the water surface.

Statistical analysis

A principal component analysis of the physico-chemical parameters (standardized values) of the ambient and interstitial water and the sediment was performed, in order to illustrate: 1. the influence of differences in the water chemistry between the main channels of the rivers Rhine and Meuse on the water chemistry of the floodplain lakes, and 2. the relationship between the hydrology (floods, seepage) and the water chemistry of the floodplain lakes. The parameters on which the PCA was based are presented in Table 2. In order to correlate site scores on the most important principal components (PC1, PC2 and PC3) with real values of

Table 2. Pearson correlation coefficients between the loadings of the sampling sites on PC1, PC2 and PC3, and some physico-chemical parameters of the water, interstitial water and sediment of the floodplain lakes.
$n = 100$ sites. *** = $p < 0.001$; ** = $0.001 < p < 0.01$; * = $0.01 < p < 0.05$.

	PC1	PC2	PC3
	water		
Na	0.86***	0.13	0.11
Cl	0.87***	0.14	0.03
EC	0.68***	0.61***	0.09
K	0.57***	0.23*	0.14
Mg	0.54***	0.39***	−0.45***
SO_4	0.52***	−0.21*	−0.02
Ca	0.08	0.83***	0.06
HCO_3	−0.08	0.82***	−0.09
Acidity	−0.26**	0.48***	0.25*
pH	0.20	−0.59***	−0.32***
NO_3	0.20*	−0.01	0.38***
NH_4	0.27**	0.21*	0.42***
d-PO_4	0.08	0.16	0.42***
Si	−0.22*	0.61***	0.26**
Fe	−0.22*	0.23*	0.03
Zn	−0.13	0.51***	0.31***
Al	0.18	0.16	−0.01
	interstitial water		
Na	0.89***	−0.02	0.01
Cl	0.85***	−0.02	0.10
K	0.36***	−0.28***	−0.08
Mg	0.56***	−0.17	−0.54***
Ca	0.40***	0.03	−0.50***
HCO_3	0.26**	0.49***	−0.36***
pH	0.40***	0.04	−0.22*
NO_3	0.38***	−0.25*	0.20*
NH_4	0.21*	−0.22*	0.01
d-PO_4	0.37***	−0.13	0.51***
Si	0.43***	−0.19	0.29**
Fe	0.00	−0.34***	0.41***
Zn	0.26**	−0.07	0.35***
Al	0.27**	−0.47***	0.27**
	sediment		
Loss on ignition	−0.12	0.49***	−0.22
% Variance	20	15	9

physico-chemical parameters, Pearson correlation coefficients were calculated. A Wilcoxon test (Sokal & Rohlf 1981) was used to test groups of floodplain lakes of the rivers Rhine and Meuse for significant differences in water chemistry and sediment characteristics. In order to detect correlations between major ions in the ambient water, and in order to relate the flooding regime to physico-chemical parameters of water and sediment, a Spearman rank correlation test was performed. All calculations were made on an IBM 3090 mainframe, using the Statistical Analysis System (SAS Institute Inc. 1989).

Results

Ordination and correlations

A multivariate analysis of physico-chemical parameters of the water and sediment of 100 lakes within the floodplains of the rivers Rhine and Meuse in The Netherlands reveals the major environmental factors affecting the water chemistry. The ordination of physico-chemical parameters visualizes the position of the sampling sites in a vector space of data (Fig. 3). The position of these sites reflects similarities and dissimilarities: sites with very similar physico-chemical parameters are grouped together, while dissimilar sites appear further apart from each other in the PCA-plot. The first three principal components (PC1, PC2 and PC3) account for 44% of the total variation in the physico-chemical data (Table 2). The eigenvalues of PC1, PC2 and PC3 were 7.6, 5.7 and 3.3 respectively. A plot of the first and second principal component axes shows that the sites are arranged along the first axis by the drainage basins in which they are located (R. Rhine or R. Meuse). A plot of the first and third principal component axes shows that the sites are arranged along both axes by their annual flood duration (Fig. 3).

Table 2 shows the Pearson correlation coefficients between the loadings of the sampling sites on the first three principal components and the physico-chemical parameters of the water, the interstitial water and the sediment of the sampling sites. The scores of the sites on PC1 show highly significant positive correlations ($p < 0.001$) with the major ions (e.g. sodium, chloride, potassium, magnesium, sulphate) of the ambient and interstitial water and with nutrients (nitrate, dissolved phosphate, silicate) of the interstitial water. The scores of the sites on PC2 show highly significant positive correlations ($p < 0.001$) with the calcium and bicarbonate concentations of the ambient water, with the interstitial bicarbonate concentration and the organic matter content (as loss on ignition) of the sediment of the water bodies. The scores of sites on PC3 show highly

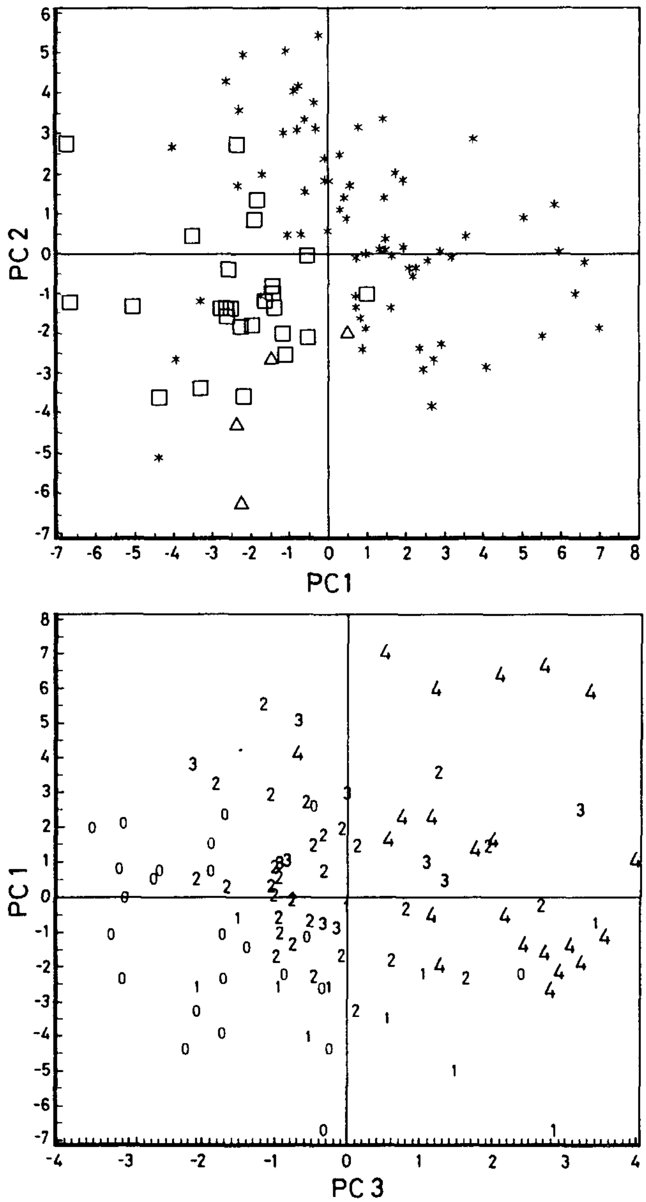

Fig. 3. Ordination plots of the sampling sites, based on physico-chemical data of water, interstitial water and sediment. Above. Plot of first (PC1) and second (PC2) principal component axis. Stars represent sites along the Lower Rhine; squares represent sites along the river Meuse; triangles represent sites in ancient floodplains, no longer influenced by rivers. Below. Plot of first (PC1) and third (PC3) principal component axis. Numbers represent the long-term (1901—1985) average annual flood duration of the sites (0: 0, 1: 0—3, 2: 3—20, 3: 20—40 and 4: 40—365 days year^{-1}).

significant positive correlations ($p < 0.001$) with the levels of nutrients (nitrate, dissolved phosphate) in the ambient and interstitial water, and with the concentrations of heavy metals (Fe, Zn) in the interstitial water (Table 2).

Table 3 shows the interrelations between the major ions in the floodplain lakes studied. Highly positively correlations ($p < 0.001$) were found among concentrations of sodium, potassium, magnesium, chloride and sulphate. The same was true ($p < 0.001$) among the concentrations of calcium, magnesium and bicarbonate. A clear negative correlation ($p < 0.01$) was found between bicarbonate and sulphate concentrations (Table 3).

Table 3. Spearman rank correlations among major ions in the superficial water of 100 floodplain lakes along the rivers Rhine and Meuse.
*** = $p < 0.001$; ** = $0.001 < p < 0.01$; * = $0.01 < p < 0.05$; $n = 100$ observations.

	Na	K	Mg	Ca	Cl	HCO_3
K	0.53***					
Mg	0.43***	0.23*				
Ca	0.11	0.05	0.43***			
Cl	0.98***	0.52***	0.48***	0.14		
HCO_3	−0.01	−0.04	0.43***	0.87***	0.00	
SO_4	0.45***	0.38***	0.22*	−0.08	0.46***	−0.31**

In order to test for significant differences in chemistry between the floodplain lakes of R. Rhine and those of the R. Meuse, a Wilcoxon test was applied (Table 4). Because major differences in chemistry could also be attributed to the annual flood duration (Fig. 3), a Wilcoxon test was applied both for a group of very frequently flooded lakes and for a group of seepage lakes. Differences in water chemistry between the floodplain lakes of the river Rhine and those of the river Meuse concerned concentrations of chloride, sodium, magnesium, sulphate, potassium, calcium and bicarbonate (alkalinity), all of which were significantly higher in the ambient water and/or in the interstitial water of the R. Rhine floodplain lakes. Sodium and chloride had their highest concentrations in the ambient as well as in the interstitial water of the R. Rhine floodplain lakes (Table 4).

Spearman rank correlation tests between the annual flood duration and the physico-chemical parameters (Table 5) show that the concentrations of sodium, chloride, nitrate and dissolved phosphate of the ambient water and the concentrations of sodium, chloride, dissolved phosphate, silicate,

Table 4. Mean values (± S.D.) of physico-chemical parameters of the superficial water and interstitial water in two hydrologically contrasting groups of floodplain lakes along the rivers Rhine and Meuse during 1987/1988. Only parameters which are significantly different (Wilcoxon test) within the groups of lakes between these river systems have been indicated.
n = number of lakes. *** = $p < 0.001$; ** = $0.001 < p < 0.01$; * = $0.01 < p < 0.05$.

		R. Rhine		R. Meuse		
		river influence via very frequent inundations				
	unit	Mean ($n = 12$)	(S.D.)	Mean ($n = 12$)	(S.D.)	p
		superficial water				
Cl	μmol l^{-1}	2700	(500)	1400	(100)	***
Na	μmol l^{-1}	2300	(500)	1200	(200)	***
Mg	μmol l^{-1}	420	(30)	290	(20)	***
SO_4	μmol l^{-1}	680	(120)	510	(60)	***
K	μmol l^{-1}	110	(20)	90	(10)	**
EC	μS cm^{-1}	570	(100)	420	(50)	***
		interstitial water				
Cl	μmol l^{-1}	3100	(1000)	1500	(500)	***
Na	μmol l^{-1}	4000	(1200)	1700	(500)	***
Mg	μmol l^{-1}	1100	(350)	560	(160)	***
Ca	μmol l^{-1}	6300	(1010)	4500	(1500)	**
HCO_3	μmol l^{-1}	17300	(6400)	9500	(3400)	**
K	μmol l^{-1}	840	(350)	440	(180)	**
		river influence via seepage				
		($n = 16$)		($n = 4$)		
		superficial water				
Cl	μmol l^{-1}	1800	(700)	800	(300)	*
Na	μmol l^{-1}	1400	(600)	700	(300)	*
Mg	μmol l^{-1}	460	(60)	260	(120)	*
Ca	μmol l^{-1}	1600	(600)	1100	(150)	*
EC	μS cm^{-1}	470	(120)	300	(60)	*
		interstitial water				
Cl	μmol l^{-1}	2000	(800)	1000	(500)	*
Na	μmol l^{-1}	2300	(900)	1100	(500)	*

Table 5. Spearman rank correlation coefficients between the long-term average annual flood duration and physico-chemical parameters of water and sediment in floodplain lakes along the rivers Rhine and Meuse.
n = number of floodplain lakes. *** = $p < 0.001$; ** = $0.001 < p < 0.01$; * = $0.01 < p < 0.05$.

	R. Rhine	R. Meuse
n	70	26
	superficial water	
Na	0.46***	0.74***
Cl	0.39***	0.85***
EC	0.24*	0.63***
K	0.41***	0.11
SO_4	0.32**	0.32
Mg	−0.28*	0.56**
Ca	−0.14	0.49*
HCO_3	−0.29**	0.09
Acidity	−0.24*	0.19
pH	0.06	0.04
NO_3	0.46***	0.62***
NH_4	0.37***	0.30
d-PO_4	0.43***	0.66***
Si	−0.21	0.21
Turbidity	0.39***	−0.10
Fe	−0.08	−0.42*
Zn	0.03	0.12
Al	0.24*	−0.40*
	interstitial water	
Na	0.53***	0.44*
Cl	0.45***	0.59***
K	0.40***	−0.42*
Mg	0.14	−0.31
Ca	−0.03	−0.29
HCO_3	0.34**	0.15
pH	0.15	0.10
NO_3	0.22	0.12
NH_4	0.26*	0.08
d-PO_4	0.65***	0.68***
Si	0.48***	0.62***
Fe	0.37***	0.53**
Zn	0.30**	0.61***
Al	0.34**	0.45*
	sediment	
Loss on ignition	−0.14	−0.39*
Grain size	0.09	0.49**

iron, zinc and aluminium of the interstitial water in the floodplain lakes of the lowland reaches of the rivers Rhine and Meuse increase with increasing flooding duration.

Seasonal fluctuations

Seasonal fluctuations in solar radiation, wet precipitation and fluctuations in hydrological and physico-chemical parameters of the Lower Rhine and five floodplain lakes along a flooding gradient are presented in Figs. 4, 5 and 6. Because the levels of chloride are highly positively ($p < 0.001$) correlated with those of sodium and potassium, and because the levels of bicarbonate are highly positively ($p < 0.001$) correlated with those of calcium and magnesium (Table 3), only the fluctuations of the major anions are presented here.

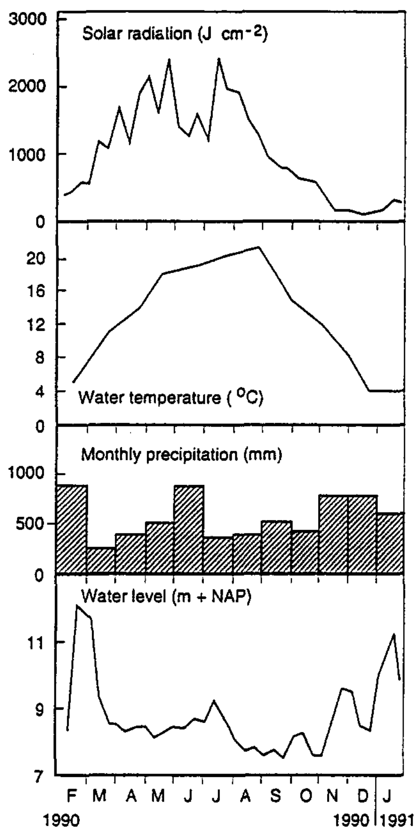

Fig. 4. Seasonal fluctuations in solar radiation (ten day means, measured at De Bilt), water temperature of the Lower Rhine at Nijmegen, wet precipitation (monthly totals, measured near Nijmegen) and water level of the Lower Rhine at Nijmegen.

During 1990 peaks in solar radiation occurred in May and July. Water temperature strongly increased during spring and showed maximum values in August. Precipitation was highest in February and June, and lowest during the summer period. The hydrology of the Lower Rhine showed the normal situation for the Netherlands, with high water levels occurring mainly during the winter period, viz. February 1990 and January 1991 (Fig. 4).

Chlorinity exhibited strong seasonal fluctuations in the main channel, but minor fluctuations in the floodplain lakes (Fig. 5). The chlorinity of the main channel was negatively correlated with the water level in the river (Spearman correlation coefficient: −0.77, $p < 0.001$). Figure 5 shows that chloride levels were higher in frequently flooded lakes than in infrequently flooded lakes and seepage lakes for most of the year, except during floods, when levels of chlorinity in flooded lakes were as high as those in the main

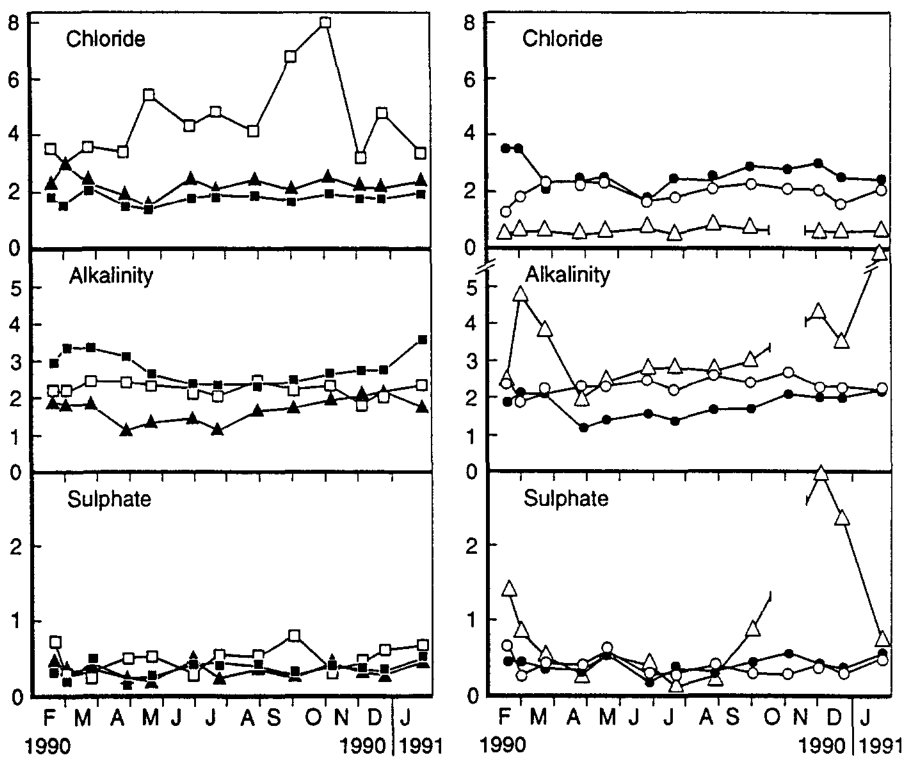

Fig. 5. Seasonal fluctuations in chlorinity, alkalinity and sulphate levels (in μmol l^{-1}) in left: the main channel of the Lower Rhine (open squares), Lake Waaienstein (closed triangles) and Lake Duivelswaai (closed squares), and right: Lake Ewijk (closed circles), Lake Oude Waal (open circles) and Pond G (open triangles).

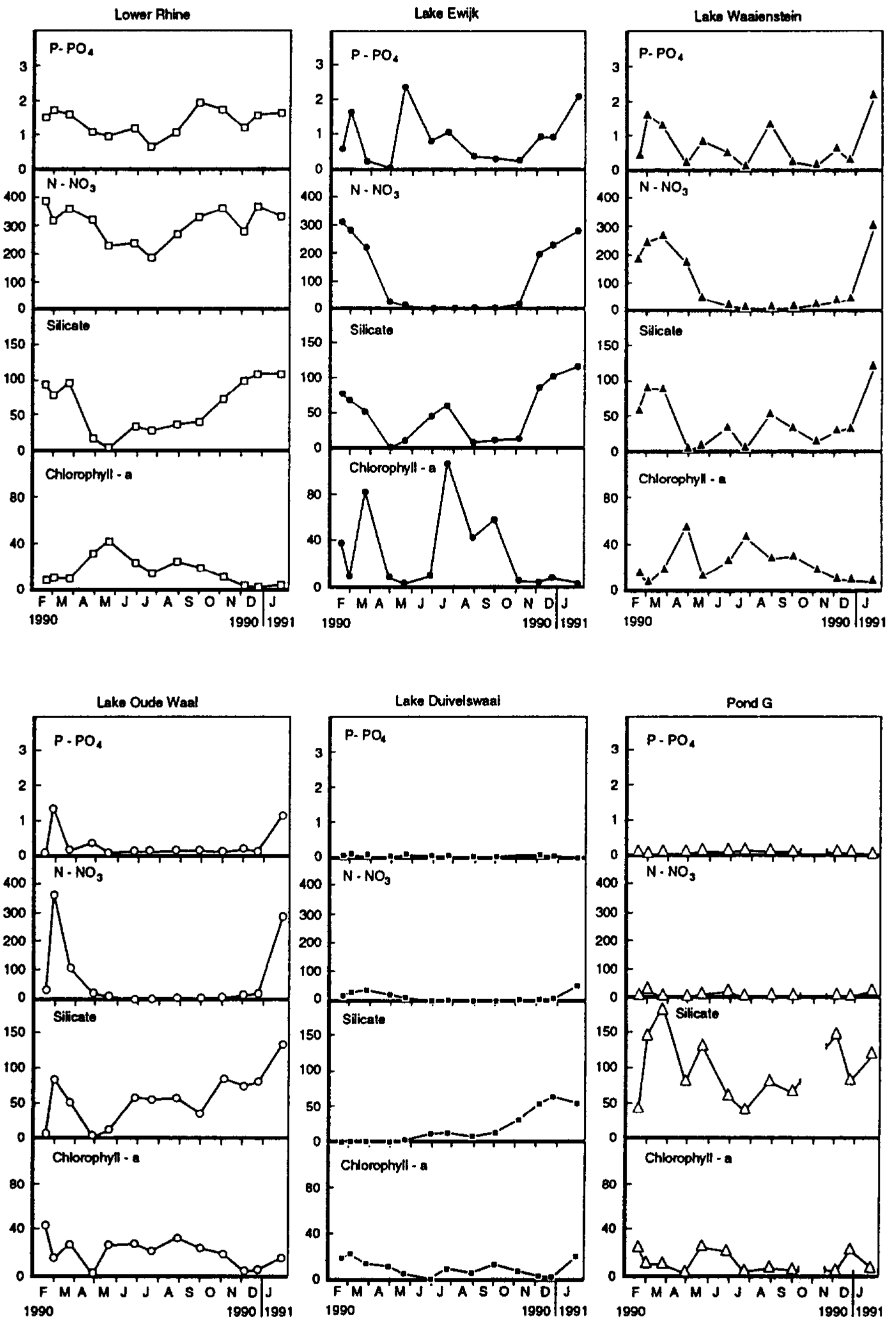

Fig. 6. Seasonal fluctuations in nutrients (in μmol l^{-1}) and chlorophyll-a (in μg l^{-1}) of the main channel of the Lower Rhine, Lake Ewijk, Lake Waaienstein, Lake Oude Waal, Lake Duivelswaai and Pond G.

channel. Fluctuations in alkalinity were relatively large in the shallow seepage Pond G and low in the main channel. In the seepage waters Lake Duivelswaai and Pond G alkalinity strongly increased at times with high water levels in the main channel, during February 1990 and January 1991, when the water level of these lakes rose considerably as a result of seepage. Sulphate showed its greatest fluctuations in the shallow seepage Pond G, with extremely high levels in November when the pond was filled by inflow of phreatic water after a period of drought when the sediment dried out.

Large seasonal fluctuations also occurred in the concentrations of the plant nutrients nitrate, dissolved phosphate and dissolved silicate (Fig. 6). Dissolved silicate in the main channel was inversely correlated (Spearman correlation coefficient: −0.93, $p < 0.001$) with the phytoplankton biomass (as chlorophyll-a). Concentrations of nitrate and dissolved phosphate in the main channel were slightly reduced from April until September, which is the growing season, but not depleted, as was the case with silicate (Fig. 6). Nitrate and dissolved phosphate in the floodplain lakes Waaienstein, Ewijk, and Oude Waal showed their highest concentrations during periods of flooding (Fig. 6), indicating riverine input of these nutrients. In the frequently inundated lakes Ewijk and Waaienstein silicate depletion occurred during April—May and during July—August, unlike the other lakes and the main channel, where silicate depletion occurred only during February—April or not at all (Pond G).

Table 6 shows the annual mean concentrations of major ions, nutrients, chlorophyll-a and nutrient ratios in the main channel of the Lower Rhine and five lakes along an inundation gradient. It can be seen that the annual mean levels of (dissolved inorganic) N and P and the annual mean chlorophyll-a concentrations in the floodplain lakes increase with increasing flood duration, whereas the annual mean Si/N and Si/P ratios decrease (Table 6). The annual mean N and P concentrations in the floodplain lakes showed a clear positive correlation with annual mean chlorophyll-a levels (Spearman correlation coefficients: 0.97 and 0.99, $p < 0.001$) and with the annual flood duration (Spearman correlation coefficients: 0.99 and 0.97, $p < 0.001$). The annual flood duration of the lakes was inversely correlated with the annual mean Si/N and Si/P ratios (Spearman correlation coefficients: −0.79, $p < 0.10$ and −0.87, $p < 0.05$). The composition of the phytoplankton in the frequently flooded lakes Ewijk and Waaienstein in August showed a dominance of chlorophytes, euglenophytes and cyanobacteria, instead of diatoms, which were dominant in less frequently flooded lakes at that time (Table 7).

Table 6. Annual mean values ($\pm$S.D., $n = 12$) of physico-chemical parameters for the main channel and five floodplain waters along a flooding gradient of the Lower Rhine during 1990. Flood duration = longterm average annual flood duration in days per year (1901–1985). All parameters in $\mu mol\ l^{-1}$, except pH (pH-units) and Chlorophyll-a (in $\mu g\ l^{-1}$).

	River Lower Rhine	Lake Ewijk	Lake Waaienstein	Lake Oude Waal	Lake Duivelswaai	Pond G
Flood duration	–	67	23	3	0	0
Na	3900 (1300)	2100 (500)	1700 (300)	1600 (300)	1500 (200)	520 (100)
Cl	4400 (1500)	2600 (500)	2100 (400)	2000 (400)	1700 (200)	590 (100)
EC	800 (160)	580 (80)	520 (130)	520 (40)	560 (130)	570 (260)
K	180 (40)	140 (30)	150 (30)	130 (30)	110 (10)	70 (30)
SO_4	520 (160)	420 (100)	350 (90)	410 (130)	370 (90)	860 (900)
Mg	440 (70)	400 (70)	340 (100)	400 (100)	410 (90)	580 (130)
Ca	1700 (200)	1100 (300)	1000 (300)	1400 (200)	1200 (400)	1900 (1200)
HCO_3	2200 (200)	1800 (300)	1800 (400)	2300 (200)	2800 (400)	3700 (1900)
pH	7.8 (0.1)	8.1 (0.5)	8.0 (0.3)	7.9 (0.2)	8.0 (0.2)	7.8 (0.3)
NO_3	310 (60)	120 (130)	110 (110)	70 (120)	15 (15)	10 (20)
NH_4	20 (10)	30 (30)	30 (20)	20 (20)	15 (15)	20 (20)
d-PO_4	1.4 (0.4)	0.9 (0.7)	0.8 (0.7)	0.3 (0.4)	0.1 (0.0)	0.2 (0.2)
Si	60 (40)	50 (40)	40 (40)	60 (40)	20 (20)	110 (60)
Chl-a	16 (12)	29 (35)	26 (20)	19 (10)	10 (7)	11 (9)
Si/N	0.2 (0.1)	0.3 (1.0)	0.3 (0.2)	4.4 (8.7)	1.0 (1.0)	10.6 (13.9)
Si/P	40 (20)	70 (60)	60 (40)	300 (200)	400 (700)	2400 (2900)

Table 7. Relative abundance (%) of the major phytoplankton groups in the main channel and five floodplain waters along an inundation gradient of the Lower Rhine. Data from August (three samples per water body). Flood duration = longterm average annual flood duration in days per year (1901—1985). Miscellaneous includes Pyrrhophyta, Cryptophyta and Chrysophyta.

Location	River Lower Rhine	Lake Ewijk	Lake Waaienstein	Lake Oude Waal	Lake Duivelswaai	Pond G
Flood duration	—	67	23	3	0	0
Year of sampling	1987	1988	1987	1987	1988	1988
Cyanobacteria	5	20	12	4	8	9
Bacillariophyceae	65	5	27	68	55	60
Euglenophyta	0	20	4	4	4	3
Chlorophyta	28	50	54	21	30	24
Miscellaneous	2	5	3	3	3	4

Discussion and conclusions

Impact of drainage basin

The ordination of physico-chemical parameters of 100 floodplain lakes along the lower reaches of the rivers Rhine and Meuse reveals differences in chemistry between these lakes according to the drainage basin in which they are located (Fig. 3). These differences in chemistry are most pronounced in the ambient and interstitial water of frequently flooded lakes and concern concentrations of major ions, such as sodium, chloride, magnesium, potassium and sulphate, all of which are highest in the lakes along the Lower Rhine. The levels of these ions in the rivers Rhine and Meuse have increased enormously since 1900, as a result of domestic and industrial sewage (Zuurdeeg 1980; Van der Weijden & Middelburg 1989). At present the highest concentrations of the major ions are found in the main channel of the Lower Rhine, due to the more extensive mining activities in its drainage basin, compared with those in the River Meuse (Van den Brink et al. 1991b). Concentrations of sodium and chloride in particular have increased enormously over the years, especially in the Lower Rhine. Levels of sodium and chloride in the main channel of this river are nowadays sixteen times as high as those measured a century ago, whereas the levels of sulphate have increased by a factor of two during this period (Van den Brink et al. 1991b).

Both in the frequently flooded lakes and in the seepage lakes the highest concentrations of sodium and chloride were found in the ambient and interstitial water of the river Rhine floodplain lakes (Table 4). This must be due to the present differences in water chemistry between the rivers Rhine and Meuse with respect to sodium and chloride concentrations, as the original levels in these rivers were similar (Zuurdeeg 1980). Because differences with respect to sodium and chloride concentrations between lakes in different drainage areas have also been found for seepage lakes, it is very likely that these ions are transported not only via flood water, but also via groundwater fluxes from the main channel towards the water bodies behind the main dyke. This view is further corroborated by a comparison between recent (Anonymous 1989; own measurements) and historical data (Van Heusden 1945) on chloride levels in the main channel and seepage lakes along the Lower Rhine. From 1938 to 1988 the annual mean chloride concentration in the main channel increased by a factor of 2, from 1.9 to 4.2 μmol l^{-1} (Van Heusden 1945; Anonymous 1989). Over the same period the mean chloide concentrations measured in seepage lakes along the Lower Rhine (summer measurements) increased by approximately the same factor, from 1 to 1.8 μmol l^{-1} (Van Heusden 1945; Table 4).

Gradients and seasonal fluctuations of major anions

Chloride concentrations show major fluctuations in the main channel of the Lower Rhine, as a result from seasonal differences in river discharges. By contrast, minor fluctuations in the floodplain lakes have been found over the year, which indicates that chloride is a conservative ion in these water bodies. In the floodplain lakes of the rivers Rhine and Meuse, the levels of chloride show a clear positive correlation with the annual flood duration ($p < 0.001$) (Table 5). As a result of the longer period of connection between the river water and that of the floodplain lakes, the input of chloride is largest in frequently inundated lakes. Because choride is a conservative ion the higher input of chloride in the frequently inundated lakes results in higher concentrations in these lakes (Table 6; Fig. 5). Alkalinity (or bicarbonate) shows the opposite trend: levels are higher in seepage waters than in frequently flooded lakes (Table 6; Fig. 5). The relatively higher levels in the seepage waters cannot be entirely explained by an input of carbonate-rich groundwater during high river discharges via seepage, as the alkalinity of the phreatic aquifer (2 meq l^{-1}) is much lower than the levels measured during seepage (3.5 meq l^{-1} in the deep Lake Duivelswaai; 5—9 meq l^{-1} in the shallow Pond G). Most probably alkalinity is generated in these seepage waters via the sulphate reduction process (Stumm & Morgan 1981; Giblin et al. 1990; Kling et al.

1991). It is assumed that sulphate enters seepage lakes via percolation of river water through the main dyke and is retained in the sediment as sulphide. Because the sediment of seepage lakes is not removed via flooding, there is a net retention of sulphur in these lakes, unlike the situation in frequently flooded lakes, where sulphur is removed with the sediment via strong currents which occur during the floods. Evidence for a major contribution of sulphate reduction to the alkalinity generation is provided by the decreases in sulphate levels in Pond G after periods of seepage and the simultaneous increases in alkalinity (Fig. 5). Moreover, the increases in alkalinity during February 1990 and December 1990–January 1991 (respectively 2 and 6 meq l^{-1} HCO_3^-) were about twice as high as the decreases in sulphate concentrations during these periods (respectively 0.9 and 3.2 meq l^{-1} SO_4^{2-}), which is in agreement with the ratio [produced HCO_3^-]/[reduced SO_4^{2-}] of the sulphate reduction process (Stumm & Morgan 1981). Levels of sulphate and alkalinity were particularly high in the shallow seepage pond G when it was refilled via seepage after a period of drought, during which the pond ran dry. Because of its shallowness and the accumulation of sulphides in the sediment of this pond, large fluctuations in sulphate concentrations and alkalinity occur as a result from oxidation-reduction processes in response to running dry and refilling. After the spring floods, a decrease in alkalinity was observed in all floodplain lakes, which can be attributed to calcium carbonate precipitation, a common phenomenon in hardwater lakes (Wetzel 1975; Moss & Balls 1989).

Loading and seasonal depletion of nutrients: impact on phytoplankton

In the main channel of the eutrophic Lower Rhine the concentrations of nitrate and dissolved phosphate are extremely high all the year round, as a result of sewage and agricultural runoff in the drainage areas (Van der Weijden & Middelburg 1989; Kempe et al. 1991), so that depletion of these nutrients by growth of phytoplankton or aquatic macrophytes does not occur (Fig. 6). The riverine phytoplankton, which is dominated by diatoms, is limited by silicate and light (Friedrich & Viehweg 1984; Admiraal et al. 1990).

In the lentic floodplain waters the concentrations of nitrate and dissolved phosphate show a flooding gradient: highest levels have been measured in most frequently flooded lakes (Tables 5, 6). Because levels of nitrate and dissolved phosphate in the main channel are extremely high all the year round, a high riverine input of these nutrients in the floodplain lakes might be expected during floods. The levels of nitrate and dissolved phosphate in the floodplain lakes indeed showed highest concentrations during floods (Fig. 6). During the growing season, when no floods occurred, nitrate became depleted in all floodplain lakes studied. During the same period dissolved phosphate was depleted in Lake Oude Waal, Lake Duivelswaai and Pond G, but not in the frequently flooded Lakes Ewijk and Waaienstein (Fig. 6). Although floodplain lakes often function as nutrient traps (Hamilton & Lewis 1987; Forsberg et al. 1988; Junk et al. 1989; Pedrozo et al. 1992), our results indicate that there are different losses of N and P. In the frequently flooded lakes peaks in chlorophyll-a and dissolved phosphate repeatedly occurred after each other, suggesting a regeneration of phosphate from the P-loaded sediments of these lakes after depletion by phytoplankton. The observation that the levels of exchangeable P in the sediment were highest in frequently flooded lakes is in good agreement with this (Table 5).

In eutrophic river systems, hydrology has a dramatic impact on the phytoplankton development in floodplain lakes: during 1990 the annual mean chlorophyll-a concentrations in the frequently inundated Lake Ewijk (29 $\mu g\ l^{-1}$) and Lake Waaienstein (26 $\mu g\ l^{-1}$) were much higher than that in the main channel (16 $\mu g\ l^{-1}$) or in the infrequently inundated Lake Oude Waal (19 $\mu g\ l^{-1}$). Annual mean chlorophyll-a levels were lowest in seepage waters (10—11 $\mu g\ l^{-1}$). The annual maximum chlorophyll-a level of Lake Ewijk (120 $\mu g\ l^{-1}$) occurred during the summer (Fig. 6). During this period the chlorophyll-a level in this lake was four to ten times higher than the levels in the other floodplain lakes. The high summer chlorophyll-a levels in Lake Ewijk, and to a lesser extend those in Lake Waaienstein resulted from blooms of cyanobacteria (e.g. *Aphanizomenon flos-aquae*) and chlorophytes (e.g. *Scenedesmus*). In the other floodplain lakes the summer phytoplankton was dominated by diatoms (e.g. *Cymbella, Diatoma, Fragilaria, Melosira, Synedra*). The higher chlorophyll-a levels in frequently flooded lakes most probably result from the input of relatively large quantities of nitrate and phosphate during floods, in addition to a shift in the nutrient ratios (Si/N and Si/P), due to silicate depletion as a result of diatom blooms. Such shifts in nutrient ratios have been related to eutrophication processes, which can be observed as a shift in phytoplankton communities from a diatom dominance towards a dominance of cyanobacteria, often resulting in higher chlorophyll-a levels (Officer & Ryther 1980; Moss & Balls 1989; Admiraal & Van der Vlugt 1990; Horn & Horn 1990). Indeed, the annual mean N and P levels in the floodplain lakes showed a clear positive correlation with annual mean chlorophyll-a levels ($p < 0.001$) and with the average annual flood duration ($p < 0.001$). Hence, it can be stated that the increased levels of riverine N and P are responsible for the eutrophication of floodplain lakes along the rivers Rhine and Meuse in The Netherlands.

Impact of hydrology

The present study shows that the water chemistry and phytoplankton development in floodplain lakes along the eutrophic and polluted rivers Rhine and Meuse are strongly related to the water chemistry in the main channels, as well as to the hydrology (Tables 4, 5, 6; Figs. 3, 5, 6). This was also found to be true for the more pristine tropical river-floodplain ecosystems, such as the Amazon (e.g. Forsberg et al. 1988), the Orinoco (e.g. Hamilton & Lewis 1987), and the Parana (e.g. Pedrozo et al. 1992), and may be a general phenomenon of large river-floodplain systems (Junk et al. 1989), despite strong differences in water chemistry and hydrology among river-floodplain systems.

In Fig. 7 a conceptual model is presented about the relationship between the fluxes of ions via floods and seepage on the one hand, and the levels of ions and the development of micro- and macrophyte communities in floodplain lakes on the other hand. Because of the high concentrations of major ions, nutrients and (heavy) metals in the main channels of anthropogenically influenced river-floodplains, such as the Lower Rhine and Meuse (Zuurdeeg 1980; Van der Weijden & Middelburg 1989), there is a net input of these chemicals in the lentic floodplain waters, mainly via inundation. The longer the annual flood duration, the longer the period of connection between the river and the lake water, and the higher the concentrations of salts, nutrients and (heavy) metals in the water and/or

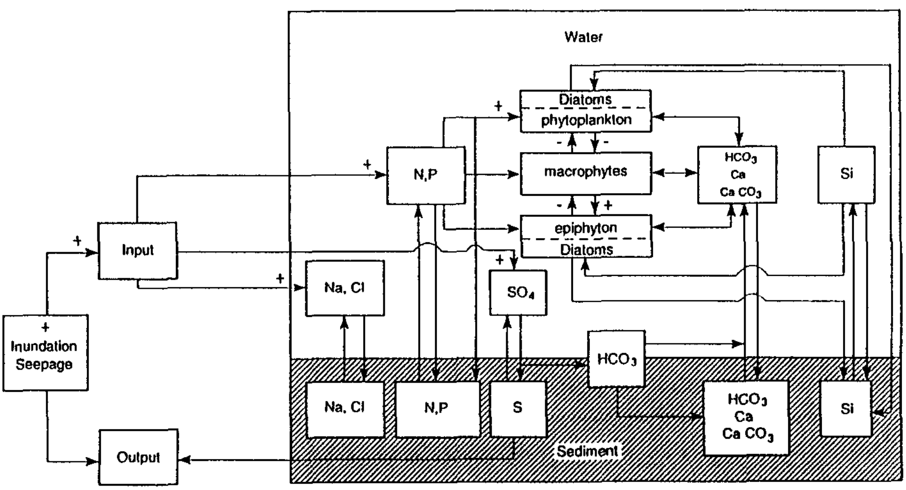

Fig. 7. Conceptual model of the impacts of hydrology on the ion fluxes, and the algal and macrophyte development within floodplain lakes along polluted and eutrophic rivers. +/− indicates a major increase or decrease along the direction of the arrows.

sediment of these lakes. Apart from an input of chemicals via flood water fluxes there is a transport of several water-soluble ions, such as sodium, chloride and sulphate, via groundwater fluxes (Fig. 7). In seepage lakes and infrequently flooded lakes sulphate reduction processes are responsible for the high levels of alkalinity in these lakes. These alkalinization processes are probably triggered via the input of sulphate from the main channel by seepage and floods.

The hydrology of the eutrophic rivers Rhine and Meuse clearly exercises its impact on the phytoplankton development, and consequently on the development of macrophytes, in the lentic floodplain systems, through the input of large quantities of nutrients (N, P) via inundations (Figs. 6, 7). Especially in frequently flooded lakes high chlorophyll-a levels occur as a result of blooms of cyanobacteria and chlorophytes (Tables 6, 7), which hinder the development of submerged macrophytes (Table 1; Fig. 7). Restoration of connections between the main channels of the eutrophic Lower Rhine and Meuse and associated floodplain lakes will inevitably result in hypertrophic conditions in these lakes. In order to maintain the well developed aquatic vegetation (and the associated fauna) in infrequently flooded lakes, and in order to restore these communities in frequently flooded lakes, a low input of nutrients, salts and other pollutants is essential (Van den Brink & Van der Velde 1991). Hence rehabilitation of the degraded river-floodplain ecosystems of the Lower Rhine and Meuse should not merely focus on restoration of connections, but should also include water quality measures which reduce the loads of nitrogen, phosphate, sulphate, chloride and sodium.

Acknowledgements

This study was financially supported by the Dutch Institute for Inland Water Management and Waste Water Treatment (RIZA, Lelystad, The Netherlands) and the Sandoz Rhine Fund (Basel, Switzerland). The authors would like to thank Prof. C. den Hartog, Dr. J. G. M. Roelofs and M. M. van Katwijk for critically reading the manuscript and for their stimulating discussions, and Dr. J. F. M. Geelen, E. F. M. Geilen, A. M. H. J. Neven and M. G. Versteeg for pratical assistance. The Illustration Service of the Faculty of Sciences was very helpful in drawing the figures.

References

Admiraal W & Botermans YJH (1989) Comparison of nitrification rates in three branches of the lower river Rhine. Biogeochemistry 8: 135–151

Admiraal W & Van der Vlugt JC (1990) Impact of eutrophication on the silicate cycle of man-made basins in the Rhine delta. Hydrobiol. Bull. 24: 23—36

Admiraal W, Breugem P, Jacobs DMLHA & De Ruyter van Steveninck ED (1990) Fixation of dissolved silicate and sedimentation of biogenic silicate in the lower river Rhine during diatom blooms. Biogeochemistry 9: 175—185

Amoros C, Roux AL, Reygrobellet JL, Bravard JP & Pautou G (1987) A method for applied ecological studies of fluvial hydrosystems. Regulated Rivers: Research & Management 1: 17—36

Amoros C & Roux AL (1988) Interaction between water bodies within the floodplains of large rivers: function and development of connectivity. In: Schreiber KF (Ed) Connectivity in landscape ecology. Proceedings of 2nd international seminar of the 'International Association for Landscape Ecology'. Münsterische Geographische Arbeiten 29: 125—130

Anonymous (1989) Jaarboek van Afvoeren, Waterstanden, Golven en Waterkwaliteit. Rijkswaterstaat, Lelystad-Den Haag

Bravard JP, Amoros C & Pautou G (1986) Impact of civil engineering works on the succession of communities in a fluvial system. Oikos 47: 92—111

Forsberg BR, Devol AH, Richey JE, Martinelli LA & Dos Santos H (1988) Factors controlling nutrient concentrations in Amazon floodplain lakes. Limnol. Oceanogr. 33: 41—56

Friedrich G & Viehweg M (1984) Recent developments of the phytoplankton and its activity in the Lower Rhine. Verh. Internat. Verein. Limnol. 22: 2029—2035

Giblin AE, Likens GE, White D & Howarth RW (1990) Sulfur storage and alkalinity generation in New England lake sediments. Limnol. Oceanogr. 35: 852—869

Hamilton SK & Lewis Jr. WM (1987) Causes of seasonality in the chemistry of a lake on the Orinoco River floodplain, Venezuela. Limnol. Oceanogr. 32: 1277—1290

Hendrikson A (1965) An automated method for determining low level concentrations of phosphate in fresh and saline waters. Analist 90: 29—34

Horn H & Horn W (1990) Growth of blue-green algae in the Saidenbach reservoir and its relationship to the silicon budget. Int. Revue ges. Hydrobiol. 75: 461—474

Junk WJ, Bayley PB & Sparks RE (1989) The flood pulse concept in river-floodplain systems. In: Dodge DP (Ed) Proceedings of the International Large River Symposium, Can. Spec. Publ. Fish. Aquat. Sci. 106: 110—127

Kamphake LJ, Hannah SA & Cohen JM (1967) Automated analyses for nitrate by hydrazine reduction. Wat. Res. 1: 206

Kempe S, Pettine M & Cauwet G (1991) Biogeochemistry of European rivers. In: Degens ET, Kempe S & Richey JE (Eds) Biogeochemistry of Major World Rivers (pp 169—211). Wiley & Sons Ltd., London

Kempers AJ & Zweers A (1986) Ammonium determination in soil extracts by the salicylate method. Comm. Soil Sci. Plant Anal. 17: 715—723

Kling GW, Giblin AE, Fry B & Peterson BJ (1991) The role of seasonal turnover in lake alkalinity dynamics. Limnol. Oceanogr. 36: 106—122

Minshall GW, Cummins KW, Petersen RC, Cushing CE, Bruns DA, Sedell JR & Vannote RL (1985) Developments in stream ecosystem theory. Can. J. Fish. Aquat. Sci. 42: 1045—1055

Moss B & Balls H (1989) Phytoplankton distribution in a temperate floodplain lake and river system. II. Seasonal changes in the phytoplankton communities and their control by hydrology and nutrient availability. J. Plankton Res. 11: 839—867

O'Brien JE (1962) Automated analyses of chloride in sewage. Wastes Engineering 33: 670—672

Officer CB & Ryther JH (1980) The possible importance of silicon in marine eutrophication. Mar. Ecol. Progr. Ser. 3: 83—91

Pedrozo F, Diaz M & Bonetto C (1992) Nitrogen and phosphorus in the Parana River floodplain waterbodies. Arch. Hydrobiol./Suppl. 90: 171—185

Peierls BL, Caraco NF, Pace ML & Cole JJ (1991) Human influence on river nitrogen. Nature 350: 386—387

Petts GE (1989) Historical Change of Large Alluvial Rivers. Western Europe. J. Wiley & Sons Ltd., London

Roijackers RMM (1985) Phytoplankton Studies in an Nymphaeid-Dominated System. Thesis Catholic University, Nijmegen, The Netherlands

SAS Institute Inc. (1989) SAS/STAT User's Guide, Version 6, vols 1 & 2. Gary, NC, USA

Sokal RR & Rohlf FJ (1981) Biometry. The Principles and Practice of Statistics in Biological Research. W.H. Freeman & Co., San Francisco

Stumm W & Morgan JJ (1981) Aquatic Chemistry: An Introduction Emphasizing Chemical Equilibria in Natural Waters. 2nd ed. Wiley Interscience, New York

Technicon Autoanalyzer Methodology (1981) Industrial Method 635—81W. New York

Van den Brink FWB & Van der Velde G (1991) Macrozoobenthos of floodplain lakes of the rivers Rhine and Meuse in The Netherlands: a structural and functional analysis in relation to hydrology. Regulated Rivers: Research & Management 6: 265—277

Van den Brink FWB, Van der Velde G & Cazemier WG (1990) The faunistic composition of the freshwater section of the River Rhine in The Netherlands: present state and changes since 1990. In: Kinzelbach R & Friedrich G (Eds) Biologie des Rheins. Limnologie aktuell 1: 192—216

Van den Brink FWB, Van der Velde G & Bij de Vaate A (1991a) Amphipod invasion on the Rhine. Nature 352: 576

Van den Brink FWB, Maenen MMJ, Van der Velde G & Bij de Vaate A (1991b) 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. Verh. Internat. Verein. Limnol. 24: 2693—2699

Van der Velde G, Van den Brink FWB, Van der Gaag M & Bergers PJM (1990) Changes in numbers of mobile macroinvertebrates and fish in the River Waal in 1987, as studied by sampling cooling-water intakes of a power plant: first results of a Dutch Rhine biomonitoring project: In: Kinzelbach R & Friedrich G (Eds) Biologie des Rheins. Limnologie aktuell 1: 325—342

Van der Velde G, Van Urk G, Van den Brink FWB, Colijn F, Bruggeman WA & Leuven RSEW (1991) Rein Rijnwater, een sleutelfactor in chemisch oecosysteemherstel. In: Hekstra GP & Van Linden FJM (Eds) Flora en fauna chemisch onder druk (pp 231—266). Pudoc, Wageningen, The Netherlands

Van der Weijden CH & Middelburg JJ (1989) Hydrogeochemistry of the River Rhine: long-term and seasonal variability, elemental budgets, base levels and pollution. Wat. Res. 23: 1247—1266

Van Heusden GPH (1945) Waarnemingen in eenige 'Wielen' in de Betuwe. Tijdschr. Kon. Ned. Aardr. Gen. 62: 118—141

Wetzel RG (1975) Limnology. WB Saunders Co., Philadelphia

Zuurdeeg BW (1980) De natuurlijkc chemische samenstelling van Maaswater. H_2O 13: 2—7