Self-purification process and retention of nitrogen in floodplains of River Nemunas

Saulius Vaikasas and Antanas Dumbrauskas

ABSTRACT

Due to its catchment size and its significant level of agricultural pollution, the Nemunas river basin has been identified as an agricultural hot spot in the Baltic Sea basin. On average, the total annual inorganic nitrogen runoff into the river is 26.9×10^6 kg, which corresponds to a load of 275 kg km^{-2} yr^{-1}. A submerged floodplain, covering 605 km^2 of the River Nemunas lowland, maintains the natural retention threshold for pollutants in the water of the main canal and the outfall at Curonian Lagoon, as well as improving farming conditions in the inundated meadows of the valley. It also increases the sedimentation and nitrogen retention capacities of the Nemunas catchment. It has been estimated that about 40% of the fine suspended sediments can be retained and deposited in the flooded meadows of the delta. Controlled inundation of the floodplains in the Nemunas delta may reduce its runoff nitrogen load by 21 kg km^{-2} per flood event. As a result, nitrogen concentration decreases by approximately 8–10%, causing a self-purification process in the flooded area. Nitrogen retention is dependent upon the velocities of the flood current and has mostly been observed in zones of stagnating water.

Key words | floodplain, flow, nitrogen, retention, sediment

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INTRODUCTION

It is known that elevated concentrations and an excess of nutrients lead to eutrofication of surface waters. Since ecosystems are water-dependent, this will have a severe impact on the aquatic life: its diversity and all the aquatic ecosystem in general (Mason 1994; Smith *et al.* 1999; Hilton *et al.* 2006).

Large rivers are conduits for nutrients and sediments from continents to the sea, but swamp and wetland areas can enhance denitrification and are valuable for both wildlife conservation and nutrient retention.

Thus, water is the main agent for the transport of nutrients in both dissolved and solid forms. But when the nutrients have entered the surface water, they can be absorbed by solid particles, assimilated by plants or transformed by bacteria. It decreases excess concentration of nitrogen load and can be referred as a "self-purification process in the surface water" (Jansson *et al.* 1994; Edwards 1998). To investigate this phenomenon, research was initiated to determine whether the nitrogen load entering marine areas could be reduced by complementary control of the nitrogen transport in streams. Since it is known that wetlands can retain nitrogen, they have been suggested as nitrogen load traps. It was investigated that nitrogen removal in wetlands depends mainly on denitrification and sedimentation, and the water retention time is the most critical factor for removal of nitrogen (Jansson *et al.* 1994). On the other hand, it was established that the efficiency and possibilities for the use of wetlands to reduce nitrogen transport in streams depends on climatologically and hydrological prerequisites such as the turbidity and velocity distribution in water volumes of the flooded area. The purpose of this study was to evaluate the process,

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possibilities and efficiency of nitrate removal from stream water in the Nemunas floodplain in Lithuania. Because water flow dynamics during flood plain inundation is complicated and the nitrate retention time dependent on the water discharge distribution must be different in separate parts of this 30,000 ha wetlands, the nitrogen retention process in the Nemunas floodplain can be investigated only by means of flood dynamics modelling (Vaikasas & Rimkus 1997; Juskauskas & Balodis 2000; Malisauskas & Sileika 2002).

The Nemunas river basin, which covers an area of 97,860 km^2, is the fourth largest to enter the Baltic Sea (via the Curonian Lagoon). Lithuania has 48% of the river length, draining more than 47% of the country. The river has 600 km^2 of floodplains in its delta. The density of the hydrographical network of the Nemunas basin in Lithuania is 1.10 $km\,km^{-2}$, and 82% of this network is either regulated or converted into drainage channels. Channels are maintained as water receivers from drained lands and cover the greatest part of the river basin, collecting the pollutants from all diffused sources. Zalakevicius (2000) has shown that surface waters in Lithuania receive 40% of pollutants from these types of sources.

The annual runoff into the Nemunas basin approaches $22.1 \times 10^9\,m^3$. Over the last decade, the total annual dissolved inorganic N (DIN) discharge from the Nemunas basin into the Baltic Sea ranged between $16.2–42.7 \times 10^6$ kg (averaging 26.9×10^6 kg) (Annals 1993–2002). This discharge is in line with the inorganic N load in river runoff of 167–436 $kg\,km^{-2}\,yr^{-1}$ (an average of 275 $kg\,km^{-2}\,yr^{-1}$).

Due to a significant level of pollution from agriculture, the Nemunas basin has been identified as a hot spot in the Baltic Sea region (Cetkauskaite *et al.* 2001). It has been estimated that it would cost billions of ECU to reduce the inputs of pollutants from land sources into the sea. The overall target adopted by the HELCOM Ministerial Declaration of 1988, to reduce the nutrient load to the Baltic Sea by 50% before 1995, was not achieved by any of the Contracting Parties (Ollikainen & Honkatikia 2001; Sileika *et al.* 2003). In fact, the nitrate nitrogen (NO_3-N) load from agricultural basins into Lithuanian rivers actually increased (Sileika *et al.* 2003).

It took a long time to recognise that an interaction between a river and its valley is of great importance to the ecological functioning of the river (Hynes 1975). River valley restoration may contribute much to river function and have an immediate effect on it (Iversen *et al.* 2000). A special effect on water purification and pollutant removal can be determined in wetlands possessing a large filtering and pollutant retaining capacity (Jansson *et al.* 1994; Lars & Mosiej 2000). During flood events, when water overflows the riverbanks, certain hydrological conditions characteristic of floodplain wetlands may also occur in inundated river valleys, sometimes lasting for several months.

Studies done on the floodplain of the Nemunas delta, where there are a range of summer polders (with dykes protecting against summer flooding) and winter polders (never flooded), revealed that the nutrient content in the soils of flooded polders was higher than in non-flooded ones (Malisauskas & Sileika 2002). This fact suggests that it may be possible to retain nutrients from floodwater in summer polder soils.

The objective of the following study was to assess the potential for improving water quality by using controlled flooding of the Nemunas delta to reduce the N concentration and load in the River Nemunas when entering the Baltic Sea. This paper analyses the nitrogen retention results based on hydraulic modelling of the distribution of water flow velocities in the upper part of the Nemunas delta (Figure 1).

MATERIALS AND METHODS

The study was carried out in the Lithuanian section of the Nemunas basin, during the period 1994–2002 (Figures 1 and 2). Two methods were applied: (1) field studies of N concentrations in the River Nemunas inundated delta and (2) modelling the flood dynamics in the river delta valley.

To assess the affect of inundation on NO_3-N retention in the Nemunas delta, investigations were carried out during the spring floods in 1994, 1995, 1996 and 2002. At the same time, the turbidity of the floodwater was studied. Maximum floodplain discharges were, in chronological order, 2,100 $m^3\,s^{-1}$ (probability of 10%), 1,300 $m^3\,s^{-1}$ and 910 $m^3\,s^{-1}$.

Figure 1 | Nemunas catchment area.

Using bottle-type point-integrated samplers and a survey boat, 234 water samples were taken from the whole flooded area of the delta (Figure 2). Concentrations of NO_3-N were determined using the method mentioned above. A turbidity optical measurer, in combination with water samples taken for data calibration, was used to assess turbidity and suspended sediment fractions (Rimkus & Pukštas 2003*a*,*b*).

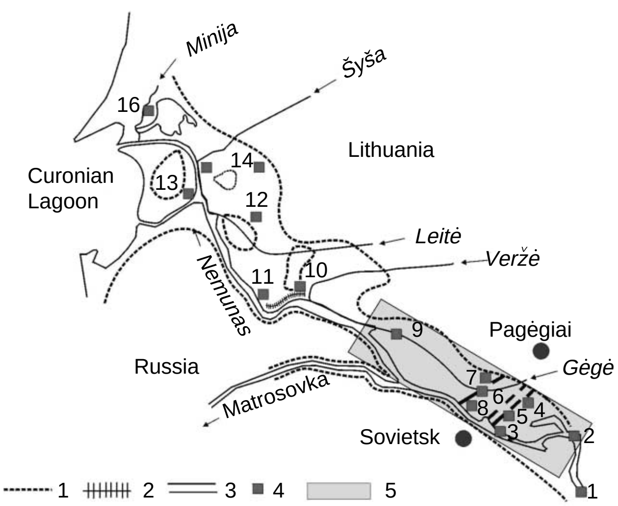

Figure 2 | The River Nemunas delta (400 km^2): 1—line of flooding; 2—non-flooded embankment; 3—causeway; 4—sampling spot; 5—section of valley where modelling was completed. The sampling spots: 1–3, 11, 13, 15—close to the main river canal; 4–8—in valley stream zones; 9, 10, 12, 14 and 16—in stagnant water zones.

To be able to quantify the NO_3-N load reduction when water flows through the flooded delta valley, the flow velocity and water delay in the valley needed to be assessed. As flooding conditions were complicated, flow velocity dynamics in the valley were simulated physically (hydraulic model scales 1:600 and 1:50) and mathematically by solving both Saint-Venant and mass-balance Equations (Vaikasas & Rimkus 2003, 2004).

The quasi-2D hydrodynamic model (Rimkus & Vaikasas 1999) for sediment and pollutant transport, along with empirical Equation (2) (Vaikasas & Rimkus 2003) evaluating the NO_3-N concentration decrease in floodwater, were used to quantify the retention of NO_3-N in floodplains (Rimkus *et al.* 2007):

$$\frac{\partial \bar{C}}{\partial t} + u\frac{\partial \bar{C}}{\partial x} + v\frac{\partial \bar{C}}{\partial y} = \frac{1}{h}\frac{\partial}{\partial x}\left(hD_x\frac{\partial \bar{C}}{\partial x}\right) + \frac{1}{h}\frac{\partial}{\partial y}\cdot\left(hD_y\frac{\partial \bar{C}}{\partial y}\right) - S, \quad (1)$$

where $\bar{C}$–depth-average suspended sediment or nutrient concentration; u, v–depth-average horizontal and vertical flow velocities; D_x, D_y–coefficients of turbulent diffusion in x and y directions; h–water depth and S–deposition/erosion/source term.

$$C_t = C_0\,\mathrm{e}^{-kt} \quad (2)$$

where C_t–NO_3-N concentration after water detention time t in inundated valley; C_0–initial NO_3-N concentration in floodwater; k–empirical coefficient based on data from 1994, 1996 and 1999 and t–water mass detention time in floodplain.

Mass-balance calculations were carried out. Field data of water velocities and flow rate distributions, along with the data from previous experiments with hydraulic (physical) flow models, were used to verify the water mass distribution and detention in the inundated valley as well as values of the empirical coefficient k calibration (Vaikasas & Rimkus 1997; Vaikasas 2001):

$$k = \ln(C/C_0)/t \quad (3)$$

The calculations were performed for the inundated 23 km upper section of the delta valley (Figure 2). Water flow for the calculation was divided into flow strips with equal discharges. Sediment deposition as well as flow mass detention was calculated along each flow strip, and thus the distribution of sediments and flow rates was determined in the floodplain area. Thus this model became quasi-two-dimensional As a detailed GIS database of the delta area had been developed in 2003 (Ascila *et al.* 2002), it enabled the development of 1D and 2D hydrodynamic models and the production of maps of inundated areas (Figure 2), along with the supply of other useful information. As input data for the hydraulic model, Smalininkai's hydrological data was used (Annals 1993–2002).

RESULTS

Influence of inundations in the delta on water quality

By coupling the 1D hydrodynamic model with ArcGIS tools, the inundated areas for real floods were estimated. The conclusion drawn from this experiment was that the inundated area largely depended on the form of the floodplain cross section, which was mostly trapezoidal in the delta area. This meant that a large part of the delta was flooded by an average spring flood discharge. Continuing discharge then caused the depth of water in the floodplain to increase, but not the area covered by water. Similar results were obtained using the digital terrain model with water level data gathered along the floodplain. It was sufficient for water levels to reach 50% of the maximum level when 80% of the area was flooded.

The data analysis of floodwater turbidity and NO_3-N concentrations revealed that a special distribution of these floodwater characteristics occurred in the flooded Nemunas delta, which depended on the distribution of flow velocities and the water retention time in the floodplain (Table 1).

NO_3-N concentrations, as well as turbidity values, were less in the zones of stagnant water. The NO_3-N concentrations dropped from $3.0\,mg\,l^{-1}$ to $1.7\,mg\,l^{-1}$ as water flowed from the valley-flooding zone to the river outfall in the Curonian Lagoon. The degree of NO_3-N reduction depended on the length of time that floodwater was delayed in the valley (Figure 3).

Water that was part of a more intensive flood was found to be more polluted in the delta, as NO_3-N reduction appeared to be slower during larger flood events. This can be seen as an increasing k value of 0.007, 0.016 and 0.029 for the years 1994, 1996 and 2002, respectively, following the decrease in abundance of water in the flood events (Table 2). According to the calculations, the k value was a bit different and changed within the interval (-0.006) to (-0.037). This might have been caused by different conditions of denitrification process every year.

Table 1 | Water turbidity and NO_3-N concentrations found in the Nemunas delta during the spring flood of 1994

Sampling spot no. (see Figure 2)	Location with respect to stream	Turbidity ($mg\,l^{-1}$)	NO_3-N ($mg\,l^{-1}$)
1	R	40.00	3.00
2	R	18.00	3.00
3	R	10.00	2.30
11	R	6.40	2.50
13	R	6.00	4.20
15	R	5.40	2.50
4	V	8.40	2.50
5	V	7.40	3.10
6	V	6.00	2.50
7	V	7.60	2.50
8	V	6.60	2.50
9	S	3.40	2.00
10	S	7.00	2.00
12	S	7.00	2.30
14	S	4.40	3.00
16	S	6.00	1.70

Note: R—river main canal; V—valley stream zones; S—stagnant water zones.

The spring flood event of 1994 with mean $k = 0.007$ was modelled (Table 3). Calculations on denitrification in the flooded delta were performed by adapting Equation (1) for our mathematical model DELTA (Vaikasas 2001). The maximum discharge of the Nemunas in the inundated floodplain reached $2{,}100\,m^3\,s^{-1}$ and the initial NO_3-N concentration C_0 was $3.00\,mg\,l^{-1}$. The smaller the discharge entering the valley, the slower was the flow velocity, resulting in longer water residence times there. Conversely, floodwater residence times were shorter in the valley when water levels were higher. Thus it can be seen that the degree of decrease in NO_3-N concentration in the flooded valley was determined by the water residence times (Table 3). However, the absolute decrease in NO_3-N concentration was fairly constant, at an average of $0.45\,mg\,l^{-1}$.

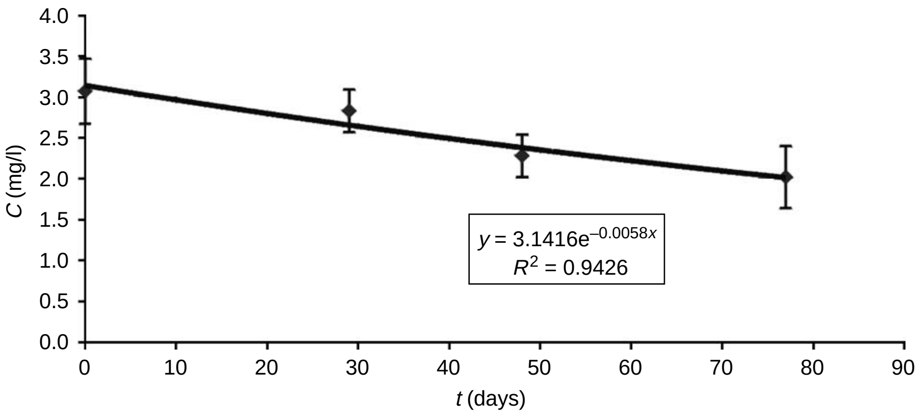

Figure 3 | Dependence of NO_3-N concentrations (C_t, mg l^{-1}) on water delay (t, days) in the delta in the years 1994, 1995, 1996 and 2002, respectively.

The contamination level appeared to have no effect on the relative decrease in concentration.

The rate of decrease in NO_3-N concentration indicates the intensity of the self-purification processes occurring in the water flowing through the inundated valley. In the case of the simulated section of the Nemunas delta, it was calculated that approximately 2.1×10^6 kg of NO_3-N may have been retained during the spring flood of 1994 (Table 4).

DISCUSSIONS

The process of NO_3-N removal from river water is rather complicated. It is not solely dependent on the water retention time in a flooded valley, but is actually determined by many conditions: climatic, topographical, hydrological, the physical and chemical characteristics of floodwater, etc. The N removal rate depends, for example, on both water temperature and the N loading rate (Weisner *et al.* 1994), as well as on the activity of facultative anaerobic bacteria (Tiedje 1988). As anoxic conditions are preferable for denitrification, the N removal potential ought to increase when it reaches the underlying anoxic water column layers and bottom sediment. In this respect, the inundated floodplains are similar to wetlands.

Little NO_3 reduction occurred in cold floodwater with a low oxygen demand, while denitrification may have been favoured in stagnant areas where the water retention time greatly exceeded the water delay in active flow zones (Reddy *et al.* 1980; Stober *et al.* 1997). Because the Spring stream water temperatures are too low and quick flows contribute in the main river canal, in-stream nitrogen retention occurs in the floodplain only. According the study of Mourad (2008), retention in the main stream canal removes only approximately 1% in that period. However,

Table 2 | NO_3-N concentrations (C_t, mg l^{-1}) measured at the spots at variable distances from the Nemunas outfall, water delay time (t, d) and empirical coefficient (k) calculated according to Equation (3)

	Years											
	1994				1996				2002			
Distance from outfall (km)	Q_{max}	C_t	t	k	Q_{max}	C_t	t	k	Q_{max}	C_t	t	k
106	2,100	2.5	0	–	1,300	2.0	0	–	910	1.0	0	–
73		2.3	10	0.008		1.7	12	0.016		0.8	13	0.017
45		2.2	18	0.006		1.5	30	0.016		0.6	22	0.032
5		–	–	–		1.3	29	0.016		0.4	33	0.037
Mean				0.007				0.016				0.029

Note: Q_{max}—maximum valley discharge ($m^3 s^{-1}$).

Table 3 | Decrease in NO_3-N concentrations during the flood event of 1994. The results were obtained by simulating an actual flood event in the 23 km upper section of the Nemunas delta valley

Floodwater level altitude (m)	Discharge of valley flow ($m^3\,s^{-1}$)	Water residence time in the valley (d)	Initial NO_3-N concentration C_0 ($mg\,l^{-1}$)	NO_3-N concentration decrease (%)	($mg\,l^{-1}$)
8.57	2,100	18	3.00	14	0.41
8.50	2,000	19		18	0.46
8.25	1,583	22		40	0.54
8.00	1,188	23		55	0.47
7.75	813	24		66	0.43
7.50	484	26		76	0.42
7.25	250	29		83	0.44
				Mean:	0.45

our experience showing that nitrogen retention in the Nemunas delta floodplain can be a 10 times greater decrease of NO_3^- anions after the outflow of the streams during the 1987–1991 year period is also fixed by Katutis (2002, see Table 5). It can be see that concentrations of N-NO_3 decrease even to 32–38% after their retention in the floodplain.

The significant nitrogen retention effect of the floodplain sediments was found in many lowlands of rivers. For example, it was established that only approximately 1/3 of the sediment transported by the River Rhine reaches the North Sea (Middelkoop & van Haselen 1999). The rest is deposited on the floodplain, where the water moves much more slowly, thus allowing sediment to settle. A significant effect of suspended sediment retention on the deposition of nutrient salts was also found in the Nemunas floodplain (Vaikasas 2001; Vaikasas & Rimkus 2003).

The lower the flood events occurring in the inundated delta, the lower were the average flow velocities obtained. As these velocities decreased, the water delay in the delta increased, resulting in a decrease in flow turbulence, an augmentation in the settling of suspended matter and shifts in the temperature conditions. These changes may have favoured denitrifying bacteria, so that NO_3-N concentrations decreased in the water flowing through the inundated floodplains of the Nemunas delta.

In the result, water of a more intensive flood was more polluted. However, the denitrification process was slower during a greater flood (1994) due to lower bacteria concentrations. This is indicated by an increasing k value when floodwater volume decreases ($k = 0.007$, 0.016 and 0.029 in 1994, 1996 and 2002 accordingly). The changes in bacteria activity and the coefficient value are obvious and related to floodwater volume. Presumably, these changes are caused by certain natural factors of the year (e.g. air temperature). The coefficient k depends on the factors mentioned and thus a new additional member must be introduced into the formula to estimate these factors. However, due to a relatively small number of physical observations performed, not all peculiarities of the process have been revealed yet, therefore an additional detailed study is required. Our developed formula estimates only the time factor. Although the objective for a more detailed study of the denitrification process has not been set yet, the results can already be foreseen.

Table 4 | Retention of NO_3-N, due to the self-purification of floodwater while it flowed through the inundated 23 km upper section of the Nemunas delta in the spring flood event of 1994

Valley discharge ($m^3\,s^{-1}$) Fluctuation interval	Average in the interval	Discharge duration (h)	NO_3-N retention ($\times 10^6$ kg)
100–250	177.5	408	0.11
250–484	376.1	528	0.30
484–813	629.1	324	0.32
813–1,188	988.8	180	0.30
1,188–1,583	1,368.6	204	0.54
1,583–2,000	1,776.5	150	0.44
2,000–2,100	2,047.0	24	0.07
		Total	2.08

Table 5 | The distribution of NO_3^- anions during the 1987–1991 floods in the Nemunas valley (according to measuring data from Katutis (2002))

District	Anions NO_3^- (mg/l)
The Jūra river valley (inflow)	4.8
The Jūra river (out flow)	3.1
The Nemunas river valley above Rambynas (inflow)	4.7
The Nemunas river valley above Plaškiai (outflow)	2.9
The Nemunas river valley above Silininkai (inflow)	4.5
The Nemunas river in the Curonian Lagoon (outflow)	3.0

The figure (2.1×10^6 kg per flood event) for the amount of NO_3-N retained in these inundated floodplains was derived from the simulated section only, so the total amount of retained NO_3-N for all of the delta floodplains should be greater. Nevertheless, even this derived figure is fairly significant, as it indicates a decrease of about 21 kg km^{-2} per flood event in the discharged NO_3-N load from the Nemunas basin into the Baltic Sea.

When the River Nemunas floods the delta, a large amount of suspended matter settles there. During the years from 1950 to 1991, this amount averaged $1.2–1.5 \times 10^6$ kg km^{-2} yr^{-1} of fine clay and silt particles, and approximately 12,000 kg km^{-2} yr^{-1} of organic matter (Vaikasas & Rimkus 2003). Over this 41-year period, along with these sediments, the delta floodplain soils were naturally fertilised with 0.25×10^6 kg of potassium, 0.95×10^6 kg of phosphorus and 38×10^6 kg of calcium (Vaikasas 2001). It is clear, therefore, that the flooding of the Nemunas delta floodplains contributes to the retention of contaminants that would otherwise settle in the Curonian Lagoon. However, it does also help to improve, to some extent, the fertility of the natural meadows in the floodplain.

The River Nemunas is currently classified as low polluted. Mean yearly concentrations of inorganic N in the lower reaches of the river fluctuate between 1.0–1.9 mg l^{-1} (Annals 1993–2002; Cetkauskaite *et al.* 2001). Since DIN concentrations in the watershed drainage channel water were at least four times higher than those found in the Nemunas itself, assessment of the effect of floodplain inundation on the reduction of N load, from the perspective of the river basin, showed the importance of addressing all ways and means of preventing pollution, and stimulating and maintaining the self-purification processes of stream water.

Larger flooded territories in the Nemunas valley allow for a greater variation of flow velocities and for stagnant water zones that enhance nutrient retention. With this in mind, the management of polder dykes (both summer and winter) could be adjusted to control the water flow dynamics in inundated floodplains. By maintaining the summer polder drainage systems to lower the soil water level and to augment the soil saturation capacity before flooding, N retention in the delta floodplains could be enhanced. However, an extension of the floodplain area is not possible without first embanking the main channel of the river. In the case of the Nemunas delta floodplains, the possible extension the floodplain area might be a consideration (initially politically) as the Nemunas delta in the Kaliningrad region is protected from any flooding by high winter dykes (Malisauskas & Sileika 2002).

Due to the reasons mentioned above, and because of the denitrification process observed in zones of stagnant water, the effect of flood water purification does not exceed 8–10%. Consequently, to reduce the amount of biogenic matter in the Nemunas and the Curonian Lagoon, the stimulation of flood deposit sedimentation as well as the lower water flow speed due to a denser vegetation cover and dispersing flows in the delta can be suggested.

CONCLUSIONS

1. By means of mathematical simulation of denitrification and flood water volume distributions it was established that N-NO_3 decreasing in the Nemunas valley water occurs about 4–5 times more intensively thon in the main canal water.
2. The gross nitrogen retention effect during the floods in the upstream water of the Nemunas delta is less than 8–10% of the total nitrogen load. It depends on the initial biogenic matter concentration, flood water volume distribution, inundation duration and other flood current conditions.
3. The estimated effects of self-purification processes during floods on water quality on the Lithuanian side of the Nemunas delta area are significant and require adequate

attention to be paid to the adjustment of polder systems, so as to stimulate the improvement of water quality, not only in the river itself, but also in the Curonian Lagoon and in the Baltic Sea.

4. As more open areas are left for flooding, water will remain in the flooded areas for longer periods. Some insignificant changes to summer polder systems and dykes may have beneficial effects on self-purification processes.

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