



## Nutrient uptake and benthic regeneration in Danube Delta Lakes

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**Abstract.** We investigated the nutrient uptake capacity of three lakes (Uzlina, Matita and Rosu) within the Danube Delta during high water level in June and low water level in September 1999. Special emphasis was placed on nutrient cycling at the sediment-water interface and on the self-purification capacity of the lakes in the Danube Delta. In order to estimate the nutrient uptake of selected lakes we present in this paper the results of water analyses, benthic flux chamber experiments and deck incubation experiments of <sup>15</sup>N-labeled sediment cores at the inflow and the outlet of the lakes. The external input of dissolved inorganic nitrogen and silica into the lakes decreases with increasing distance to the main Danube branches whereas the total dissolved phosphorus input is independent of the hydrological distance to the main branches. The nutrient loading is highest in the inflow channels, and decreases towards the outflow of the lakes. In June, the uptake of NO<sub>3</sub><sup>-</sup>, TDP and Si(OH)<sub>4</sub> in the lakes was higher than in September. In contrast, NH<sub>4</sub><sup>+</sup> uptake was more intense in September, when benthic release was more intense as well. On average, about 76% of the external plus internal nitrogen and phosphorus input into the lakes was taken up by macrophytes and phytoplankton during the growing season, whereas the uptake of external nutrient input amounted to about 43%. The benthic release of ammonia and silica increases from June to September and indicates, that part of the nutrients taken up during the growing season might be released during winter. We estimate the net impact of the Delta on the nutrient reduction of the Danube during the growing season is about 4.3%, assuming 10% of the Danube water is flowing through the Delta.

### Introduction

The Danube discharges up to  $8 \times 10^5$  t a<sup>-1</sup> total inorganic nitrogen,  $0.32 \times 10^5$  t a<sup>-1</sup> total phosphorus and  $3 \times 10^5$  t a<sup>-1</sup> dissolved silica into the Black Sea (Cociasu et al. 1996). Compared to the early sixties (Almazov 1961), the loads of inorganic nitrogen and phosphorus of the Danube River increased five- and two-fold, respectively, whereas the silica load decreased by a factor of three (Cociasu et al. 1996). The increased nutrient load leads to eutrophication in the river system and the coastal Black Sea.

Before entering the Black Sea, the Danube forms a wide branching delta. The Danube Delta is the second largest river delta in Europe. It is located between 28°45' E and 29°46' E longitude and 44°25' N and 45°37' N latitude ( $\approx 5800 \text{ km}^2$ , Figure 1), confined by the Bugeac Plateau to the north and by the Dobrogea region to the south (Panin 1996). The development of the delta starts at the point where the Danube river's main channel divides into the three main branches: the northern Chilia, the central Sulina and the southern Sfântu Gheorghe. A mosaic of shallow lakes and channels, fringed by reed, lies between these branches. During the period of high water from April to June, most of the delta plain is flooded. When the water table decreases to a minimum from September to November, the water flows back from inundated, standing reed areas surrounding the lakes into the lake. The Danube Delta, with its small channels, lakes and wetlands represents a natural filter for various contaminants and nutrients transported in solution or adsorbed onto suspended matter. However, the capacity of the delta system to retain these compounds has been diminished due to land reclamation for agricultural activities near the Danube River and inside the delta. Furthermore, the hydrology within the delta was modified by engineering works such as drainage programs, dike building, impoundments and channel dredging. Before 1980, about 3% of the total Danube discharge was flowing through the Delta; the rest was flowing in the three main branches. The water input into the Delta increased up to 10% of total discharge after the channels "Caraorman", "34-miles" and "6-meander cut" were built (Bondar 1996). Gastescu et al. (1999) estimate the average water residence time in the Delta as 2.2 months at present. With increasing water flow through the Delta and higher nutrient concentrations, eutrophication of the delta lakes became a serious problem.

A survey of the trophic state of selected Danube Delta lakes by the Romanian Danube Delta Institute and the Dutch Institute for Inland Water Management and Waste Water Treatment (RIZA) revealed that the Lakes Uzlina, Matita and Rosu were mesotrophic to eutrophic (Oosterberg et al. 2000). Levels of dissolved nitrogen and phosphorus in lakes of the delta are lower than those in the main channels (Buijse et al. 1997); however, the nutrient elimination in the lakes has not been studied in detail. The hydraulic residence time is a critical factor for removal of nutrients such as nitrate (Höhener and Gächter 1994; Mengis et al. 1997a; Steingruber et al. 2001a). According to Jansson et al. (1994) lakes remove more nutrients than small wetlands. Therefore, as a first step towards an assessment of nutrient retention in the delta lakes, we analyzed nutrient uptake and turnover during two expeditions in summer of 1999.

Specific questions we address are:

- What is the nutrient input into the Delta lakes with respect to the distance from the main Danube branches? What are the nutrient sources and sinks in the delta lakes?
- What is the amount of benthic nutrient cycling and denitrification compared to the input?
- How important is the nutrient uptake by algae and macrophytes during summer? What is the nutrient retention capacity of the lakes during the growing season?

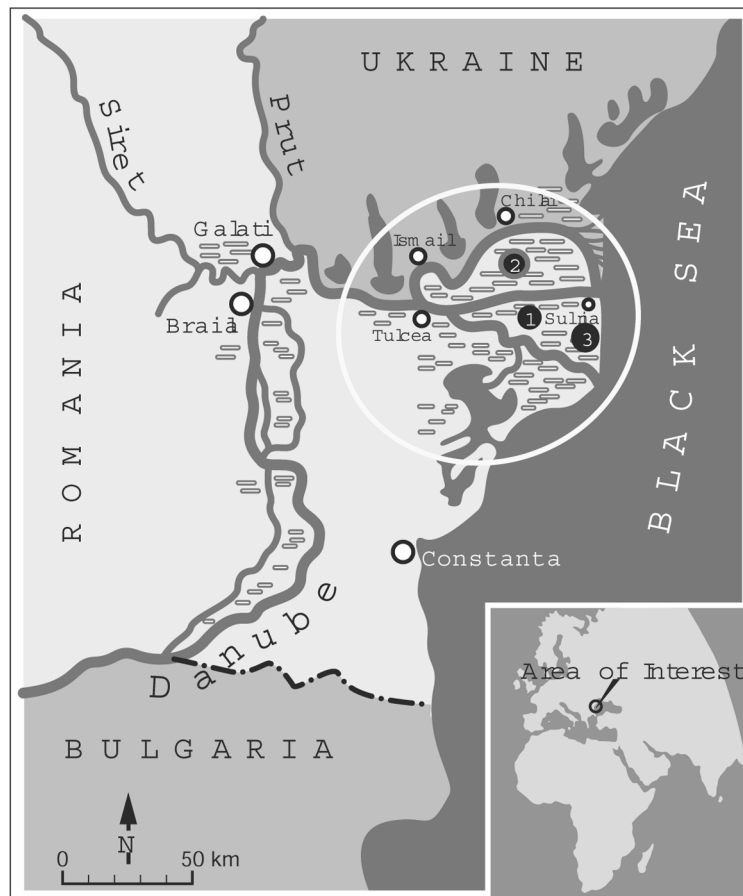


Figure 1. Location of the research area within the Danube Delta. The Danube Delta is marked with a circle. 1-Lake Uzlina, 2-Lake Matita, 3-Lakes Rosu/Rosulet.

We analyzed the nutrient dynamics of the three Delta Lakes (Uzlina, Matita and Rosu/Rosulet) during high water level in June and low water level in September 1999 using benthic flux chambers and an input-output analysis of dissolved inorganic nitrogen, total dissolved phosphorus and silica.

## Material and methods

### *Study sites*

The water level of the Danube and within the delta rises to maximum values from April to June and decreases to a minimum in September and October (Panin 1996). During our field campaign in 1999, the water levels of the Danube at Tulcea before



Figure 2. Location of the Lakes Uzlina, Matita and Rosu/Rosulet within the Danube Delta. White crosses indicate sampling stations at the inflow and outflow of each lake.

entering the Delta (June 3.3 m relative to the Black Sea level at Sulina, mMNS, and September 1.7 mMNS, Bondar unpublished data) were within the hydrological mean and comparable to those in 1997 during the RIZA field campaign (June 3 mMNS and September 1.8 mMNS, Constantinescu and Menting (2000)). According to Oosterberg et al. (1997), the nutrient loading of the lakes decreases as a function of distance from the main branches in the delta. Nutrient input into the Danube Delta lakes is highly variable in space and time.

In our study, we have chosen three representative lakes (Figure 2). All three lakes have a broad reed fringe and are shallow, with a maximum depth of 2.8 to 3.5 m during high water level and 2.1 to 2.9 m during low water level. These shallow throughflow lakes do not stratify. The hydraulic residence time varies between two weeks and two months. Table 1 summarizes the morphological and hydrological characteristics and the chlorophyll data for the characterization of biological activity.

Lake Uzlina is situated within the fluvial delta plain in the Gorgova-Uzlina complex, very close to the southern Danube branch, Sfântu Gheorghe, at the head of a through-flow chain (Figure 2). This lake is strongly influenced by Danube inputs from the Sfântu Gheorghe branch. Lake Matita is located within the fluvial delta plain in the Matita-Merhei complex between the Chilia and Sulina branches.

Table 1. Hydrologic data of Lakes Uzlina, Matita and Rosu/Rosulet in 1999, based on a one-dimensional water circulation model of the Danube Delta (Bondar unpubl. data 2000) and chlorophyll concentrations in the surface water at high water level in June and low water level in September, measured at the lake's in- and outflow

Parameters	Units	Lake Uzlina		Lake Matita		Lake Rosu + Rosulet	
		June	Sept.	June	Sept.	June	Sept.
Lake surface (open water)	km <sup>2</sup>	4.7		6.4		17.8	
Lake volume	10 <sup>6</sup> m <sup>3</sup>	15.5	10.7	17.8	13.4	58.9	47.8
Average depth	m	3.3	2.3	2.8	2.1	3.5	2.9
Average through-flow	m <sup>3</sup> s <sup>-1</sup>	17	4	13	3	45	13
Hydraulic residence time	days	11	33	16	60	15	43
Chl. <i>a</i> inflow	μg l <sup>-1</sup>	0.38	0.76	0.38	3.89	0.49	3.96
Chl. <i>a</i> outflow	μg l <sup>-1</sup>	0.52	1.98	0.75	3.40	0.93	4.65

The lake is not directly influenced by any of the Danube distributaries. The water flowing into the lake has already passed through a system of meandering channels rich in aquatic vegetation and small lakes fringed by reed. Lakes Rosu/Rosulet are located in the Rosu-Puiu complex that belongs to the marine delta plain. They are situated between the central and southern branches of the Danube Delta: Sulina and Sfântu Gheorghe. The present water flow is maintained by a sequence of artificial channels. The flow direction depends on the height of the water level in the Delta compared to the Black Sea. In late fall and winter, when the water level in the Delta is low, severe easterly winds might push Black Sea water into the main branches thus reversing the flow direction. In general, the hydraulic gradient prevents salt-water input into the lakes. Lakes Rosu/Rosulet represent two separate parts of one lake divided by submerged discontinuous sand bars, covered by reed, and floating *Phragmites* plaurs (floating reed islands).

### Sampling

Two stations, nears the inflow and at the outflow of the lakes were sampled. The sampling sites were visited in June at high water level and in September at low water level. At each station, we followed the same procedure: Water samples were taken with a Niskin bottle at three depths (surface, mid depth, near bottom). In addition, water samples were taken from the inflow channel. Benthic fluxes of oxygen and nutrients across the sediment-water interface were measured with two benthic flux chambers. Design and function of the device is described in detail in Mengis et al. (1997b) and Tengberg et al. (1995). The benthic Lander was lowered to the bottom, the flux chambers were pushed into the sediment and the top lids closed after half an hour. Spring actuated syringes were used to take 10 water samples of 50 ml from each chamber in two-hour intervals. During operation, the flux chambers were stirred continuously at a velocity of about 1 rps resulting in a corresponding boundary layer thickness of about 0.8 mm (Höhener 1990). In one

flux chamber the oxygen concentration and pH were recorded continuously by an O<sub>2</sub> and pH sensor coupled to a Seabird Electronics (SBE 16) sealogger unit. The device was retrieved after 21 h.

#### *Analytical procedures*

Total alkalinity was measured in all samples by titration of 5 ml of the sample with 0.01 mM HCl to pH 4.3. The pH and alkalinity measurements were carried out within four hours after retrieval of the flux chambers and sampling.

Filtered aliquots of the water samples and the syringes from the flux chamber were analysed on board by standard colorimetric methods (Deutsche Einheitsverfahren zur Wasser-, Abwasser- und Schlammuntersuchung 1995) for dissolved ammonium (phenolphthorite method) with a "MERCK SQ 300" photometer. NO<sub>3</sub><sup>-</sup> was analysed by standard colorimetric methods (2,6 dimethylphenol method, respectively) on board with a "PROCON" autoanalyzer. Total dissolved phosphorus (TDP) was measured after peroxodisulfate digestion with the ammoniummolybdate method on a "PROCON" autoanalyzer at EAWAG. Si(OH)<sub>4</sub> was analysed photometrically with the molybdenum blue method. POC and PN in the suspended particulate matter (SPM) and the sediment were measured with a C/N analyzer (Elementar, vario el). For suspended matter analysis, 60 ml of water samples were filtered on pre-combusted GF-F filters. C:N:P ratios in this paper represent the molar ratios of the concentrations of carbon, nitrogen and phosphorus.

Denitrification experiments of <sup>15</sup>N labeled sediment cores were carried out on board applying the isotope pairing technique in a batch mode assay (Steingruber et al. 2001b). At each station, six sediment cores (6 cm diameter) were placed in an incubation tank filled with bottom water of the same station. One core was equipped with an O<sub>2</sub> probe to measure oxygen consumption, a second core was used as reference core and four replicate cores were labeled with <sup>15</sup>N. The sediment surfaces were adjusted to have approximately 9 cm of sediment and 13 cm of overlaying water. The overlaying water was stirred with a magnetic stirrer. <sup>15</sup>N as NO<sub>3</sub><sup>-</sup> (approximately 10% of the initial NO<sub>3</sub><sup>-</sup> concentration) was added to the water in the tank after the reference core was closed and mixed well. Then the remaining four cores were closed. During the experiments, the cores were stored in the dark at *in situ* temperatures (25 °C/20 °C). The sediment overlaying water was sampled every hour until 20% of oxygen was consumed. Aliquots of 5 ml were transferred in He-filled and 250 μl 50% ZnCl<sub>2</sub> containing gastight vials. The samples were analyzed for the <sup>15</sup>N/<sup>14</sup>N ratio of N<sub>2</sub> with a continuous flow isotope ratio mass spectrometer (Micromass Isoprime) at EAWAG. The standard deviation of the <sup>30</sup>N<sub>2</sub>/<sup>28</sup>N<sub>2</sub> measurements is 0.07E-3. Aliquots of 5 ml were sampled to measure NO<sub>3</sub><sup>-</sup> consumption with the method mentioned above. Denitrification rates were calculated according to Nielsen and Revsbech (1994) and Steingruber (2001) from end-point measurements. We use the denitrification rate of unlabelled <sup>14</sup>NO<sub>3</sub><sup>-</sup> (D<sub>14</sub>) as approach to natural *in situ* denitrification, since we added <sup>15</sup>N as NO<sub>3</sub><sup>-</sup> to ambient nitrate.

Samples for chlorophyll analyses were filtered on 0.45  $\mu\text{m}$  GF filters stored deep frozen until analyzed at GeoEcoMar. Chlorophyll was extracted with acetone and measured on a Hach DREL 2000 spectrophotometer by the method of Parsons et al. (1984). Calculation of the amount of chlorophyll pigments in the extract solution was performed using the Jeffrey & Humphrey's trichromatic equations (Parsons et al. 1984).

#### Data analysis

Benthic fluxes were calculated by a linear fit of the concentration changes versus time. Fluxes  $F$  in  $\text{mmol m}^{-2} \text{day}^{-1}$  were then calculated according to:

$$F_{\text{benthic}} = h \frac{\partial C}{\partial t} \quad (1)$$

Where  $h$  is the height (m) of the enclosed water column in the flux chamber and  $\partial C/\partial t$  ( $\text{mmol m}^{-3} \text{d}^{-1}$ ) represents the accumulation rate of a compound in the benthic chamber. Fluxes were determined independently in the two chambers A and B of the benthic Lander. The benthic release  $F_{\text{benthic}}$  for the entire lake was estimated as the average of two deployments of the benthic chambers near the inflow and the outflow. The relevant data are summarized in Tables 4 and 5.

We used a simple box model (Figure 3) to calculate the nutrient budget of the lakes at the time of each expedition. During the two campaigns, we measured the nutrient input and output of the lake through the main channels. Average nutrient concentrations were calculated from measurements at three depths (Tables 2 and 3). We had to neglect advective water flow through the reed belts of the lakes and groundwater exchange, because these factors were not accessible within the frame of our project. Therefore, our estimates of nutrient uptake and storage relied mainly on water exchange of the lakes through the main channels. The observed parameters were evaluated with the following equation for short-term nutrient storage in the lakes, all terms are calculated in  $\text{mmol m}^{-2} \text{day}^{-1}$ :

$$\Delta = F_{\text{in}} + F_{\text{benthic}} - F_{\text{out}} - F_{\text{uptake}} \quad (2)$$

$\Delta$  represents the changes in concentration of solutes and water volume of the lake. It corresponds to a balance between inflow of nutrients in the lake ( $F_{\text{in}}$ ) and the benthic release ( $F_{\text{benthic}}$ ) minus the outflow of nutrients ( $F_{\text{out}}$ ), and gross uptake by nutrient consumption via phytoplankton and macrophytes plus net sedimentation ( $F_{\text{uptake}}$ ). Benthic release is typically a source term. It represents the internal loading from the sediment. In the case of consumption,  $F_{\text{benthic}}$  is negative. Similarly,  $F_{\text{uptake}}$  represents nutrient uptake by growing biomass. We expect that this term changes sign in late autumn and winter. Our study, however, was confined to the growing season. Since our measurements were performed within 2 days per lake during each campaign, changes in lake volume and average concentration are small,



we assume  $\Delta = 0$ . Under these conditions Equation (2) can be rewritten and gross uptake is calculated as

$$F_{\text{gross uptake}} = F_{\text{in}} - F_{\text{out}} + F_{\text{benthic}} \quad (3)$$

I.e. the biomass uptake term is calculated from the input-output balance and the internal loading term  $F_{\text{benthic}}$ . We define difference between input and output as net uptake  $F_{\text{net uptake}}$ , which will vary according to the hydrologic conditions and the season.

$$F_{\text{net uptake}} = F_{\text{in}} - F_{\text{out}} \quad (4)$$

The in- and outflow of nutrients ( $F_{\text{in}}$  and  $F_{\text{out}}$ ) in  $\text{mmol m}^{-2} \text{day}^{-1}$  were calculated by multiplying the nutrient concentration at in- and outflow of the lakes (mM) by the average through-flow of the lake ( $\text{m}^3 \text{day}^{-1}$ ) and divided by the lake's surface ( $\text{m}^2$ ). The input-output balance is based on hydrological data and lake morphology (Table 1) and water chemistry (Tables 2 and 3). We found good agreement between the hydrological parameters in Table 1 and the data of the global Danube model based on SOBEK by Delft Hydraulics (Constantinescu and Menting 2000). Therefore, we estimate the errors in our hydrologic data to be about the same. Delft Hydraulics estimates the accuracy of the global model about 5%. The local sub-models amplify the variation in the boundary condition by a factor 2–4. In comparison, the error of the chemical measurements is of minor importance and given for the water analysis in Tables 2 and 3 and for the benthic flux experiments in Tables 3 and 4.

Our attempt to determine net sedimentation with radionuclide dating of the sediment failed due to the high sediment resuspension and mobility of these shallow river lakes. The nitrogen cycle will be discussed in terms of measured denitrification rates and benthic fluxes of  $\text{NO}_3^-$  and  $\text{NH}_4^+$ .

## Results

In the following chapter, we briefly describe the results for the three lakes. We compare the inflow and outflow concentrations and evaluate nutrient uptake and benthic fluxes during the campaigns in June and September 1999.

### *Lake Uzlina*

The inflowing water in the lake derives almost directly from the Danube. The hydrological distance to the southern Danube branch Sfântu Gheorghe is short and hence, the travel time of the water only about 0.2 days (Constantinescu and Menting 2000). In June at high water level, we measured in the inflow channel  $96 \mu\text{M NO}_3^-$  and  $1.3 \mu\text{M}$  total dissolved phosphorous (TDP, Table 2). In the lake, the concentration of  $\text{NO}_3^-$  decreased from  $95.5 \mu\text{M}$  at the inflow to  $28 \mu\text{M}$  at the out-



Table 2. Averaged values and standard deviation from three depths of alkalinity, oxygen, total dissolved phosphorus (TDP), nitrate, ammonia, silica POC, PN and the molar C:N ratio of particles in the water of Lakes Uzlina, Matita and Rosu in June 1999. Channel denotes the water in the inflow channel before entering the lake. Inflow refers to the inflow area in the lake and outflow to the outflow area of the lake

Sample	Alkal. mM	O <sub>2</sub> mM	TDP μM	N-NO <sub>3</sub> <sup>-</sup> μM	N-NH <sub>4</sub> <sup>+</sup> μM	Si(OH) <sub>4</sub> μM	POC μM	PN μM	C:N
<b>Uzlina</b>									
channel	<b>2.12</b> ± 0.01	<b>0.21</b> ± 0	<b>1.33</b> ± 0.57	<b>95.5</b> ± 5.7	<b>6.10</b> ± 3.28	<b>76.4</b> ± 0.2	<b>27.5</b> ± 3.5	<b>7.9</b> ± 0.01	<b>4</b> ± 0.4
inflow	<b>2.97</b> ± 0.03	<b>0.24</b> ± 0.16	<b>1.05</b> ± 0.05	<b>86.0</b> ± 9.8	<b>3.61</b> ± 1.79	<b>64.9</b> ± 0.9	<b>19.4</b> ± 4.1	<b>9.8</b> ± 0.4	<b>2</b> ± 0.4
outflow	<b>2.09</b> ± 0.37	<b>0.24</b> ± 0.02	<b>1.10</b> ± 1.0	<b>27.9</b> ± 9.8	<b>3.93</b> ± 2.24	<b>13.8</b> ± 6.5	<b>10.5</b> ± 5.9	<b>7.6</b> ± 0.4	<b>2</b> ± 0.8
<b>Matita</b>									
channel	<b>1.96</b> ± 0.01	<b>0.03</b> ± 0.01	<b>2.03</b> ± 0.02	b.d.	<b>0.82</b> ± 0.04	<b>59.2</b> ± 2.9	<b>7.49</b> ± 1.7	<b>1.4</b> ± 0	<b>4</b> ± 0.8
inflow	<b>2.98</b> ± 0.02	<b>0.10</b> ± 0.04	<b>2.68</b> ± 0.23	b.d.	<b>0.87</b> ± 0.76	<b>55.3</b> ± 6.2	<b>48.0</b> ± 10.2	<b>7.4</b> ± 2.3	<b>6</b> ± 4.7
outflow	<b>3.12</b> ± 0.08	<b>0.17</b> ± 0.07	<b>1.97</b> ± 0.16	b.d.	<b>0.23</b> ± 0.21	<b>70.9</b> ± 16.7	<b>37.2</b> ± 10.4	<b>5.2</b> ± 1.1	<b>7</b> ± 4.7
<b>Rosu</b>									
channel	–	<b>0.17</b> ± 0.01	<b>1.49</b> ± 0.06	<b>1.85</b> ± 0.23	<b>2.75</b> ± 1.27	<b>100</b> ± 5.0	<b>32.9</b> ± 1.8	<b>2.1</b> ± 1.2	<b>17</b> ± 7.2
inflow	<b>3.14</b> ± 0	<b>0.26</b> ± 0.06	<b>1.58</b> ± 0.13	<b>1.98</b> ± 0.37	<b>4.04</b> ± 2.22	<b>77.1</b> ± 8.5	<b>36.1</b> ± 6.9	<b>3.6</b> ± 0.7	<b>11</b> ± 3.6
Rosulet	<b>3.36</b>	<b>0.12</b>	<b>0.36</b>	<b>0.97</b>	b.d.	<b>91.9</b>	<b>30.5</b>	<b>2.4</b>	<b>13</b>
outflow	± 0	± 0.03	± 0.08	± 0.57		± 22.4	± 4.1	± 0.4	± 1.9

b.d. means below detection limit

flow. The N:P ratio decreased from 85 at the inflow to 32 towards the lake outflow. From June to September the concentration of TDP increased from 1 μM to 2.5 μM. In September, the TDP concentration decreased from 2.5 μM at the inflow to 0.7 μM at the outflow (Table 3), resulting in N:P ratios of 47 and 61 at the inflow and outflow, respectively. The NH<sub>4</sub><sup>+</sup> concentrations decreased slightly from June to September. In September, the inflow channel had 116 μM NO<sub>3</sub><sup>-</sup> (Table 3), leading to high NO<sub>3</sub><sup>-</sup> concentrations in the lake of about 114 μM.

In June, at high discharge, the turbid water from the inflow channel cleared after a few hundred meters. During this time, Lake Uzlina was characterized by dense growth of macrophytes, particularly *Ceratophyllum demersum*, *Trapa natans* (water chestnut), *Potamogeton* sp. and the filamentous algae *Hydrodictyon reticulatum*. Phytoplankton was present at low concentrations (Table 1). However, the clear water was a temporary phenomenon. In September, Lake Uzlina was turbid and showed a greenish color due to decomposing macrophytes, overgrowing of filamentous algae and intense development of phytoplankton. An obvious decrease in the Si(OH)<sub>4</sub> concentration from the inflow to the outflow points to uptake by dia-

Table 3. Averaged values and standard deviation from three depths of alkalinity, oxygen, total dissolved phosphorus, nitrate, ammonia, silica, POC, PN and the molar C:N ratio of particles in the water of Lakes Uzlina, Matita and Rosu in September 1999

Sample	Alkal. mM	O <sub>2</sub> mM	TDP μM	N-NO <sub>3</sub> <sup>-</sup> μM	N-NH <sub>4</sub> <sup>+</sup> μM	Si(OH) <sub>4</sub> μM	POC μM	PN μM	C:N
<b>Uzlina</b>									
channel	<b>2.94</b> ± 0.02	<b>0.22</b> ± 0	<b>2.30</b> ± 0.18	<b>116</b> ± 0	<b>0.84</b> ± 0.05	<b>93.5</b> ± 5.8	<b>172</b> ± 7	<b>4.7</b> ± 0	<b>37</b> ± 1.5
inflow	<b>2.93</b> ± 0.01	<b>0.22</b> ± 0	<b>2.48</b> ± 0	<b>114</b> ± 0.8	<b>2.74</b> ± 0.02	<b>91.3</b> ± 1.3	<b>93</b> ± 9	<b>1.8</b> ± 0.6	<b>57</b> ± 13
outflow	<b>3.00</b> ± 0.01	<b>0.36</b> ± 0	<b>0.68</b> ± 0.02	<b>39.4</b> ± 0.9	<b>1.94</b> ± 0.2	<b>40.0</b> ± 0	<b>59</b> ± 8	<b>1.8</b> ± 0.6	<b>39</b> ± 17
<b>Matita</b>									
channel	<b>3.31</b> ± 0	<b>0.20</b> ± 0.01	<b>1.94</b> ± 0	<b>22.7</b> ± 3.5	<b>2.18</b> ± 0.53	<b>89.3</b> ± 8.7	<b>163</b> ± 13	<b>3.6</b> ± 1.2	<b>53</b> ± 21
inflow	<b>3.29</b> ± 0.01	<b>0.26</b> ± 0.07	<b>1.75</b> ± 0.26	<b>22.2</b> ± 0.3	<b>1.59</b> ± 0.08	<b>90.2</b> ± 1.5	<b>85</b> ± 13	<b>6.7</b> ± 1.5	<b>13</b> ± 2
outflow	<b>2.68</b> ± 0.01	<b>0.33</b> ± 0.02	<b>0.57</b> ± 0.06	<b>0.49</b> ± 0.12	<b>1.04</b> ± 0.05	<b>16.4</b> ± 3.1	<b>189</b> ± 51	<b>17.0</b> ± 4.6	<b>11</b> ± 0.3
<b>Rosu</b>									
channel	<b>2.96</b> ± 0.04	<b>0.36</b> ± 0.01	<b>0.38</b> ± 0.05	<b>0.19</b> ± 0.04	<b>0.73</b> ± 0.1	<b>19.4</b> ± 0.5	<b>69</b> ± 10	<b>17.2</b> ± 1.8	<b>4</b> ± 1
inflow	<b>3.11</b> ± 0.05	<b>0.33</b> ± 0.02	<b>0.39</b> ± 0.03	<b>0.18</b> ± 0.05	<b>0.84</b> ± 0.05	<b>26.9</b> ± 1.5	<b>186</b> ± 30	<b>19.3</b> ± 1.1	<b>9</b> ± 1
Rosulet	<b>3.12</b>	<b>0.33</b>	<b>0.26</b>	b.d.	<b>0.84</b>	<b>14.8</b>	<b>216</b>	<b>17.4</b>	<b>12</b>
outflow	± 0.03	± 0.01	± 0.01		± 0.16	± 0.8	± 76	± 5.3	± 0.5

b.d. means below detection limit

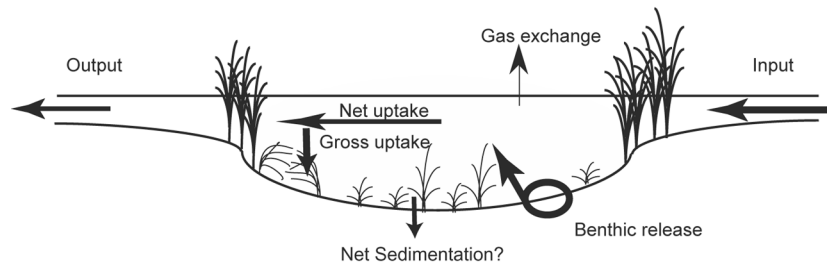


Figure 3. Simple box model for the nutrient balance applied to the Danube Delta Lakes.

toms. The C:N ratio of the SPM increased from 1–4 in June to 22–70 in September. Low C:N ratios are typical for sewage material (Stumm and Morgan 1981) and C:N ratios > 40 are typical of plant detritus, especially from reed (Schlegel 1985). Low C:N ratios in suspended solids in several places of the Delta were also reported by Bostan (2001) and are due to input of man-made sewage from point sources.

Table 4. Benthic fluxes (F) in  $\text{mmol m}^{-2} \text{d}^{-1}$  in chambers A and B in Lakes Uzlina, Matita and Rosu in June 1999. Flux values marked with \* are not considered because of bioturbation in the chamber. Negative fluxes indicate consumption. S is the standard deviation of the flux.  $R^2$  is the correlation coefficient of the regression

Location		$\text{O}_2$	$\text{NH}_4^+$		$\text{NO}_3^-$		$\text{HPO}_4^{2-}$		$\text{Si(OH)}_4$	
			A	B	A	B	A	B	A	B
Uzlina	F	<b>-36.2</b>	<b>5.67</b>	<b>4.99</b>	<b>-2.53</b>	b.d.	<b>0.76</b>	<b>0.94</b>	<b>7.49</b>	<b>6.03</b>
Inflow	S	$\pm 3.8$	$\pm 1.1$	$\pm 0.35$	$\pm 0.66$		$\pm 0.12$	$\pm 0.15$	$\pm 0.44$	$\pm 0.92$
	$R^2$	0.94	0.83	0.96	0.65		0.83	0.84	0.97	0.84
Uzlina	F	<b>-385*</b>	<b>14.9*</b>	<b>7.08</b>	b.d.	<b>-4.93</b>	<b>11.1*</b>	<b>1.08</b>	<b>25.5*</b>	<b>2.33</b>
Outflow	S	$\pm 89.1$	$\pm 2.59$	$\pm 0.5$		$\pm 1.03$	$\pm 1$	$\pm 0.37$	$\pm 1.27$	$\pm 0.56$
	$R^2$	0.9	0.8	0.96		0.93	0.94	0.52	0.98	0.68
Matita	F	<b>-9.39</b>	<b>2.22</b>	<b>3.71</b>	<b>0.33</b>	<b>-0.25</b>	<b>0.14</b>	<b>0.02</b>	<b>5.97</b>	<b>10.7</b>
Inflow	S	$\pm 0.64$	$\pm 0.34$	$\pm 0.44$	$\pm 0.07$	$\pm 0.04$	$\pm 0.02$	$\pm 0.02$	$\pm 1.46$	$\pm 2.17$
	$R^2$	0.96	0.88	0.9	0.75	0.79	0.88	0.01	0.7	0.75
Matita	F	<b>-24.1</b>	b.d.	<b>1.35</b>	b.d.	b.d.	<b>0.18</b>	<b>0.14</b>	<b>2.6</b>	<b>3.9</b>
Outflow	S	$\pm 3.8$		$\pm 0.24$			$\pm 0.04$	$\pm 0.07$	$\pm 1.7$	$\pm 0.52$
	$R^2$	0.93		0.83			0.75	0.72	0.23	0.87
Rosu	F	<b>-36.4</b>	<b>2.39</b>	<b>3.67</b>	<b>-0.27</b>	b.d.	<b>0.68</b>	<b>0.61</b>	<b>5.77</b>	<b>10.7</b>
Inflow	S	$\pm 18.9$	$\pm 1.18$	$\pm 1.06$	$\pm 0.16$		$\pm 0.14$	$\pm 0.03$	$\pm 2.2$	$\pm 1.9$
	$R^2$	0.79	0.34	0.6	0.26		0.74	0.99	0.46	0.79
Rosulet	F	<b>-45.3</b>	<b>3.72</b>	<b>6.69</b>	<b>1.55</b>	<b>1.05</b>	<b>0.04</b>	<b>0.04</b>	<b>13.5</b>	<b>14.1</b>
Outflow	S	$\pm 2.01$	$\pm 0.72$	$\pm 1.02$	$\pm 0.14$	$\pm 0.22$	$\pm 0.03$	$\pm 0.02$	$\pm 0.86$	$\pm 2.11$
	$R^2$	0.97	0.77	0.86	0.99	0.88	0.1	0.47	0.97	0.85

b.d. means below detection

Benthic fluxes were determined quite precisely in Lake Uzlina because the exchange rates were high. One exception was chamber A at the outflow in June, where bioturbation by mussels produced unrealistic high values (Table 4). When oxygen gets low in the chamber, their intense bioturbation enhances the flux rates. These results were disregarded, since mussel patches were not a common feature in the lake. In both seasons, the highest benthic  $\text{NO}_3^-$  consumption and highest benthic  $\text{NH}_4^+$  release were observed in Lake Uzlina, compared to Lakes Matita and Rosu/Rosulet (Tables 4 and 5). The  $\text{NH}_4^+$  release was twice as high as benthic  $\text{NO}_3^-$  uptake. According to Equation (3), the highest gross nutrient uptake per  $\text{m}^2$  was found in Lake Uzlina and accounted for 74%, 84%, 67% and 85% of the overall input of TDP,  $\text{NH}_4^+$ ,  $\text{NO}_3^-$  and  $\text{Si(OH)}_4$  in June, respectively (Table 6). In September during low water level, the gross uptake in the lake accounted for 88%, 99%, -70% and 84% of the overall input of TDP,  $\text{NH}_4^+$ ,  $\text{NO}_3^-$  and  $\text{Si(OH)}_4$ , respectively (Table 6).

A loss of  $12.9 \text{ mmol NO}_3^- \text{ m}^{-2} \text{ d}^{-1}$  in June and of  $9.4 \text{ mmol NO}_3^- \text{ m}^{-2} \text{ d}^{-1}$  in September was due to denitrification. This accounted for 41% and 115% of the external inorganic nitrogen input in June and September, respectively. The concentration of inorganic nitrogen decreased about three-fold from inflow to outflow both in June and in September.

Table 5. Benthic fluxes (F) in  $\text{mmol m}^{-2} \text{d}^{-1}$  in chambers A and B in Lakes Uzlina, Matita and Rosu in September 1999. Flux values marked with \* are not considered because of bioturbation in the chamber. Negative fluxes indicate consumption. S is the standard deviation of the flux.  $R^2$  is the correlation coefficient of the regression. Oxygen was not measured in Uzlina and Rosu due to sensor damage

Location	O <sub>2</sub>	NH <sub>4</sub> <sup>+</sup>		NO <sub>3</sub> <sup>-</sup>		HPO <sub>4</sub> <sup>2-</sup>		Si(OH) <sub>4</sub>		
		A	B	A	B	A	B	A	B	
Uzlina	F		<b>6.51</b>	<b>12.3</b>	<b>-8.6</b>	<b>-7.95</b>	<b>0.07</b>	<b>0.05</b>	<b>5.44</b>	<b>9.98</b>
Inflow	S		± 0.22	± 0.49	± 0.27	± 0.26	± 0.03	± 0.03	± 1.36	± 1.38
	$R^2$		0.99	0.99	0.99	0.99	0.34	0.24	0.67	0.87
Uzlina	F		<b>1.62</b>	<b>17.2</b>	<b>-2.03</b>	<b>-7.52</b>	<b>0.06</b>	<b>0.76</b>	<b>6.63</b>	<b>22.2</b>
Outflow	S		± 0.22	± 2.96	± 0.32	± 0.59	± 0.04	± 0.8	± 1.06	± 3.4
	$R^2$		0.89	0.8	0.84	0.95	0.28	0.92	0.83	0.84
Matita	F	<b>-49.0</b>	<b>10.0</b>	<b>6.24</b>	<b>1.14</b>	<b>1.48</b>	<b>0.25</b>	<b>0.2</b>	<b>22.8</b>	<b>6.44</b>
Inflow	S	± 3.4	± 1.1	± 0.5	± 0.38	± 0.5	± 0.03	± 0.04	± 4.9	± 1.1
	$R^2$	0.96	0.96	0.95	0.82	0.9	0.93	0.78	0.75	0.8
Matita	F	<b>-41.1</b>	<b>b.d.</b>	<b>0.11</b>	<b>b.d.</b>	<b>-0.32</b>	<b>0.03</b>	<b>0.06</b>	<b>b.d.</b>	<b>7.18</b>
Outflow	S	± 2.9		± 0.08		± 0.09	± 0.01	± 0.01		± 0.34
	$R^2$	0.99		0.2		0.86	0.62	0.82		0.98
Rosu	F		<b>1.98</b>	<b>5.16</b>	<b>0.12</b>	<b>0.02</b>	<b>0.02</b>	<b>0.04</b>	<b>3.88</b>	<b>8.06</b>
Inflow	S		± 0.31	± 0.69	± 0.02	± 0.01	± 0.005	± 0.01	± 1.8	± 2.09
	$R^2$		0.85	0.87	0.9	0.31	0.8	0.82	0.4	0.65
Rosulet	F		<b>12.4</b>	<b>10.7</b>	<b>b.d.</b>	<b>-0.01</b>	<b>0.05</b>	<b>0.01</b>	<b>20.2</b>	<b>19.4</b>
Outflow	S		± 0.76	± 0.9		± 0.01	± 0.01	± 0.01	± 1.61	± 2.23
	$R^2$		0.97	0.95		0.02	0.65	0.1	0.95	0.9

b.d. means below detection

### Lake Matita

The water entering the lake traveled a long distance through unaltered channels, rich in aquatic vegetation. In June, Lake Matita had almost clear water. Macrophytes were less dense than in Lake Uzlina, and were dominated by *Ceratophyllum demersum*, *Nymphaea alba* and *Nuphar lutea*. The chlorophyll concentrations were higher than in Lake Uzlina (Table 1). From June to September the chlorophyll concentrations increased by a factor of 10. The C:N ratio of suspended particulate matter was about 7 in June and 11–13 in September.

In June, the concentration of TDP in Matita was highest among the three lakes. This seems to be surprising, given the remote location of this lake. In contrast, nitrate was undetectable. We therefore suppose, that nitrogen was growth limiting for phytoplankton. From June to September, the nitrate concentration increased, whereas TDP slightly decreased (Tables 2 and 3). In September, the nutrient ratio at the lake inflow (Si:N:P 48:13:1) did not indicate clear growth limitation for phytoplankton by any single nutrient. Towards the lake outflow, nitrate decreased rapidly, leading to a Si:N:P ratio of 29:3:1.

On average, benthic fluxes in Lake Matita were lower than in Lake Uzlina. Nitrate consumption could not be measured at the outflow in June because the con-

Table 6. Gross nutrient uptake and its percentage of external plus internal input, and net uptake and its percentage of external input in June (high water level) and in September (low water level)

Gross uptake		P m mol m <sup>-2</sup> d <sup>-1</sup>		N - NO <sub>3</sub> m mol m <sup>-2</sup> d <sup>-1</sup>		N - NH <sub>4</sub> <sup>+</sup> m mol m <sup>-2</sup> d <sup>-1</sup>		Si(OH) <sub>4</sub> m mol m <sup>-2</sup> d <sup>-1</sup>								
Lake		June	September	June	September	June	September	June	September							
Uzlina	1.0	74%	0.4	88%	17.5	67%	-1.1	-70%	6.6	84%	9.3	99%	24.6	85%	14.8	84%
Matita	0.1	28%	0.2	89%	0.02	100%	1.7	99%	2.5	98%	5.5	99%	3.8	23%	15.1	96%
Rosu	0.6	88%	0.04	70%	1.0	82%	0.06	100%	4.7	100%	7.6	99%	12.8	39%	13.2	93%
Net uptake		P m mol m <sup>-2</sup> d <sup>-1</sup>		N - NO <sub>3</sub> mmol m <sup>-2</sup> d <sup>-1</sup>		N - NH <sub>4</sub> <sup>+</sup> m mol m <sup>-2</sup> d <sup>-1</sup>		Si(OH) <sub>4</sub> m mol m <sup>-2</sup> d <sup>-1</sup>								
Lake		June	September	June	September	June	September	June	September							
Uzlina	0.1	17%	0.1	70%	21.2	71%	5.4	66%	0.7	36%	-0.1	-131%	3.5	82%	3.8	57%
Matita	0.01	3%	0.06	71%	0	0%	0.9	98%	0.1	72%	0.05	52%	-2.0	-20%	2.9	82%
Rosu	0.3	76%	0.01	32%	0.2	48%	0.01	100%	0.6	100%	-0.01	-15%	1.8	8%	0.3	24%

centrations were below the detection limit (Table 4). The benthic  $\text{NO}_3^-$  consumption was more than one order of magnitude lower than in Lake Uzlina. The denitrification rate was much lower than in Lake Uzlina as well, since the  $\text{NO}_3^-$  concentration in the water was very low. In June, denitrification amounted to  $0.17 \text{ mmol m}^{-2} \text{ d}^{-1}$ . In September, a denitrification rate of  $0.22 \text{ mmol m}^{-2} \text{ d}^{-1}$  was measured. On average, denitrification accounted for 119% and 22% of the external inorganic nitrogen input in June and September, respectively. The concentration of inorganic nitrogen decreased from inflow to outflow three-fold in June and up to 16-fold in September. This is probably more related to the higher nitrogen availability in September than a result of the longer water residence time of 60 days.

In June, the gross nutrient uptake was 28%, 98%, 100% and 23% of the overall TDP,  $\text{NH}_4^+$ ,  $\text{NO}_3^-$  and  $\text{Si(OH)}_4$  input, respectively (Table 6). The benthic flux of  $\text{NH}_4^+$  was one order of magnitude higher than the external input. In September at low water level, with a water residence time of 60 days, more than 90% of the external and internal nutrient inputs were taken up.

#### *Lakes Rosu/Rosulet*

These two connected lakes are larger and deeper than Lakes Uzlina and Matita. The water entering the lakes flows through a sequence of natural and artificial channels. In June as in September, Lakes Rosu/Rosulet were turbid due to phytoplankton and high suspended matter load. From June to September, the chlorophyll concentration increased five to ten times (Table 1). However, the C:N ratio of the SPM did not change much, from 11–13 in June to 9–12 in September. Macrophytes were present in low density at the lakes shore, (*Ceratophyllum demersum*, *Nymphaea alba*, *Potamogeton crispus*). These lakes are characterized by lower nutrient concentrations than Lake Uzlina, but in general higher than Lake Matita. In June, TDP concentrations were  $0.4\text{--}1.6 \mu\text{M}$  (Table 2). Nitrogen concentrations ranged from 1 to  $6 \mu\text{M}$ , resulting in a N:P ratio of about three. From June to September the nutrient concentrations decreased four to six times (Tables 2 and 3). Within the lake, only  $\text{NO}_3^-$  decreased significantly from  $0.18 \mu\text{M}$  at the inflow to less than  $0.01 \mu\text{M}$  at the outflow.

In June the gross nutrient uptake accounted for 88%, 100%, 82% and 39% of the overall TDP,  $\text{NH}_4^+$ ,  $\text{NO}_3^-$  and  $\text{Si(OH)}_4$  inputs (Table 6). In September, 70% TDP and 93%  $\text{Si(OH)}_4$  were taken up. Nitrogen was taken up almost completely in the lake. The nitrogen concentration decreased six-fold from June to September. Little nitrogen was delivered from the inflow channel. Most of the nitrogen load originated from benthic release. Uptake was partly compensated by high benthic  $\text{NH}_4^+$  release. Besides ammonification, benthic nitrification was a significant internal source for nitrogen. In June, a denitrification rate of  $1.2 \text{ mmol m}^{-2} \text{ d}^{-1}$  was measured. In September, denitrification was very low ( $0.04 \text{ mmol m}^{-2} \text{ d}^{-1}$ ). Denitrification decreased from 115% of the external inorganic nitrogen input in June to 69% in September.

## Discussion

We divide the discussion into five parts. First, we evaluate our data by comparing them with those from previous investigations in the Danube Delta. In the second section, we discuss the different nutrient loading of the three lakes in June and September and we assess the net nutrient uptake. Third, we consider the nutrient uptake by different types of biota. Observed benthic turnover times will illustrate the importance of benthic-pelagic coupling in these lakes. A detailed comparison between benthic fluxes and gross uptake during the growing season is given in the fourth section. Finally, we use the data to estimate the net rates of primary production, nitrogen fixation and nitrification.

### *Evaluation of the data*

Lake Uzlina, located close to the southern Danube branch, had higher nutrient concentrations than those receiving water from meandering channels, rich in aquatic vegetation. Oosterberg and Bogdan (2000) measured comparable phosphorus concentrations ( $1.5 \mu\text{M}$ ) but significantly higher nitrate concentrations ( $\text{NO}_3^- = 166 \mu\text{M}$ , Table 2) in Lake Uzlina in spring 1997 and 1998. Their autumn values of phosphate were comparable; the nitrate values ( $\text{NO}_3^- = 25 \mu\text{M}$ , Table 3) were lower than ours. The nitrate concentration at the inflow of Lake Matita was much lower than at the Uzlina inflow. Consequently, an appreciable amount of nitrate was removed on the way from the Danube branch to the lake. For Lake Matita, Oosterberg and Bogdan (2000) do not report spring values of phosphate and nitrate. In September, they found phosphate concentrations that are comparable to ours; the nitrate concentrations ( $36 \mu\text{M}$ ) were somewhat higher than ours (Table 3). The turbid state of Lake Rosu throughout the growing season seemed to be a permanent phenomenon. This was also reported for the previous years by Ibelings et al. (2000). The spring phosphorus values measured by Oosterberg & Bogdan were comparable to ours, whereas the  $\text{NO}_3^-$  values were more than one order of magnitude larger than ours. For summer, Oosterberg and Bogdan (2000) report three times higher phosphate concentrations and one order of magnitude higher  $\text{NO}_3^-$  concentrations. The seasonal variations in phosphorus, with higher values in summer, are rather related to the redox conditions on the lakes bottom than to changes in the flow pattern. In summary, the phosphorus loading of the three lakes seems to follow a rather constant pattern over the three years covered by the two studies (1997 to 1999). The nitrate loading, however, is quite variable between the years, which may reflect large differences in the denitrification intensity from one year to the other.

### *Nutrient loading and net uptake*

The external loading of the three lakes in June with total dissolved phosphorus was within a remarkably narrow range of  $0.3\text{--}0.4 \text{ mmol m}^{-2} \text{ d}^{-1}$  (Figure 4). The direct input of water from the Danube into Lake Uzlina, however, provided a very high load of dissolved inorganic nitrogen of more than  $30 \text{ mmol m}^{-2} \text{ d}^{-1}$ . Lake Rosu



was exposed to 30 times less nitrogen input and Matita had a 200 times lower external nitrogen load. The silica input was almost similar for Uzlina and Rosu; the Matita inputs were lower by a factor of 2. This pattern is summarized in Figure 4. It illustrates a preferential depletion of nitrogen due to uptake and denitrification in the channel system of the Delta. Lakes at the end of a chain of channels are also likely to obtain smaller Si-inputs, due to diatom blooms during the flooding in early summer. Figure 4 also compares the net uptake ( $F_{in} - F_{out}$ ) of the three lake systems. In June, Lake Rosu showed the highest net phosphorus uptake (about  $0.3 \text{ mmol m}^{-2} \text{ d}^{-1}$ ) while Lake Matita represented only a very little sink ( $0.01 \text{ mmol m}^{-2} \text{ d}^{-1}$ ). Two mechanisms might contribute to this observation: Benthic remobilisation provided enough phosphorus or nitrogen limited productivity in Lake Matita. About  $\frac{2}{3}$  of the high nitrogen load was retained in Lake Uzlina by uptake or denitrification or transformed into organic nitrogen by biological processes. Similar efficiencies for net DIN uptake were observed in the two other lakes. However, Table 6 reveals that Lake Matita received exclusively  $\text{NH}_4^+$  in the input probably from benthic liberalization in upstream lakes and channels, while DIN load of Rosu and Uzlina consisted of both, nitrate and ammonia.

A clear gradient in the net silica uptake was observed in June: Silica was efficiently removed from the flow-through water by diatoms in the macrophyte-dominated lake Uzlina (about  $19 \text{ mmol m}^{-2} \text{ d}^{-1}$ ). Lake Rosu showed an order of magnitude smaller net uptake and Lake Matita at the end of a channel system acted even as a net source for silica. In that case, benthic remineralization must have out-competed the biological uptake.

In September, the general through-flow was reduced by factors of 3–4 (Table 1). The input fluxes were reduced accordingly except that the pattern for Lakes Matita and Rosu was now reversed. Lake Rosu had the lowest external loading with all three nutrients in September (Figure 4). Probably the input channels at low water levels received substantial quantities of outflow from the reed beds with low concentrations of inorganic nutrients. In a nutrient budget study of a reed bed, Oosterberg and Bogdan (2000) found efficient nitrogen removal in spring and summer and some phosphorus removal in spring, resulting in lower concentrations in the reed bed water than in the river. In contrast, they found phosphorus release in summer. The higher inputs in Lake Matita probably were due to outflow from surrounding lakes, where intense benthic mineralization increased the nutrient loads. A correct interpretation of the biological nutrient uptake must therefore include benthic processes.

#### *Uptake mechanisms by biota*

Most nutrients in the Danube Delta System are taken up by plants and stored in a temporary pool, the plant biomass. Part of that eventually accumulates with the organic detritus in the sediments. Another part is remineralized and released as inorganic forms during benthic recycling, and another fraction is converted to particulate/dissolved organic phosphorus and nitrogen and eventually washed out from the lakes. This last fraction is less bio-available and was not a focus of our study. We

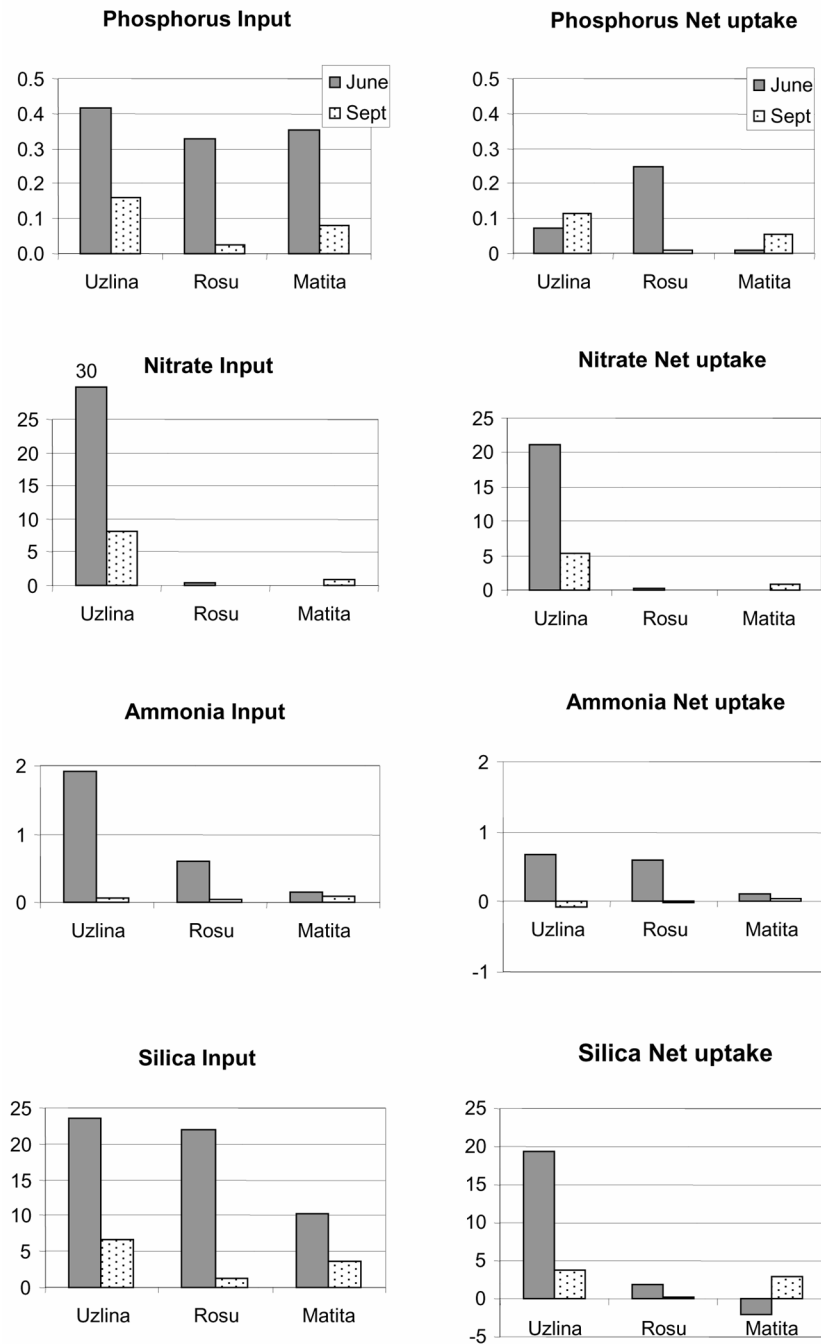


Figure 4. External nutrient input and net nutrient uptake according to equation 4 (in  $\text{mmol m}^{-2} \text{day}^{-1}$ ) in Lakes Uzlina, Matita and Rosu/Rosulet at high water level in June and low water level in September 1999. Net nutrient uptake was calculated from input minus output. Negative values of the net uptake indicate net release.

assume that the large reed beds and floating plaurs of *Phragmites australis* play the most important role in nutrient uptake in the Danube Delta. Within the open water, submerged and emergent macrophytes were important for nutrient uptake in Lakes Uzlina and Matita in June. After of some macrophyte species died in autumn, the importance of phytoplankton in nutrient uptake increased in the delta lakes. Phytoplankton can remove nutrients very effectively from the water column but have the fastest decomposition rates (half-life 0.5 month) among aquatic plants (Twilley et al. 1986). The breakdown of different *Phragmites australis* fractions occurs on time scales of months to years (Gessner 2000). Some of the nitrogen in *Phragmites* is stored in the rhizomes during winter (van der Linden 1980). Hence, only a part of the nutrients in the plant will be released during decomposition of the upper part of the plant. The decomposition rates decrease in the order emergent macrophytes > submerged macrophytes > macroalgae > phytoplankton (Findlay et al. 1990). In lakes dominated by phytoplankton and macroalgae we expect a faster benthic nutrient recycling than in lakes with macrophyte flora. The Danube Delta therefore consists of a cascade of biotic nutrient pools with different residence times. We assume that the nutrient regeneration in the water column is low compared to benthic regeneration, because the organic matter settles rapidly to the bottom in these shallow lakes. However, the benthic measurements neglect part of the mineralization of macrophytes in the water column. Frequent sediment resuspension make for a close benthic-pelagic coupling.

We calculated theoretical benthic nitrogen turnover times by dividing the nitrogen inventory in the flux chamber by the corresponding benthic flux. It represents the time necessary to replace the nutrients in the flux chamber by benthic supply. The turnover time in the flux chamber is a theoretical measure for the intensity of the benthic processes. Short turnover times indicate rapid decomposition of the organic matter. We do not estimate the nutrient turnover in field situations, since the water depth in the lakes varies up to 1 m between high and low water level. In general, the shortest nutrient turnover times appeared in Lakes Rosu/Rosulet in June and September (Table 7). These lakes were characterized by intense phytoplankton growth and sparse vegetation during both seasons. Longest turnover times were calculated for Lake Uzlina, which was characterized by dense growth of macrophytes. In September at low water level when filamentous algal beds overgrow the aquatic vegetation (own observation, Coops and Hanganu (2000)), the turnover times appear to be shorter (Table 7). Lake Matita shows shorter turnover times than Lake Uzlina. In Lake Matita, macrophytes were not as abundant as in Lake Uzlina. In contrast, filamentous algae were more dominant. From these results we hypothesize that benthic nutrient turnover is most intense in the phytoplankton dominated Lakes Rosu/Rosulet.

#### *Benthic mineralisation and gross biological nutrient uptake*

Detailed comparisons of the four dominant nutrient fluxes  $F_{in}$ ,  $F_{out}$ ,  $F_{benthic}$  and  $F_{gross\ uptake}$  according to equation 3 for the three lakes are documented in Figures 5, 6, 7 and 8 for the two field campaigns in June and September 1999.

Table 7. Theoretical benthic turnover times of ammonia and nitrate (in hours), calculated by dividing the nutrient inventory in the flux chamber by the corresponding benthic flux

Station	Turnover times (hours)			
	June		September	
	$\text{NH}_4^+$	$\text{NO}_3^-$	$\text{NH}_4^+$	$\text{NO}_3^-$
Uzlina inflow	1.5	73	1	58
Uzlina outflow	9	7	1.5	53
Matita inflow	0.6	14	1	8
Matita outflow	1	–	21	7
Rosu inflow	8	20	1.5	7
Rosulet outflow	0.06	2	0.4	48

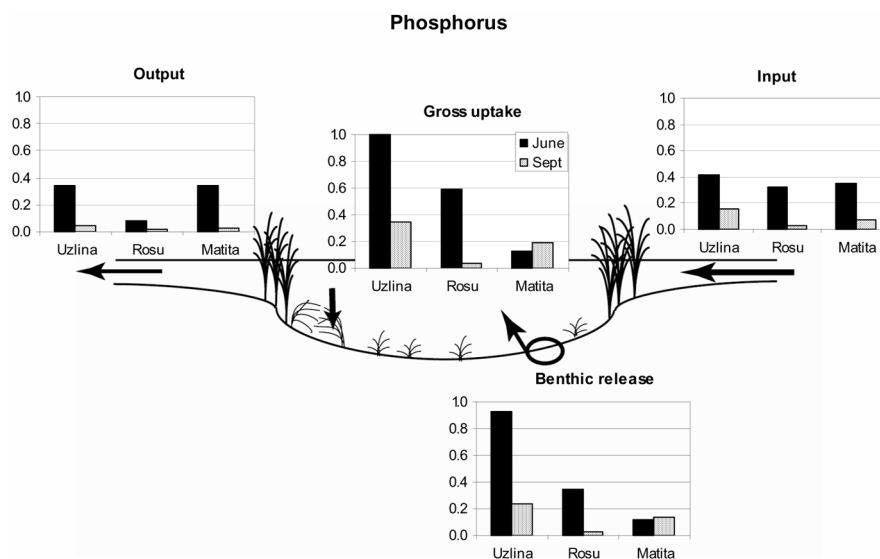


Figure 5. Gross uptake and benthic release of total dissolved phosphorus according to equation 3 (in  $\text{mmol m}^{-2} \text{day}^{-1}$ ), in Lakes Uzlina, Matita and Rosu/Rosulet at high water level in June and low water level in September 1999. Black bars and gray bars represent June and September values, respectively.

The June data in Figure 5 and 6 reveal that the intensity of benthic phosphorus and ammonia release follows the series Uzlina > Rosu > Matita. The gross biological uptake of P, N, and Si follows the same pattern, which reflects the flow distance from the Danube River (Figures 5, 6, 7 and 8). The N:P ratios of the gross uptake ( $F_{\text{gross uptake}}$ ) are approximately 24, 10 and 20 in Lakes Uzlina, Rosu and Matita. In Lake Uzlina (Figure 5), the internal loading with benthic phosphorus is twice as large as the external inputs. It is the crucial factor for maintaining high diatom productivity in this macrophyte-dominated lake. In Lake Rosu, the external load and the benthic flux ( $F_{\text{in}}$  and  $F_{\text{benthic}}$ ) of phosphorus are of the same order of magnitude. However, the low N:P ratio in the gross uptake indicates nitrogen fixation by

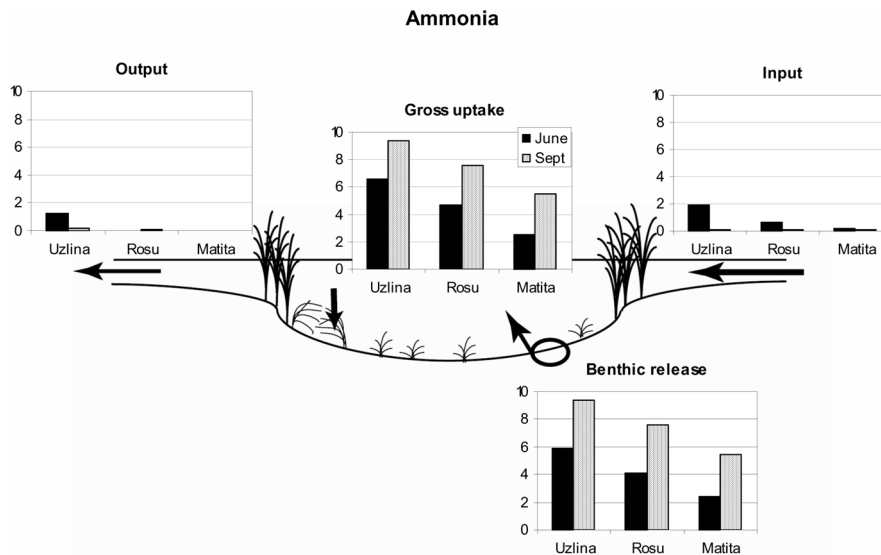


Figure 6. Gross uptake and benthic release of ammonia according to equation 3 (in  $\text{mmol m}^{-2} \text{ day}^{-1}$ ) in Lakes Uzlina, Matita and Rosu/Rosulet at high water level in June and low water level in September 1999. Black bars and gray bars represent June and September values, respectively.

blue-green algae in Rosu during June. In Lake Matita, biological productivity is limited by benthic ammonia release, because nitrogen concentration in the inflow is extremely low (Figures 6 and 7). External loading with P and internal loading with  $\text{NH}_4^+$  provide quite a balanced nutrient source in the uptake flux (N:P = 20, Figures 5 and 6).

During the field campaign at low water level, the external inputs were significantly lower, in general. The benthic fluxes of TDP reflect these; they mirror the pattern of the external inputs in all three lakes (Figure 5). Both benthic Si and  $\text{NH}_4^+$  fluxes remained quite constant (Figures 8 and 6), however. Consequently, the N:P ratios in the calculated gross uptake were 25, 200 and 38 in Lakes Uzlina, Rosu and Matita, respectively. These high values indicate that ammonia removing processes other than uptake by plants were active in September. The  $\text{NO}_3^-$  balance for Lake Uzlina results in a negative nitrate uptake, i.e. ammonia will be an important source for the observed denitrification flux in the benthic chamber (Figure 7). By analogy, coupled nitrification-denitrification probably was active in Lake Matita and Lakes Rosu/Rosulet, although we could not detect clear fluxes due to the low nitrate concentration in the water column.

The benthic release of  $\text{NH}_4^+$  and phosphorus, averaged over the lake surface, exceeded the external input in September and in June (Figures 5 and 6). That means, the high nutrient load of the lakes is not only maintained by nutrient rich water from the inflow (external source) but also has an internal source, the benthic release from decomposition of organic material. The high  $\text{NH}_4^+$  uptake cannot cope with the increasing benthic  $\text{NH}_4^+$  release in September due to increased decompo-

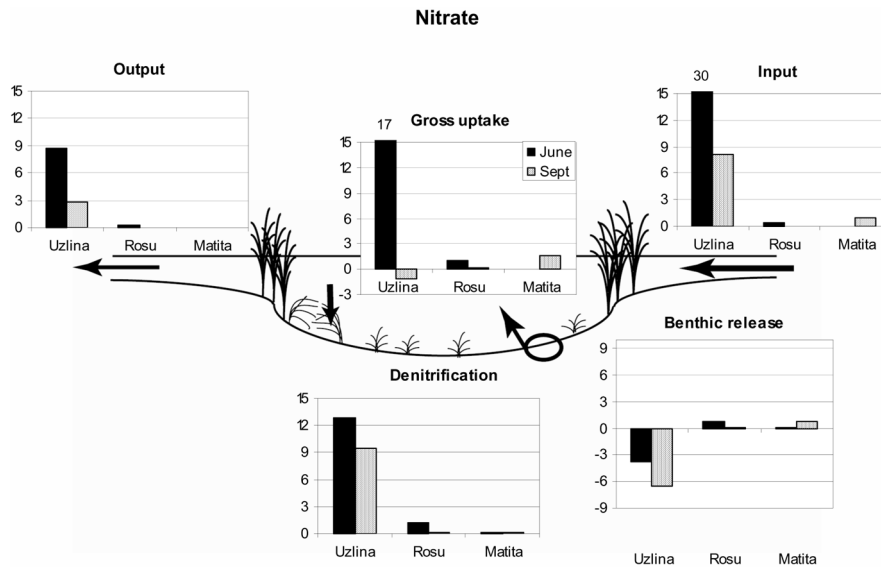


Figure 7. Gross uptake, benthic release and denitrification of nitrate according to equation 3 (in  $\text{mmol m}^{-2} \text{ day}^{-1}$ ) in Lakes Uzlina, Matita and Rosu/Rosulet at high water level in June and low water level in September 1999. Negative values indicate benthic consumption. Black bars and gray bars represent June and September values, respectively.

sition of organic material in autumn.  $\text{NH}_4^+$  release by remineralisation of organic material out-competes nitrification under these conditions. In general, the benthic fluxes of nitrogen and silica were higher in September. We therefore suspect that later in the season, when biological activity decreases and fewer nutrients are taken up, the nitrogen concentration at the outflow of the lakes further increases. In contrast, we found no indication that benthic phosphorus release increases at the end of the growth season. We suppose that phosphorus release during winter remains low due to wind-driven ventilation of the shallow water resulting in retention of the phosphorus on iron oxy-hydroxides on the aerated lake bottom. For instance, Oosterberg and Bogdan (2000) found accumulation of phosphorus dominating outside the growth season, and decrease or even switch to a release during the growth season. However, it remains difficult to estimate the extent of nutrient release over the whole year as long as no winter investigations are available.

#### *Nitrogen fixation*

We based our nitrogen budget on inorganic nitrogen. Due to restrictions of the project, we were not able to determine organic nitrogen. It is likely that a part of the inorganic nitrogen entering the lake is turned into organic nitrogen and is leaving the lake as dissolved organic nitrogen. In wetland ponds in Switzerland, Steingruber (2001) found DON was almost negligible in the surface water entering the ponds but 35% of the total nitrogen export consisted of DON. The ponds, as delta

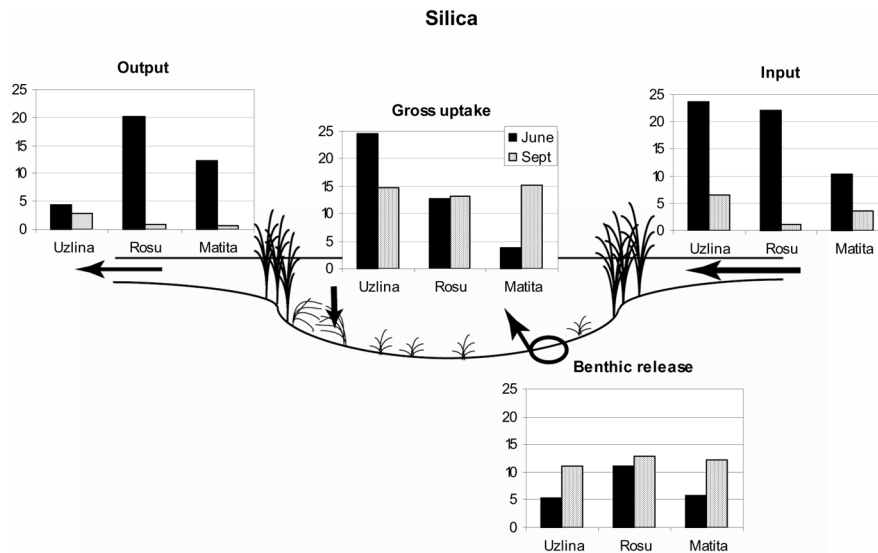


Figure 8. Gross uptake and benthic release of silica according to equation 3 (in  $\text{mmol m}^{-2} \text{day}^{-1}$ ) in Lakes Uzlina, Matita and Rosu/Rosulet at high water level in June and low water level in September 1999. Black bars and gray bars represent June and September values, respectively.

lakes might do, act as a source of DON. Howard-Williams et al. (1983) found in lab experiments the same percentage of DON in nitrogen release from decomposing watercress in aerobic conditions. More than 50% of the regenerated nitrogen was nitrate. We therefore assume our calculated nitrogen retention in the lakes being somewhat high.

Comparison of the denitrification losses in the Danube Delta Lakes with the shallow, unstratified Lake Vallentuna in Sweden (Ahlgren et al. 1994) shows that a higher percentage of the external nitrogen input is denitrified in the Danube Delta lakes. We measured in Lake Uzlina denitrification losses of 56% of an input of 1314 kg inorganic nitrogen per day, in Lake Matita denitrification losses of 34% of an input of 52 kg nitrogen per day and in Lakes Rosu/Rosulet denitrification losses of 116% of an input of 133 kg nitrogen per day, on average of the June and September measurements. (Ahlgren et al. 1994) report denitrification losses of 12% of an input of 38 kg nitrogen per day from its tributaries, on annual average. In general, the Delta Lakes show distinct seasonality in the denitrification activity, with higher rates in June at lower ambient oxygen concentrations.

#### *Trophic state of the lakes and estimate of plant biomass production*

According to Vollenweider (1982)'s definition of eutrophic lakes, that is chlorophyll *a* concentration  $> 7 \mu\text{g l}^{-1}$ , TDP  $> 1.6 \mu\text{M}$  and nitrogen  $> 64 \mu\text{M}$ , all investigated lakes meet at least one criterion. Lake Uzlina exceeds the nitrogen limit in June and September and the TDP limit in September. Lake Matita exceeds the TDP limit



in both month and Lakes Rosu/Rosulet exceed the TDP limit in June. In September, Lakes Matita and Rosu/Rosulet had chlorophyll *a* concentrations higher than  $7 \mu\text{g l}^{-1}$ . However, the Vollenweider definition seems not satisfactory for ranking the lakes. The potential plant biomass production should be taken into account as well. The nutrients are stored in plant biomass, adsorbed onto suspended particles (phosphorus) and are subject to sedimentation. From gross nutrient uptake as a measure of biomass accumulation in a lake we estimate the upper limit of uptake in plant biomass at Redfield ratio (C:N:P 106:16:1, Redfield (1934)). However, we consider that using Redfield ratio gives only a very rough estimate on the plant productivity of a lake since part of the biomass consists of submerged and emergent macrophytes with other nutrient demands than phytoplankton.

#### *Lake Uzlina*

The highest nutrient uptake was observed in this macrophyte-dominated lake. The net nitrogen uptake in Lake Uzlina is in the same range like reported for shallow hypertrophic lakes in Denmark (Jensen et al. 1992) but considerably higher than in Lake Vallengtuna in central Sweden (Ahlgren et al. 1994). In June, an upper limit of  $16 \text{ mmol N m}^{-2} \text{ d}^{-1}$  and  $1 \text{ mmol P m}^{-2} \text{ d}^{-1}$  might have been converted to plant biomass. In September, the maximum nutrient uptake amounts to  $6 \text{ mmol N m}^{-2} \text{ d}^{-1}$  and  $0.3 \text{ mmol P m}^{-2} \text{ d}^{-1}$ . The corresponding upper limit production of organic carbon in plant biomass is then about 106 and  $37 \text{ mmol C}_{\text{org}} \text{ m}^{-2} \text{ d}^{-1}$  in June and September, respectively. That means 6 and 2 tons organic carbon in plant biomass per day might have been produced in the lake in June and September, respectively. This represents a typical net production of eutrophic lakes, according to Schwoerbel (1999).

#### *Lake Matita*

In June, almost all  $\text{NH}_4^+$  supplied from the inflow channel plus benthic recycling is probably taken up by macrophytes and phytoplankton (Figure 5). In theory, the low N:P ratio in the water favors the development of nitrogen fixers like cyanophyceae and allows a "luxury" uptake of P. We calculated the gross uptake of TDP is 28%. According to the low N:P ratio in the lake water we would expect a gross uptake of only 2% P. The benthic TDP release was lower as in the other lakes. Howard-Williams (1985) observed low recycling rates when the available pool of nutrients is large compared to the internal load. In September, nitrogen was not limiting phytoplankton growth, which resulted in an increase in chlorophyll. Probably all  $\text{NO}_3^-$  was turned into plant biomass and/or the organic nitrogen pool.

We estimate the upper limit of nutrient turnover in plant biomass of  $2.1 \text{ mmol N m}^{-2} \text{ d}^{-1}$  and  $0.1 \text{ mmol P m}^{-2} \text{ d}^{-1}$  for June and  $3 \text{ mmol N m}^{-2} \text{ d}^{-1}$  and  $0.2 \text{ mmol P m}^{-2} \text{ d}^{-1}$  for September. The corresponding values of organic carbon production of 14 and  $20 \text{ mmol m}^{-2} \text{ d}^{-1}$  or 1.1 and 1.6 tons carbon in plant biomass in June and September are in the range of the net production of oligotrophic lakes (Schwoerbel 1999).

### *Lakes Rosu/Rosulet*

These lakes show the largest difference in nutrient retention between June and September (Figure 6). Considerably fewer nutrients were retained in September than in June. In June, the upper limit of nitrogen and phosphorus conversion in plant biomass is about  $5.7 \text{ mmol N m}^{-2} \text{ d}^{-1}$  and  $0.4 \text{ mmol P m}^{-2} \text{ d}^{-1}$ . This is equivalent to  $38 \text{ mmol C}_{\text{org}} \text{ m}^{-2} \text{ d}^{-1}$ . In September, the nutrient uptake by plants is lower, about  $0.6 \text{ mmol N m}^{-2} \text{ d}^{-1}$  and  $0.04 \text{ mmol P m}^{-2} \text{ d}^{-1}$ , giving about  $4 \text{ mmol C}_{\text{org}} \text{ m}^{-2} \text{ d}^{-1}$ . In other words, the upper limit of plant organic carbon production amounts to 8 tons per day in June and 0.8 tons per day in September. On average, Lakes Rosu/Rosulet has the potential of plant biomass production of a mesotrophic lake.

## Conclusions

Delta lakes are efficient sinks for nutrients during the growing season. The uptake capacity between June and September is mostly more than 76% of the internal plus external nutrient input, on average, both in macrophyte and phytoplankton dominated lakes. The net uptake in the growing season amounts to 43% of the external input, of phosphorus, nitrogen and silica on average.

Since 10% of the Danube water is flowing through the Delta, the net impact of the Delta on the reduction of the nutrient load during the growing season might be 4.3%, assuming the nutrient uptake in the investigated lakes is representative for all lakes and affects all the water flowing through the Delta.

The benthic release is an important internal nutrient source of the Danube Delta lakes. This internal source even surpasses the external input of TDP and ammonia from the inflow channels. In September, the benthic internal loading of silica surpasses the external loading as well. In September, the delta lakes tend to be an ammonia source.

The external dissolved inorganic nitrogen and silica input into the lakes decreases with hydrological distance to the main Danube branches. The external phosphorus input seems to be independent from the distance to the main branches.

Annual nutrient budgets were not feasible within this study. Therefore, we have no information on the long-term nutrient retention in the Danube Delta lakes. Further investigations should include measurements of organic nitrogen, nutrient uptake and release by macrophyte litter and monitoring in winter.

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