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SILICA RETENTION IN THE IRON GATE I RESERVOIR ON THE DANUBE RIVER: THE ROLE OF SIDE BAYS AS NUTRIENT SINKS

DANIEL F. McGINNIS,* SERGHEI BOCANIOV,[1] CRISTIAN TEODORU, GABRIELA FRIEDL, ANDREAS LORKE[2] and ALFRED WÜEST

Limnological Research Center, EAWAG, CH-6047 Kastanienbaum, Switzerland

ABSTRACT

There are longstanding concerns about the environmental impacts of super-dams such as Iron Gate I, the Danube River's largest hydropower scheme. Iron Gate I is suspected of trapping up to 80% (~590 000 tons per year) of dissolved silica in the form of sedimenting diatom frustules and 30 000 000 tons per year of suspended solids. This study, however, indicates that (i) conditions are unfavorable for primary production in Iron Gate I except for the small quiescent center of Orsova Bay, and the diatom production is much too low for the suspected silica uptake; (ii) Orsova Bay is the most important sediment trap as resuspension does not occur, with ~1% (82 000 tons per year) suspended solids retention, and (iii) also the only significant silica trap, with ~0.2% (1000 tons per year) retention. It is most conservatively estimated that no more than 5% of dissolved silica can be retained by the Iron Gate I reservoir, and therefore the earlier estimate of the huge retention can definitely be ruled out. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: bays; Danube; dams; downstream effects; silica retention; suspended solids

INTRODUCTION

Impoundments on large rivers have significant downstream ecological and social implications (Rosenberg *et al*., 1995; McCully, 1996; Vörösmarty *et al*., 1997), as recently reviewed and summarized by the World Commission on Dams (WCD, 2001). Many of these alterations have obvious impacts on fish populations, migration and biodiversity (Preece and Jones, 2002; Quinn and Kwat, 2003), river ecosystems (Ward and Stanford, 1995; Hart and Poff, 2002), downstream sediment loads (Vörösmarty *et al*., 2003; Walling and Fang, 2003), lake and downstream vegetation (Nilsson *et al*., 1997) and changes to downstream thermal regimes (Sherman, 2000; Preece and Jones, 2002). In some cases, dams release anoxic bottom-water, which can lead to downstream fishkills (Beutel and Horne, 1999). While most of these alterations are apparent and well recognized, other changes are more subtle and much more difficult to detect, quantify and predict. Among those are the impacts of biogeochemical cycling of water mass constituents (Rosenberg *et al*., 1997; Friedl and Wüest, 2002).

In this paper, we focus specifically on one of these biogeochemical cycling effects, damming-induced dissolved silica (DSi) trapping. Longer hydraulic retention times (HRTs) and lower currents, both associated with damming, lead to a decrease in suspended solids and turbidity, an increase in thermal stratification and light availability, and subsequently to higher autochthonous primary production, which removes nutrients from downstream waters. These downstream effects have been especially noted in regions of intense damming, such as in the north of Europe (Conley *et al*., 2000). Increased *in situ* diatom production and subsequent algal sedimentation are the key processes thought to explain the downstream DSi decline observed in several dammed rivers. This argument has been raised to explain the DSi decrease measured in the Danube Delta and Black Sea (Humborg *et al*., 1997).

*Correspondence to: Daniel F. McGinnis, FZL-EAWAG, Applied Aquatic Ecology, Seestrasse 79, CH-6047 Kastanienbaum, Switzerland.
E-mail: dan.mcginnis@eawag.ch
[1]Now at Department of Biology, University of Waterloo, Waterloo, Ontario, Canada.
[2]Now at Limnological Institute, University of Konstanz, D-78464 Konstanz, Germany.

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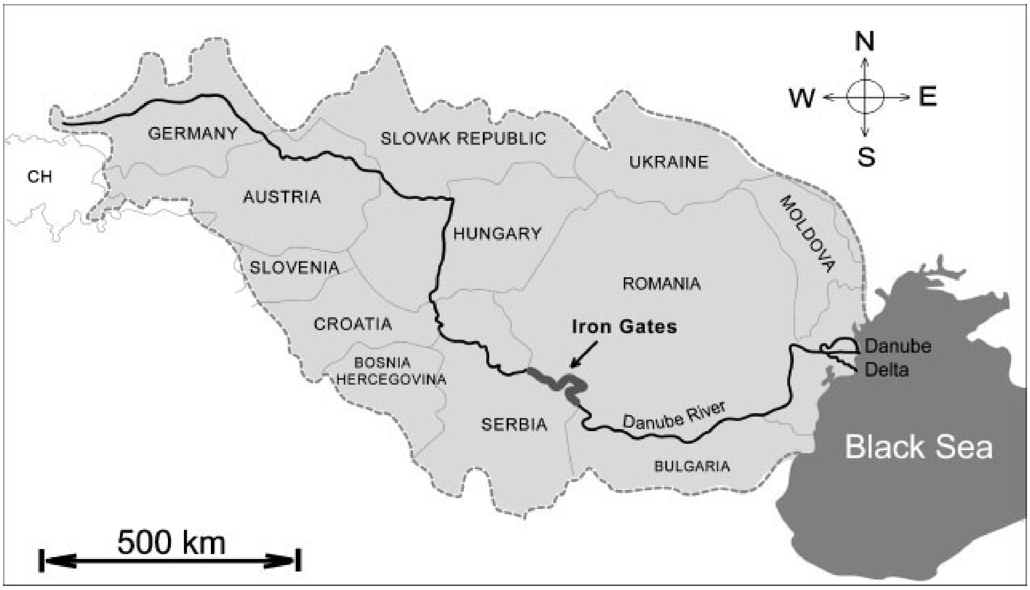

Figure 1. Danube River and drainage basin. Iron Gate I and II are located on Serbian–Romanian border near Bulgaria

DSi concentrations at the Danube Delta dropped by approximately two-thirds in the 1970s, which coincided with the construction of the Iron Gate I Reservoir in 1972 (Orsova, Romania; Figure 1), and may have shifted the algal species composition from diatoms to nuisance blue–green algae on the Black Sea shelf, resulting in a reduced fish-catch (Humborg *et al*., 1997; SCOPE, 1999; Humborg *et al*., 2000; Lancelot *et al*., 2002). Additionally, a 20 000–30 000 kt yr^{-1} (kt = 1000 metric tons) decrease in sediment load has also been documented since the construction of the Iron Gate system, resulting in erosion at the Danube Delta and Black Sea coastline (Panin *et al*., 1999; Reschke, 1999; Panin and Jipa, 2002; Reschke *et al*., 2002). Because the Iron Gate I (1) is the largest (in volume and power production) of the dams on the Danube River and (2) was constructed during the period of the observed DSi and sediment load decrease, it is controversially discussed as the major cause of these declines (Humborg *et al*., 1997; Garnier *et al*., 2002; Friedl *et al*., 2004; Teodoru and Wehrli, 2005). This riverine reservoir is indeed of enormous dimensions: at full-pool it stores 2.1 km^3 of water, is 135 km in length with a surface area of about 104 km^2, and has a power generation capacity of 2100 MW (Aquaproiect, 2003).

As settling diatom frustules in Iron Gate I are thought to be the mechanism for 70–80% ($\sim$590 kt yr^{-1}) of the DSi reduction, the sediment retention capacity of the reservoir is also clearly important. Friedl *et al*. (2004), however, showed a total of only 16 kt DSi yr^{-1} retention (4% of the incoming load), 37 times less than the previously published results. This 16 kt DSi yr^{-1} retention was determined by measuring weekly DSi concentrations in the reservoir inflow and outflow over 11 months in 2001, whereas the DSi retention estimates by Humborg *et al*. (1997) were based on the change in DSi concentrations far downstream at the Danube Delta and the biogenic silica (BSi) concentrations determined from only one sediment core from the reservoir (Humborg *et al*., 1997; Reschke, 1999; Friedl *et al*., 2004). Model simulation results performed by Garnier *et al*. (2002) also suggest that the construction of the Iron Gate I did not significantly retain silica.

Diatom production and sedimentation must occur in Iron Gate I in order to trap DSi. These processes occur mainly in areas of reduced velocity, longer HRTs and water column stratification. An empirical relationship was given by Straškraba and Hocking (2002) that demonstrates the relationship between increased stratification and HRTs for Central European reservoirs as

$$\Delta T_{\mathrm{Max}0,30} = 20(1 - \exp(-0.0126\,\mathrm{HRT})) \tag{1}$$

where $\Delta T_{\mathrm{Max}\ 0,30}$ is the maximum temperature difference between the surface and 30 m depth and HRT is in days. Longer HRTs are likely to exist in the newly formed side bays in Iron Gate I, Orsova and Eselnita (Figure 2), which

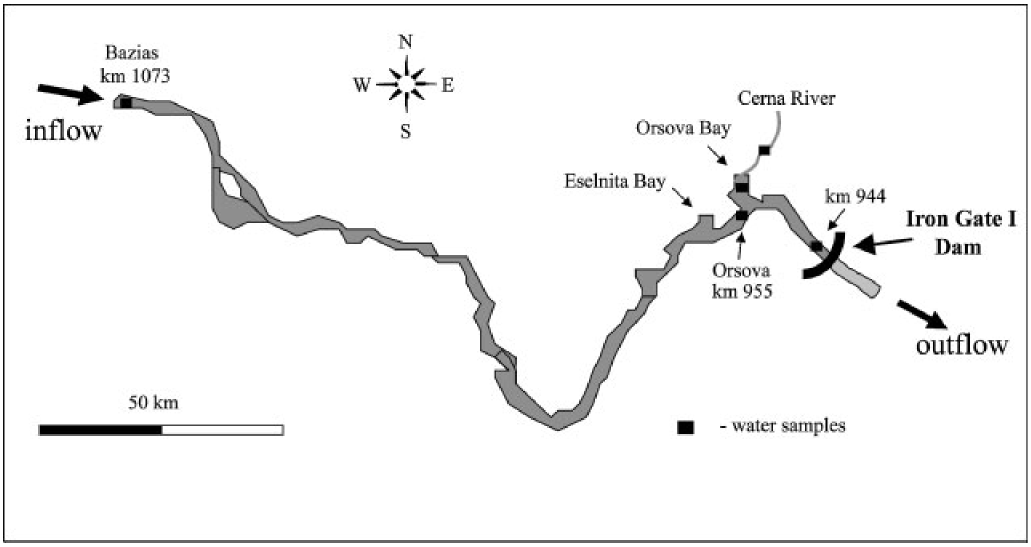

Figure 2. Map showing Iron Gate I reservoir and the selected system boundaries, as well as Orsova Bay and Eselnita Bay. Black squares indicate water sampling locations

did not exist prior to construction, and are the most likely sites for DSi elimination from the Danube River water. However, even if we conservatively hypothesize that all DSi loading to Orsova Bay (the largest bay in Iron Gate I) could be taken up and assuming an HRT favorable for diatom growth of 2 days (corresponding to ~5% of the Danube water), then the maximum uptake of DSI could not exceed this ~5% limited by the hydrodynamics. The fact that data for the study by Humborg *et al*. (1997) were collected a large distance away for the Iron Gate reservoirs in the Danube River Delta probably leads to the dramatic difference from the 4% removal determined by Friedl *et al*. (2004). To resolve the disparity in the two DSi retention estimates, we therefore critically analyze the hydrodynamics of the reservoir as the key determinant of whether Iron Gate I can indeed support primary production and sedimentation, and in which areas they are more likely to occur.

We study the lower main branch and two side bays, Orsova and Eselnita (Figure 2; Figure 3), of Iron Gate I. Using field data and various analytical approaches, we focus on hydrodynamics to determine the degree to which DSi loss can occur by establishing (1) whether Iron Gate I is stably stratified so that primary production is supported, (2) whether significant sedimentation occurs in the identified regions and (3) the overall contribution of the lower main branch and the two adjacent bays to sediment and DSi retention. In this paper, we will demonstrate that the major conclusions regarding the 4% DSi removal in Iron Gate I that were reached by Friedl *et al*. (2004) are justified, and therefore other causes of the observed DSi depletion should be explored.

STUDY SITE AND EXPERIMENTAL APPROACH

The Danube River drains the largest basin in Western Europe; at 817 000 km^2, it includes at least 15 countries (Figure 1; Panin and Jipa, 2002). The source originates in the Black Forest in Germany and flows east for approximately 2850 km before it discharges an annual average of approximately 6300 $m^3 s^{-1}$ into the Black Sea (Garnier *et al*., 2002). The construction of the Iron Gate I dam on the Danube created several quiescent zones for potential algal growth. The focus of this paper is to characterize the hydrodynamics at the three locations in the Iron Gate I that encompass these major quiescent zones: the lower main branch, Orsova Bay and Eselnita Bay (Figure 2; Figure 3).

The lower branch of the reservoir is defined as the 11 km long section between Orsova Bay and the dam, which has a total volume of 0.3 km^3 (Figure 2), with Orsova Bay the largest bay within the entire reservoir (Figure 3). The basic morphometric characteristics of the bays were determined from the maps and transects obtained during the March 2001 cruise (Table I). The mouth of Orsova Bay is about 13–15 m deep, depending on the water level

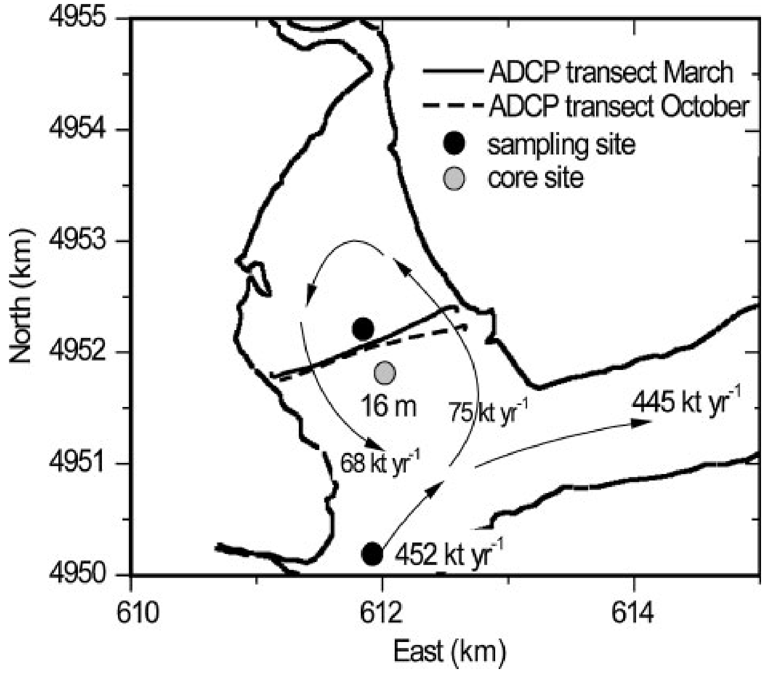

Figure 3. Orsova Bay and sites for water sampling (black), sediment core (grey) and ADCP transects (solid and broken lines). The numbers indicate dissolved silica transport (in kt yr^{-1}) from the mass balance obtained from the 11-month-long monitoring. Values into and out of the bay are estimates based on fractional loading to the bay

in the reservoir. Eselnita Bay, located approximately 17 km upstream from the dam (Figure 2), is the second largest bay examined. Several methods were used at the study sites to determine the HRT, the extent of stratification, the potential for primary production and their role as sediment and DSi sinks.

The study was carried out in 2001 and consisted of two cruises (March 18–28 and October 14–19) as well a regular weekly water quality sampling program between 1 February and 20 October 2001 within and downstream of the reservoir (Figure 2; Teodoru and Wehrli, 2005). The hydrodynamics was investigated using acoustic Doppler current profiler (ADCP) measurements, conductivity–temperature–depth profiles (CTD), water sampling, thermistors and chlorophyll measurements (Table II). On both cruises, velocity and acoustic backscatter profiles were obtained using a boat-mounted ADCP. To determine sedimentation rate and deposition/resuspension locations, a sediment core was obtained. The weekly monitoring stations included the inflow at Bazias (river km 1073), 300 m upstream of Orsova Bay (955 km), one station in Orsova Bay and the Cerna River and 2 km downstream of the dam (Figure 2). These samples were analyzed for dissolved silicate, nutrients and suspended solids (see Teodoru and Wehrli, 2005). Thermistors were installed at two depths at each study site. Additionally, chlorophyll profiles were obtained almost weekly at these locations throughout the year. Table II provides a summary of measurements performed.

ADCP measurements were performed in the lower branch and in Orsova Bay (Figure 3) to directly map the horizontal current pattern and the HRT during both cruises (number of transects in Table II). The ADCP (RD Instruments Workhorse, 614 kHz) was attached to the boat facing downwards. The boat was driven slowly ($\sim 2\,km\,hr^{-1}$) while the ADCP recorded the three-dimensional velocity components and acoustic backscatter strength within 50 cm vertical bins throughout the water column. ADCP backscatter was then calibrated to estimate suspended solids concentrations in the water column.

Chlorophyll profiles were measured with a Minitracka *in situ* miniature fluorimeter (Chelsea Instruments). Profiles were measured at 1 m depth intervals, and the voltage was recorded. The device was calibrated in March 2001 in a laboratory setting. The Minitracka chlorophyll measurements are therefore only intended to provide a qualitative estimate of where production is occurring.

Table I. Morphometry of Eselnita and Orsova Bays

	Orsova Bay	Eselnita Bay
Area, $10^6\,m^2$	$A_{OB} = 4.5$	$A_{EB} = 0.49$
Volume, $10^6\,m^3$	$V_{OB} = 47.0$	$V_{EB} = 2.5$
Maximum depth, m	20.4	10.0
Mean depth, m	10.3	5.1
Annual water level fluctuations, m	2.7	2.7

Table II. Overview on collected data during the two 2001 cruises and the continuous sampling

Data type	18–28 March			14–19 October		
	Orsova Bay	Eselnita Bay	Main branch	Orsova Bay	Eselnita Bay	Main branch
ADCP transects	3	—	2	2	—	3
Chlorophyll*	3(27)	—	2(54)	—	—	—
CTDs	4	2	7	4	—	6
Sediment cores	2	—	7	—	—	—
Sediment traps$^+$	1	1	1	—	—	—
Thermistors$^+$	2	2	2	2	2	2
Water samples*	2(29)	—	3(68)	4	—	6

*Amount in parenthesis indicates weekly, 11-month-long sampling.
$^+$Measurements were continuous over entire, 11-month-long sampling.

CTD profiles were measured using a SeaBird SBE19 CTD profiler. The SBE19 samples at 2 Hz and measures, besides conductivity, temperature and depth, also dissolved oxygen, light transmission (at 660 nm) and pH.

Nutrient analysis. Water samples were filtered through a 0.45 μm polycarbonate membrane immediately after sampling and stored in 50 ml plastic bottles in a cool box. Within one day the samples were analyzed photometrically for dissolved silicate and other nutrients (not included in this work) following standard methods (Strickland and Parsons, 1968). Biogenic silica (BSi) was analyzed by ICP-OES (inductively coupled plasma optical emission spectroscopy) after leaching 30 mg sample aliquots with 1 M NaOH solution at 90°C for 3 hours (Mortlock and Froechlich, 1989). The standard deviation of the method was 9% of the mean.

Sediment core was obtained in March 2001 from Orsova Bay using a gravity corer (Kelts *et al*., 1986). The sediment core was analyzed at the EAWAG laboratory. The core was opened, cut into halves for description and photographic documentation, and sampled every 1 cm. For dating, freeze-dried samples were analyzed for ^{137}Cs and ^{210}Pb activity in a germanium well detector (Goldberg, 1963; Krishnaswami *et al*., 1971). Calculations were made according to the constant international concentration method (Appleby and Oldfield, 1978).

Suspended solids. Estimates were obtained from water samples collected with Niskin bottles at various depths at each study site. The light absorption was measured using the MERCK Spectroquadrant NOVA 60 photometer following the standard photometric methods (DEV, 1996). The standard deviation of the measurement was 10%. The light absorption was then used in a linear correlation to provide suspended solids concentration.

Thermistors. Minilog 12 and 8 bit (Vemco) were moored at the surface (0.6 m deep) and at the bottom (26 m deep) ~0.8 km upstream of the dam, and in Orsova (although the bottom thermistor was lost) and Eselnita (0.8 m and 6.5 m deep) Bays. The thermistors collected data from 27 March to 19 October, 2001 with a 30 minute sampling interval.

HYDRODYNAMICS IN THE LOWER IRON GATE I

The hydrodynamics in the Lower Iron Gate I determine the extent to which DSi loss can occur due to diatom production and subsequent sedimentation. Therefore, using various analyses, we determine whether the necessary

density stratification and residence time scales occur to support primary production in the three study regions (lower main branch, Eselnita Bay and Orsova Bay).

Lower main branch

In the lower main branch, the extent of thermal stratification was determined from two thermistors, moored at the surface and bottom ~0.8 km upstream of the dam. The near-bottom and near-surface temperature exhibited almost daily stratification, although the temperature differences were quite small for the entire period with a maximum difference of about 3°C in early August (Figure 4). This weak stratification was due to the short HRT of 0.4–1.5 days, which was calculated using the April–October 2001 exchange rates (ranging from 2400 to 9700 $m^3 s^{-1}$ with an average of 5500 $m^3 s^{-1}$) and an average volume of 0.3 km^3 for the lower 11 km in front of the dam. The nearly daily well mixed conditions in the main branch of Iron Gate I were also attributed to large water inflows, and the daily disruption of stratification by night-time cooling (and by some flow-related turbulence). In summary, the HRT is too short and the diurnal stratification is interrupted too frequently (typically daily) to maintain a reasonable level of primary production. This conclusion is underscored by the low chlorophyll-a measurements in the main branch (Figure 5) as well as the absence of an algal layer in the ADCP backscatter signal (not shown).

Eselnita Bay

In contrast to the main branch, Eselnita Bay was occasionally stratified, as determined by temperature observations from the surface and near-bottom moored thermistors (Figure 6). The water column was nearly isothermal in early spring, with diurnal stratification becoming apparent later in the spring. The highest temperature difference (~3°C) was observed in early July. Apart from daily stratification, the thermistor data indicate the development of a weak but stable stratification (defined as more than three days in duration) in the following time periods; mid-March (5 d); the entire month of May; mid-June (7 d) and approximately half of August. The extent of stratification is much higher in Eselnita Bay than in the lower branch, and could potentially support algal growth.

Due to the rough wave regime in Eselnita Bay, ADCP transects could not be performed to determine exchange rates $\tau_{EB}^{-1} = Q_{EB}/V_{EB}$, where Q_{EB} is the exchange flow and V_{EB} is the volume. However, the exchange was estimated using a heat budget approach based on continuous temperature data collected in Eselnita Bay (T_{EB}) and in the Danube River (T_{DR}) with the following assumptions: (1) the temperature of the bay (T_{EB}) was defined as the

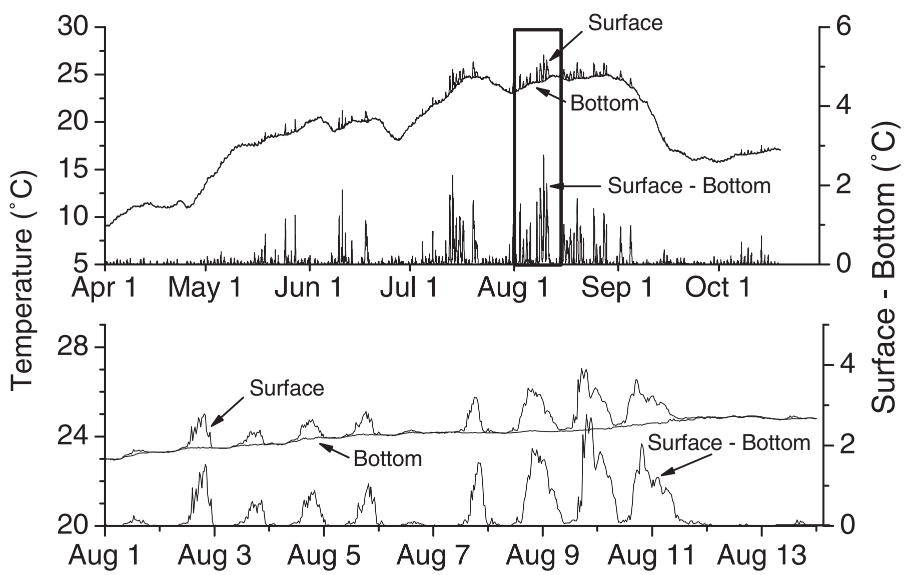

Figure 4. Upper panel: surface ($z = 0.8$ m) and bottom (0.4 m above the bottom) temperatures, as well as their differences, in Orsova Bay through the entire season. Lower panel: the same as the upper panel (area in rectangle), but for the period of maximum stratification, 1–14 August 2001

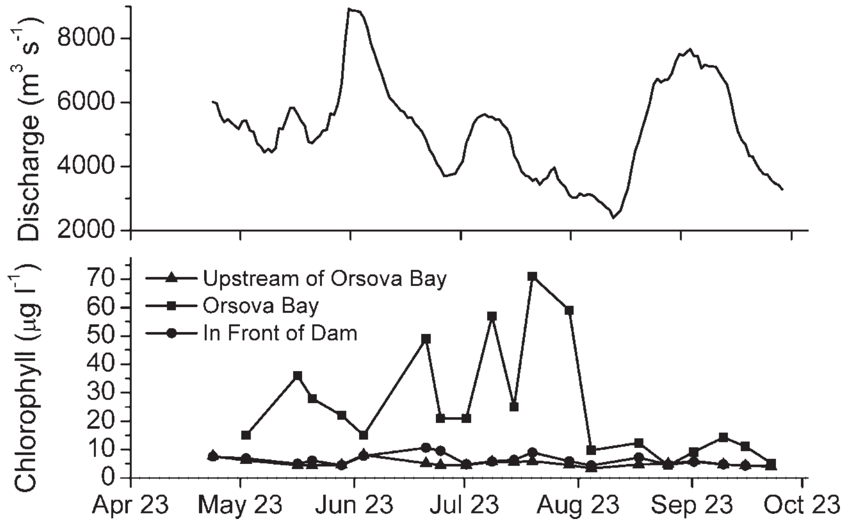

Figure 5. Discharge from the dam (top). Chlorophyll-a values measured upstream of Orsova Bay (Orsova), in Orsova Bay and at the dam (bottom). The slight increase in chlorophyll-a values at the dam is suspected to be flushed diatoms from Orsova Bay. Values are more qualitative given the uncertainty in response of the fluorimeter due to time of day (sunlight exposure) and algae type

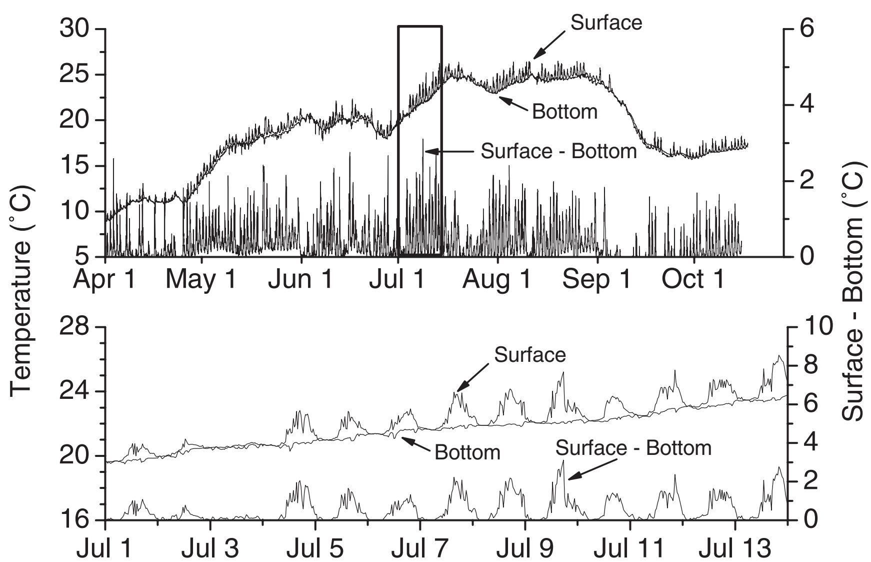

Figure 6. Upper panel: surface ($z = 0.8$ m) and bottom (0.4 m above the bottom) temperatures, as well as their differences, in Eselnita Bay through the entire season. Lower panel: the same as the upper panel (area in rectangle), but for the period of maximum stratification, 1–14 July 2001

average of the surface and bottom temperature, (2) heat interactions were only considered between Danube River water and the atmosphere, H_{net} (W m^{-2}), and (3) other heat exchanges, such as sediment heat exchange, were neglected. The heat balance is given by

$$\frac{\partial T_{\text{EB}}}{\partial t} = \tau_{\text{EB}}^{-1}(T_{\text{DR}} - T_{\text{EB}}) + \frac{H_{\text{net}} A_{\text{EB}}}{\rho c_{\text{w}} V_{\text{EB}}} \tag{2}$$

where A_{EB} and V_{EB} are the Eselnita Bay surface area and volume, respectively, and ρc_{w} is the specific heat capacity of water.

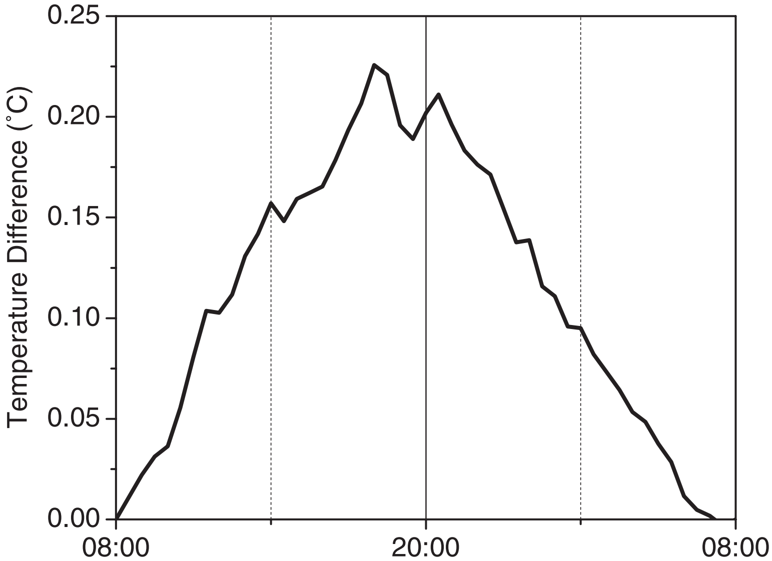

Figure 7. The five-day averaged difference (3–8 May 2001) between the momentary temperature and the baseline (night) Danube water temperature

The temperature in the Danube increases during daytime (when the atmospheric heat flux H_{net} is positive) against its base line, and decreases during night time (when the heat flux is negative) until reaching again the base line temperature (Figure 7). By calculating the heat attributed to these daily temperature fluctuations for a given time interval, the atmospheric heat flux H_{net} can be determined by

$$H_{\text{net}} = \frac{\partial T_{\text{DR}}}{\partial t} z_{\text{DR}} \rho c_{\text{w}} \tag{3}$$

where z_{DR} is the average depth of the Danube River (described below). For the example given in Figure 7, the heat flux from the atmosphere was calculated as the five-day average from 3 to 7 May, 2001. The temperature difference was then averaged for each 30-minute time step (Figure 7), with the two slopes, $\partial T_{\text{EB}}/\partial t$, representing the heat gain and loss intervals (heat gain from 8:00 to 18:00, and heat loss from 18:00 to 8:00). The temperature in Eselnita Bay was then calculated for different water exchange rates, and compared with the measured temperatures. By assuming an arbitrary Q_{EB}, $\partial T_{\text{EB}}/\partial t$ can be estimated as a function of time by Equation (2) and compared with the observed development of T_{EB}.

The slopes $\partial T_{\text{EB}}/\partial t$ are $0.0216\,\text{K}\,\text{h}^{-1}$ (heat gain during day) and $-0.0178\,\text{K}\,\text{h}^{-1}$ (heat loss during night) (Figure 7). The average depth of the Danube River, $z_{\text{DR}} = 18.5\,\text{m}$, is taken over the distance the water travels for the 8 h heating period (9 km upstream with $\nu = 0.3\,\text{m}\,\text{s}^{-1}$). The heat flux, H_{net}, from Equation (3) was $470\,\text{W}\,\text{m}^{-2}$ and $-390\,\text{W}\,\text{m}^{-2}$, respectively. Using a least-squares fit for exchange flow (Q_{EB} varying from $50\,\text{m}^3\,\text{s}^{-1}$ to $100\,\text{m}^3\,\text{s}^{-1}$), Equations (2) and (3) provide the closest fit for $Q_{\text{EB}} = 75\,\text{m}^3\,\text{s}^{-1}$ (less than 1% of Danube flow, Q_{DR}; Figure 8), with a corresponding HRT of $V_{\text{EB}}/Q_{\text{EB}} = 0.4\,\text{d}$. Therefore, even if primary production occurs in Eselnita Bay, given the high exchange flow and low HRT, it can be concluded that the effect of this side bay is not significant for the overall reservoir primary production.

Orsova Bay

During the March and October 2001 cruises, ship-mounted ADCP velocity profiles (Plate 1(a)–(c) and Plate 2(a)–(c)) were measured at approximately the same locations in Orsova Bay near the mouth (Figure 3). Plate 1(a) and Plate 2(a) show the direction of flow (northerly inflow on the east side of the bay and a southerly outflow on the west side of the bay), demonstrating the basin-scale flow vorticity. Using Plate 1(b) and Plate 2(b) the inflow and outflow velocities, cross-sectional area, and the exchange flow with the Danube were determined

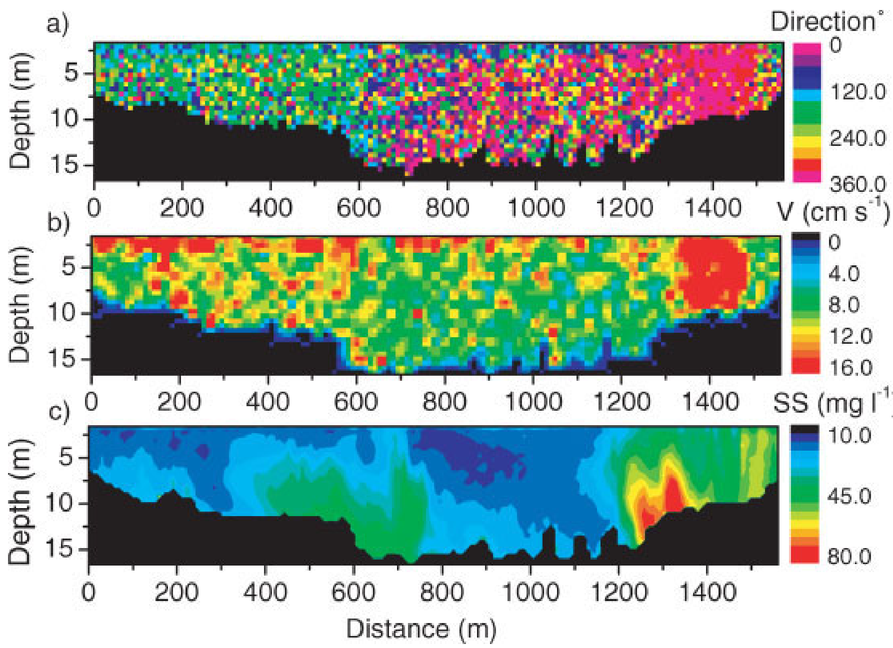

Plate 1. ADCP transect (Figure 3) through Orsova Bay in March 2001. 0 m corresponds with the east side of the bay. (a) A northerly inflow on the east side and a southerly outflow on the west side. (b) The velocity magnitude; (c) suspended solids (SS) estimates from backscatter signal strength, indicating a greater particle concentration entering Orsova Bay

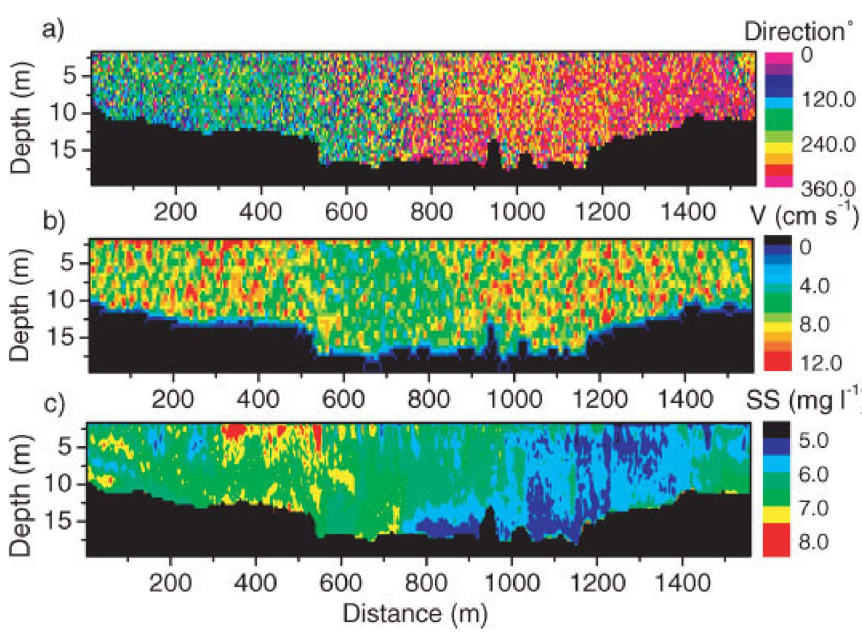

Plate 2. ADCP transect (Figure 3) through Orsova Bay in October 2001. 0 m corresponds with the east side of the bay. (a) A northerly inflow on the east side and a southerly outflow on the west side. (b) The velocity magnitude; (c) suspended solids (SS) estimates from backscatter signal, indicating a greater particle concentration leaving Orsova Bay

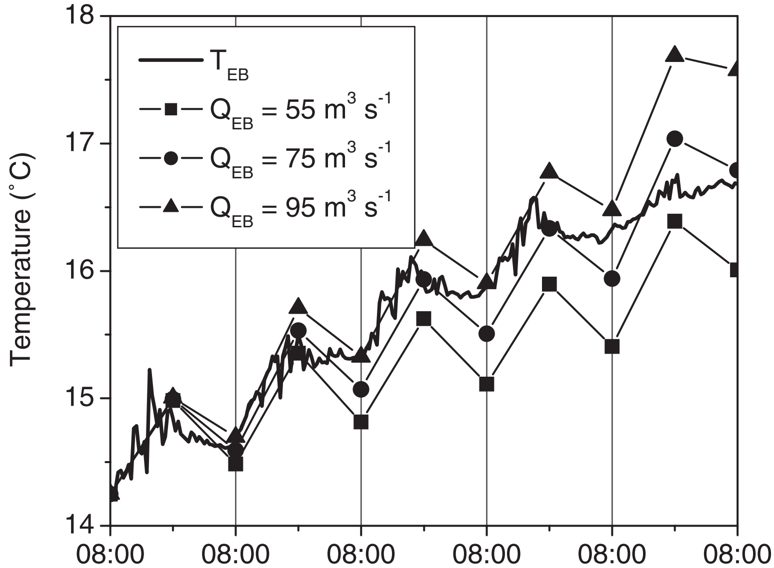

Figure 8. Temperature according the heat budget predictions (Equations (2) and (3)) for different exchanges Q_{EB} into Eselnita Bay compared with measured temperature T_{EB} during five-day calculation (3–8 May 2001)

(Table III). The results indicate that significant portions, from 14% (March: $Q_{OB} = 1130 \pm 70\,m^3\,s^{-1}$) to 26% (October: $Q_{OB} = 840 \pm 66\,m^3\,s^{-1}$), of river water enters Orsova Bay (Table III). Assuming a linear relationship between the Danube flow and the exchange flow, an estimate can be made for the HRT in Orsova Bay. The estimated HRTs are generally between 0.5 and 0.6 d, which, like the main branch HRTs, are likely to inhibit stratification and primary production.

For verification of the heat budget method used above, calculations were performed for Orsova Bay for the same time interval (3–8 May, 2001) and compared with the ADCP estimates. The heat flux is also assumed to be the same for Orsova Bay and for the Danube. The average depth, z_{DR}, was determined to be 19.9 m. The atmospheric heat flux, H_{net}, was slightly different from the upper stretch (see previous section) and was calculated from Equation (3) as $502\,W\,m^{-2}$ from 8:00 to 18:00 and $-414\,W\,m^{-2}$ from 18:00 to 8:00. From Equation (2), the average temperature in Orsova Bay is calculated for different water exchange rates (Q_{OB} varied from 800 to $1450\,m^3\,s^{-1}$). The bottom thermistor in Orsova Bay was lost, therefore the bottom temperatures in Orsova Bay are assumed to be close to those measured nearby at the bottom of the Danube River. The least-squares estimation of the temperatures calculated for the water exchange rate yielded $Q_{OB} = 1150\,m^3\,s^{-1}$, which corresponds well to the $Q_{OB} = 1130\,m^3\,s^{-1}$ calculated using the ADCP method, demonstrating the robustness of this approach.

Based on these results, it is known that stratification occurs only sporadically (particularly in the lower main branch), and it is typically destroyed during night-time cooling and high flow. The lack of stratification and short HRTs did not support primary production in most cases. ADCP (see next section) and chlorophyll measurements (Figure 5) suggest some primary production in the quiescent center of Orsova Bay. To estimate an upper limit for potential DSi removal, we therefore use a combination of ADCP and suspended solids measurements, core analysis and water column sampling, as described in the following section.

SEDIMENTATION

Sediment deposition

DSi has only a low affinity for adsorption to particulate matter and consequently DSi can only leave the Danube River water by means of deposition of *in situ* silica frustules produced by diatoms. We therefore studied the locations and extent of the sedimentation of suspended solids by determining particle concentrations and loadings at different locations.

Table III. Basic hydrology of the Danube River, and results from ADCP transects in Orsova Bay

Parameter	March 25	October 18
Danube flow rate, $m^3 s^{-1}$	8200	3300
Elevation (asl), m	66.6	68.5
Velocity into Orsova Bay, $cm s^{-1}$	10.8	8.9
Velocity out of Orsova Bay, $cm s^{-1}$	11.4	8.0
Cross-sectional area at ADCP transect, m^2	20 400	19 800
Exchange flow Q_{OB}, $m^3 s^{-1}$	1130	840
% of Danube flow rate (Q_{OB}/Q_{DR})	14	26
Hydraulic residence time $HRT = V_{OB}/Q_{OB}$, d	0.48	0.65

During the 11-month 2001 study, suspended solids were measured almost weekly at Bazias (135 km upstream from the dam), and just upstream of Orsova Bay (Figure 2). The suspended solids load at Bazias was 8900 kt yr^{-1}, while just upstream of Orsova Bay the load was still 5500 kt yr^{-1} (38% reduction; Teodoru and Wehrli, 2005). It should be noted that these loads should contain significantly smaller uncertainties (the integration was based on 34 samples of Q_{DR} and concentration over 11 months) than the earlier estimates of over 20 000 kt yr^{-1} (Panin *et al.*, 1999; WCD, 2001).

While the sedimentation rates obtained by Teodoru and Wehrli (2005) represent a nearly year-long average deposition over the entire reservoir, particle concentrations measured along the Iron Gate I in October 2001 at 4 m depth (except near Orsova Bay, where it was taken at 1 m depth) reveal a six-day snapshot of sediment deposition in the lower Iron Gate I. Figure 9 demonstrates a general decrease in particle concentrations from 7.25 to 5.0 mg l^{-1} (30%) as water approaches the dam from Eselnita Bay. This 30% reduction in particle concentrations in the lower Iron Gate I is in good agreement with the 38% obtained by Teodoru and Wehrli (2005) between the point of inflow and Orsova for 2001; however, it is likely overestimated due to the low river discharge ($Q_{DR} = 3300\, m^3 s^{-1}$) and slower velocities. Furthermore, a significant fraction of sedimentation that occurs in the main branch during low flow periods is probably resuspended during high flow events. However, as Orsova Bay is shielded from high currents, even during such high flow events, it is reasonable to assume that this bay is a primary sediment sink.

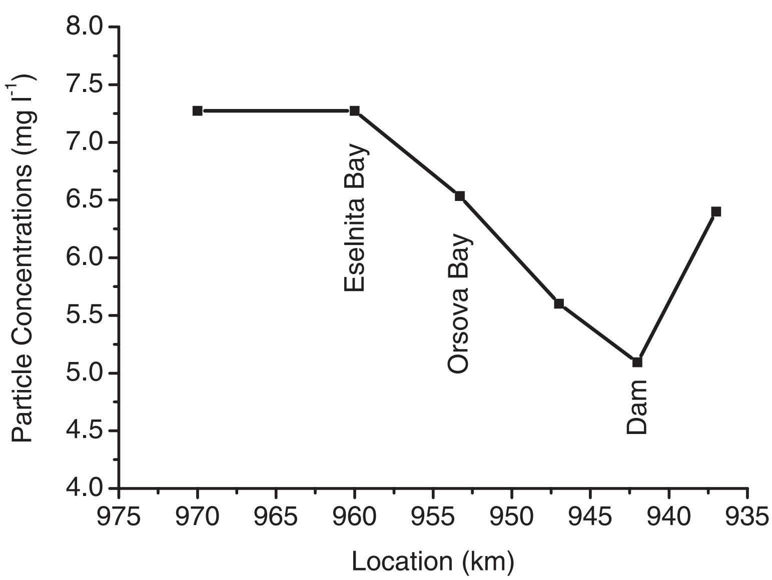

Figure 9. Particle concentrations in the Danube River (October 2001)

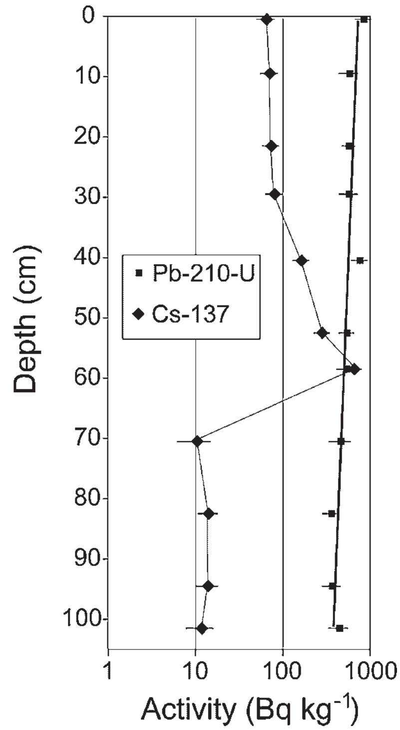

Figure 10. Sediment core dating from Orsova Bay showing cesium (Cs) and lead (Pb) profiles. The peak on the Cs curve occurs between 60 and 70 cm, showing a maximum from the Chernobyl accident in 1986. The core is also dated from the slope of the Pb-210-U profile (half-life 22.3 years), where the U indicates that the Pb-210 is part of the uranium-238 decay series

A sediment core obtained from Orsova Bay was dated to obtain the annual deposition of the sediment loading (Teodoru and Wehrli, 2005). The sedimentation rate of $S = 4.9\,\mathrm{cm\,yr^{-1}}$, determined for the core using ^{210}Pb and ^{137}Cs radionuclides (Figure 10), is in excellent agreement with the value of $S = 5\,\mathrm{cm\,yr^{-1}}$ calculated by Reschke (1999) for Eselnita Bay. The sediment mass accumulation in Orsova Bay ($A_{\mathrm{OB}} = 4.5\,\mathrm{km^2}$) was then calculated from $A_{\mathrm{OB}} S \rho_s (1 - F)$, where $F = 0.85$ is the water content and $\rho_s = 2.5\,\mathrm{g\,cm^{-3}}$ is the particle density. It yielded an annual sediment retention of $82\,\mathrm{kt\,yr^{-1}}$, or 1% of the load measured at Bazias ($8900\,\mathrm{kt\,yr^{-1}}$; Teodoru and Wehrli, 2005).

During the March and October 2001 cruises, the ADCP measurements were used to obtain the instantaneous sediment deposition in Orsova Bay. A relationship between the ADCP backscatter strength (dB) and the particle concentration ($\mathrm{mg\,l^{-1}}$) was established from suspended solids samples simultaneously collected along the Danube during both cruises (Figure 11). Plate 1(c) and Plate 2(c) show two of the contour plots of suspended solids from the ADCP transects in Orsova Bay (Figure 3). The backscatter signal was stronger during the March cruise than during the October cruise (Figure 11), resulting from the higher discharge in March, which led to larger suspended particles and higher concentrations.

In March, there were more particles flowing into Orsova Bay ($34\,\mathrm{mg\,l^{-1}}$; Plate 1(c)) than flowing out ($26\,\mathrm{mg\,l^{-1}}$), based on the backscatter signal correlation (Figure 11). It was estimated that the bay retained $\sim 8\,\mathrm{mg\,l^{-1}}$ ($\sim$24%) of the inflowing suspended solids during this day. Assuming 14% water exchange (Table III), the 24% particle removal yields $290\,\mathrm{kt\,yr^{-1}}$ sedimentation in Orsova Bay. This deposition represents only 3.4% of the suspended sediment load into the Iron Gate Reservoir at Bazias. The deposition in Orsova Bay is significant as almost no resuspension will occur.

However, the ADCP backscatter measurements from October 2001 in Orsova Bay reveal enhanced backscatter strength in the outflow, equivalent to a 25% increase of suspended solids (Plate 2(c)). This supposed increase was determined by applying the suspended solids calibration curve (Figure 11) to the backscatter signal. As the average velocity is only between 8 and $9\,\mathrm{cm\,s^{-1}}$, it is impossible that resuspension is occurring. During the warmer weather and lower exchange flows, primary production may occur in the quiescent center of the bay,

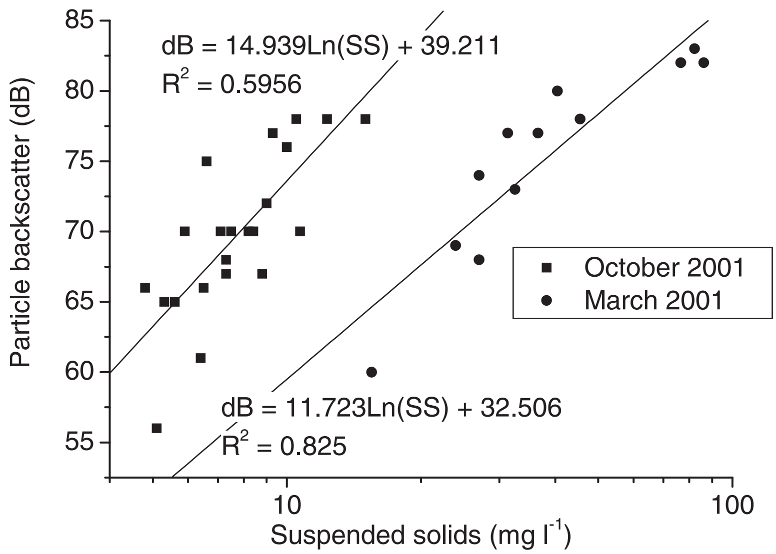

Figure 11. Relationship between ADCP particle backscatter (dB) and concentration of suspended solids (SS) (mg l^{-1}) based on data obtained during the March and October 2001 cruises

and the apparent increase in suspended solids is most probably attributed to a stronger backscatter signal from flushed algae as observed by Lorke *et al*. (2004) in a freshwater lake. The conclusion is reinforced by higher chlorophyll-a values in Orsova Bay in Summer/Fall 2001 (Figure 5).

Assuming an average sedimentation in Orsova Bay of $2 \pm 1\%$ for suspended solids from both the sediment core (1%) and the ADCP estimate (3.4%), it is reasonable to assume this value as an upper limit of DSi removal via diatom settling, as this is the maximum sedimentation that can occur.

Silica loss

A DSi balance was performed based on the 2001 data to determine the loss in Orsova Bay. River flow and exchange flow were multiplied by the DSi concentrations to determine the loading into Iron Gate I (Bazias), at the dam, immediately upstream of, and in Orsova Bay. The loading curves (Figure 12) were then numerically integrated to obtain the annual mass loading.

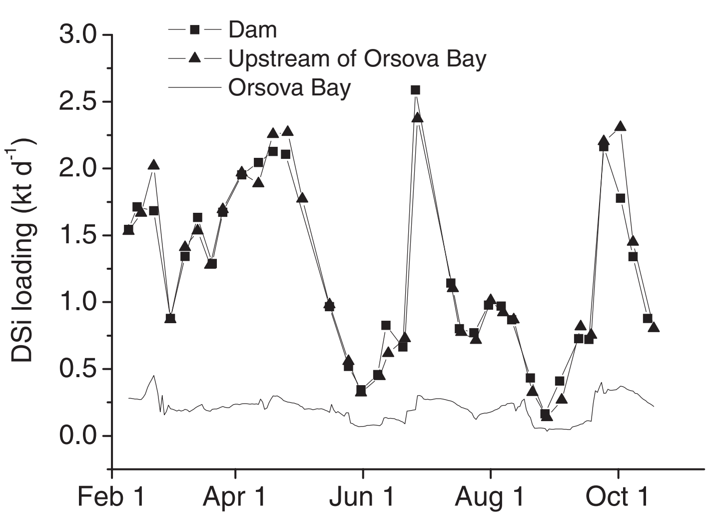

Figure 12. DSi loading upstream of Orsova Bay (452 kt yr^{-1}) and at the dam (445 kt yr^{-1}) based on individual measurements (as points on the curve), and estimated fractional loading into Orsova Bay (75 kt yr^{-1})

If we assume for a conservative upper limit that all the DSi entering Orsova Bay is taken up by diatoms and that there is no DSi loss in the main branch (a reasonable assumption given the short HRT), then a maximum of 3.4% (from the suspended solids budget) of the DSi would be removed. For the DSi load of 460 kt yr^{-1} measured at Bazias (different calculation procedures result in a slightly higher value than the $\sim$400 kt yr^{-1} reported by Friedl *et al*., 2004), at most $\sim$16 kt yr^{-1} DSi would be retained in Orsova Bay. This is reasonably consistent with the observation of 452 kt yr^{-1} DSi just upstream of Orsova Bay (Figure 3), and between 445 and 450 kt yr^{-1} DSi leaving the reservoir at the dam. Given these DSi values (445 and 452 kt yr^{-1}), between 2 and 7 kt yr^{-1} of DSi is taken up by the diatoms in Orsova Bay during 2001. Note that these values have a large degree of uncertainty and only indicate DSi uptake, and not necessarily loss, from the Danube water. The DSi loss through deposition was estimated from the analysis of a sediment core.

The sediment core analysis revealed an average biogenic Si (BSi—silica in the form of diatom frustules) content of 14.9 mg g^{-1}, yielding a BSi accumulation rate of 1.2 kt yr^{-1}, which is in reasonable agreement with the 2–7 kt yr^{-1} DSi retention estimated from the (not very accurate) mass balance. Despite this uncertainty, we conclude that only a fraction of the DSi taken up by the diatoms is actually deposited in Orsova Bay; the larger part is washed out of the bay.

DISCUSSION

The high flow and exchange rates and short HRTs prevent the development of a stable stratification and limit primary production in the Iron Gate I reservoir. The HRTs, which are typically shorter than the diatom doubling time scales ($\sim$0.5–2 d; Reynolds, 1997), do not allow the development of a significant quantity of phytoplankton and subsequent silica uptake. Although production does occur in quiescent zones, i.e. the side bays, we identified only the center of Orsova Bay ($\sim$1.5 km^2) as a location of significance.

Of the 452 kt yr^{-1} DSi loading upstream of Orsova Bay, only about 2–7 kt yr^{-1} is taken up by diatom production and, of this, only 1.2 kt yr^{-1} (0.2%) was deposited in the sediments as BSi determined from the sediment core. The remainder is likely washed out of the reservoir, as indicated by the October ADCP backscatter transects (Plate 2(c)). This is further supported by the slight increase in chlorophyll content downstream of Orsova Bay (Figure 5) and downstream diatoms detected by microscopy (Friedl *et al*., 2004). Although there is considerable uncertainty in the 2–7 kt yr^{-1} estimate, there is a solid independent upper limit given by the 3.4% removal (16 kt yr^{-1}) of the particles, as determined in the previous section.

However, this maximum of 3.4% DSi removal (16 kt yr^{-1}) assumes that the diatoms settle at the same rate as the suspended solids. Diatoms have highly variable settling rates depending on the species, and can vary as much as from 0.02 m s^{-1} (Riley, 1943) to nearly 30 m s^{-1} (Eppley and Sloan, 1966; Wüest *et al*., 2005). Based on their density, they settle more slowly than inorganic suspended solids, which, coupled with the 10 m average depth of Orsova Bay (Table I), gives significant opportunity for algae to be washed out of the bay, and perhaps the entire reservoir.

As a rough verification of DSi uptake, the expected chlorophyll concentration in Orsova Bay can be estimated by the Redfield ratio. Assuming that for every mole of chlorophyll (molecular weight $\sim$900 g mol^{-1}) produced 16 moles of DSi is utilized (Turner *et al*., 1998; Tada *et al*., 2000), a DSi uptake of 1.2 kt yr^{-1} in Orsova Bay should correspond to an average chlorophyll concentration of approximately 80 $\mu g\, l^{-1}$. While this is a highly uncertain estimate, this value agrees well with the chlorophyll concentrations measured in Orsova Bay in 2001 (Figure 5). However, if the 600 kt yr^{-1} DSi loss reported by Humborg *et al*. (1997) occurred entirely within Iron Gate I, the resulting chlorophyll concentrations would be much higher than ever measured. Therefore, while we have shown that production and sedimentation do occur in Orsova Bay, they contribute minimally to the DSi uptake.

Previous literature suggests that 50% (or 20 000–30 000 kt yr^{-1}) of the suspended sediment entering Iron Gate I is retained within the reservoir (Humborg *et al*., 1997; Panin *et al*., 1999). While it was verified that 56% (5000 kt yr^{-1}) of suspended sediments were retained in 2001, the total load itself was only 8900 kt yr^{-1} (Friedl *et al*., 2004). Consequently, the retention is also much smaller than postulated. If we considered the sediment removal of 82 kt yr^{-1} in Orsova Bay (4.5% of the total surface area of the Iron Gate I) to be representative for the entire reservoir, then only $\sim$20% (or 1800 kt yr^{-1} of the 8900 kt yr^{-1} suspended solids) would be removed.

Although this value is inconsistent with the observed reduction of 58% of the particle mass within the reservoir, it may not account for resuspension and bedload transport.

While it is clear that significant sediment retention occurs in Iron Gate I, due to the riverine nature of the reservoir little production occurs, particularly in the main branch. Orsova Bay was identified as the only zone supporting production; however, it is likely that most of the algae are flushed out into the main branch, and perhaps entirely out of the reservoir. While no significant DSi retention was observed in Iron Gate I, the role of side bays in reservoirs as a potential nutrient and sediment sink has clearly been demonstrated.

Typically, damming a river decreases the water velocity, which increases sedimentation and results in greater light penetration, stratification and algae growth. In side bays, this effect is enhanced due to even lower water velocities and sheltering from high flow events. While Iron Gate I is an example of a straight river-run reservoir with only a single relatively large side bay, the importance of side bays as nutrient and sediment sinks will be much more significant in reservoirs with many large side bays, such as Itaipú dam (the worlds largest hydropower project) on the Brazilian–Paraguayan boarder (Norton *et al*., 2001).

CONCLUSIONS

Previous studies (Humborg *et al*., 1997) suggested that Iron Gate I is a significant dissolved silica (DSi) sink; however, Friedl *et al*. (2004) showed that the DSi retention in Iron Gate I was only 4% in 2001. Therefore, the internal hydrodynamics of Iron Gate I were investigated to determine which level of primary production and subsequent DSi loss is supported. The two mechanisms required for the long-term removal of DSi from the Danube River water in the Iron Gate reservoir are diatom production and subsequent net deposition of their frustules, both of which are significantly driven by the hydrodynamics. In this study, therefore, we focused on the hydrodynamics of the lower Iron Gate I. This region experiences the lowest currents in the entire reservoir, and is consequently the top candidate as a sediment and nutrient sink. Although we found Orsova Bay to be the only significant production and retention site, the net deposition is consistently low for both DSi and suspended solids. This conclusion is backed by the following observations.

(1) The hydraulic residence time (HRT) for the lower Iron Gate I during the warm (primary production) period of the year 2001 (April–October) is in the range of 10 h (April 26: $Q_{DRmax} = 9700\,m^3\,s^{-1}$) to 36 h (September 2: $Q_{DRmin} = 2400\,m^3\,s^{-1}$), with an average value of 26 h ($Q_{DRaver} = 5500\,m^3\,s^{-1}$). This short HRT prevents the formation of 'isolated, stratified' water bodies and therefore hardly affects dissolved substances, and is too short for significant algal growth.
(2) Significant primary production occurs mainly in quiescent zones such as in the center of Orsova Bay. On average, only about 20% of the Danube water passes through Orsova Bay; the effect of algal growth on the elimination of DSi is limited. Although it is estimated in this study that $460\,kt\,yr^{-1}$ of DSi entered Iron Gate I in 2001, we found only 1 to a few $kt\,yr^{-1}$ deposited in the Orsova Bay, as determined from biogenic silica measurements in the sediment core.
(3) ADCP measurements in the main branch near Orsova Bay showed average currents in the Danube in the range of $13\,cm\,s^{-1}$ (October 2001) to $37\,cm\,s^{-1}$ (March 2001), with water entering Orsova Bay slowing down to less than $10\,cm\,s^{-1}$. Therefore, Orsova Bay, which did not exist before the construction of the dam, is a sink for 82 to $290\,kt\,yr^{-1}$ of sediment, based on dating the sediment core and particle balancing. Given the low sedimentation rate and low DSi deposition, it is suggested that the 2–7 $kt\,yr^{-1}$ DSi 'loss' in Orsova Bay estimated from the DSi mass balance (see above) is due to production of diatoms that are subsequently flushed out of the reservoir.
(4) The combination of low diatom production and subsequent sedimentation indicate that Iron Gate I is not a significant DSi sink. As only $\sim 1\,kt\,yr^{-1}$ DSi is retained in Orsova Bay, which accounts for 4.5% of the total area, it is conservatively estimated that only 5% ($22\,kt\,yr^{-1}$) would be retained if extrapolated to the entire reservoir area of $104\,km^2$. This is in good agreement with the 4% determined by Friedl *et al*. (2004).

Based on the results of the present study, it is clear that Iron Gate I is more similar to a river than a reservoir (long and narrow, well mixed and turbid; exhibiting weak stratification with relatively high average water velocities) and

that the conversion of the river into a 135 km long reservoir is not expected to significantly change water quality, with respect to algal production and silica retention.

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