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Nutrient Retention in the Danube's Iron Gate Reservoir

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There are long-standing concerns about the environmental impacts of large dams such as Iron Gate I, the Danube River's largest hydropower scheme, which stretches for 135 kilometers along the river, covers an area of 104 square kilometers, and contains up to 2.1 cubic kilometers of water [*Friedl and Wüest*, 2002]. During the onset of Black Sea coastal eutrophication resulting from increased nitrogen (N) and phosphorus (P) loads, the dissolved silica (DSi) concentration at the Danube discharge was reported to have decreased by approximately two thirds [*Cociasu et al.*, 1996]. Coinciding with the completion of Iron Gate I in 1972, researchers pointed to DSi removal in the reservoir to explain the shift in algal dominance in the Black Sea from diatoms to nuisance blue-green algae, which apparently resulted in reduced fish-catches.

The study presented here, however, points to the contrary. Impounded water behind Iron Gate I presently accumulates N and P via remobilization from the sediments [*Teodoru and Wehrli*, 2005] and loses (retains) at most 5% DSi via sedimentation as biogenic silica particles [*Friedl et al.*, 2004; *McGinnis et al.*, 2006].

In addition, water reaching the reservoir is already nutrient- and sediment-depleted [*Teodoru and Wehrli*, 2005]. Though Iron Gate I was at first considered as an obvious culprit for silica and sediment depletion [*Humborg et al.*, 1997; *Panin et al.*, 1999] seen in water downstream—due to the dam's immense size—this study found that most of the sediment and DSi retention occurs in the many reservoirs in the river's headwaters. Internal processes within reservoirs, and not the size of the impoundment, control the overall nutrient and sediment budget. Therefore, it appears that large reservoirs are not always the most relevant causes for biogeochemical changes, and the effects of all dams and hydraulic alterations along the entire river stretch must be considered.

By C. Teodoru, D. F. McGinnis, A. Wüest, and B. Wehrli

The Controversy

Central to the Iron Gate I controversy is the postulation that the construction of the dam resulted in the retention of significant amounts of sediment and nutrients, particularly silicon [*Cociasu et al.*, 1996; *Humborg et al.*, 1997]. Increased in situ diatom production in the reservoir due to longer water residence times and subsequent algal sedimentation was thought to account for DSi retention in Iron Gate I of up to 600 kilotons per year (1 kiloton = 1ˆ3 metric tons [*Cociasu et al.*, 1996; *Humborg et al.*, 1997]), comprising 75% of the incoming load.

Independently, it was postulated that 20,000–30,000 kilotons per year of sediments (50–70% of the incoming load) were trapped annually by Iron Gate I, accelerating coastal erosion [*Humborg et al.*, 1997; *Panin et al.*, 1999]. A nutrient balance study of the Danube basin indicated a considerable discrepancy between the estimated input from the catchment and the loads entering the Black Sea [*Zessner and Kroiss*, 1998], and Iron Gate I again was suspected for the reductions of 750–1000 kilotons per year N and 90–150 kilotons per year P.

Reservoirs do have far-reaching effects on local hydrology and downstream receiving waters. The damming of rivers increases the residence time and water temperature, decreases turbidity, modifies thermal stratification, and therefore usually enhances in situ primary production, which affects the carbon and nutrient balance [*Friedl and Wüest*, 2002; *McGinnis et al.*, 2006]. While anthropogenic inputs sometimes compensate for N and P removal, very little DSi replenishment occurs, because rock-weathering is the only source.

The hydrodynamic characteristics within the Iron Gate I reservoir, however, do not support increased primary productivity, and only minimal DSi retention occurs, mostly in the reservoir's only large, quiescent side bay [*McGinnis et al.*, 2006; *Teodoru et al.*, 2006]. Iron Gate I is an example of a straight run-of-river reservoir with only one relatively large

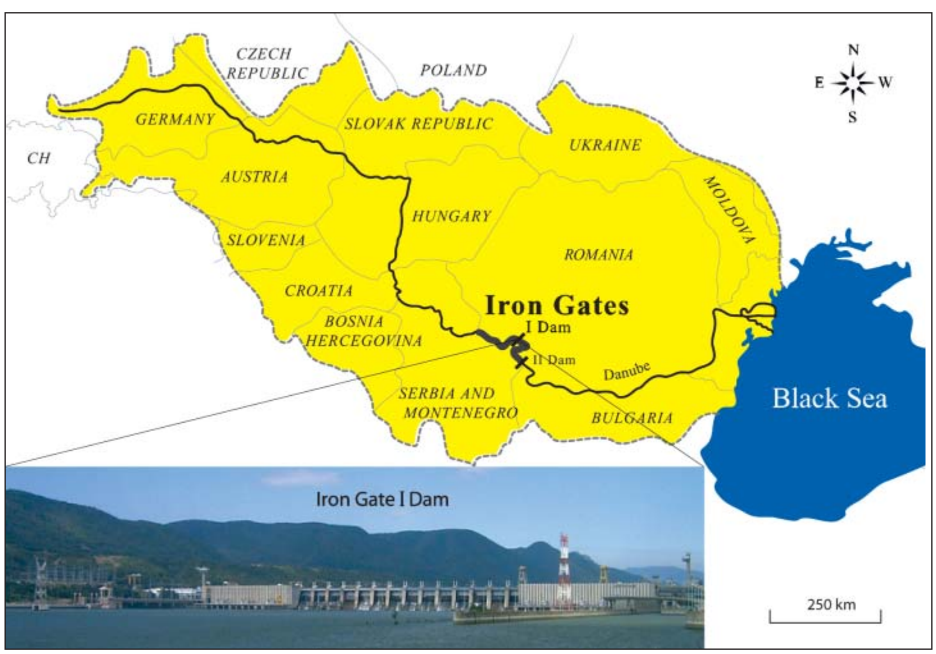

Fig. 1. The Danube River with its large catchment shared by 17 European countries (Italy and Albania, contributing ~0.1%, are not shown in this figure) and locations of Iron Gate I and II reservoirs.

side bay; however, the importance of side bays as nutrient and sediment sinks is more significant in reservoirs with many large side bays, such as Itaipú Dam, the world's largest hydropower project, located on the border of Brazil and Paraguay.

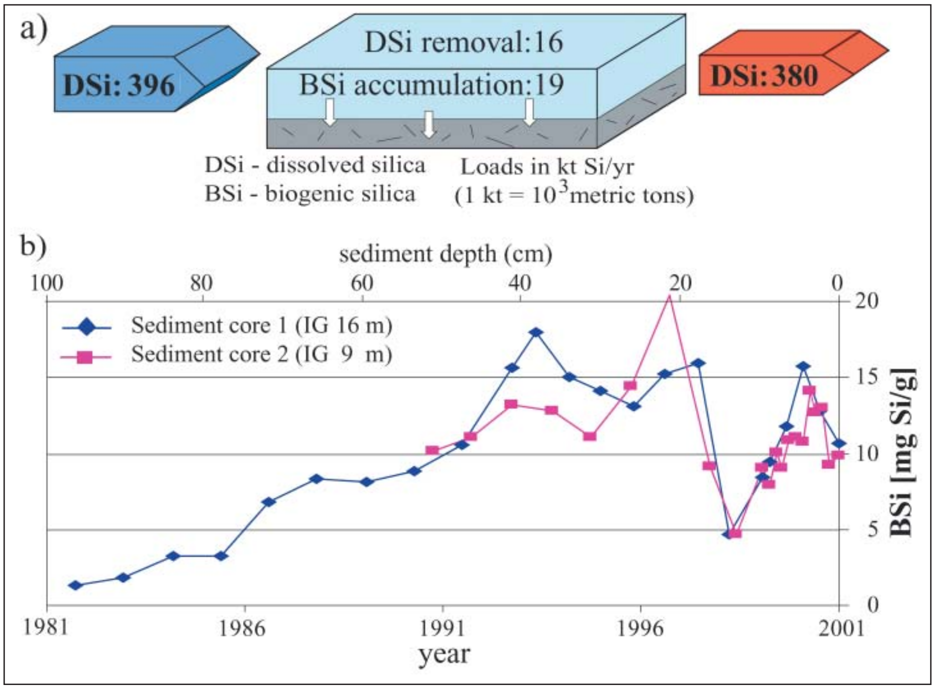

Fig. 2. (a) Mass balance for DSi and the BSi retention in the Iron Gate I reservoir calculated for 2001. (b) Comparison between the BSi concentration profiles in the sediments of Iron Gate I and the coastal Black Sea.

Damming the Danube River

The Danube River, the second largest in Europe, is 'the most international river in the world' with a watershed covering regions of 17 different countries (Figure 1). Originating in the Black Forest Mountains of Germany, the Danube River flows east over 2850 kilometers to the Black Sea. Its drainage basin of over 817,000 square kilometers covers about 30% of western and eastern Europe.

Many dams have been built on the Danube and its tributaries, with the density reaching one dam every 17 kilometers in the Upper Danube (the river's first 1000 kilometers). Located approximately 900 kilometers upstream from the Black Sea (Figure 1), Iron Gate I has an annual average discharge of 175 cubic kilometers per year. The hydropower scheme consists of two dams: the Iron Gate I Dam, constructed in 1972, and the smaller Iron Gate II Dam, completed downstream in 1984 [*Teodoru and Wehrli*, 2005]. The following analysis concentrates on the Iron Gate I reservoir.

Sediment and Nutrient Study

A monitoring program was carried out between 1 February and 31 December 2001 and is still providing significant data for investigating the controversial role of Iron Gate I on the downstream Black Sea coastal ecology. Weekly measurements of physical and chemical constituents were obtained in correlation with analyses of sediment chronology and the particulate components of cores and sediment traps.

The average water residence time of approximately five days, and water velocities in the range of 30–40 centimeters per second, demonstrate the riverine nature of the Iron Gate I reservoir. A mass balance of total suspended solids (TSS) yielded a sediment accumulation of 5000 kilotons per year, or 55% of the incoming load [*Teodoru and Wehrli*, 2005]. Compared with the postulated retention of up to 20,000–30,000 kilotons per year [*Humborg et al.*, 1997; *Panin et al.*, 1999], the present accumulation is four to six times lower. In fact, the incoming TSS of 9000 kilotons per year measured in 2001 is less than half of the postulated retention, and clearly implies upstream sediment retention.

Weekly DSi measurements were used to determine an influent load of 396 kilotons per year and an output load of 380 kilotons per year, indicating 5% retention (16 kilotons per year, Figure 2a [*Friedl et al.*, 2004; *McGinnis et al.*, 2006]). This DSi removal is almost 40 times lower than the suggested retention of 600 kilotons per year [*Humborg et al.*, 1997]. Average biogenic silica (BSi) concentrations (biological uptake of DSi and subsequent conversion into solid form) from sediment cores and traps revealed a BSi accumulation of 19 kilotons per year (Figure 2a [*Teodoru et al.*, 2006]), very close to the DSi removal of 16 kilotons per year.

The silica retention in the Iron Gate I reservoir determined from the BSi core profiles shows an increasing trend over the past 20 years (Figure 2b). Slow BSi dissolution coupled with high burial rates suggests that the increasing BSi concentration is due to enhanced diatom growth. Because the present sedimentary BSi levels are currently at a maximum for the past 20 years, the current retention of 19 kilotons per year BSi in the Iron Gate I reservoir represents the highest on record. With an even smaller BSi retention in the past, Iron Gate I could not have induced a substantial DSi depletion at the coastal Black Sea.

On the basis of sediment core analyses, the nutrient accumulation in the Iron Gate I reservoir for 2001 was calculated as 10 kilotons per year total nitrogen (TN) and 1.7 kilotons per year total phosphorus (TP), which corresponds to a total retention of 5% and 10%, respectively. These values are about two orders of magnitude lower than the postulated retention of 750–1000 kilotons per year TN and 90–150 kilotons per year TP [*Zessner and Kroiss*, 1998]. It was further found that the reservoir acts as a nutrient source, with 17% N and 10% P increases in the outflow in 2001, which are likely due to sediment release and external anthropogenic sources.

Marginal Nutrient Retention

With nutrient retention rates one to two orders of magnitude lower than previous studies suggest, the biogeochemical impact of Iron Gate I on the coastal Black Sea ecology is marginal. Sediment retention, however, is substantial. The dam retains more than 50% of the incoming suspended solids (excluding resuspension from flood events). Other changes such as human activities, fishing, coastal pollution, and eutrophication must explain the disastrous ecological changes in the coastal Black Sea ecosystem.

The decreased DSi concentrations at the Black Sea's coastal waters are assumed to be caused by heavy damming of the Danube headwaters. Possible mechanisms contributing to DSi removal include eutrophication in upstream reservoirs, clogging of the riverbed, and decreasing the lateral connectivity with riparian aquifers typically rich in DSi. Channeling large areas of the river stretch and reducing the natural water level fluctuations that control the silicon weathering rates also may have lowered the DSi loads. However, these studies demonstrate that the construction of Iron Gate I, the largest impoundment on the Danube, played only a minor role in changing the nutrient loads to the Black Sea.

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Author Information

Cristian Teodoru, Eawag, Swiss Federal Institute of Aquatic Science and Technology, Kastanienbaum, Switzerland and Institute of Biogeochemistry and Pollutant Dynamics, ETH Zurich (Swiss Federal Institute of Technology), Switzerland, E-mail: cristian.teodoru@eawag.ch; Daniel F. McGinnis, Eawag, Swiss Federal Institute of Aquatic Science and Technology; Alfred Wüest and Bernhard Wehrli, Eawag, Swiss Federal Institute of Aquatic Science and Technology and Institute of Biogeochemistry and Pollutant Dynamics, ETH Zurich.

Data Acquisition for Volcano Monitoring

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In the past decade, systems and techniques for volcano monitoring activities have improved rapidly. The scientific community focused on the development of new methods and techniques, while the electronic systems for experimental activity and monitoring networks were developed mainly by commercial companies.

However, these commercial systems often do not fit simultaneously all the needs of geophysical research. A new project, led by the Italian Institute of Geophysics and Volcanology (INGV) 'Osservatorio Vesuviano' (OV) in Naples is trying to fill this niche with the development of data acquisition systems for multiparametric volcanic monitoring.

The INGV-OV is monitoring high-risk active volcanic areas such as Vesuvius, the Phlegrean Fields, and Stromboli through the acquisition of several geophysical parameters, including seismic, infrasonic, strain, and geochemical data. In such multiparametric data collection, each type of data requires a different acquisition system; some of these parameters require continuous data acquisition, whereas others may need particular actions to be made on the sensors or at the acquisition site. To perform many tasks and to be adaptable to the specific requirements of each type of data acquisition, instruments need to be modular and flexible.

Volcano monitoring often is characterized by the need for instrument installations in remote places, usually reachable only on foot. In such places, the only power source is energy provided by solar panels and stored in accumulators. For this reason, there is the need for low power consumption by field electronics instruments in order to minimize the number of solar panels and accumulators to be transported and installed.

Thus, such a complex acquisition model requires low power, modularity, and adaptability for several field applications. Currently, commercial solutions are task-oriented and do not simultaneously fit all of these needs. Moreover, these commercial instruments often are 'black boxes' for which the final user only has limited possibilities to adapt the hardware to his particular needs. For instance, placement of a data-logger in areas unreachable by global positioning system (GPS) signals requires a technical action (usually the separation of the GPS receiver) that is achievable only by the manufacturer.

In this context, the INGV-OV decided to start a new technological research project with the goal of studying, developing, and producing a data acquisition system specifically devoted to multiparametric volcanic monitoring. This project was named GILDA, for Geophysical Instrument for Low-Power Data Acquisition.

The first phase of the project involved the development of a basic electronic system to accomplish essential functions, such as analog to digital conversion of sensor signal, station status monitoring, time labeling of data, and data transmission, with the main goal of low power consumption. Other fundamental characteristics include a high resolution in analog to digital conversion, a high dynamic range as required by most of the signals produced in volcanic environments, a versatile usage configuration, and a low cost production. In a subsequent phase, a complete system with all features of modularity and flexibility will be realized.

The first prototype of the basic system is currently undergoing testing. This first GILDA version (code-named Lilith) is a multiboard system composed of a high-resolution (24-bit) analog to digital converter (ADC) board with four channels, a central processing unit board, a timing board, and a GPS receiver unit. All of these boards and the power section are housed and interconnected on a main board. The main board also is equipped with an eight-channel 12-bit ADC, in order to obtain device status information (temperature, power consumption, battery voltage, solar panel power, and so forth). Expansion ports are available to connect a third medium-resolution 16-bit ADC for low-rate

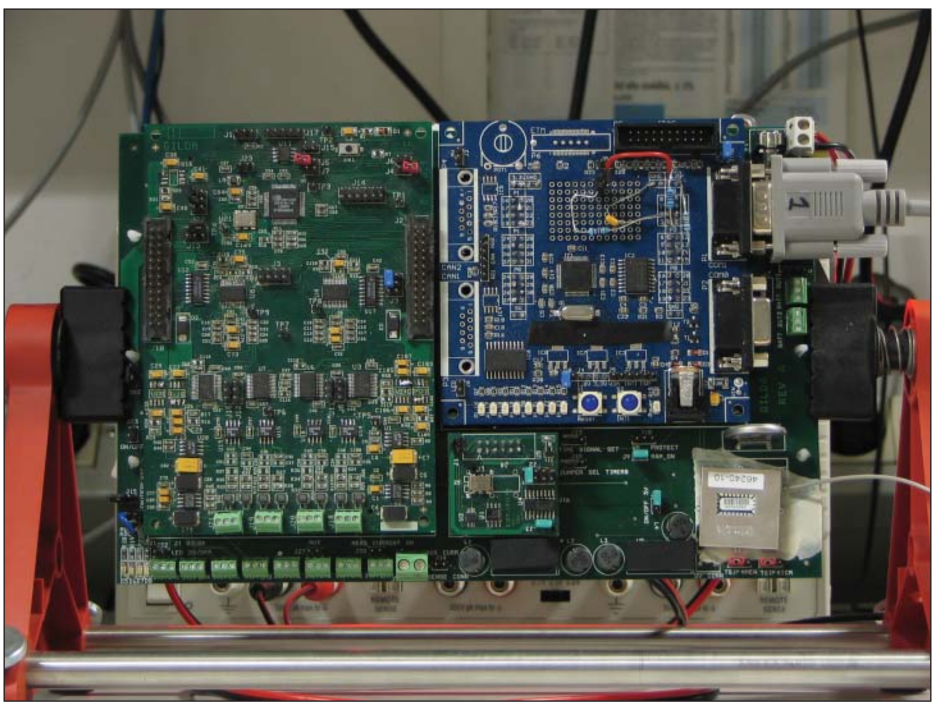

Fig. 1. The first prototype of the basic GILDA system. Visible at the left is the ADC board; the microcontroller board is on the top right, and the timing board as well as the GPS unit are on the bottom right.

By M. Orazi, M. Martini, and R. Peluso