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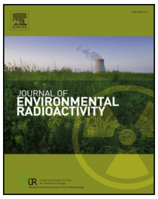

# Investigation of sedimentation rates and sediment dynamics in Danube Delta lake system (Romania) by $^{210}$Pb dating method

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## ABSTRACT

Being a dynamic environment associated with complex costal, fluvial and marine processes, only a few studies regarding the evolution of the Danube Delta and the human impacts on its ecosystem have been carried out. Being a sensible to all processes occurring in its catchment area, information is stored in the deposited sediments, which can be used as tracers for natural and anthropogenic processes. The aim of this study is to determine a detailed reconstruction of the sedimentation rates in the last century by applying the $^{210}$Pb dating method validated by $^{137}$Cs profiles. Additionally, the impacts of the construction of river-regulating structures (mainly the Iron Gates Hydro-Energetic Power Plants) are investigated, along with the assessment of natural phenomena (floods, storms etc.). To achieve this, 26 sediment cores from seven lakes were collected. $^{210}\mathrm{Pb}_{sup}$ and $^{137}$Cs were determined using gamma spectrometry, while $^{210}\mathrm{Pb}_{tot}$ was measured via alpha spectrometry ($^{210}$Po), using the CRS model for age determination. From the assessed lakes, the most affected was the Matiţa Lake with a maximum sedimentation rate of 10.93 $\mathrm{g\,cm^{-2}\,yr^{-1}}$ and the least affected was the Isac Lake. Average sedimentation rates are: 0.95 $\mathrm{g\,cm^{-2}\,yr^{-1}}$ for Cruhlig Lake, 0.70 $\mathrm{g\,cm^{-2}\,yr^{-1}}$ for Uzlina Lake, 0.44 $\mathrm{g\,cm^{-2}\,yr^{-1}}$ for Isac Lake, 0.47 $\mathrm{g\,cm^{-2}\,yr^{-1}}$ for Cuibida Lake, 0.51 $\mathrm{g\,cm^{-2}\,yr^{-1}}$ for Iacob Lake, 1.00 $\mathrm{g\,cm^{-2}\,yr^{-1}}$ for Matiţa Lake and 0.76 $\mathrm{g\,cm^{-2}\,yr^{-1}}$ for Merhei Lake. Physical parameters (water content, porosity and bulk density) and LOI (organic matter and inorganic carbon content) were determined for each core to differentiate organic and non-organic sedimentation. Beside the natural influences, it is difficult to track the effects of the Iron Gates and not all analysed lakes were suitable for this task. The 1940–1970 period and the following ten years were compared in means of sedimentation: a decrease in sedimentation can be observed in four of the lakes: 59% in Cruhlig Lake, 16% in Uzlina Lake, 10% in Iacob Lake and 42% in Isac Lake, leading to an average 32% for the four lakes. The other three lakes show increasing tendencies of 39% in this period: 87% in Matiţa Lake, 6% in Merhei Lake and 24% in Cuibida Lake. Sedimentation rates show growths of 3 times after 1989, the most affected being the two northern lakes (3 times increase in both Matiţa Lake and Merhei Lake) and the four central lakes (2 times in case of Cuibida Lake, 3 times in Iacob Lake, 3 times in Isac Lake and 4 times in Uzlina Lake) with an average increase of 3 times, while the southern one (Cruhlig Lake) 2 times.

## 1. Introduction

Lake ecosystems react sensibly to the processes occurring in their catchment areas. Therefore the information stored in the sediments is often useful tools for exploring the natural and anthropogenic changes in their environment. Such an ecosystem is represented by the Danube Delta. Having a catchment area of 4152 $\mathrm{km}^2$, which includes regions of Central and Eastern Europe, it is the second largest delta of the continent, being part of the UNESCO world heritage (Sommerwerk et al., 2009). The sedimentation processes and the associated morphological changes within the Danube Delta and along the deltaic coast are complex and little understood. The rates of the sedimentation processes are continuously changing on different time-scales (e.g. macro-scale changes related to climate and sea level; meso-scale changes of the solid discharge, hydrodynamic characteristic or physical conditions of the river bed) due to both natural and anthropogenic factors. Major human interventions (e.g. dams, hydro-energetic power plants, meanders cut offs, artificial channel cuttings, protection walls) have been performed within the Danube Basin in the last century (Coman, 2002). Insights into the spatial and temporal sedimentation rate dynamics during the

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last two centuries represent a major challenge for the better understanding the development phenomenology of the Danube Delta. Comprehending the feed-back between the sedimentation processes and the morphological changes is a crucial step in predicting how a sedimentary system will evolve in the near future and in assessing its vulnerability to the extreme events (e.g. sea level rise, storms, floods, droughts) related to the widely acknowledged climate changes.

A series of published papers on shelf mud focus on the large dispersal systems associated with subaqueous-deltas, e.g. Amazon, Ganges–Brahmaputra, Changjiang–Huanghe, Fly River and describe continental shelves in west of the Mississippi Delta (Kuehl et al., 1982, 1986; DeMaster et al., 1985; Alexander et al., 1991; Harris et al., 1993; Lesueur et al., 2001; Tichenor et al., 2016). Starting with the end of the 1970's researches were made on the sedimentation of the rivers forming delta (Nittrouer et al., 1979; Michels et al., 1998), some of these being still in progress (Jweda and Baskaran, 2011; Humphries et al., 2010). The ongoing studies have extended from the recently deposited sediment to the maritime shelves in the screening of the anthropic factors (Xu et al., 2008; Canuel et al., 2009). The human impact on the sedimentation processes from the Danube Delta has been previously approached by means of some geographic and geomorphologic methods such as the comparison of historical bathymetric maps (Constantinescu et al., 2010) or the behaviour of hydrodynamic modelling of extreme events (e.g. floods). The application of the radiometric method on Danube Delta sediments can be found in the literature investigating the pollutant agents (heavy metals) in recent sediment layers (Woitke et al., 2003; Vukovic et al., 2013). The accumulation rate of recent sediments using radiocesium profiles was not yet done using the $^{210}$Pb dating methods (Dinescu and Duliu, 2001; Florea et al., 2011).

For aquatic sediments, the use of $^{210}$Pb ($T_{1/2}$ = 22.2 yr) (Duenas et al., 2003), originating from the decay of atmospheric $^{222}$Rn, is a well-established method to estimate sediment ages and sedimentation rates on a time scale of up to 100 years. The $^{210}$Pb method was first developed by Goldberg (1963), then applied on lake sediments by Krishnaswamy et al. (1971) and subsequently introduced to marine sediments by Koide et al. (1972). More recent studies applied the $^{210}$Pb radiometric method in studies of changes due to human-induced geomorphic processes and climate changes in riverine-lacustrine systems, estuaries or bays in different parts of the world (Appleby and Oldfield, 1978; Sert et al., 2012; Jweda and Baskaran, 2011; Sabaris and Bonotto, 2011; Bruschi et al., 2012; Mabit et al., 2014; Delbono et al., 2016).

The detailed reconstruction of the sedimentation rates by means of high resolution radiometric methods during the last two centuries will help isolate and quantify the impact of the human interventions. Of all the anthropogenic interventions, the Iron Gate Hydro-Energetic Power Plants have the highest effect on the sediment quantity which arrives in Danube Delta. The dams were constructed in 1972 (Iron Gate I located at km 942 of the Danube) and in 1986 (Iron Gate II localized 68 km downstream) and represent the largest hydropower dam and reservoir system along the entire Danube. The reservoir of Iron Gate I of 3.2 billion $m^3$ volume and 270 km total length (up to Novi Sad, Serbia) (ICPDR, 2015), trapping some 20 million tons of sediment per year (Laszlo, 2007). The total drainage area upstream of the Iron Gate I is 577,000 $km^2$, representing 250–300 km upstream the Danube River. The annual water flow of the Danube River is 110–220 109 $m^3$, while daily discharges range between 1500 and 15000 $m^3 s^{-1}$. The suspended sediment concentrations in the Danube River are in the $10^{-3}$ to $10^{-1}$ kg $m^{-3}$ range, while the sediment volumes entering the reservoir are considerably larger: 7–30 million tons per year (Laszlo, 2007). The dams interrupted the natural sediment transport in the Upper Danube, retaining approximately two-thirds of the suspended solids. Therefore, sediment delivery to the Delta decreased from 53 to 18 million tone per year (Duțu et al., 2014), resulting in severe coastal erosion (Sommerwerk et al., 2009), and therefore assuming that there should be an observable variation in the sedimentation rates of the lakes after their implementation, downstream of the two dams.

While between 1971 and 1980 the Danube River's solid discharge was of 1308 kg $s^{-1}$, between 1981 and 1990 this value decreased to 926 kg $s^{-1}$. The maximal value was recorded in 1941 ($192 \times 10^6$ tons $yr^{-1}$) and the minimal in 1921 ($19.8 \times 10^6$ tons $yr^{-1}$). The average transported sediment quantity per year shows a decreasing tendency (Coman, 2002). The present study aims to present the changes in the sediment dynamics of the Danube Delta by analysing 7 lakes and 26 sediment cores and pointing out the period before and after the construction of the Iron Gates, indicating its effects. Some of the results are already presented in published articles, which partially (the dynamic of Iacob and Merhei lakes (Begy et al., 2014, 2015; Simon et al., 2016), or integrally include the description and justification of the changes in sedimentation rates (Begy et al., 2016).

## 2. Materials and methods

### 2.1. Study site

More than 300 lakes are situated between the three branches of the Danube Delta. Halfway through the delta, the branches of the Danube River cut through a marine levee, where they form the natural boundaries of four hydrological sub-units or lake complexes, namely from west to east: Sontea-Furtuna, Gorgova-Uzlina, Matița-Merhei and Roșu-Puiu (Oosterberg et al., 2000).

Through this study seven lakes with an average of four sediment columns were investigated. A gravity corer was used for sampling with a sampling tube of 60 cm and, respectively, 120 cm. The location of the lakes and the sampling points can be seen in Fig. 1, and a detailed description of these and sediment cores are presented in Table 1.

Situated north to the Sfântu Gheorghe Branch in the marine delta, the genesis of the Cruhlig Lake is in correlation with the gradual closing of a lagoon. The lake can be accessed through a channel south to the Sfântu Gheorghe Branch.

Placed in Grogova-Uzlina hydrological sub-unit close to the Mahmudia Meander, the Uzlina Lake is connected to the Sfântu Gheorghe Branch and joined by two lateral channels to the Isac Lake. The Iacob and Isac lakes are both situated in the first part of the marine Danube Delta, south to the Sulina Branch, but without having a direct connections to it. In the present, the basin of the Iacob Lake is connected to the rest of the deltaic system with a secondary channel in the south of the lake, being indirectly connected to the Sulina Branch. The basin of the Isac Lake is a part of the Uzlina and Isac lake system and has three entry channels: one in the north-eastern, one in north-western and the last one in the southern part of lake. This has indirect connection to Sfântu Gheorghe Branch through the Uzlina Lake, while the north-eastern and north-western channels are connected to each other and start at the Caraorman Channel.

The Cuibida Lake is situated between the Isac Lake and Caraorman Channel. This lake is connected to the Sulina Branch with two entry channels in the southern and the western part of the lake. The sediment cores taken from this lake are situated in the proximity of the entry channels, which connect the lake to the Sulina Branch.

The Matița and Merhei lakes are situated in the fluvial part of the Danube Delta, between the Chilia and Sulina branches. Although their positions are further away from the main branches, the sources of suspended sediments are provided by numerous secondary channels, diminishing the sediment quantity reaching the two lakes.

### 2.2. Physical parameters

Every sediment core was sub-sectioned into 1–2 cm layers. Wet and dry weight were measured (sediments were dried at 75 °C in a drying oven for 24 h) and physical parameters such as porosity, water content and wet and dry bulk density were calculated.

LOI (Loss On Ignition) measurements were carried out on each sediment core. Sub-samples were dried in a drying oven at 105 °C to