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# Contents



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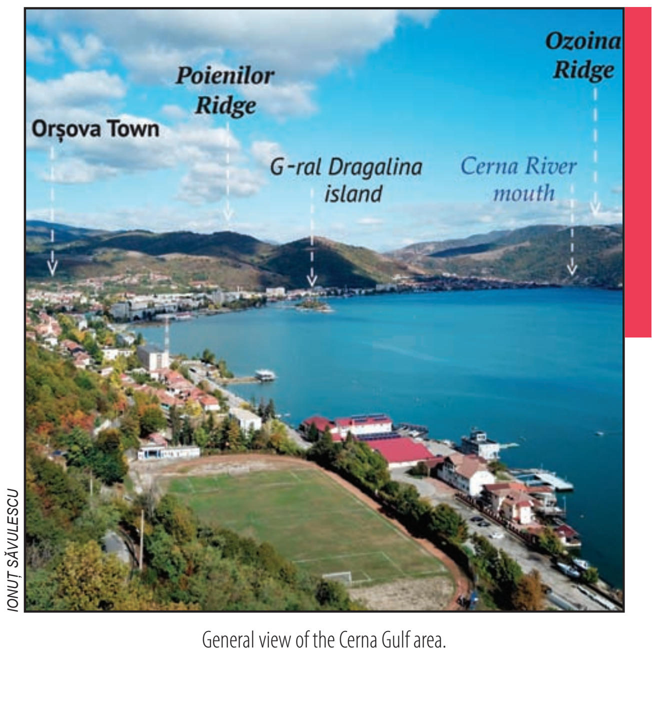
# THE IMPACT OF LARGE DAMS ON FLUVIAL SEDIMENTATION: THE IRON GATES RESERVOIR ON THE DANUBE RIVER

Constantin Nistor, Ionuț Săvulescu, Bogdan-Andrei Mihai, Liliana Zaharia, Marina Vîrghileanu, Sorin Carablaisă




General view of the Cerna Gulf area.

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# The impact of large dams on fluvial sedimentation: The Iron Gates Reservoir on the Danube River

ABSTRACT: Dam construction is one of the major human pressures impacting fluvial processes, including topography and hydro-sedimentary flows, as a result of the change in flow regime from fluvial to fluvial-lacustrine. This paper investigates geomorphic changes at Iron Gates I, the largest reservoir on the Danube River, completed in 1972 for hydropower and navigation. The study focuses on a gulf area that emerged at the mouth of the Cerna River into the reservoir, highlighting spatial changes in topography and sediment distribution, based on a diachronic analysis of two datasets before and after the dam was built: one extracted from historical topographic maps and the other obtained from a bathymetric echo sounding survey, integrated within a GIS analysis. The results reveal the dominance of the sedimentation process, with an alluvium layer thickness up to 14 m. The current sediment pattern has changed the submerged morphology, leading to the formation of an alluvial fan at the mouth of the Cerna River and of a sedimentary bar between the Cerna Gulf and the Danube River's channel. The siltation process together with the current underwater morphology limits ship traffic and the storage capacity of the reservoir.

KEY WORDS: hydropower dam, Iron Gates reservoir, sedimentation, topography, Cerna Gulf, Danube River

# Vpliv velikih jezov na rečno sedimentacijo: Primer zajezitve Železna vrata na Donavi

POVZETEK: Gradnja jezov je eden največjih človeških pritiskov, ki zaradi spremembe pretočnega režima iz rečnega v rečno-jezerskega vplivajo na rečne procese, vključno s topografijo in vodno-sedimentnimi tokovi. Namen prispevka je raziskati geomorfne spremembe znotraj zajezitve Železna vrata I, največje zajezitve na reki Donavi, ki je bila dokončana leta 1972 in je namenjena proizvodnji hidroenergije ter plovbi. Študija se osredotoča na zaliv, ki je nastal ob izlivu reke Cerne v akumulacijsko jezero, s poudarkom na prostorskih spremembah v topografiji in razporeditvi usedlin. Raziskava temelji na diahroni analizi dveh nizov podatkov pred in po zgradbi jezu: prvi je bil izvzet iz zgodovinskih topografskih zemljevidov, drugi pa pridobljen z batimetrično sonarsko raziskavo, integrirano v GIS okolju. Rezultati razkrivajo prevlado sedimentacije z debelino aluvialnega sloja do 14 m. Sedanji vzorec sedimenta je spremenil potopljeno morfologijo, kar je povzročilo nastanek vršaja ob ustju reke Cerne in sedimentnih nanosov med zalivom Cerna in Donavo. Proces siltacije skupaj z današnjo podvodno morfologijo omejuje ladijski rečni promet in tudi sedimentno zmogljivost akumulacije.

KLJUČNE BESEDE: jez hidroelektrarne, akumulacija Železna vrata, sedimentacija, topografija, zaliv Cerna, reka Donava

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# 1 Introduction

The construction of large dams and reservoirs has many and complex environmental, economic, and social impacts (Hohensinner et al. 2011; Zhang et al. 2016). Among the major consequences are alterations of hydro-sedimentary flows and geomorphic changes, both upstream and downstream from the dam (Brandt 2000; Zhou et al. 2011; Čanjevac and Orešić 2018; Li et al. 2018). Therefore, as a result of the transition from a fluvial to a fluvial-lacustrine flow regime upstream from the dam, sediment retention and shore abrasion processes become dominant (Petkovic, Dragovic and Markovic 1999; Repnik Mah, Mikoš and Bizjak 2010; Vukovic, Vukovic and Stankovic 2014). Generally, sediment distribution into reservoirs is related to erosion and accumulation processes (Zahar, Ghorbel and Albergel 2008), influenced by the incoming flow and sediment load, as well as the bottom morphology and the water level (Evrad et al. 1985). On the other hand, downstream from the dam, the liquid and solid flows considerably decrease, fluvial erosion intensifies, and the riverbed changes from a depositional regime from before dam construction to an erosional one (Castillo et al. 2007; Li et al. 2016).

The Iron Gates I (IG I) dam, known as *Porțile de Fier I* in Romanian and *Djerdap* in Serbian, is 1,278 m long and 60 m high. It was built about 900 km from the mouth of the Danube River at the Black Sea, mainly for hydropower and flood control, as well as to improve river transportation conditions in the Iron Gate Gorge area (Netzband 2007) between Romania on the north side and Serbia on the south side (Figure 1). Upstream from the IG I dam a reservoir more than 140 km long was formed, covering an area of about 100 km$^2$ and storing a volume up to 2.4 km$^3$ at the maximum retention level of 69.5 m (Aquaproiect 1992; Pop 1996). The hydropower plant has a total installed power of 2,136 MW, which is shared equally between the neighboring countries, Romania and Serbia (Pop 1996).

After it attained operational level in 1972, the IG I reservoir strongly affected the hydro-sedimentary flows and processes upstream and downstream from the dam. Upstream from the dam, the water level rose by about 30 m and the fluvial regime turned into a fluvial-lacustrine regime. Before the construction of the reservoir, the Danube River had high water levels in the spring and low levels in the fall, but later the water level and discharge regimes were strongly influenced by exploitation of the reservoir. As a result of the regulatory flow function of the reservoir, the discharge increases during low-water periods (in winter and fall), and it decreases during high-water periods in order to mitigate flood magnitudes (Zaharia 2010).

Regarding sediments, it is estimated that the IG I reservoir retains up to 77% of the suspended sediment volume supplied by the Danube River (Panin and Jipa 1998; Teodoru and Wehrli 2005; Babic Mladenovic et al. 2017). The sediments are deposited in layers of variable thickness, depending on the bottom morphology, the incoming flow velocity, and the underwater stream distribution (Evrad et al. 1985). The sedimentation process is more intensive within the small inlets or gulfs formed at the tributaries' mouths, as well as at the reservoir tail and in low areas where the flow is slow (Rădoane and Rădoane 2005). In some inlets with low flow rates (e.g., at Dubova and Svinița), the sediment layer exceeds 11 m in thickness (Zaharia 2010). The alluvium retention in the IG I reservoir had a direct effect on sediment reduction in the Danube Delta (Panin and Jipa 2002; Giosan et al. 2014; Constantinescu et al. 2015; Oaie et al. 2015). The annual average volume of suspended sediment supplied by the Danube River in its delta decreased by more than 50% after construction of the IG I dam (Zaharia et al. 2011; Zaharia and Ioana-Toroimac 2013).

This paper investigates the geomorphic changes induced by development of the IG I reservoir, as well as the spatial distribution and the dimension of sediment deposits, in order to provide useful information for reservoir management. The study focuses on the Cerna Gulf area, located north of the main stream of the Danube, in Romania, about 20 km upstream from the dam. This is the first study focusing on the Cerna Gulf, an important area in terms of economic activities at IG I reservoir, where the ship-building industry and river transportation are dominant activities.

# 2 Material and methods

## 2.1 Study area

The Cerna Gulf is located in a mountainous area in Iron Gates Natural Park (Figure 1), between kilometers 953 and 955 from the mouth of the Danube. It was artificially formed after construction of the IG I dam, when water accumulated in the reservoir flooded the floodplain and the lowest terraces of the Danube Valley. The Cerna River is the largest tributary of the Danube in this area, with a length of 87 km and a catchment area of 1,360 km² (Aquaproiect 1992). It has an annual average flow rate of about 20 m³/s and it carries about 3 kg/s of suspended sediments (Sârbu 2001). Before the reservoir was built, the Cerna River flowed into the Danube near the old town of Orşova, which developed on the floodplain and the two lowest terraces. Today this area is covered by water. The old confluence point was located 4 km downstream from the current position. The Cerna Gulf extends over almost 500 hectares and reaches a depth of 24 m. It is almost 3.4 km long and about 1.4 km wide. The gulf is surrounded by hills with elevations up to 460 m and slopes up to 50 degrees, formed by easily erodible sedimentary rocks, clays, marls, sands, and gravels. The lithology and the morphometry of this area is favorable for the occurrence of many morphodynamic processes, such as sheet erosion and landslides. Gully erosion is also widespread during the heavy rains of the early summer season. The materials eroded from the surrounding slopes, as well as those resulting from the abrasion processes, contribute to siltation of the gulf, affecting local economic activities, including the shipyard and the port.

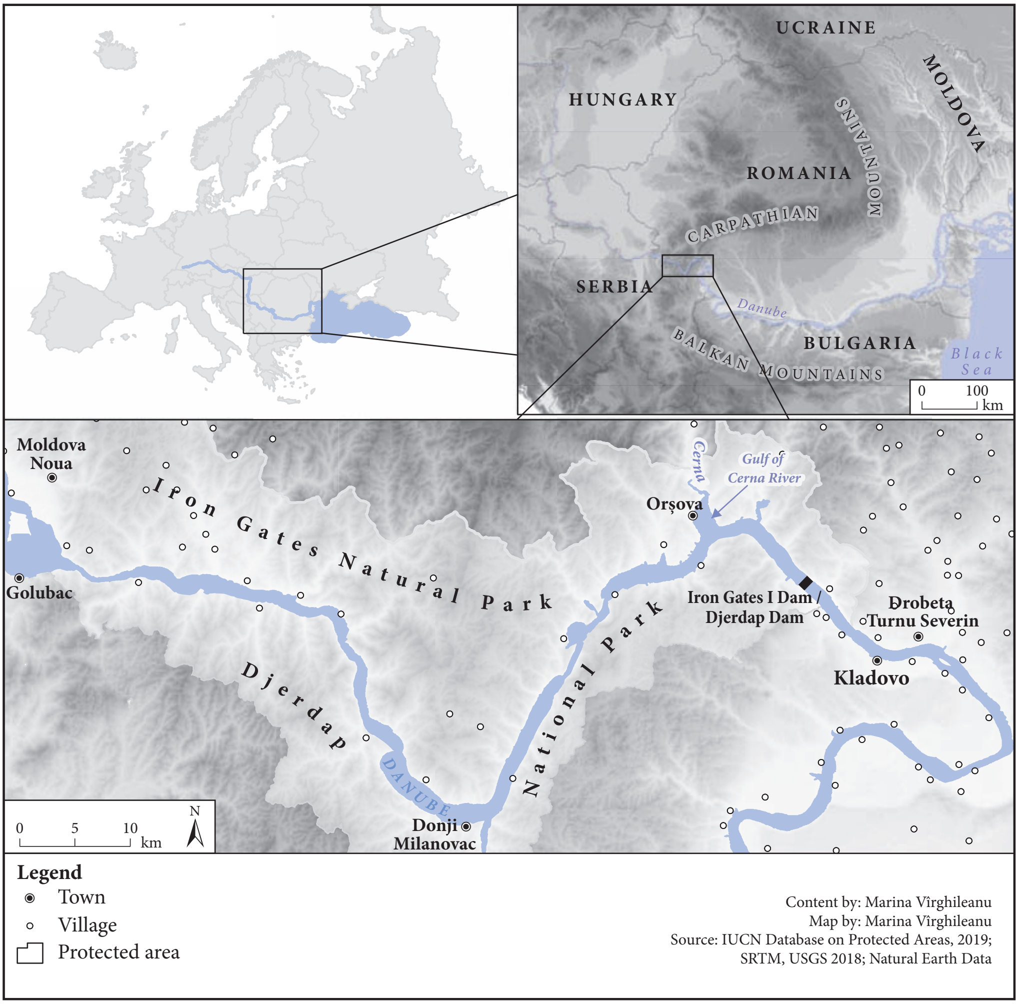



Figure 1: Location map of the study area.

## 2.2 Data and methods

The analysis follows two directions: reconstruction of the topography before the flooding of the Cerna Valley as a result of the formation of the IG I reservoir, and modeling the current submerged morphology within the Cerna Gulf. Based on these approaches, the changes in submerged morphology were revealed through a diachronic analysis (Figure 2).

The reconstruction of the former topography before the construction of the reservoir was based on military topographic maps at a 1:20,000 scale from 1939 (Romanian Army Shooting Map 1939) and 1:25,000 scale from 1952, edited by the Military Mapping Directorate (DTM). These maps were used to extract vector data representing contours at a 10 m interval, elevation points, and the stream network. These datasets were integrated into a spatial interpolation to obtain the Digital Elevation Model (DEM) of the study area. CORONA KH-4B satellite images from 1968 (Mihai, Nistor and Simion 2016) and the geomorphic map from the Iron Gates Atlas (Posea, Grigore and Popescu 1976) were used to map the old floodplain micro-landforms.

The current submerged topographic model was generated using bathymetric measurements collected with an echo sounder instrument. The survey was performed during two field campaigns, on March 29th and October 25$^{th}$, 2017, following previously drawn boat tracks. These 33 transects, with an interval of 100 m, were perpendicular to the former Cerna River's channel direction. Throughout those transects, the water depths were measured every 10 m, using a Garmin GPS map 298 single-beam sounder (Table 1). The sounder was sunk into the water at a depth of 0.30 m and set at a cone angle of 10° with a 200 kHz signal frequency for a clear view. Route coverage control was accomplished using the GIS MapPlus / iPhone 6s application with an accuracy of 2 to 3 m at an average boat speed of 10 km/h. The interconnected GPS/EGNOS system

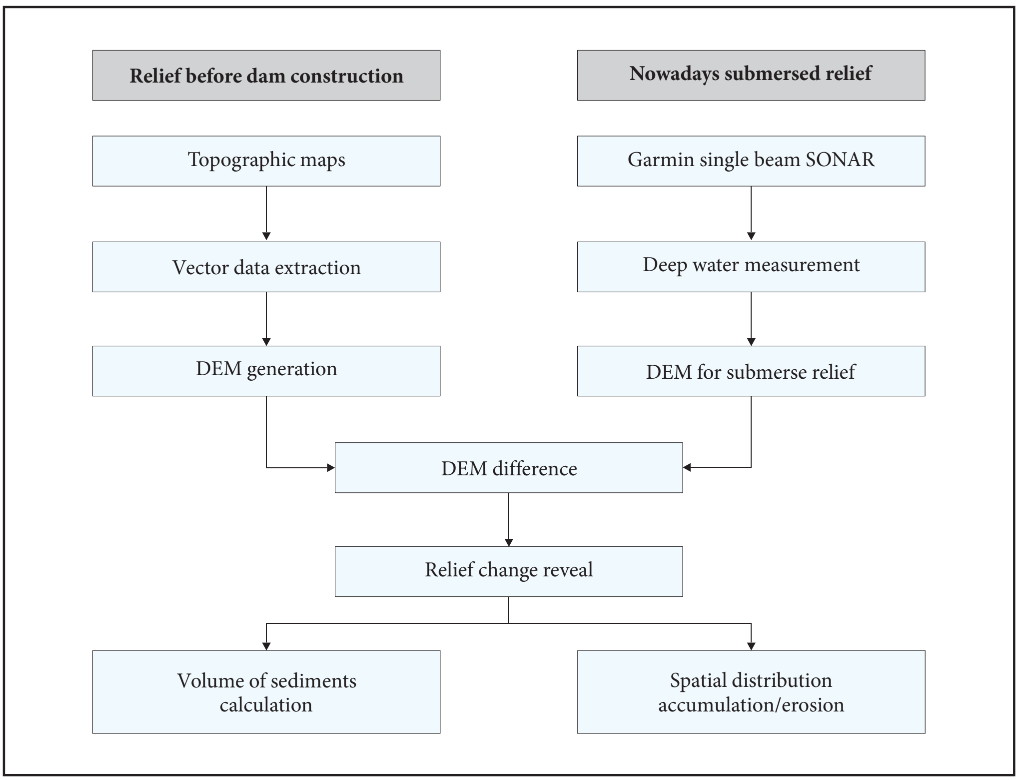



Figure 2: Workflow of the analysis.

provided the *xy* coordinates for each measurement in the GCS/WGS 84 coordinate system. In order to increase the data density during the measurements, another 1,351 observation points were manually recorded. All the data collected during the field surveys comprises 5,551 measurement points.

The values measured during both time periods were correlated with the variation in the water level of the Danube (Table 2) provided by the River Administration of the Lower Danube, a subsidiary of the Drobeta Turnu-Severin Navigable Way Agency (AFDJ) (River Administration of the Lower Danube 2017).

Table 1: Echo sounding survey parameters used for data collection during field surveys for bathymetric measurements.

| Data | March 29th, 2017 | October 25th, 2017 |
|---|---|---|
| Boat speed | 9 km/h | 8 km/h |
| Number of observations | 3,235 | 2,316 |
| Track length | 31.9 km | 13.7 km |
| Measurement time | 3h 33' | 1h 50' |
| Area covered | 400 ha | 140 ha |
| Distance between point observations | 10 m | 10 m |
| Offset | 0.3 m | 0.3 m |

Table 2: Reference values used for bathymetric data calibration.

| Data | March 29th, 2017 | October 25th, 2017 |
|---|---|---|
| Black Sea – Sulina/Constanța correction | +0.224 m | +0.224 m |
| Daily water level | 68.744 m | 69.444 m |
| Water level correction | +0.7 m | – |

The elevation of the corresponding points for the submerged landforms was calculated as the difference between the corrected water level and the measured water depths, using the formula $H = W_l - W_d$, where $H$ = elevation of the submerged topography (in m), $W_l$ = daily water level (in m), and $W_d$ = water depth (in m).

The daily water level values ($W_l$) for the first field survey, obtained from the AFDJ authority, were calibrated with the difference measured during the second survey. The water depth values were also corrected with the offset values adapted to the depth at which the sounder was sunk into the water. Then the elevation of the submerged topography (*H)* was correlated with the sea level value difference between the Sulina and Constanța reference points on the Black Sea coast (Table 2).

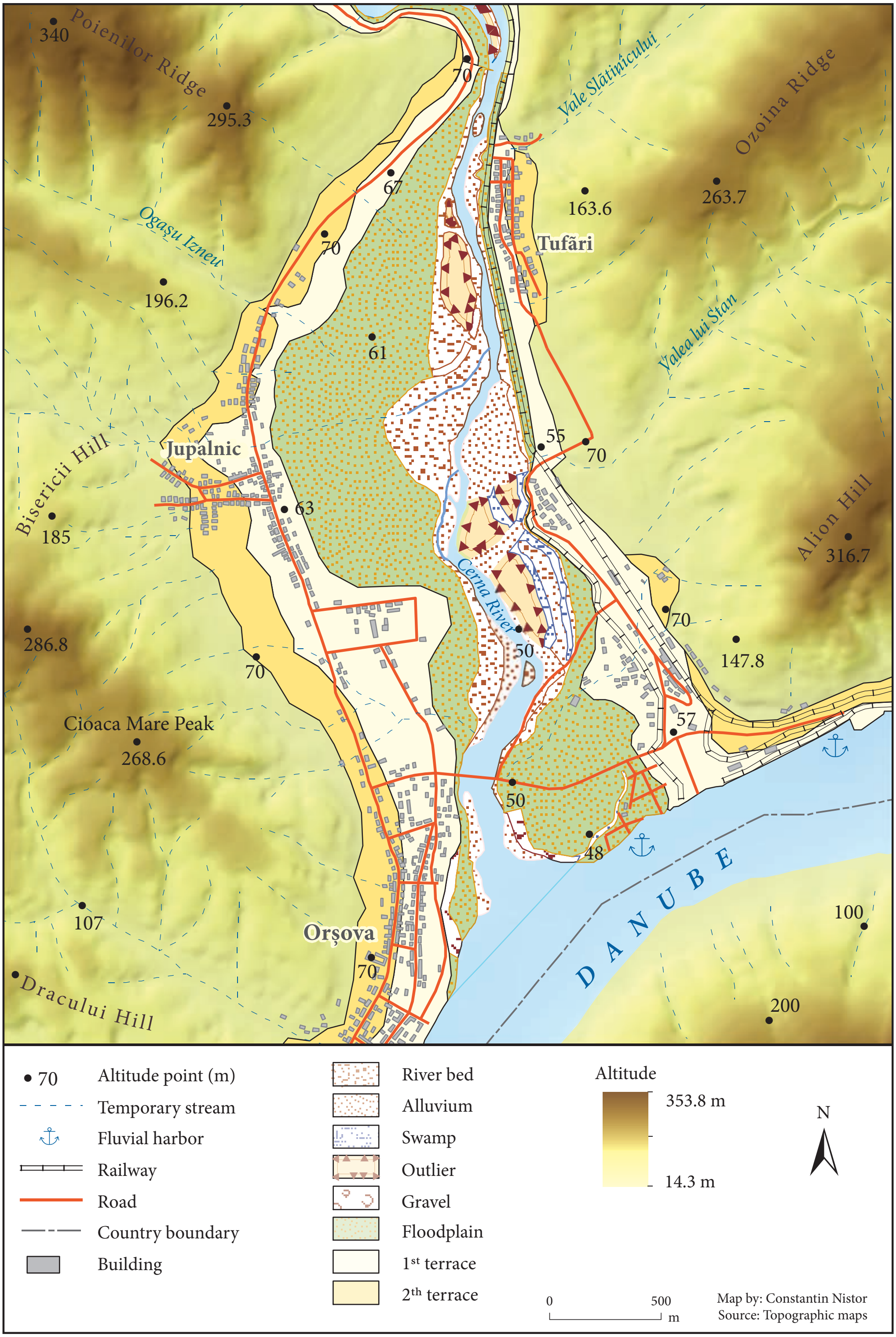
The topographic changes caused by development of the IG I reservoir were obtained as the difference between both elevation models: the first corresponding to the former topographic configuration (1939) and the second produced with the help of the in situ measurements of the submerged topography (2017).

The changes in the topography were highlighted within three cross-profiles from representative sectors of the Cerna Gulf, based on data extracted from the 1939 topographic map and on bathymetric measurements from 2017. These profiles show the spatial magnitude of the erosion and accumulation processes.

# 3 Results

The primary topography, prior to the formation of the IG I reservoir, was shaped by the Cerna and Danube rivers. The confluence area was a floodplain 500 to 700 m wide, bordered by two terraces where several settlements developed: the town of Orșova and the villages of Jupalnic and Tufări. Along the former floodplain, the Cerna River had several braided streams, sand accumulations, small islands, and marshes, typical for the natural evolution of the confluence area (Figure 3).

Figure 3: Fluvial morphology of the confluence area between the Cerna and Danube rivers in 1939, prior to the formation of the Iron Gates I reservoir. ➤



Poienilor Ridge
340
295.3
70
67
Vale Slătiniᶜului
Ozoina Ridge
Ogaşu Izneu
163.6
263.7
Tufări
196.2
Valea lui Stan
61
Jupalnic
55
70
Bisericii Hill
63
185
Alion Hill
316.7
Cerna River
70
147.8
286.8
70
50
57
Cioaca Mare Peak
268.6
50
48
107
D A N U B E
100
Orşova
70
Dracului Hill
200
70 Altitude point (m)
Temporary stream
Fluvial harbor
Railway
Road
Country boundary
Building
River bed
Alluvium
Swamp
Outlier
Gravel
Floodplain
1st terrace
2th terrace
Altitude
353.8 m
14.3 m
N
0
500
m
Map by: Constantin Nistor
Source: Topographic maps

The current depth configuration of the Cerna Gulf is closely linked to the old micro-landforms and to the sedimentation processes. In this respect, Figure 4 illustrates the correspondence between the deepest bathymetric points and the former channel of the Cerna River. Low water depths were also found close to the left bank, where submerged stream cutting is intensive. Except for the areas of the highest micro landforms that featured the former topography of the Cerna Valley, low water depths were found at the mouth of Cerna River and in the junction area between the Cerna Gulf and the Danube River channel, caused by a large accumulation of sediments.

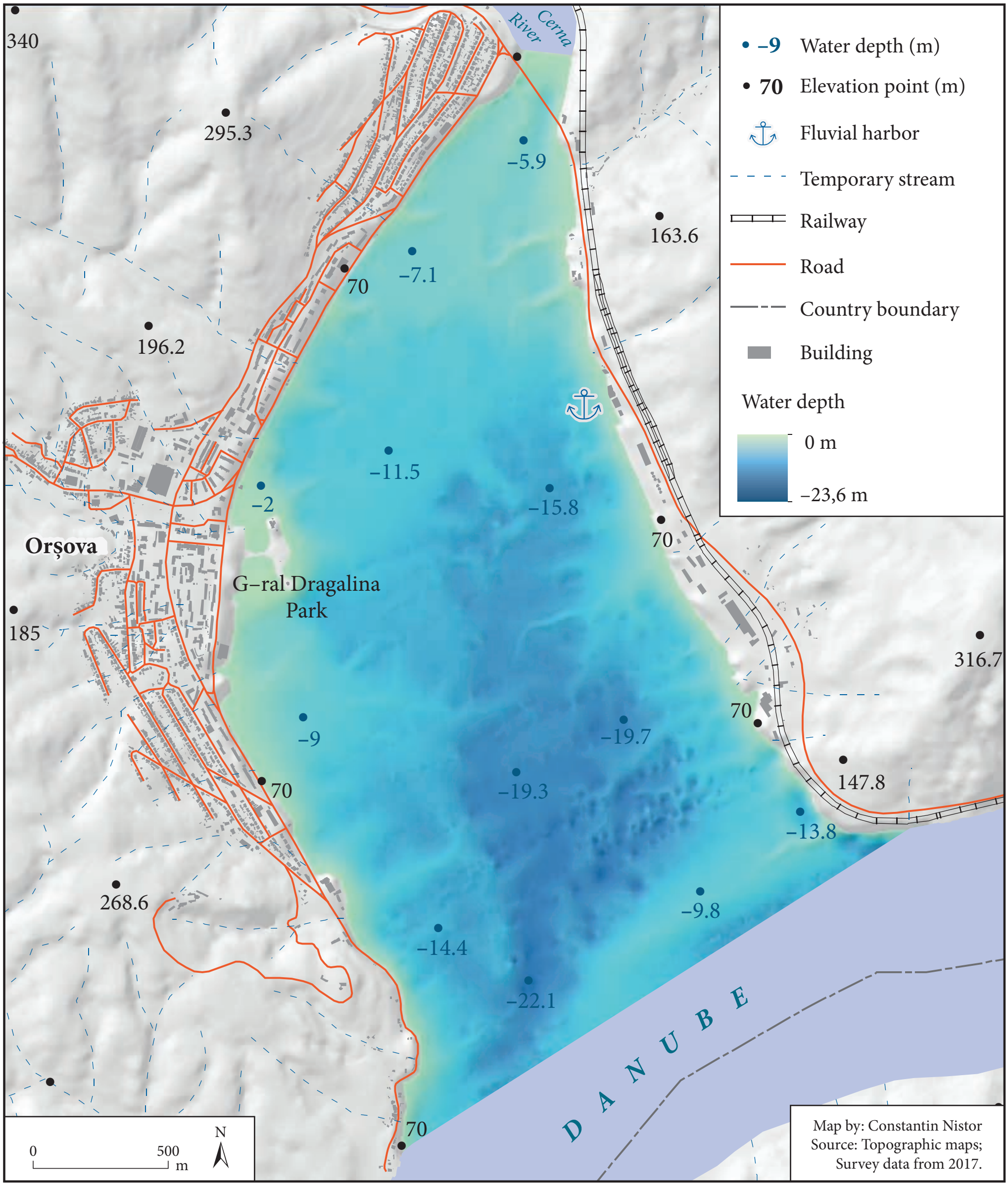



Figure 4: Current bathymetric configuration of the Cerna Gulf (2017).

The spatial distribution of topographic changes between 1939 and 2017 shows accumulation areas, marked by positive values, as well as erosion areas, marked with negative values, separated by sectors of minimal change. The analysis of the spatial distribution of the changes reveals the presence of three distinct sectors, marked on the map in Figure 5 as a, b, and c.

The first sector corresponds to the Cerna River fan deltas (Goudie 2006), at the entrance into the reservoir. This conical deposit is 1,300 m long, with a maximum width of 350 m. The granulometry classes feature 10% gravel in the upper section, 70% sand, and 20% silt in the lower part (Sârbu 2001). The bathymetric

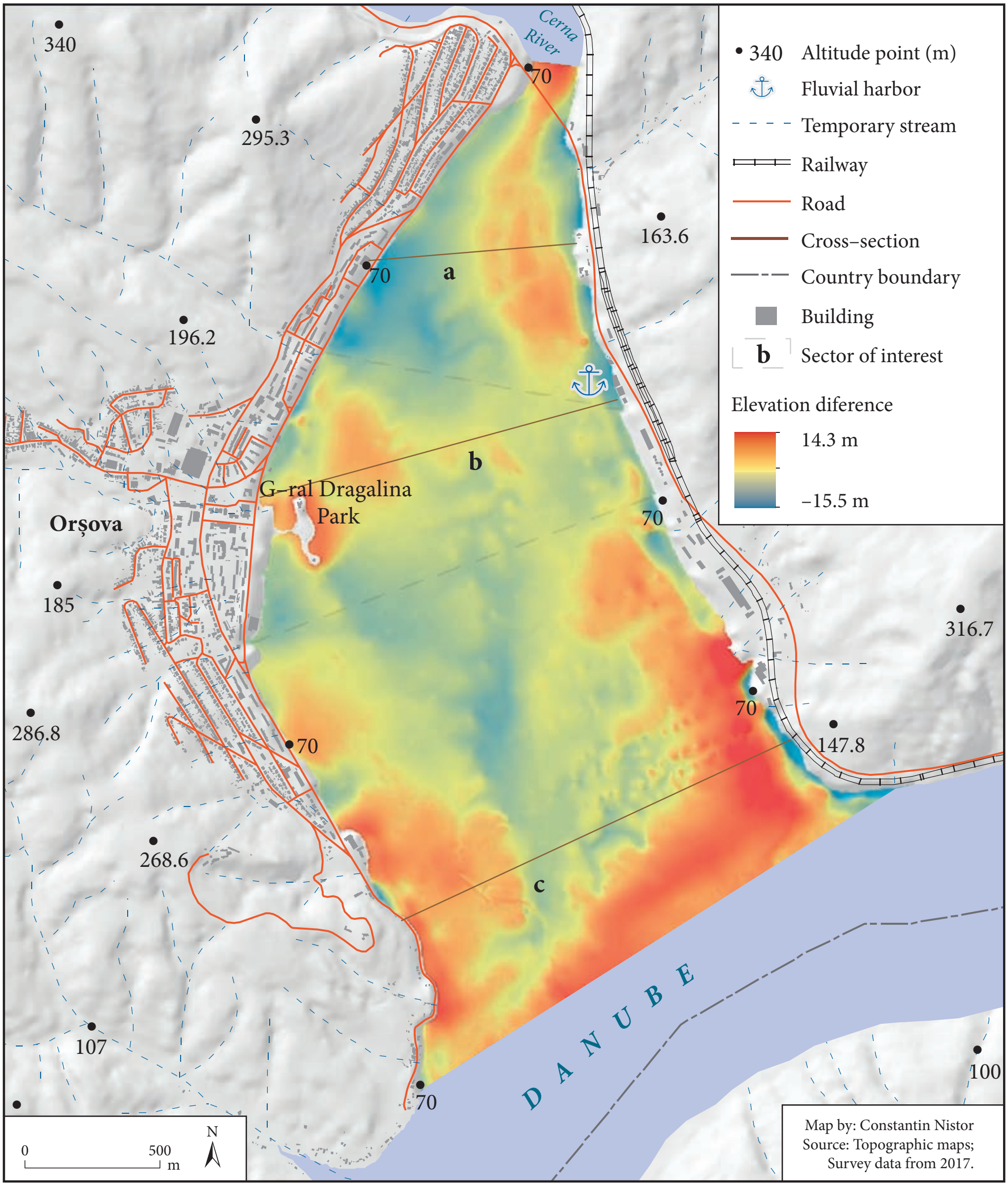



Figure 5: Map of topographic changes from 1939 to 2017 in the Cerna Gulf area.

profile crossing the first sector (Figure 6a) highlights the accumulation process in the central part with an alluvium thickness up to 5.5 m. It shows that the former channel of the Cerna River is completely covered by a sediment layer corresponding to the alluvial fan.

The second sector corresponds to the junction area of the main streams of the Cerna and Danube rivers. Sediments are distributed over a large surface due to the circular submerged stream generated by the Danube River, which crosses the former channel of the Cerna River. Anthropogenic structures, such as the General Dragalina Town Park island and the ship pontoons, influenced the configuration of the submerged landforms in this sector. Moreover, significant alluvium inflow is due to sediments carried by temporary streams to the right slope of the gulf, especially after major rainfall periods in April, May, and June.

The profile crossing the central area of the Cerna Gulf (Figure 6b) shows that the initial landforms – the extensive floodplain and the terraces of the Cerna River – were covered by sediments with a diverse and changing morphology. The accumulation process is dominant because the thickness of the sedimentary layer reaches 5 to 6 m in the western part of the profile due to lateral sediment inflow and the development of the artificial island in front of Orșova's new downtown. On the eastern edge of the gulf, which corresponds to Orșova's port area, the cross-profile indicates degradation of the topography because of excavation work along the new highway and railway embankments and cuttings (before 1970).

The third sector is influenced by the main stream of the Danube River, whose sediment supply is substantial. Within this sector, the sediments cover a compact area with a thickness up to 14 m and a maximum width over 500 m, similar to a cross-bar. The Cerna Gulf is located where the Danube River changes its flow direction from 40° NE to 80° E. This change of about 40° has significant effects on the river hydrodynamics with a higher inertia of flow. The main stream of the Danube, featuring a linear trajectory imposed by the alignment of the riverbed, tends to maintain its direction when entering the gulf area.

The profile crossing the third sector (Figure 6c) highlights the intensity of the accumulation process, mainly along with the lateral parts of the gulf. The old town of Orșova, located in the western part of the gulf, is covered with a sediment layer 5 to 6 m thick. On the opposite side, the sediment thickness reaches 12 m, but near the left shore the elevation decreased by 7 m in 2017 as an effect of anthropogenic reshaping of slopes prior to the development of the reservoir between 1965 and 1972. The central part of the gulf is affected by erosion processes.

The spatial analysis of the negative changes to the topography in the Cerna Gulf area reveals an unequal distribution that can be linked to various processes such as fluvial erosion, lacustrine abrasion, and anthropogenic processes. Many areas affected by negative changes are located near shorelines, where the elevation differences reach −15 m. These differences can be explained by the anthropogenic transformation of landforms and fluvial erosion. Engineering work such as blasting and reinforcement of slopes were required to rebuild the national/European highway from Bucharest to Timișoara and the main railway sectors 20 m higher than their original position. Other work was necessary for the construction of three road and railway viaducts crossing the main tributaries in the Cerna Gulf: the Cerna, Slătinicului, and Valea lui Stan rivers. Moreover, the port area and the dockyard site are regularly dredged in order to maintain a constant depth. Downstream from the town of Orșova, the Danube River's flow velocity generates submerged cutting of streams into the left slope, with effects on the channel and bank erosion.

The central area of the gulf is marked by negative changes of as much as −3 m, corresponding to the former channel of the Cerna River. During the periods with high flow rates, the alluvia are removed and the bottom of the gulf is eroded.

Other areas affected by negative changes are related to anthropogenic excavations such as slope tilting and to lacustrine abrasion caused by short-term variations in the water level due to reservoir management work.

# 4 Discussion

Under natural conditions, the beds of the Cerna and Danube rivers were paved with coarse deposits containing gravels mixed with sands known as the facies of the Danube. Measurements performed in 1968, 1973, 1975, and 1976 at km 955 on the Danube River revealed a positive balance for the former settlement site at Orșova, featuring an accumulation process with a sediment thickness between 1.0 and 2.5 m (Vespremeanu and Posea 1988).

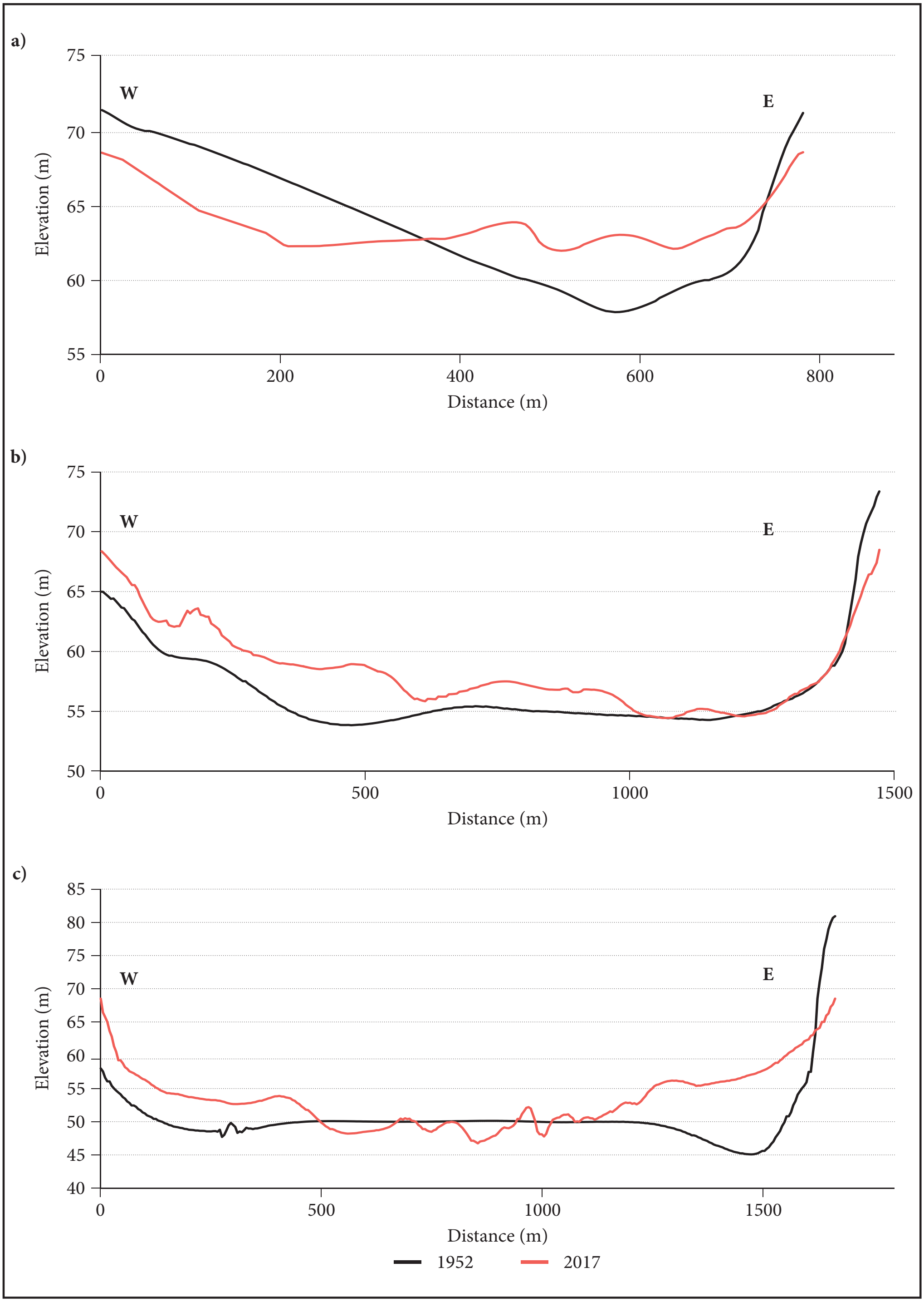



Figure 6: Cross profiles in the Cerna Gulf area, showing the topography before and after the Iron Gates I reservoir formation: a) first study sector, b) second study sector, c) third study sector.

The analysis of the spatial distribution of the sediments confirms the current siltation trend in the IG I reservoir (Diaconu 2005; Zaharia 2008; Babic Mladenovic, Kolarov and Damjanovic 2013). Our study maps for the first time the development of an alluvial bar tending to close the Cerna Gulf. Diaconu (2005) identified a similar distribution of sediments in the study area, mentioning intensive accumulation at the mouth of the Cerna River and also in the eastern part of the gulf, together with a deepening trend along the west shoreline. Șelău (2010) mentioned the development of a submerged alluvial deposit about 1 km long up to the entrance of the Cerna River into the gulf and a sediment cover more than 6.0 m deep.

For the entire gulf area, it has been clearly observed that the maximum thickness of the sediments reaches 14 m with a mean value of 3.8 m. This is related to a period of 45 years, from 1972 to 2017, at a mean rate of 8.2 cm/year. Other in situ measurement data obtained under similar environmental conditions at the confluence of the Topolnica River with the Danube on the Serbian side show a rate between 3 and 10 cm/year (Vukovic, Vukovic Stankovic 2014).

The lacustrine abrasion process is related to the water level oscillation as a main effect of reservoir management, together with the waves generated by international ship traffic of goods and passengers. Previous studies showed that the annual water level oscillations at the Orşova hydrometric station can reach 6.2 m, with a maximum rate of 1.3 m per day (Zaharia 2008). Fast and high-level variations reduce the stability of the neighboring slopes and shorelines, causing their collapse in extreme conditions. The abrasion process mainly affects the steeper shorelines, which can retreat by about 1 m/year (Zaharia 2008), contributing to the sediment supply to the reservoir.

The results were validated by measuring the sediment volumes accumulated, calculated through GIS spatial analysis. These were compared with the measured suspension sediment volumes supplied to the reservoir by the Cerna River. Sârbu (2001) estimates that the Cerna River has a suspended sediment discharge of 95,541.4 tons/year, which amounts to 1.8 million $m^3$ based on a sample density of 2,400 kg/$m^3$, according to Oaie et al. (2015), for 45 years since the IG I reservoir was formed. This value is similar to our estimate of 1.72 million $m^3$.

The project for electricity production in this section of the Danube Basin was extended for tributary rivers as well. In this respect, two other reservoirs, Lake Valea lui Iovan and Lake Hercule, were built upstream, along the Cerna Valley sector for power generation and flood prevention (Pop 1996). The construction of these reservoirs along the Cerna River in 1983, with a water volume of 138 million $m^3$, led to a decrease in the river flow rate from 35 $m^3/s$ to 18.5 $m^3/s$ (Sârbu 2001; Hrvatin et al. 2019). As a consequence, the stream power flowing into the Cerna Gulf significantly decreased. The alluvium did not reach the Danube River's main channel, leading to the development of the fan delta in the upper section of the Cerna Gulf.

The damming of the Danube River altered the sediment flow from 67.5 million tons/year before the reservoir formation to 30 million tons/year measured at the discharge mouths (Panin and Jipa 1998). The decrease of the sediment volume supplied by rivers into the sea is a general feature for most dammed rivers (Stănică and Panin 2009). For example, the sediment amounts of the Yellow River in China decreased by three times after the construction of the Sanmenxia Dam and Xiaolangdi Dam (Yonggui et al. 2013). The same situation occurred after the construction of the Aswan High Dam in 1964 on the Nile River in Egypt (Gu, Chen and Salem 2011; Kantoush and Sumi 2013). The Mississippi River in North America, one of the most modified rivers (Kesel 2003), has had a total decrease in sediment flow from 400 million tons/year to 200 million tons/year (Allison et al. 2012; Meade and Moody 2009), leading to erosion processes on 60% of the deltaic coast (Bentley et al. 2014). For the Danube, the Gabčíkovo–Nagymaros Dams led to the retention of 70% of sediments transported (Smith, Szilágyi and Horváth 2002).

# 5 Conclusion

This study provides the first detailed map of the submerged relief of the Cerna Gulf, which developed after the Danube River was dammed and the IG I reservoir formed. These results highlight the spatial distribution of accumulation sectors, which reach 14 m in thickness, as well as areas with negative changes in topography caused by anthropogenic work together with erosion processes.

The Cerna Gulf is a characteristic area along the Danube River where accumulation processes exceed erosional ones by a ratio of 4:1, emphasizing a smooth lake clogging tendency. Sediment deposition changed the submerged morphology during the last 45 years, leading to the accumulation of an alluvial fan at the mouth of the Cerna River and an alluvial bar between the Cerna Gulf and the main channel of the Danube River. The siltation process has a negative effect on river transportation as well as on the sustainability of the port in Orșova, which specializes in coal and coke transport. It also has a negative impact on emerging tourism traffic and on shipyard activities, which involve the production of hulls. In addition, it decreases the volume of water storage and accelerates the eutrophication level. For this reason, periodic dredging activities are required to allow ships to access the Orșova port basin.

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# 6 References

Allison, M. A., Demas, C. R., Ebersole, B. A., Kleiss, B. A., Little, C. D., Meselhe, E. A., Powell, N. J., Pratt, T. C., Vosburg, B. M. 2012: A water and sediment budget for the lower Mississippi–Atchafalaya River in flood years 2008–2010: Implications for sediment discharge to the oceans and coastal restoration in Louisiana. Journal of Hydrology 432-433. DOI: https://doi.org/10.1016/j.jhydrol.2012.02.020

Aquaproiect. Atlasul Cadastrului apelor din România. Bucharest, 1992.

Babic Mladenovic, M., Kolarov, Damjanovic, V., Radosavljevic, P. 2017: Comparison of the »natural« and the present sediment regime of the Danube River. Water Research and Management 1-3.

Babic Mladenovic, M., Kolarov, V., Damjanovic, V. 2013: Sediment regime of the Danube River in Serbia. International Journal of Sediment Research 28-4. DOI: https://doi.org/https://doi.org/10.1016/S1001-6279(14)60006-8

Bentley, S. J., Freeman, A. M., Willson, C. S., Cable, J. E., Giosan, L. 2014: Using what we have: Optimizing sediment management in Mississippi River delta restoration to improve the economic viability of the Nation. Perspectives on the restoration of the Mississippi Delta. Estuaries of the World. Dordrecht. DOI: https://doi.org/10.1007/978-94-017-8733-8_6

Brandt, S. A. 2000: Classification of geomorphological effects downstream of dams. Catena 40-4. DOI: https://doi.org/https://doi.org/10.1016/S0341-8162(00)00093-X

Čanjevac, I., Orešić, D. 2018: Changes in discharge regimes of rivers in Croatia. Acta geographica Slovenica 58-2. DOI: https://doi.org/10.3986/AGS.2004

Castillo, V. M., Mosch, W. M., García, C. C., Barberá, G. G., Cano, J. A. N., López-Bermúdez, F. 2007: Effectiveness and geomorphological impacts of check dams for soil erosion control in a semiarid Mediterranean catchment: El Cárcavo (Murcia, Spain). Catena 70-3. DOI: https://doi.org/https://doi.org/10.1016/j.catena.2006.11.009

Constantinescu, Ş., Achim, D., Rus, I., Giosan, L. 2015: Embanking the lower danube: From natural to engineered floodplains and back. Geomorphic Approaches to Integrated Floodplain Management of Lowland Fluvial Systems in North America and Europe. New York. DOI: https://doi.org/10.1007/978-1-4939-2380-9_11

Diaconu, D. C. 2005: Caracteristici morfologice ale cuvetei Golfului Orșova.Comunicări de Geografie. Bucharest.

Evrad, J., McManus, J., Jobson, H. E., Jiahua, F., Bruk, S. 1985: Methods of computing sedimentation in lake and reservoirs. Belgrade.

Giosan, L., Syvitski, J., Constantinescu, S., Day, J. 2014: Climate change: Protect the world's deltas. Nature 516-7529. DOI: https://doi.org/10.1038/516031a

Goudie, A. S. 2006: Global warming and fluvial geomorphology. Geomorphology 79-3,4. DOI: https://doi.org/10.1016/j.geomorph.2006.06.023

Gu, J., Chen, Z., Salem, A. 2011: Post-Aswan dam sedimentation rate of lagoons of the Nile Delta, Egypt. Environmental Earth Sciences 64. DOI: https://doi.org/10.1007/s12665-011-0983-2

Hohensinner, S., Jungwirth, M., Muhar, S., Schmutz, S. 2011: Spatio-temporal habitat dynamics in a changing Danube River landscape 1812–2006. River Research and Applications 27-8. DOI: https://doi.org/10.1002/rra.1407

Hrvatin, M., Ciglič, R., Lóczy, D., Zorn, M. 2019: Določanje erozije v gričevjih severovzhodne Slovenije z Gavrilovićevo enačbo. Geografski vestnik 91-2. DOI: https://doi.org/10.3986/GV91206

Kantoush, S. A., Sumi, T. 2013: Reservoir sedimentation and sediment management techniques in the Nile River basin countries. Advances in River Sediment Research. Internet: http://ecohyd.dpri.kyoto-u.ac.jp/content/files/sumi-paper/2013/c144.pdf (3. 9. 2020).

Kesel, R. H. 2003: Human modifications to the sediment regime of the Lower Mississippi River flood plain. Geomorphology 56-3,4. DOI: https://doi.org/https://doi.org/10.1016/S0169-555X(03)00159-4

Li, S., Li, Y., Yuan, J., Zhang, W., Chai, Y., Ren, J. 2018: The impacts of the Three Gorges Dam upon dynamic adjustment mode alterations in the Jingjiang reach of the Yangtze River, China. Geomorphology 318. DOI: https://doi.org/10.1016/j.geomorph.2018.06.020

Li, Y., Yang, G., Li, B., Wan, R., Duan, W., He, Z. 2016: Quantifying the effects of channel change on the discharge diversion of Jingjiang Three Outlets after the operation of the Three Gorges Dam. Hydrology Research 47-S1. DOI: https://doi.org/10.2166/nh.2016.016

Meade, R. H., Moody, J. A. 2009: Causes for the decline of suspended-sediment discharge in the Mississippi River system, 1940–2007. Hydrological Processes 24-1. DOI: https://doi.org/10.1002/hyp.7477

Mihai, B., Nistor, C., Toma, L., Săvulescu, I. 2016: High resolution landscape change analysis with CORONA KH-4B imagery. A case study from iron gates reservoir area. Procedia Environmental Sciences 32. DOI: https://doi.org/10.1016/j.proenv.2016.03.025

Netzband, A. 2007: Sediment management: An essential element of river basin management plans. Journal of Soils and Sediments volume 7. DOI: https://doi.org/10.1065/jss2007.02.212

Oaie, G., Secrieru, D., Bondar, C., Szobotka, Ş., Duțu, L., Stănescu, I., Opreanu, G., Duțu, F., Pojar, I., Manta, T. 2015: Lower Danube river: Characterization of sediments and pollutants. Geo-Eco-Marina 21.

Panin, N., Jipa, D. 1998: Danube River sediments input and its interaction with the North-Western Black Sea, Geo-Eco-Marina 3. Proceedings of International Workshop on »Continental Margins and Sea Level Changes«.

Panin, N., Jipa, D. 2002: Danube river sediment input and its interaction with the north-western Black Sea. Estuarine, Coastal and Shelf Science 54-3. DOI: https://doi.org/10.1006/ecss.2000.0664

Petkovic, S., Dragovic, N., Markovic, S. 1999: Erosion and sedimentation problems in Serbia. Hydrological Sciences Journal 44-1. DOI: https://doi.org/10.1080/02626669909492203

Pop, G. 1996: România, geografie hidroenergetică. Cluj-Napoca.

Posea, G., Grigore, M., Popescu, N. 1976: Terraces and leveling surfaces. The »Iron Gate« complex atlas. Bucharest.

Rădoane, M., Rădoane, N. 2005: Dams, sediment sources and reservoir silting in Romania. Geomorphology 71-1,2. DOI: https://doi.org/10.1016/j.geomorph.2004.04.010

Repnik Mah, P., Mikoš, M., Bizjak, A. 2010: Hydromorphological classification of Slovenian rivers. Acta geographica Slovenica 50-2. DOI: https://doi.org/10.3986/AGS50202

River administration of the lower Danube, 2017. Danube water levels. Internet: https://www.afdj.ro (10. 3. 2017).

Romanian army shooting map 1 : 20,000, 2346-Orșova; 2347-Ada Kaleh. Military geographical service. Bucharest, 1939.

Sârbu, I. 2001: Valea Cernei – Caracterizare fizico-geografica cu privire speciala asupra hidrografiei. PhD. thesis, University of Bucharest. Bucharest.

Șelău, N. 2010: Lacul Porțile de Fier, caracterizare fizico-geografică și funcțională. Scurt istoric. Comunicări de Geografie. Bucharest.

Smith, S., Szilágyi, F., Horváth, L. 2002: Environmental impacts of the Gabcikovo Barrage System to the Szigetköz region. Clean Technologies and Environmental Policy 4. DOI: https://doi.org/10.1007/s10098-001-0125-8

Stănică, A., Panin, N. 2009: Present evolution and future predictions for the deltaic coastal zone between the Sulina and Sf. Gheorghe Danube river mouths (Romania). Geomorphology 107-1,2. DOI: https://doi.org/10.1016/j.geomorph.2007.04.041

Teodoru, C., Wehrli, B. 2005: Retention of sediments and nutrients in the Iron Gate I Reservoir on the Danube River. Biogeochemistry 76. DOI: https://doi.org/10.1007/s10533-005-0230-6

Topographic map L-34-117-D-d (Orșova). Military mapping directorate. 1952.

Vespremeanu, E., Posea, A. 1988: Sedimentarea și sedimentele din lacul de acumulare Porțile de Fier I. Probleme de Geomorfologia Romănei II. Bucharest.

Vukovic, D., Vukovic, Z., Stankovic, S. 2014: The impact of the Danube Iron Gate Dam on heavy metal storage and sediment flux within the reservoir. Catena 113. DOI: https://doi.org/10.1016/j.catena.2013.07.012
Yonggui, Y., Xuefa, S., Houjie, W., Chengkun, Y., Shenliang, C., Yanguang, L., Limin, H., Shuqing, Q. 2013: Effects of dams on water and sediment delivery to the sea by the Huanghe (Yellow River): The special role of Water-Sediment Modulation. Anthropocene 3. DOI: https://doi.org/https://doi.org/10.1016/j.ancene.2014.03.001
Zahar, Y., Ghorbel, A., Albergel, J. 2008: Impacts of large dams on downstream flow conditions of rivers: Aggradation and reduction of the Medjerda channel capacity downstream of the Sidi Salem dam (Tunisia). Journal of Hydrology 351-3,4. DOI: https://doi.org/10.1016/j.jhydrol.2007.12.019
Zaharia, L. 2008: Impactul lacului de acumulare Porțile de Fier I asupra morfodinamicii malului și a versantului românesc. Comunicări de Geografie. Bucharest.
Zaharia, L. 2010: The iron gates reservoir: Aspects concerning hydrological characteristics and water quality. Lakes Reservoirs and Ponds 4-1.
Zaharia, L., Grecu, F., Ioana-Toroimac, G., Neculau, G. 2011: Sediment transport and river channel dynamics in Romania: Variability and control factors. Sediment Transport in Aquatic Environments. DOI: https://doi.org/10.5772/21416
Zaharia, L., Ioana-Toroimac, G. 2013: Romanian Danube River management: Impact and perspectives. European continental hydrosystems under changing water policy. Munich.
Zhang, W., Yuan, J., Han, J., Huang, C., Li, M. 2016: Impact of the Three Gorges Dam on sediment deposition and erosion in the middle Yangtze River: A case study of the Shashi Reach. Hydrology Research 47-S1. DOI: https://doi.org/10.2166/nh.2016.092
Zhou, Y., Zhang, Q., Li, K., Chen, X. 2011: Hydrological effects of water reservoirs on hydrological processes in the East River (China) basin: Complexity evaluations based on the multi-scale entropy analysis. Hydrological Processes 26-21. DOI: https://doi.org/10.1002/hyp.8406