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THE APPLICABILITY OF GIS TECHNOLOGY IN THE STUDY OF RIVERBED DYNAMICS AND MORPHOLOGY

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Abstract

This study examines the geomorphological conditions of representative gravel extraction sites along the Moldova River and assesses the impact of riverbed material extraction on the stability of the riverbed and the sediment regeneration rate. The analyzed sector spans approximately 26 km, encompassing the stretch of the Moldova River between Păltinoasa and Cornu Luncii in Suceava County, with a particular focus on the Capu Câmpului extraction site. The intensity of gravel extraction activities is reflected in the variations of suspended sediment hydrographs, which exhibit an increasing trend over time in the Moldova River, contrasting with the general decreasing trend observed in other rivers of the Siret Basin. Utilizing GIS techniques, including orthophotoplans and ArcGIS 9.2 software (via Digital Elevation Model creation), calculations were made for the volumes of mineral aggregates potentially extractable between 2017 and 2021. Previous studies have demonstrated that riverbed material extraction can lead to significant modifications in river morphology, including channel erosion and changes in hydraulic regimes, with effects on aquatic biodiversity and water quality. In conclusion, the research underscores the importance of detailed evaluation of the impact of riverbed material extraction on the geomorphological and ecological stability of the Moldova River, to support the development of sustainable management practices for fluvial resources.

Key words: *GIS techniques, riverbed, extraction.*

INTRODUCTION

Before 1990, Romania's construction materials industry faced a significant annual demand of approximately 80 million cubic meters of sorted sands and gravels (Călinoiu et al., 1988). These natural resources were regularly extracted from riverbeds and surrounding lands, playing a crucial role in supporting infrastructure development. However, ballast extraction was insufficiently regulated, leading to considerable environmental impacts, especially concerning alterations to watercourses and degradation of adjacent soils.
Following a period of economic decline, the demand for ballast increased again, reflecting a revitalization of the construction industry and, implicitly, greater pressure on natural resources. Currently, the requirements are much higher, placing considerable strain on riverbeds and the lands of major riverbeds, which are used for extracting sand and gravel. Romanescu (2009) observed this trend and emphasized that despite increased demand, there is a lack of detailed assessments of these activities' effects on riverbeds.
One of the main constraints regarding sand and gravel extraction is the imposition of quality conditions and strict environmental regulations. Consequently, the extraction area has significantly narrowed, and extraction activities are mainly concentrated in the middle and lower sectors of the minor riverbeds of major rivers, where there is greater resource availability and more flexibility in managing environmental impact. Thus, in the case of the Siret River, for example, approximately 230 gravel pits operate, with an annual production of about 2 million cubic meters of ballast, representing a considerable potential for transforming minor riverbeds (Călinoiu et al., 1988). This constitutes an important resource but poses a significant challenge for the sustainable management of river ecosystems (Gâștescu 2014). Despite this high ballast extraction potential, studies on the ecological impact of gravel pits on riverbeds are relatively limited. Romanescu (2009) observes that

comprehensive or detailed evaluations of how these gravel pits contribute to modifying riverbeds or changing river landscapes are lacking. Instead, most research focuses on isolated observations and case studies of individual rivers, limiting the general understanding of the phenomenon. This highlights the critical need for comprehensive research to systematically evaluate the effects of ballast extraction on river morphology and adjacent ecosystems. Such studies are essential for developing informed and sustainable resource management strategies. Additionally, it's important to note that changes in riverbeds resulting from ballast extraction activities can have profound effects on their biodiversity and ecological stability (Bătucă et al., 1992). For example, the disappearance of natural habitats for aquatic species and soil erosion can lead to a significant decline in biological diversity. Therefore, ballast extraction must be conducted within a regulated framework that minimizes environmental harm.

In conclusion, extracting sand and gravel from riverbeds represents a vital resource for the construction industry, but also poses major challenges for environmental conservation.

GIS technology enables the integration of various data sources, such as satellite imagery, aerial photographs, topographic maps, and remote sensing data, to provide a detailed and updated view of riverbed changes. This spatial data integration is essential for long-term monitoring, helping to document erosion, sedimentation, and channel migration processes.

Thorne et al. (2012) demonstrated that remote sensing and GIS technologies facilitate the rapid detection of river morphology changes, including erosion and channel shifts, which are often challenging to observe using conventional methods. Similarly, Goss et al. (2004) showed that GIS-based analysis of multi-temporal georeferenced data enables the monitoring of sequential riverbed changes following human interventions, such as dam construction or water diversion, revealing trends in channel migration and their ecological impacts.A relevant example highlighting the effectiveness of these tools is the study by Zhang et al. (2017), which applied GIS to assess channel changes in the Yangtze River, successfully identifying areas prone to erosion and flooding. Such spatial analyses are essential for flood disaster prevention and infrastructure protection in vulnerable regions (Vlad, 2017; Moldovan et al., 2023).

This study aims to enhance our understanding of the long-term effects of gravel pit operations on riverbeds and aquatic ecosystems (Cercel, 2019). The findings highlight the necessity for comprehensive research to systematically evaluate the impact of ballast extraction on river morphology and surrounding ecosystems. Such studies are essential for developing and implementing more effective resource management strategies that balance development with environmental conservation.

MATERIALS AND METHODS

This study employs ArcGIS 9.2 technology, encompassing: (i) the development of a Digital Elevation Model (DEM) through triangulation techniques and delineation of the study area's boundaries; and (ii) the computation of aggregate volumes resulting from both extraction and alluvial transport processes, as illustrated in Figure 1.

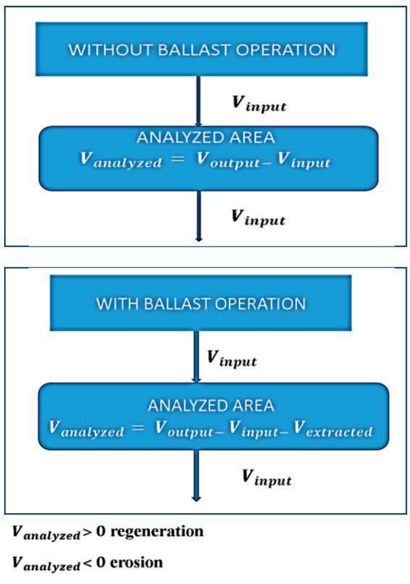


Figure 1. Calculation of aggregate volume

This methodology is applied to the profiles situated on the middle course of the Moldova

River, between Păltinoasa and Cornu Luncii localities. The research is conducted for the period 2017-2021.

Study Area

The study area is situated on the Moldova River, which is located in the northeastern part of the Eastern Carpathians and the northwestern part of the Moldavian Plateau (Figure 2).

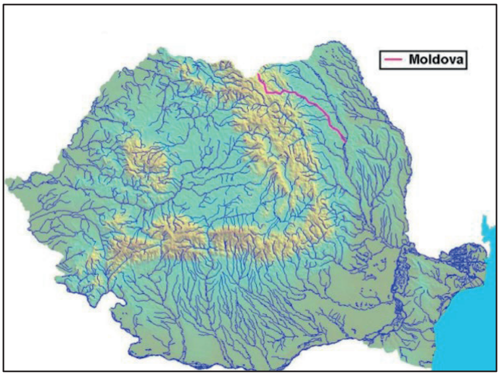


Figure 2. Location of the Moldova River on the hydrographic map of Romania (source: Wikipedia)

The Moldova Valley forms a depression between the Subcarpathians of Moldova and the Suceava Plateau, shaped by the Moldova River. Originating in the Obcina Feredeu Mountains (Suceava County), the river flows through Suceava and Neamț counties before joining the Siret River near Roman. As a right tributary of the Siret, the Moldova River features a broad and low floodplain up to Ciumulești, with its widest floodplain and terrace development observed at Baia, where the landscape adopts a depression-like character (Bartha et al., 2014; Bălan et al., 2016). The floodplain hosts a single, highly productive aquifer (yielding over 10 l/s), representing a key high-quality water reserve for eastern Romania (Cercel, 2018). The alluvial plain of the Moldova River, characterized by a grain size distribution well-suited for construction aggregates, represents one of the most significant exploitable sources in the Moldova region (Amăriucăi, 2000; Marcoie et al., 2023). This renewable resource is continuously replenished due to the river's mountainous hydrological regime, which alternates with plateau influences, and notably due to the absence of hydroelectric infrastructure in the Moldova River basin (Ichim et al., 1989). The analyzed extraction sites are located along the middle course of the Moldova River, between Păltinoasa and Cornu Luncii, entirely within the Subcarpathian sector of the Moldavian Plateau. This region is defined by hilly terrain with altitudes ranging from 400 to 600 meters, gradually decreasing from north to south.

According to detailed geomorphological mapping by Rădoane (2007), the middle sector of the Moldova River in Suceava County, between Păltinoasa and Cornu Luncii, features a well-developed alluvial plain with alluvial terraces rising 4-5 meters above the current riverbed. Key extraction perimeters within this area include Pod Izvor, Capu Câmpului, and Cornu Luncii (Figure 3).

The Capu Câmpului extraction site is located outside the built-up area (extravilan) of Capu Câmpului village, Suceava County, along the riverbed of the Moldova River, just downstream of the confluence with the Isachia stream. The operational perimeter lies between cadastral markers C.S.A. 116 and C.S.A. 117 (Figure 4).

Figure 3. Plan with the location of the three exploitation perimeters. Source: Google maps

Figure 4. Plan with the location of the Capu Câmpului exploitation perimeters. Source: Google maps

The following data sets were used in this study: updated situation plans with contour lines at a scale of 1:5000 and orthophotoplans. The contour lines were vectorized and together with the measured points on the situation plans allowed the creation of a Digital Elevation Model (Biali, 2013). The interpolation method chosen was TIN (Triangulated Irregular Network). TIN interpolation is another popular tool in GIS. A common TIN algorithm is called Delaunay triangulation.

The updated situation plans and orthophotoplans used to represent the study sectors are documents provided and authorized by ANCPI Suceava. Over these orthophotoplans, the Modova riverbed was vectorized and the positions of the transversal profiles were drawn. These profiles tracking the riverbed that frames the exploitation perimeter were maintained in the same place year after year (by means of field markers) so that the measurement results are correct and consistent in accordance with the initiated study.

RESULTS AND DISCUSSIONS

The study commenced in 2017 with field measurements conducted across five cross-sections (P1-P5). Figure 5 shows the 2017 boundary of the mineral aggregate extraction perimeter (points 1–2–3–4) along the Moldova River bed.

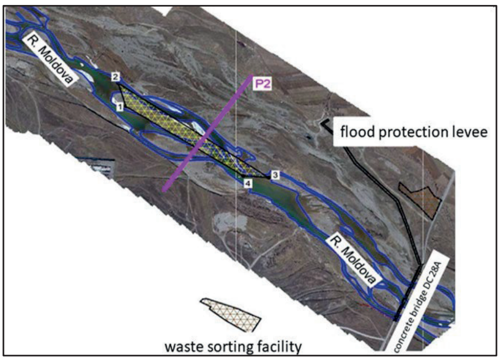
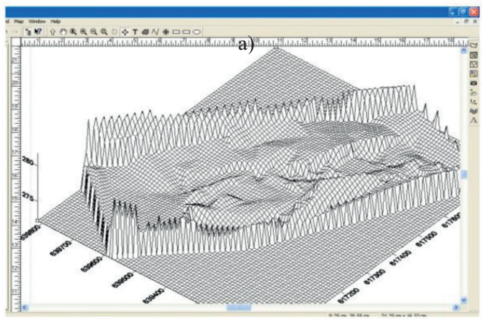


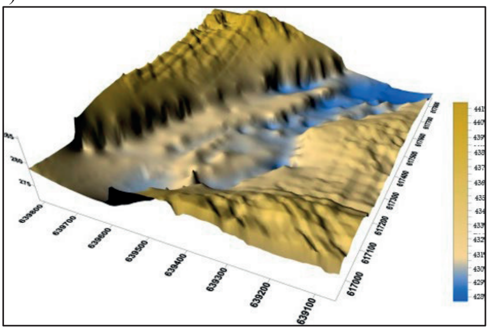
Figure 5. Orthophotomap of the Capu Câmpului perimeter from 2017

The Numerical Terrain Model in Figure 6 represents the studied Capu Câmpului sector. The hypsometry is in the range of 428 (thalweg) 441 m (left slope).

The Numerical Terrain Model served as the foundation for calculating the volumes of mineral aggregates present within the riverbed.



a)



b)

Figure 6. 3D representation of the Numerical Terrain Model for the studied perimeter
(a. wireframe; b. grid fill)

This study employs two complementary research methods: profile-based approaches and Digital Terrain Model (DTM)-based analyses. Transversal profile measurements, conducted annually within the same cross-section, yield direct and reliable results. These measurements are processed using ArcGIS 9.2 software to model the riverbed of the Moldova River. The DTM results are utilized for both aggregate volume calculations and monitoring the morphological evolution of the riverbed over time. Field measurements were performed using the Trimble® R780 GNSS receiver, an advanced geospatial instrument. The R780 features a 9 GB internal memory and operates with Trimble Access software. It incorporates Trimble Inertial Platform™ (TIP) technology, providing tilt compensation based on an Inertial Measurement Unit (IMU), ensuring resistance to magnetic interference. This system is designed to withstand harsh environmental conditions, offering high precision and reliability for geospatial data collection.

Tables 1 and 2 show the calculation of the volumes of mineral aggregates potentially exploitable in the Capu Câmpului perimeter for the year 2017 and year 2018 (without lowering below the current riverbed thalweg elevation).

Table 1. Estimated volumes of mineral aggregates exploitable in the Capu Câmpului perimeter (2017), without lowering below the current thalweg elevation

Profile	Surface	Average surface area	Partial distance	Partial volume	Total volume
P1	17.243	8.622	0.000	0.000	0.000
P2	66,628	41.936	164.548	6,900.365	6,900.365
P3	28.504	47.566	175.540	8,349.746	15,250.111
P4	13.688	21.096	112.957	2,382.950	17,633.061
P5	0.000	6.844	141.931	971.374	18,604.435
Total			**595**		**18,604.435**

The total length of the exploitation perimeter is approximately 595 meters, with a maximum extractable volume (V_{max}) of 18,600 m³. Based on the 2017 volume calculations, the sand and gravel reserve within the analyzed section - spanning approximately 595 meters of the riverbed - was estimated at V_i = 18,600 m³ per gravel bar. Figure 7 shows the 2019 boundary of the mineral aggregate extraction perimeter along the Moldova River bed.

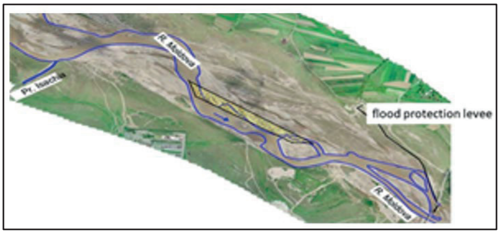


Figure 7. Orthophotomap of the Capu Câmpului perimeter from 2019

The 2019 volume calculations, based on a current measured riverbed length of 460 meters, indicate an updated reserve of V_{actual} = 20,387 m³ per gravel bar. Furthermore, a volume of V_e = 15,000 m³ of gravel was extracted from the analyzed section between 2017 and 2019, according to data reported by the operating extraction company. Based on these figures, the following resource balance equation can be established to quantify the reserve dynamics over the evaluation period:

$$V_{actual} = V_i + V_e + V_{regeneration} \quad (1)$$

The regeneration volume $V_{regeneration}$ is calculated as:

$$V_{regeneration} = V_{actual} - V_i + V_e \quad (2)$$

Applying the provided data, the regeneration volume is:

$V_{regeneration}$ = 20,387 - 18,600 + 15,000 = 16,787 mc/year.

Considering the current reserve volume of V_{actual} = 1,787,486 mc, the percentage variation in reserve volume is:

$$P_{regeneration} = 100 \cdot (V_{regeneration} / V_{actual}) \quad (3)$$

$P_{regeneration}$ = 82.34%

Note: Volume calculations can be performed using either the cross-sectional profile method or by creating a Digital Terrain Model (DTM), with the latter providing greater precision.

Table 2. Volumes of mineral aggregates potentially exploitable in the Capu Câmpului perimeter in 2019, without lowering below the existing riverbed thalweg elevation

Profile	Surface	Average surface area	Partial distance	Partial volume	Total volume
P1	0.000	0.000	0.000	0.000	0.000
P2	47.632	23.816	172.641	4,111.584	4,111.584
P3	53.561	50.597	174.732	8,840.811	12,952.395
P4	78.634	66.098	112.484	7,434.910	20,387.305
P5	0.000	39.317	0.000	0.000	20,387.305
Total			460		20,387.305

The total length of the exploitation perimeter is 460 meters, with a maximum extractable volume (V_{max}) of 20,387 m³.

Figure 8 shows the 2021 boundary of the mineral aggregate extraction perimeter (points 1–2–3–4) along the Moldova River bed.

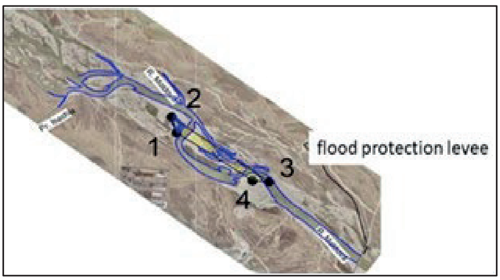


Figure 8. Orthophotomap of the Capu Câmpului perimeter from 2021

Table 3. Estimated volumes of mineral aggregates exploitable in the Capu Câmpului perimeter (2021), without lowering below the current thalweg elevation

Profile	**Surface (m^2)**	**Average Surface Area (m^2)**	**Partial Distance (m)**	**Partial Volume (m^3)**	**Total Volume (m^3)**
P1	3.912	1.956	0.000	0.000	0.000
P2	83.535	43.724	0.000	0.000	0.000
P3	30.655	57.095	174.636	9,970.823	9,970.823
P4	32.222	31.439	113.304	3,562.129	13,532.952
P5	0.000	16.111	140.379	2,261.643	15,794.595
Total			428		15,795.000

The total length of the exploitation perimeter is 428 meters, with a maximum extractable volume (V_{max}) of 15,795 m³.
According to the volume calculations performed in 2019, the reserve of sand and gravel within the approved exploitation perimeter - spanning approximately 460 meters of riverbed - was estimated at V_i = 20,387 m³ of ballast. Updated measurements in 2021 for the same perimeter, adjusted to a current riverbed length of 428 meters, indicate a revised reserve of V_{actual} = 15,795 m³. Additionally, the volume extracted from the area between 2019 and 2021 was reported as V_e = 15,000 m³, based on operator records.

Using the resource balance equation:

$V_{regeneration} = V_{actual} - V_i + V_e$,

we obtain:

$V_{regeneration} = 15{,}795 - 20{,}387 + 15{,}000 = 10{,}408$ m³,

representing the net accumulation or loss in the riverbed over the period.
The regeneration percentage is calculated as:

$P_{regeneration} = 100 \times (V_{regeneration} / V_{actual}) = 65.89\%$

Interpretation:

- $V_{regeneration} > 0$: indicates an aggradation process (material accumulation);
- $V_{regeneration} < 0$: indicates a degradation process (erosion or material loss).

An analysis of overlapping cross-sections from the years 2017, 2019, and 2021 reveals a relatively stable riverbed, with elevation fluctuations ranging from +0.12 m to –0.29 m (Figure 9). These variations are within acceptable limits and do not necessitate additional stabilization measures for the riverbed at this time.

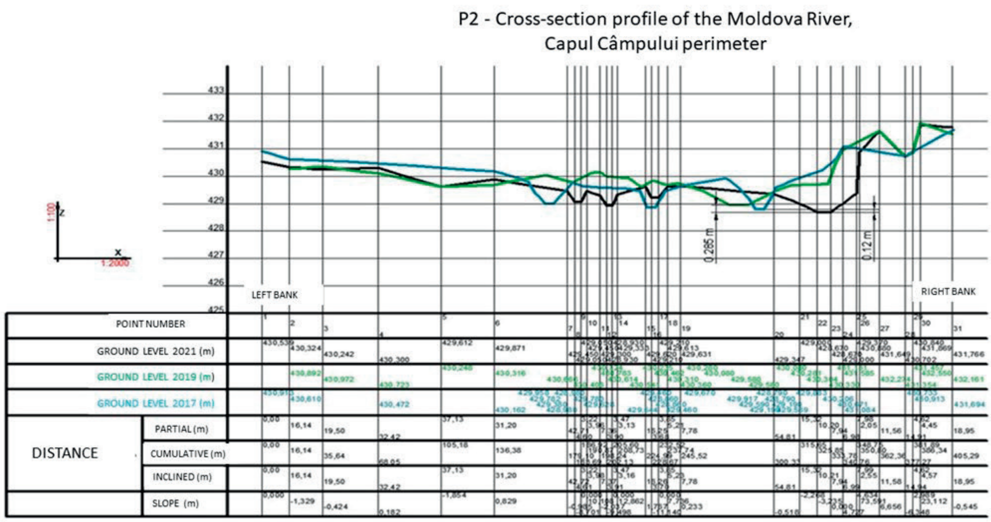


Figure 9. Cross-section of the Moldova River in the Capu Câmpului extraction perimeter area

CONCLUSIONS

Our analysis reveals that the Moldova River channel undergoes ongoing horizontal shifts, with lateral erosion occurring at an average rate of 4-5 meters per year. These processes are mainly confined to the active river corridor, which ranges in width from 500 to 800 meters.
Before 2010, approximately 15 extraction perimeters were active along the analyzed river

section. Currently, this number has significantly decreased, indicating a corresponding reduction in the volume of extracted mineral aggregates. The intensity of gravel mining activities is further evidenced by variations in suspended sediment hydrographs, which, in the case of the Moldova River, show an increasing trend over time. This contrasts with other rivers in the Siret Basin, where the general tendency is a reduction in sediment load. One plausible explanation for this divergence is the mobilization of sediments resulting from gravel extraction, a process that increases water turbidity.

The mobile riverbed depth along this section of the Moldova River has been measured at 2-3 meters, increasing to over 4 meters near the confluence with the Siret River, close to the Roman city. Cross-sectional analyses and measurements reveal a significant deepening of the riverbed in the Pod Izvor area. Long-term monitoring confirms the Moldova River's high sensitivity to two main categories of controlling factors: the natural variability of hydrological flow and anthropogenic influences. While natural factors were predominant before 1978, post-1978 observations indicate a marked dominance of human activities, particularly through an accelerated trend of riverbed incision.

In light of these findings, the following hydrotechnical interventions are proposed:

- *Channel development* through localized excavation, reprofiling of consolidated banks, and desilting, without altering the channel's width or depth.
- *Bank stabilization* in areas affected by active erosion poses risks to nearby infrastructure, using gabion walls or riprap with stone revetments.
- *Flood protection measures,* including embankments made from local materials, concrete parapets, elevation of riverbanks through reinforcement works, or the raising of existing access roads.
- *Longitudinal stabilization* through the construction of grade control structures using raw stone or gabions.

Recalibration of the channel is recommended in areas where sediment deposits or islands have formed, in order to improve flow capacity during medium and high discharge events and to restore the riverbed to dimensions derived from hydraulic modeling.

As demonstrated in this study - and supported by other research such as that conducted by Hooke (2004) - the use of GIS for monitoring land and land-use changes provides critical insights into the impact of human activities on river morphology, particularly in the context of land-use transformations.

In conclusion, GIS technology proves to be an indispensable tool for the monitoring and management of riverbed dynamics. It offers a robust and efficient methodology for spatial data collection and analysis. The application of GIS enables a comprehensive understanding of both natural and anthropogenic processes influencing river systems and facilitates the development of effective strategies for environmental protection, water resource management, and disaster risk reduction. The present study, alongside existing literature, reinforces the importance of GIS in fluvial geomorphology research and highlights its relevance in environmental policy and climate change adaptation.

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