INTENSIVE INFILLING PROCESSES OF A CUTOFF MEANDER IN THE DANUBE DELTA

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ABSTRACT

This paper documents the structure of flow and bed morphology of a cutoff meander of the Danube River in relationship with a GIS approach. The cutoffs effect produce changes in the repartition of the water and sediment fluxes between the natural channel and the man-made canal, with direct implications on the environmental evolution of the delta. The Dranov de Jos meander (Lower Dranov meander – LDM) belt seems to be one of the most affected by the rectification works performed on Sfântu Gheorghe branch between 1981 and 1992. The upstream and downstream parts of the cutoff are characterized by the decrease of the channel width by banks sedimentation (with the rate of –6.2 m/year) and at the apex zone, the bank's sedimentation is associated with intense sediment infilling of the central part of the channel, where a large deposit of 950 m in length and 190 m in width is formed.

RÉSUMÉ: Processus de colmatage d'un méandre recoupé du Delta du Danube.

Cet article s'occupe de la structure du flux liquide et la morphologie d'un méandre du delta du Danube selon l'approche SIG. Les rectifications des méandres produisent des changements dans la répartition des flux d'eau entre le chenal naturel et le chenal artificiel, avec des implications directes sur l'évolution environnementale du delta. Le méandre Dranov de Jos semble être l'un des plus affectés par les travaux de rectification réalisés sur le bras de Saint-Georges entre 1981 et 1992. Les parties amont et aval du méandre sont caractérisées par la diminution de la largeur du chenal et par la sédimentation des berges tandis que dans son apex, la sédimentation de la berge est associée à un remplissage sédimentaire intense de la partie centrale du chenal.

REZUMAT: Procese de sedimentare accentuată într-un meandru rectificat din Delta Dunării.

Acest articol analizează procese hidrologice şi morfologice care au loc de-a lungul unui meandru rectificat din delta Dunării. În general, rectificările meandrelor produc modificări ale repartiţiei fluxurilor de apă între canalul natural şi cel de rectificare, cu efecte asupra mediului înconjurător. Meandrul Dranov de Jos pare să fie unul dintre cele mai afectate meandre ale braţului Sfântu Gheorghe, în urma lucrărilor de rectificare care au avut loc în perioada dintre anii 1981 şi 1992. Părţile situate în amonte şi aval sunt caracterizate prin reducerea lăţimii în timp ce în zona de apex se observă colmatarea părţii centrale a albiei.

INTRODUCTION

The hydrotechnical works have complex environmental impacts and produce pressures and alterations of hydro-sedimentary flows downstream (Zaharia et al., 2011; Zhang et al., 2016; Li et al., 2018; Duţu Tiron et al., 2019; Nistor et al., 2021). Many studies on the meandering systems showed that the change of sinuosity rates, the reduction of the widths or changes of the meanders mobilities are the response of the channel to the construction of a reservoir upstream (Gaeuman et al., 2005; Phillips et al., 2005). Thus, dams are responsible for the morphology changes of the rivers. They produce interruptions of the river system continuity and decrease the transport of the sediments to the littoral zones (Batalla, 2003).

The Danube River is one of the most important European waterways, flowing over 2,860 km across the continent from the Black Forest Massif down to the Black Sea. The Danube drainage basin extends over 817,000 km^2 and more than 15 countries share the Danube catchment area. The average annual water discharge of the Danube River at the delta apex (Ceatal Izmail) is 6,550 $m^3.s^{-1}$. The present sediment discharge was modified by the building of the Iron Gates I and II dams and reservoirs systems (in 1972 and 1984 respectively) which induced a critical decrease in the sediment discharge from ≈ 67 million $t.yr^{-1}$ to ≈ 30-40 million $t.yr^{-1}$ (Stănică and Panin, 2009; Nistor et al., 2021).

In its delta, the Danube has built a particular area affected by multiple and complex constraints. At the scale of the drainage basin area, the river has undergone major transformations with effects on the functioning of the downstream part of its course (Tiron Duţu et al., 2019; Pacioglu et al., 2022).

GIS studies (maps analyse, aerial photographs, satellite images) were frequently used to understand the mobility and the evolution of the large fluvial channels such as the Mississippi Delta (Hooke, 1980), Rhone Delta (Antonelli et al, 2004), Rhine Delta (Berendsen et al., 2007), Danube Delta (Ungureanu and Stănică, 2000; Tiron Duţu et al., 2014), etc. Therefore, the GIS results must be correlated with *in situ* measurements (bathymetrical, hydrological, topographical and sedimentological data).

The natural chute cutoffs have been largely studied (Zinger et al., 2013; Li and Gao, 2019; Li et al., 2021; Qiao et al, 2022) than the artificial ones (Eekhout and Hoitink, 2015; Schwenk and Foufoula-Georgiou, 2016). The artificial corrections of the meanders produce fast and dramatic responses (Tiron Duţu et al., 2019; Duţu et al., 2022; Qiao et al., 2022). The scope of this study is to expand the existing knowledge of artificial cutoff and may serve as a reference to scientists interested in this topic and for the authorities involvement in the management and protection of the Danube Delta.

MATERIAL AND METHODS

Background. The St. George distributary starts from the hydrographic knot at Ceatal Sfântu Gheorghe at 108.8 km until the sea (Fig. 1). The course of the St.George branch can be subdivided into three sections (Panin, 2003, Tiron, 2010): the Dobrogean section of limited meandering (between km 104 and km 90), the free meandering segment of the St. George arm (between km 90 and km 22) and the straight downstream section between km 22 and km 0). The St. George meander loops have been rectified in 1981-1992 period; these cut-offs lead to a shortening of the distributary by about 32 km. Consequently, the free water surface slope increased and water flow velocity determined higher water and sediment discharges and important changes in the local distribution of flows (Tiron Duţu et al., 2014, 2019). A rupture of the natural bend evolution occurred – strong clogging processes are more and more active, expressed in the aggradation of the channel bed, narrowing of channels and development of bars and islands along the natural meander bends sections (Tiron Duţu et al., 2014).

The study area is represented by a former meander of the middle part of the Sfântu Gheorghe branch (Fig. 1), Dranov de Jos/Lower Dranov meander – LDM. LDM was formed at the end of the Phanagorian regression when the Black Sea level lowered by a few meters (–2/–4 m) and the relief energy increased (Panin, 2003). LDM is very elongated being the most sinuous meander loop of the Sfântu Gheorghe branch. Its length is 8.8 km, the wavelength is 1.4 km, the amplitude is 3,852 m and the sinuosity index is 6.59. During the period between 1880 and 1970, the natural channel of the LDM exhibited a continuously accentuated narrowing of 1.4 m/year between 1880 and 1910 and 1.2 m/year between 1910 and 1970 (Tiron, 2010). The water discharge transported by the artificial canal has progressively increased, from 14% in 1993, just after the rectification, to 28% in 1996 and 95% in 2020.

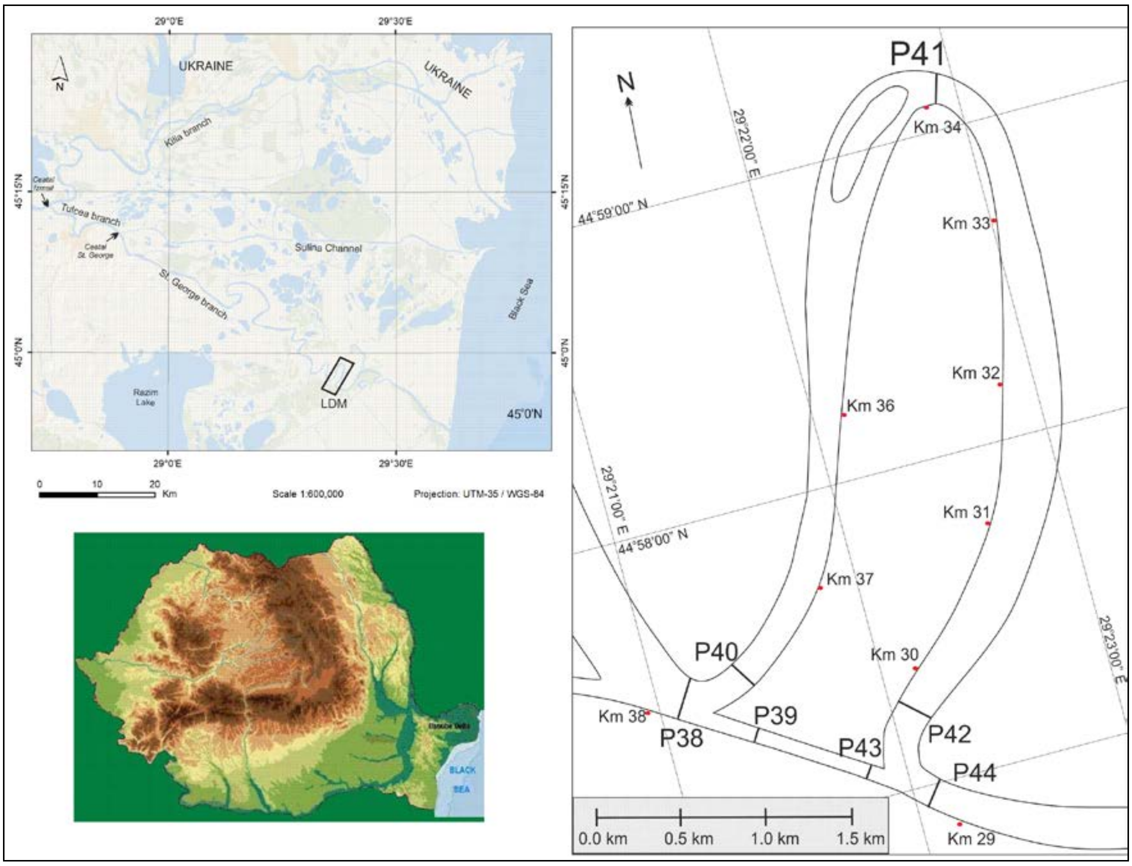

Figure 1: The Danube Delta location and the investigated cross-sections.

The hydrological measurements were made in September 2020, during the average autumn waters. An ADCP River Ray 600 kHz mounted on a power boat was used for the data acquisition. During the measurements (on 9 September 2020) the flow discharge entering in LDM was 1,237 $m^3.s^{-1}$. Seven transversal profiles were completed at relevant sections such as around the upstream bifurcation (P38, P39 and P40), around the downstream confluence (P42, P43, and P44) and along the cutoff meander in the apex zone (P41) (Fig. 1). Multiple transects of each cross-section were performed (four to six transects on each cross-section) to reduce the errors (Qiao et al., 2022).

The hydrodynamic processes were analyzed by two parameters, the stream power and the boundary shear stress using the formulas described and applied previously in the deltaic environment by many authors (Duţu et al., 2022; Qiao et al., 2022) (Tab. 1):

For the stream power the following equation was used:

$$\omega = \Omega/B\ (W \cdot m^{-2})$$

where B is the bankful channel width and **Ω** is the stream power, calculated as:

$$\Omega = \rho\ g\ Q\ S\ (W \cdot m^{-1})$$

where the representative discharge Q ($m^3 \cdot s^{-1}$) is usually taken as the bankful discharge Qbf.

The bed mean shear stress (τ_0) corresponds to the unit tractive force exerted on the bed following the equation:

$$\tau_0 = \rho\ g\ R\ S\ (N \cdot m^{-2})$$

ρ is the fluid density (1,000 $kg \cdot m^{-3}$ for sediment-free water), g is the gravitational acceleration (9.81 $m \cdot s^{-2}$), R is the hydraulic radius (m), and S is the water energy slope ($m \cdot m^{-1}$).

The topographical measurements were measured with an RTK global positioning system (TRIMBLE R4). The measurements consisted of the topographic points acquired at the water/land interface in the bank's area and the major bed at each change of the terrain slope.

For each topographic point, three sessions of measurements of five seconds were performed using the kinematic method. Thus, the coordinates and elevations were obtained in real-time through RTK technology, being instantly available in the field without requiring corrections. The National planimetric System STEREO ’70 and absolute depths (Z) in National Altimetrically System Black Sea ’75 Constanța were obtained for each measured point using the standard EN 14614:2004 (Directive 2014/101/CE).

Geographic information system (GIS) tools (Global Mapper 18) was used to compare two sets of data of Landsat 7 ETM+2000 and Lansat 2020. The error sources (RMSE) include inaccuracies from the manual delineation of banklines, water level differences, effects of vegetation, etc. To estimate the changes in the planform of LDM were determined from the two sets of remote sensing data and combined with information on average channel depth.

RESULTS AND DISCUSSION

Present time flow and morphological processes

With a sinuosity index of 6.59 and an amplitude of 3,852 m, LDM is one of the most sinuous meanders of the Sfântu George branch. The meandriforme shape has an important impact on his morphological behaviour in general and on the distribution of the flows between the former meander and the artificial canal in particular.

The water fluxes at the nodal point of bifurcation (P38 = 1,237 $m^3.s^{-1}$) are distributed unequally between the former meander (P40 = 62 $m^3.s^{-1}$) and the artificial canal (P39 = 1,156 $m^3.s^{-1}$), with a dominated discharge carried out by the artificial canal (~93.5%) (Tab. 1).

The bifurcation point (P40) corresponds to an important reduction of the depth (Tab. 1). The thalweg is decreasing from 23.1 m to 5.88 m, with a counterslope of –6.9 m/km. Here, on P40, the cross-section has an asymmetrical shape and the left bank correspond to a stagnation zone, for a distance of approximately 50-70 m from the left bank (Fig. 2).

Going downstream, the water discharge is almost constant, with a flux of 66.4 $m^3.s^{-1}$ in the apex zone and 63.2 $m^3.s^{-1}$ near the confluence (on P42). Along the former meander (P40, P41, and P42), the depths and the channel slope are lower, and the velocities decrease and are homogeneously distributed on the cross-sections (Figs. 3 and 4) and facilitate the sediment deposition (mean velocities between 0.26 $m.s^{-1}$ and 0.06 $m.s^{-1}$) (Tab. 1). Close to the confluence point, the profile P42 is asymmetrical, with a deepening toward the left bank (until 12.2 m) and a large zone of water stagnation situated on the right bank (Figs. 2 and 3).

Table 1: Hydrometrical and hydro-dynamical parameters on investigated cross-sections.

Profile	**Width (m)**	**Maximum depth (m)**	**Water discharge ($m^3.s^{-1}$)**	**Mean velocity ($m.s^{-1}$)**	**ω $W.m^{-2}$**	**τ_0 $N.m^{-2}$**
P38	171	23.1	1237	0.48	0.56	1.27
P39	137.7	21.2	1156	0.57	1.05	1.84
P40	134.2	5.88	62	0.26	0.42	0.59
P41	104.9	9.9	66.4	0.11	0.05	0.09
P42	181.4	12.2	63.2	0.06	0.01	0.02
P43	125.7	21.7	1194	0.61	1.30	2.09
P44	180.0	24.5	1272	0.44	0.42	1.05

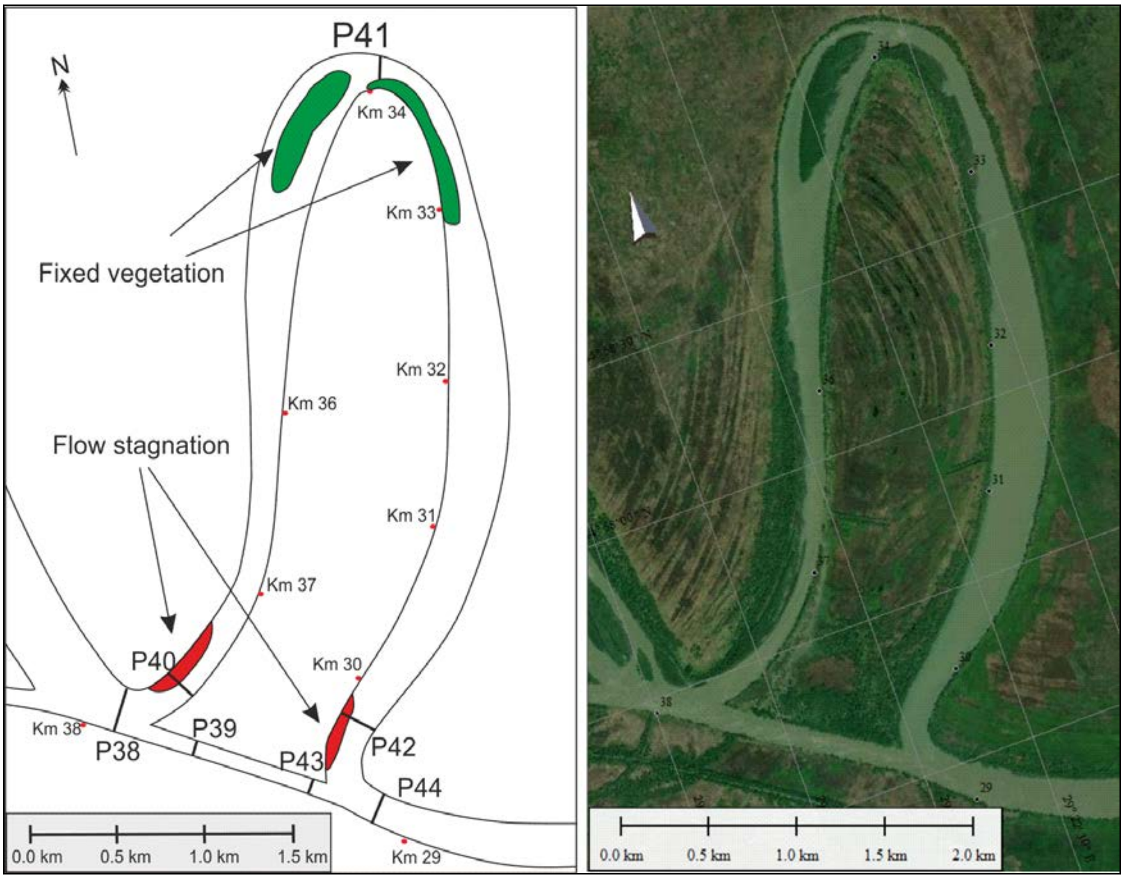

Figure 2: The flow stagnation areas (in red) and fixed vegetation area (in green) along the LDM.

The entrance in the artificial canal (P38-P39) corresponds to an increase of the velocities (from 0.48 $m.s^{-1}$ to 0.57 $m.s^{-1}$) and even higher downstream (0.61 $m.s^{-1}$ on P43) due to the reduced width of the artificial canal (max 140 m) and to the higher slope (4.1 m/km). On the artificial canal, the profiles are symmetrical in shape and many large nuclei of higher velocity (between 0.85 and 1.1 $m.s^{-1}$) are located in the central part of the cross-sections (Fig. 3).

From the hydraulic point of view, cross-sections with high stream power are found on the main channel (P38 and P44) and on the artificial canal (P39 and P43) in relationship with the reduced widths and steep slope. Along the former meander, the energy is lower and decreases with the distance, from 0.42 W.m^{-2} downstream of the bifurcation (on P40) to 0.01 W.m^{-2} close to the confluence (P42). The bed shear stress values follow the same distribution, with lower values located on the former meander (between 0.59 and 0.02 N.m^{-2}) and higher values located in the artificial canal on P39 and P43, indicating the increased erosion capacity of the channel (Tab. 1).

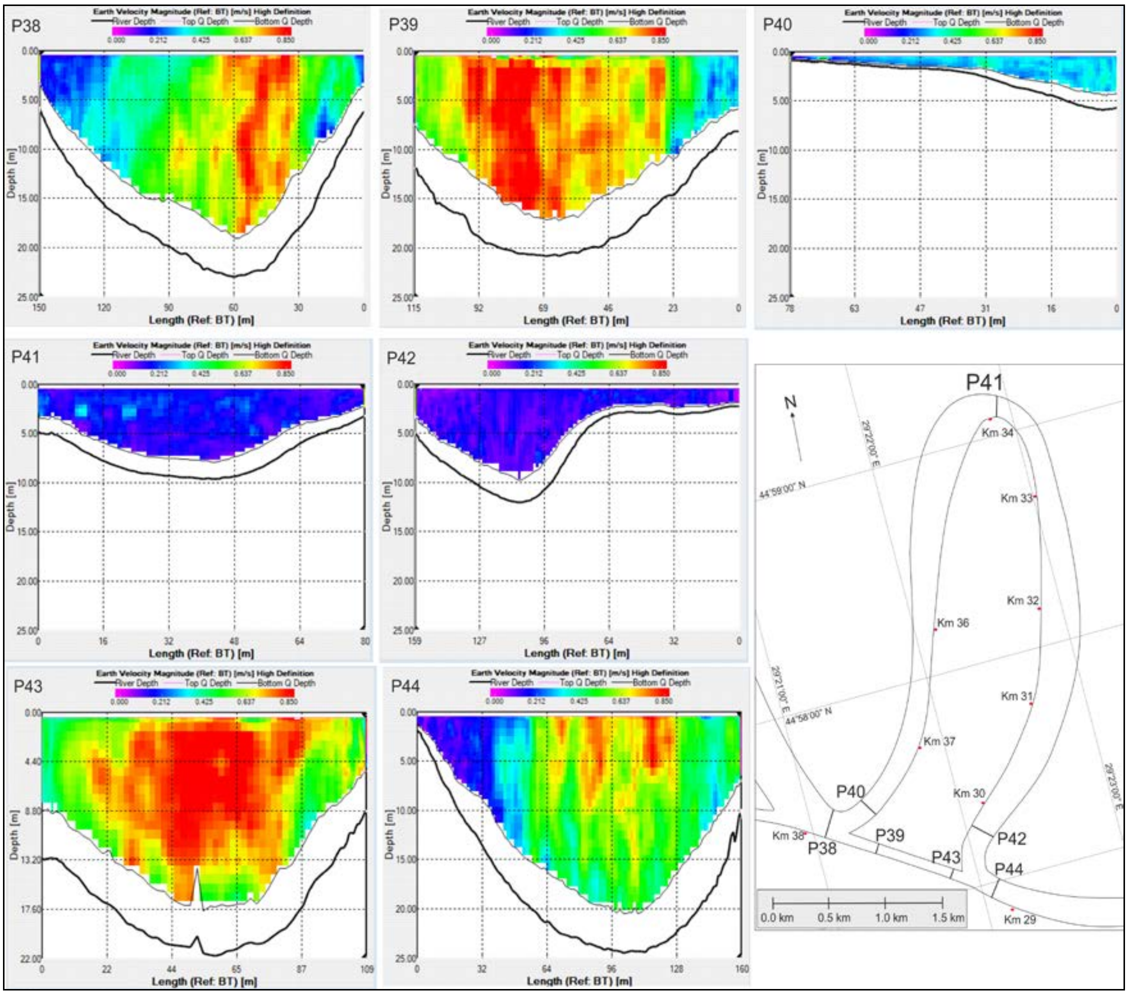

Figure 3: Distribution of the flow velocities
on each investigated cross-section.

The concept of stagnation zone was developed by Zinger et al. (2013) to examine the flow hydrodynamic characteristics and channel morphology during the evolution of chute cutoff. The authors showed that at the bifurcation and the confluence zones, the hydrodynamic processes are similar. For our case, the LDM, the hydrodynamic and morphological features are in good agreement with those obtained by Zinger et al. (2013) and later applied to an artificial cutoff in the upper Yellow River by Qiao et al. (2022).

Based on the previous research studies (Edmonds and Slingerland, 2008; Letter et al., 2008; Tiron Duţu et al., 2014) the behaviour of the meander systems is in relationship with a series of factors, such as the water flow, the channel bed slope ratio, the sinuosity, the bed grain size, water surface elevation at the bifurcation areas, the diversion angle, etc. On LDM, there is an evident inequality in the repartition of the liquid fluxes between the natural and artificial channels that obviously explain the infilling processes along the former meander. However, the water flow acceleration in the artificial canal maintains higher dynamics and enhances erosion processes, therefore, the disparity of operation of both channels that we consider the most important factor determining the sedimentation of the former meander.

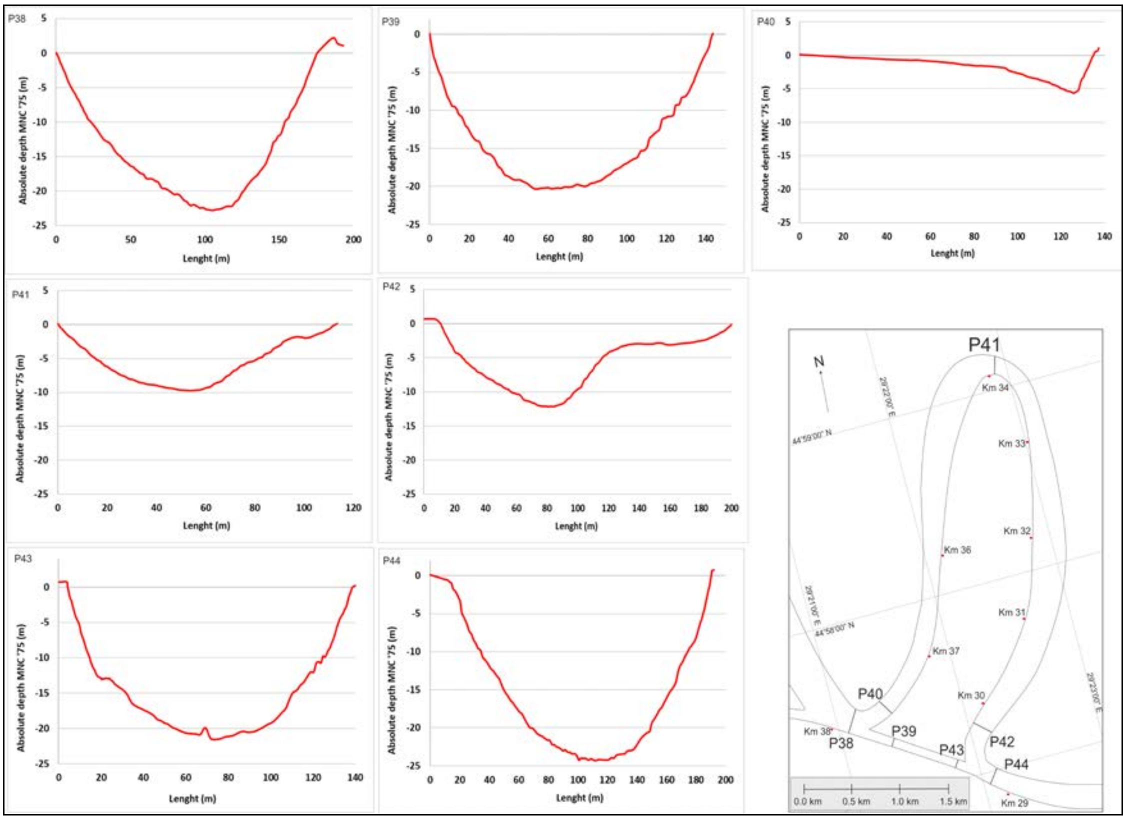

Figure 4: Topo-bathymetrical profiles
of the investigated cross-sections.

Overview of GIS imagery analyses

Channel widths are the distance measured perpendicular from a bank edge to the opposite bank edge. The LDM channel widths were measured every 300 m streamwise. By superimposition of satellite images, the evolution diagram of the channel width between 2000 and 2020 has been drawn (Fig. 5). In the last twenty years, the former meander of LDM narrowed substantially, especially in the upstream first part (between km 37.5 and km 36), with a retraction of the channel width until 124 m (approximately –6.2 m/year) (Fig. 5). Downstream, in the proximity of the apex zone (between km 34.5 and km 34), the channel is relatively stable in width, but the sedimentation remains also the dominant process. Here, sediment infilling is revealed by the formation and development of a large internal island of 950 m in length and 190 m in width shown in figure 1. The sedimentation of the convex bank is dominated downstream of the apex (between km 33.5 and km 32) with rates of –4.4 to –2.75 m/year). Close to the confluence, the channel width remains relatively stable along the analysed period, with low retraction rates (between –1.5 and 0.65 m/year).

The retraction rates are higher than those calculated by Jugaru et al. (2006) for the period 1970-2000, with a maximum of –1.5 m/year. Our data indicate that the infilling processes along the former meander are faster in the last 20 years.

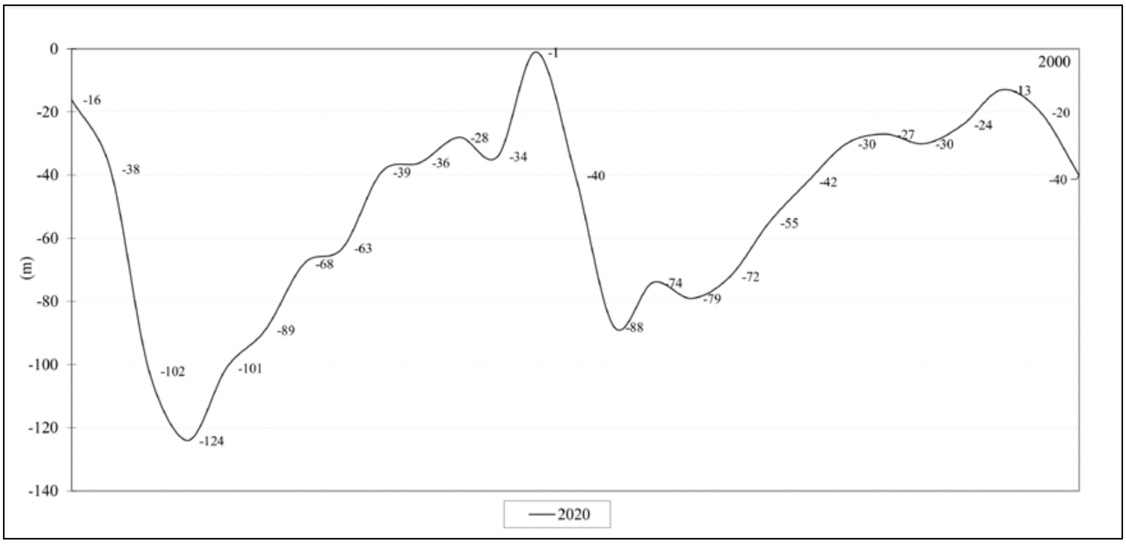

Figure 5: Evolution of the channel width between 2000 and 2020
(the x-axes represent the values from 2000).

CONCLUSIONS

According to the studies performed, the LDM is very sensitive to the meanders cut-off programme, with fast response in decreasing of its water discharges and in the changes of hydro-morphological and sedimentological processes. The study of the Lower Dranov meander reveals the need to understand the critical processes that generally affect the cutoff works. The effects of the hydrotechnical works are fast and intensive. During a period of around thirty years, the channel has undergone significant changes and important transformations. The results show that the intervention on the water transfer in a meandering system by cutoff diminishes the energy of the former meander and thus interrupts the sedimentary transit and important morphological changes. The GIS results are in good agreement with the hydrological and morphological data and interpretations. The effects of the meander cutoff, together with some other factors such as climate changes and other human interventions (i.e. reservoirs and dams, etc.) are to be found in studies related to the environmental state and biodiversity of the entire delta, which represent a current concern of the society.

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