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The Danube River Delta

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The Danube River Delta

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ISSN 2730-6674 ISSN 2730-6682 (electronic)
Earth and Environmental Sciences Library
ISBN 978-3-031-03982-9 ISBN 978-3-031-03983-6 (eBook)
https://doi.org/10.1007/978-3-031-03983-6

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

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The Danube Delta Environment Changes Generated by Human Activities

Laura Tiron Duţu, Nicolae Panin, Florin Duţu, Adrian Popa, Gabriel Iordache, Iulian Pojar, and Irina Catianis

1 Introduction

The impacts of human activities on the fluvial systems have been investigated for a long time by numerous scientists [1–8, and many others]. Human interventions in a fluvial system (dams, dikes, dredging, groins, meander bends cut-offs, etc.)

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A. M. Negm and D. C. Diaconu (eds.), *The Danube River Delta*, Earth and Environmental Sciences Library, https://doi.org/10.1007/978-3-031-03983-6_1

modify the hydrological and sedimentary characteristics of rivers that control the environment and the geo-morpho-dynamics of the river courses [9–21].

The last two centuries have been marked by the construction of dams on numerous rivers, such as the Mississippi River, Yellow River, Nile River, Danube River, etc. [9, 22, 23]. At the same time, several studies have been carried out on the impact of the abovementioned structures on the riverine environment, on hydrology, sedimentology, and morphology [23–29]. Depending on its location, environment, substrate, and variables of control, each river responds differently to disturbances induced by dams [9] as they change the seasonal variability of liquid and solid discharges [30]. [31, 32] estimated that over 40% of the water flow of the world's rivers is currently intercepted and 25% of the solid discharge is trapped behind dams. Studies by [33] show that in the modified river courses of Central Europe, 50-year-frequency floods have decreased by 20% and ten-year floods can decrease up to 75%.

An example of the extreme impact of the construction of such reservoirs is that of the two Aswan dams on the Nile (the first dam, the old one, built-in 1902, and the second, new, dam, finished in 1970); the Nile suffered a reduction in total sediment load transported downstream from 100×10^6 $t{\cdot}y^{-1}$ to almost zero [30, 34]. Meade and Parker [35] studied a similar impact on Colorado (USA), which experienced a decrease in sediment load transported from 125–150 $\times 10^6$ $t{\cdot}y^{-1}$ in 1930, to 1.1×10^6 $t{\cdot}y^{-1}$ now-a-day. The Mississippi River (at Baton Rouge) shows a similar decrease in sediment discharge between 1950 and 1975, following the construction of five dams, between 1953–1963, on Missouri [30]. Reservoirs built on the Yellow River (16 barrages, among them the Sanmenxia and Xiaolangdi dams) have induced reductions in sediment flow (up to 60%) [6] with an impact on the development of the delta and the coastline.

However, it should be mentioned that there are also rivers that have not changed their sediment regime as a result of anthropogenic interventions. Alford [36] refers to the case of Chao Phraya (Thailand), which shows no significant modification of the sediment flow following the development. Other similar cases are described by [30] on the Ob River (Siberia) and the upper Yangtze (in Yichang, China).

Besides the impact of hydropower dams and their reservoir lakes, a large number of engineering works can influence the river's hydro- and morpho-dynamical processes. The meander bends cut-offs for better navigation and for controlling the seasonal floods, stabilization of channels by embankments, etc. represents pressures on the river evolution pattern [37]. Numerous studies, theoretical, experimental, or *in situ* have shown that the modification of the sinuosity rates (in case of meandering rivers), the reduction in the variability of widths, or plan mobility could be the first response of a river to the construction of a dam [11, 27, 38–42]. Grams and Schmidt [43] demonstrated that the decrease of the channel width is not linearly correlated with the distance downstream from the dam, but is related to the degree of reduction of flood peaks induced by the dam, to the modification of sediment inputs, and local geomorphological characteristics.

In the case of meander belts cut-offs, the most important factor that influences the changes in water and sediment flows is the increase of the river free water slope.

The downstream area of the cut-off will be fed by a larger quantity of sediment resulting from the erosion of the cut-off canal and of the upstream area. Schumm [44] considers that the dynamic equilibrium of a cut-off canal will set in only after a few "local cycles" of erosion/deposition.

The best-known example of a large meander bends cut-offs program is the Mississippi River (USA) that have been performed in the 1930s to facilitate the evacuation of floodwaters and improve navigation. The river has been shortened by about 30% of its length (274 km). As the result of shortening, 15 meander bends were cut-off and isolated from the main channel. The river was shortened an additional 88 km between 1938 and 1855 by chute cut-offs. The period following the rectifications had a substantial impact on the morphology of the river by self-adjusting its course [25, 26, 45].

The Danube River (2875 km) is a major fluvial system with a drainage basin of 817 000 km^2 [46–48]. In addition, the river and its delta at the mouth in the Black Sea represent a very complex and large natural river-sea system in Europe [46]. A long history of navigation, industrial development, large-scale agriculture, more than 80 million inhabitants present across the basin, multiple hydro-energetic developments are some of the factors that influence the centuries-old evolution of the river. Its long-term evolution is marked by secular climate changes, transformations of the land use in the entire basin that have changed flow types and flood regimes, and reduced the volume of sediment inputs downstream [29, 47–56].

These impacts have been greatly amplified over the last 50 years by the water-course regulations along the Danube River and its tributaries, including the construction of the two major hydropower dams Iron Gates I in 1971 and Iron Gates II in 1984 on the Romanian—Serbian border [29, 56, 57].

In the last two centuries, several hydro-technical works have been made within the Danube Delta territory, with significant impact on the delta environmental state, on the water and sediment flows, and on the morpho-dynamics of the distributaries, natural channels, man-made canals, interdistributary lakes and polders, the coastal zone of delta front, etc. [1, 54, 56, 58, 59].

2 Study Area

The chapter aims to present the effects of human activity on the environmental state of the Danube Delta, and the fluvial response to these anthropogenic interventions.

The Danube Delta (5600 km^2) displays three main distributaries: the Kilia at North, Sulina in the middle, and St. George at South. Unlike the northern branch, which also represents the Romanian - Ukrainian border and has remained almost natural, except its secondary delta, the other two distributaries have been modified for navigation through meander bends cut-offs (Fig. 1).

Since the middle of the nineteenth century, the natural hydrological regime of the Danube distributaries was influenced and modified by human activities. Important

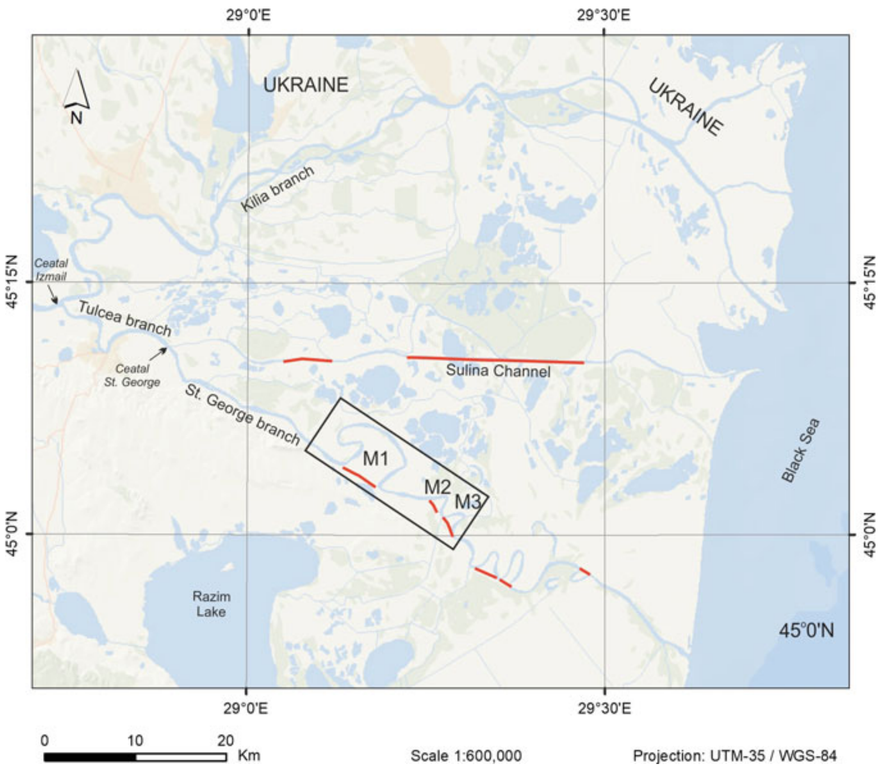

Fig. 1 The Danube Delta map (artificial canals of the rectified meanders of Sulina and St. George distributaries in red lines) and the location of the study area (Mahmudia-M1, the Upper Dunavăţ-M2, and the Lower Dunavăţ-M3 meanders) within the St. George branch

developments began after the establishment of the Danube Commission in 1856 in Galaţi, Romania [2, 54, 57, 60–64].

As a result of the extensive hydro-technical works for economic purposes, the total length of the man-made channels increased from 1743 to 3496 km [65] and the discharge of the Danube River to the delta inter-distributaries depressions increased from 167 m^3/s before 1900 to 309 m^3/s in 1921–1950 period, 358 m^3/s in 1971–1980 period and 620 m^3/s in 1980–1989 period [1, 50]. The effect was the perturbation of water circulation and sediment relocation within the delta [57].

In the deltaic depressions, during the ’60s and ’80s, a management plan was implemented for substituting the natural ecosystems with human-dominated ones (e.g., intensive fish and agricultural farms, poplar plantations). Intensive exploitation of reed and fish resources was put into action and large agricultural farms and tree plantations replaced large surfaces of wetlands from the delta [2].

The rectification of the Sulina distributary (Fig. 1) was carried out during the years 1868–1902 and shortened this branch by about 24%. The shortening and deepening of the river channel produced modifications on the hydrological regime inside the delta by increasing the water discharge of the Sulina distributary by about 10% (from 7–9% to about 20% of total Danube discharge) [54]. As a consequence, redistribution of water and sediment discharge among the delta distributaries have been recorded [53, 59, 66].

During the years 1981–1994, cut-offs of six free meanders of the St. George distributary were performed to improve navigation. The total length of the St. George branch was shortened by 32 km and consequently, the free-water surface became steeper and the flow velocity and energy (scouring and sediment load transport capacity) increased significantly. The St. George distributary water discharge increased by some 10% influencing the general water distribution among the delta distributaries [56]. The natural meander courses and the newly built cut-off canals evolved differently: clogging processes are very active within the natural courses of the rectified meander bends, while the cut-off canals are actively eroded becoming deeper and widener [54, 57, 67–70].

At almost the same period, the river and the delta systems have been deeply affected by the hydrological and sedimentary changes (reduction of the sediment discharge by some 40%) after the construction of Iron Gates I and Iron Gates II barrages. These changes are felt all along the downstream barrages river course (almost 700 km) and, especially, in the delta front coastal area [54].

3 Methods

Complex research and detailed investigation (using several modern methods and technics, such as ADCP, 3D bathymetry, diffractometry) have been performed in the Danube Delta on the St. George branch, which is considered deeply influenced by anthropic activities. Hydrological, morphological and sedimentological data are here presented. These data have been acquired along three meander loops located in the middle part of the St. George distributary: Mahmudia, Upper Dunavăţ, and Lower Dunavăţ (Perivolovca) meanders, named hereafter M1, M2, and M3, respectively. The measurements were made in two different hydrological regimes, at average to high-level waters in September 2016 and, at the end of a high peak of a flood period of spring waters, at the beginning of June 2017. The St. George branch carried out 1264 $m^3 \cdot s^{-1}$ and 2169 $m^3 \cdot s^{-1}$ during the measurements.

Hydrodynamics (ADCP). The data analysed in this chapter were acquired with two equipment, ADCP Workhorse Sentinel 600 kHz and ADCP RiverRay 600 kHz (manufactured by Teledyne RDI) mounted on a powerboat [69, 71]. During the two field campaigns, 25 transverse ADCP profiles were completed at relevant cross-sections of the three meanders: at the bifurcations (sectors A, I, and L), at the confluences (sectors G, K, and N), and along the cut-off meanders (profiles C, D, E, F, J, and M). The marks 1, 2, and 3 describe the position of each profile in the sector: location on the natural single upstream channel (1), on the former meander (2), and the cut-off canal (3) (Fig. 2).

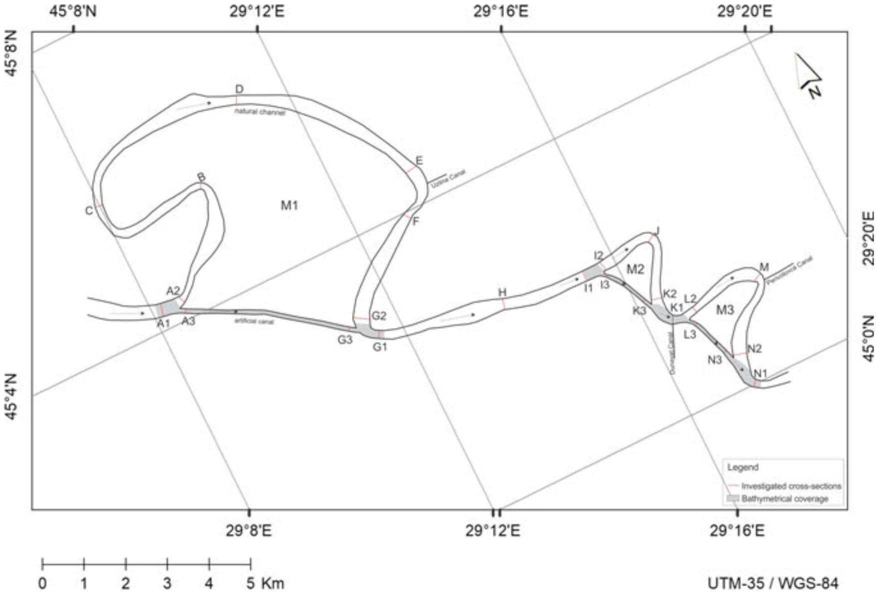

Fig. 2 Study area, the three meanders of the St. George Branch (Danube Delta). The investigated cross-sections (ADCP profiles and sediment samples) are marked with red lines and the 3D bathymetrical coverage in gray areas

Morphology 3D mapping. Multibeam sonar bathymetry data were collected during two field campaigns on NIRD GeoEcoMar's RV ISTROS, equipped with an ELAC Nautik SeaBeam 1050D multibeam bathymetric system (ELAC 1050D, 180-kHz). The depth data were processed using the software packages HDP Post/FLEDERMAUS [64, 72, 73].

Grain size analysis of bed sediments. Bottom samples were collected with a grab sediment sampler, on more than 40 sediment stations, distributed along the three meanders, on each investigated cross-section (Fig. 2). The sediment grain size analyses were done by diffractometry using the grain size laser analyzer „Mastersizer 2000E Ver.5.20 (Malvern Instruments Ltd.-Malvern UK). The equipment determines the percentages of particles in the various dimensional classes present in 0.10 μ–1 mm interval with an accuracy of 1% and a reproducibility of 99%. Particles larger than 1 mm were separated by sieving on fractions, weighed, and reported to the percentages obtained by diffractometry [74]. The texture categories (sand, silt, clays) were separated using the Udden-Wentworth logarithmic scale and for the classification of the sediments, the Shepard diagram was used [75–77].

Determination of the *suspended sediment concentrations* was made in the laboratory using the filtration method. In all the selected cross-sections, water samples (with a 5 L horizontal Niskin-type bottle) were acquired in three verticals (left balk, right bank, and center). The water samples were filtered with a Millipore filtration unit, using 4.7 cm acetate cellulose filter membranes of 0.45 μm porosity, according to STAS 6953-81.

4 Results and Discussions

4.1 Overview of Flow Processes

The water flux distribution between the natural course of meanders and cut-off canals is varying from one sector to another, depending on several factors such as the ratio between the former and the new canal length, the diversion angle, and the bed level difference between the natural channel and the cut-off canal. Representative measured velocity profiles from June 2017 are used to illustrate the 2D structure of flow at bifurcations (A1, A2, A3, I1, I3, L2, and L3), confluences (G1, G2, G3, K2, K3, N1, and N3) and on the natural course of meanders (J and M) (Figs. 4, 6, 7, 8 and 10).

4.1.1 First Cut-Off—Mahmudia Meander Belt (M1)

In September 2016, at the bifurcation (A1/A2/A3), the water flux balance is conservative (the liquid flow A2 + A3 (1220 + 25 = 1245 $m^3 \cdot s^{-1}$) is equal to the water discharge through A1 (1264 $m^3 \cdot s^{-1}$)). The cut-off channel of M1 receives 2% of the upstream flow [73]. In June 2017, at the same location, the cut-off channel of M1 receives 3.8% of the upstream flow. Upstream the cut-off canal entrance (profile A1), the core of high velocity is located on the right side and at the center of the channel. The channel bed is asymmetrical with the thalweg situated on the right side. The flow is directed toward the right bank, in the direction of the cut-off canal entrance, similar to that along the cut-off canal (profile A3). In June 2017, the cross-section through the entrance in the natural course of the meander (A2) shows a sediment deposition zone located on the left side, with low velocities values (0.4–0.6 $m \cdot s^{-1}$) (Figs. 3 and 4).

In September 2016, at lower discharge, access through this section of the natural course of the meander was not possible. The water discharge decreases progressively along the natural course of the meander, as well as the flow velocities (from 0.05 to 0.01 $m \cdot s^{-1}$ in September 2016 and from 0.44 to 0.05 $m \cdot s^{-1}$ in June 2017). The water flow velocity increased in the cut-off canal (from 0.48 $m \cdot s^{-1}$ upstream of the bifurcation, on A1, to 0.58 $m \cdot s^{-1}$ downstream, on A3) in September 2016, and respectively from 0.76 $m \cdot s^{-1}$ to 0.90 $m \cdot s^{-1}$ in June 2017) enhances incision processes within the canal.

At the confluence of cut-off canal and the natural course of the meander (profiles G1, G2, and G3) several nucleuses of higher velocities persist in the central areas of profiles G1 and G3, while the velocities of G2 (on the natural course) are very

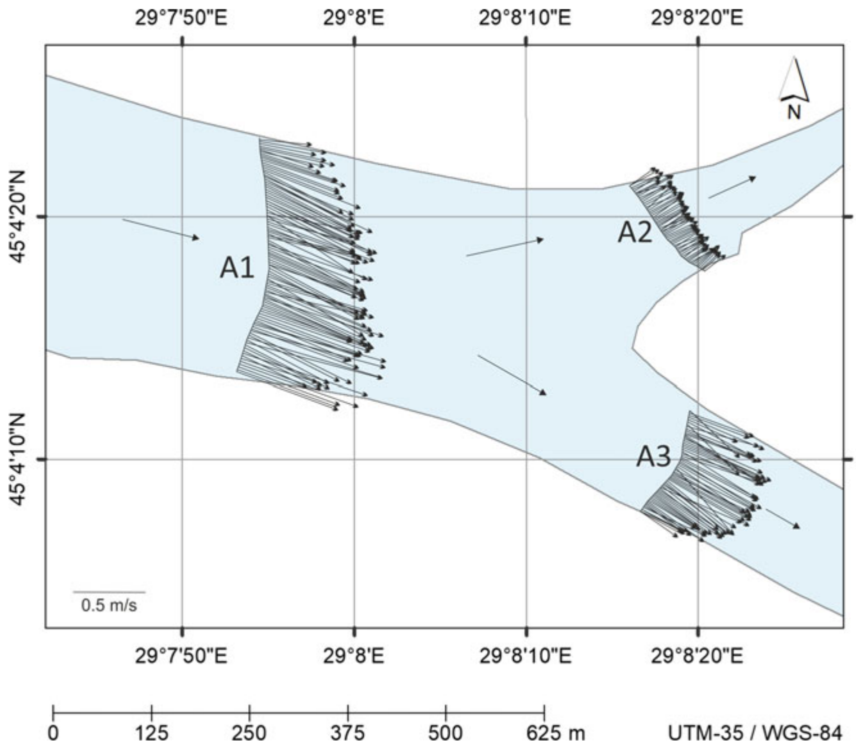

Fig. 3 Depth-averaged flow velocities (black arrows) at the bifurcation area of M1 cutoff in June 2017

low and homogeneous (0.01 m·s^{-1} in September 2016 and 0.05 m·s^{-1} in June 2017) (Figs. 5 and 6).

4.1.2 Second Cut-Off—Upper Dunavăţ Meander Belt (M2)

The percentage of upstream discharge captured by the meander natural course was over 87% of the water discharge in September 2016, and 77.7% respectively in June 2017. The water flow increase in the natural channel; incision processes are identified at the bifurcation sector (I1–I2) with high-velocity values located in the right bank of the profile I1 (Fig. 7).

The velocities are homogeneously distributed on the cross-sections, which demonstrates the active dynamics of the difluence/confluence zones of the system (Fig. 8). At the confluence (profiles K1, K2, and K3) several nucleuses of higher velocity have been observed in the central part of profiles K2 and K3 (Figs. 8 and 9).

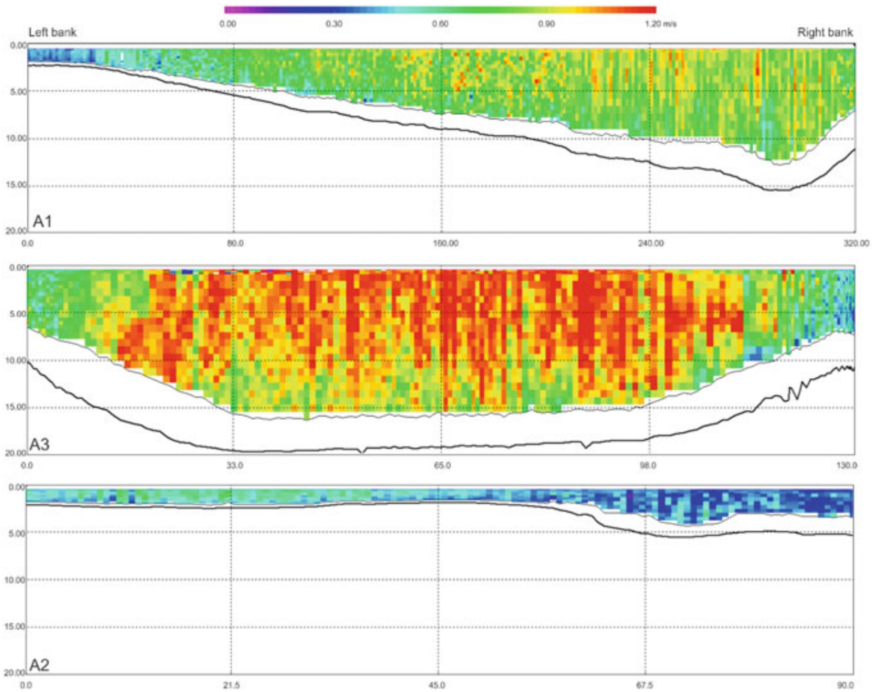

Fig. 4 Distribution of local velocities magnitude within cross-sections measured with the ADCP at the upstream bifurcation (profiles A1, A2, and A3) in June 2017

4.1.3 Third Cut-Off—Lower Dunavăţ (Perivolovca) Meander Belt (M3)

The water fluxes at the bifurcation are distributed unequally between the natural course of the meander (L2 = 25 $m^3 \cdot s^{-1}$ in September 2016, and 78 $m^3 \cdot s^{-1}$ in June 2017) and the cut-off canal (L3 = 1225 $m^3 \cdot s^{-1}$ in September 2016, and 2003 $m^3 \cdot s^{-1}$ in June 2017), with a very high flux in the cut-off canal (≈96–97% of total).

In terms of water velocities, in September 2016, the lowest average values (per cross-section) were situated between 0.16–0.50 $m \cdot s^{-1}$ on the natural channel and the highest mean velocities values were measured on the cut-off canal (around 0.70 $m \cdot s^{-1}$ in September 2016 and 1.13 $m \cdot s^{-1}$ in June 2017). The velocities are homogeneously distributed on the cross-sections (Fig. 10). At the apex zone (profile M), the asymmetric shape of the channel indicates obvious aggradation of the river bed in the central part of the channel.

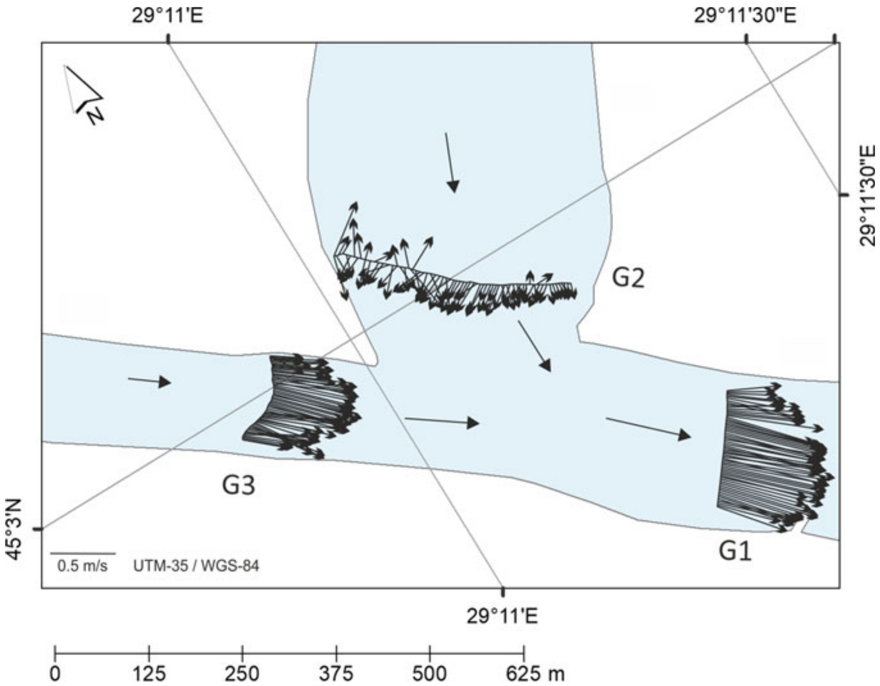

Fig. 5 Depth-averaged flow velocities (black arrows) at the confluence area on the M1 cut-off in June 2017

4.2 Bed Morphology and Bedforms Classification

The anthropic works influenced the local sedimentary transit of the St. George channel and their bed morphology differently. Figures 11 and 12 show the bathymetrical maps of the cut-off canals of the studied meanders. The canals were initially designed to be 7–8 m deep and 75–100 m wide (1984–1988) [67]. Their depth measured thirty years after (in September 2016 and June 2017) is much greater, with a maximum of 22 m and 27 m (relative water depths) for M1 and M3.

For meanders M1 and M3, the cut-off canals continue the direction of the main water flux in the natural course, and this determines the taking over of the main water discharge of the distributary by the cut-off canals, while the cut-off canal at the meander M2 which is oriented approximately at 75–80° to the direction of the main flux in the natural course, only a relatively small part of the flow of water and sediments from the natural course enter the cut-off canal. Consequently, the cut-off canals at the meanders M1 and M3, where the flow velocity is very high, are strongly eroded and their depth increased significantly while in the cut-off canal at the meander M2 no strong scouring processes are registered.

Bedforms are dynamic sediment accumulations occurring on a channel bottom, being scaled to the flow velocity and channel depth [78] and also depending on

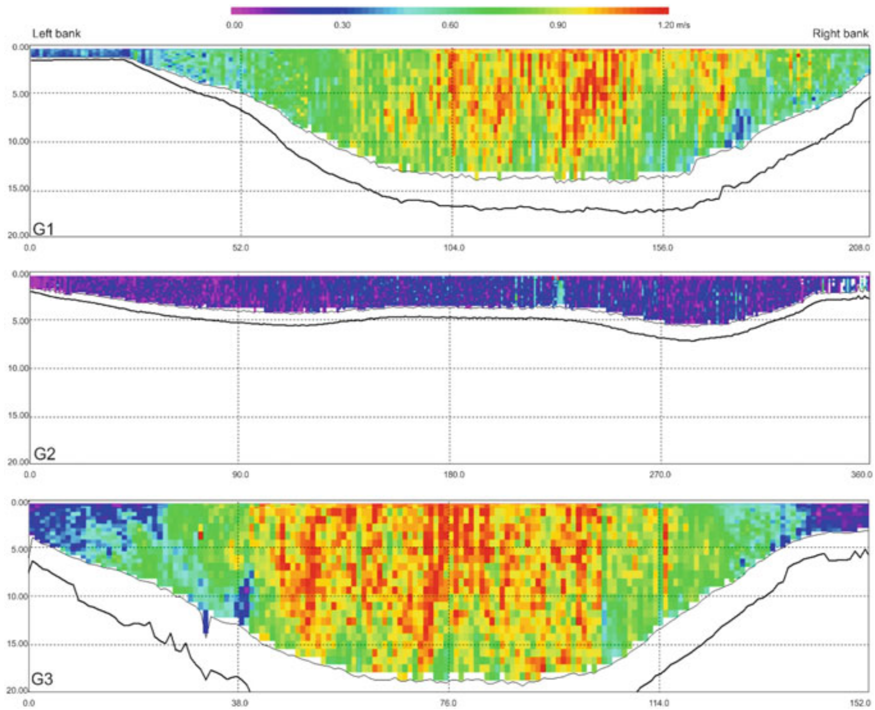

Fig. 6 Distribution of local velocities magnitude within cross-sections measured with the ADCP at the downstream confluence (profiles G1, G2, and G3) in June 2017

the texture and abundance of sediments. Various bed-form classification nomenclature for bottom sand beds are found in the literature [78–82]. Here, van Rijn's classification is applied (ripples, mega-ripples, and dunes).

The ripples, mega-ripples, small and large dunes are the most common bedforms identified along the canals. The most important factors which depend on their formation are the flow velocity, the depth of the channel, and the texture of sediments.

Ripples are primary bedforms with heights up to a few centimeters (length, $L < 0.6$ m, $H < 0.7$ m). Mega-ripples are bedforms with a length similar to water depth [80]. The water depth of the St. George branch ranges from 2 to 27 m. Consequently, mega-ripples are defined here by $L < 25$ m and $H < 1$ m. Mega-ripples have been identified all along the three cut-off canals, being the most common bedform in the study area. Mega-ripples have been measured as independent forms, or as superimposed bedforms on dunes. The measured mega-ripples dimension was between $1 < L > 25$ m and $0.5 < H > 1$ m [72].

Successions of small dunes with a height between $1 < H > 1.5$–2 m and lengths between 20–$30 < L > 400$ m are situated especially at the bifurcation (A1-A2-A3, K1-L2-L3) and confluence areas (G1-G2-G3, K1-K2-K3, N1-N2-N3). Mega-ripples were identified on the surface of all small dunes. Large dunes are quite rare, typically

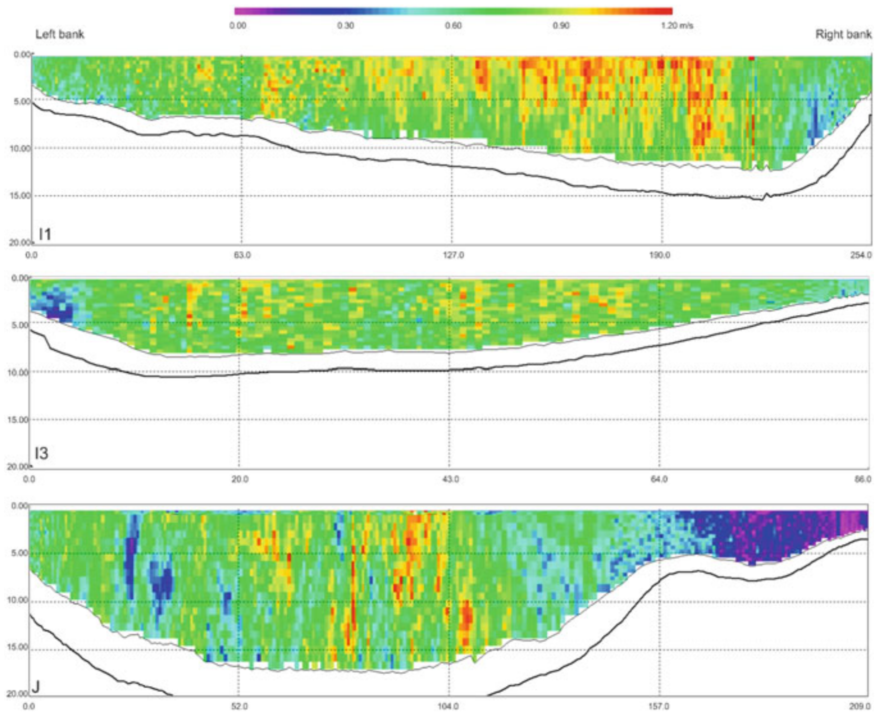

Fig. 7 Distribution of local velocities magnitude within cross-sections measured with the ADCP at the upstream bifurcation (profiles I1 and I3) and at the apex of the former meander M2 (profile J) in June 2017

greater than 400 m in length and higher than 2 m. A large dune was measured at the confluence of the M1 meander belt, measuring more than 7 m in height and more than 500 m in length (Fig. 13).

4.3 Suspended Sediment Concentrations and Sediment Fluxes

The suspended sediment load of a river varies in concentration over time and depends primarily on the precipitation regime in the river basin, the lithology of geological formations and soils within the basin but also, in the same time, on the anthropogenic factor. Most of the sediment load transported by rivers has as source the erosion of soils and geological formations. The anthropic activity (especially building, agriculture, industry) can also introduce significant amounts of sedimentary, but also dissolved fractions. In most cases, the distinction between the fraction due to the

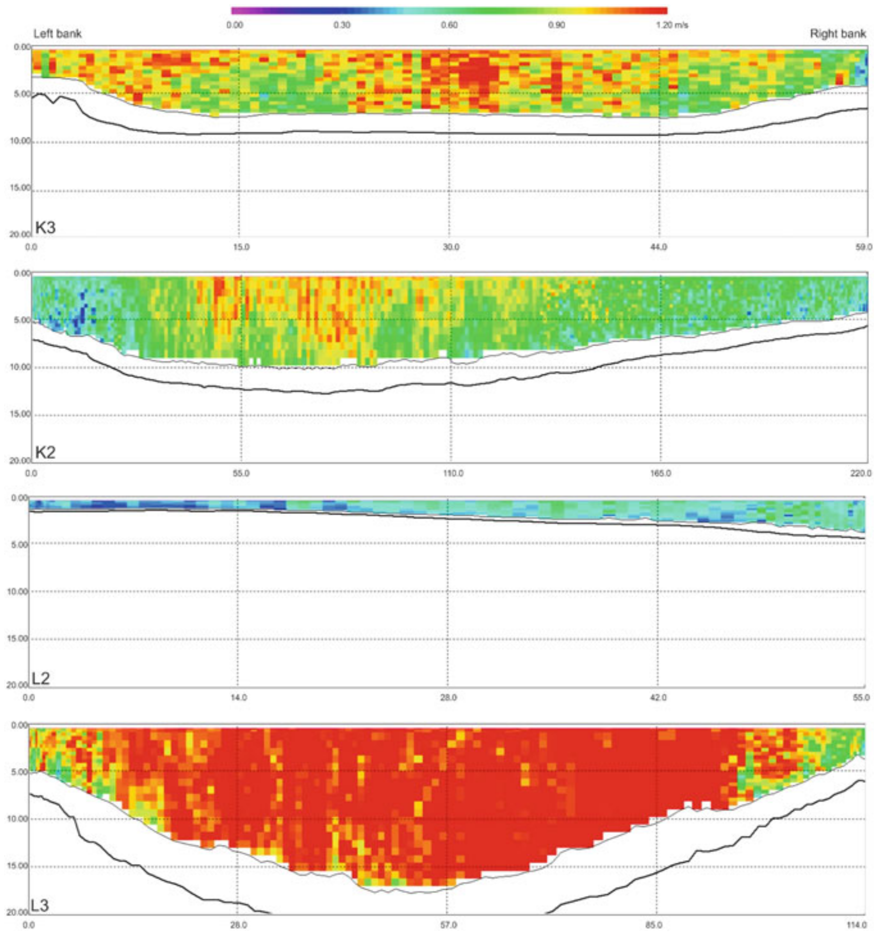

Fig. 8 Distribution of local velocities magnitude within cross-sections measured with the ADCP at the confluence of M2 and bifurcation of M3 (profiles K2, K3, L2, and L3) in June 2017

natural processes and an anthropogenic fraction is very difficult or even impossible to achieve.

Suspended sediment load represents over 80–85% of the total sediment load transported by rivers to the Sea [83]. Attention will be focused on the study of suspended sediments load concentration and suspended sediment discharge. The bedload transport is not included in the calculations of this chapter but is generally estimated as about 10% of the total sedimentary load for most of the rivers [84].

We estimated the discharge of suspended sediments by a common formula described in the literature [85, 86], which is based on correlating the concentration in suspensions with water velocity and section area (the water discharge):

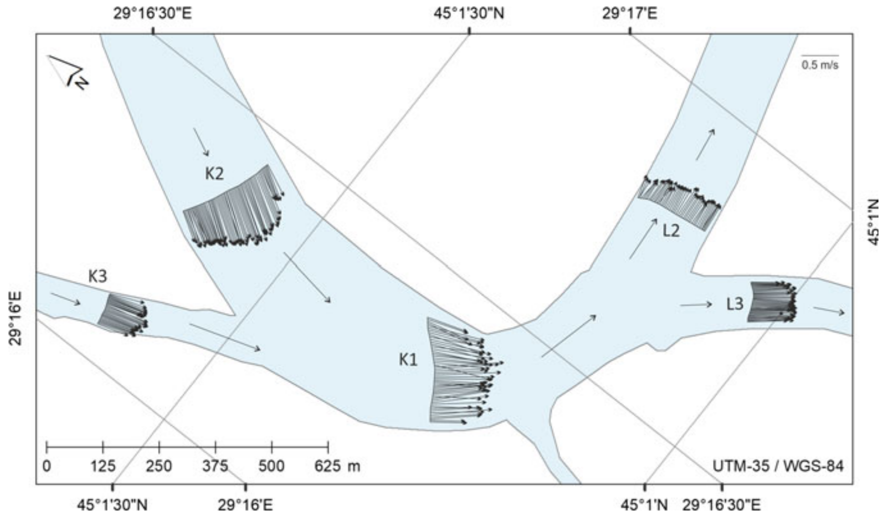

Fig. 9 Depth-averaged flow velocities (black arrows) at the bifurcation and confluence area of the M2 and M3 cutoffs in June 2017

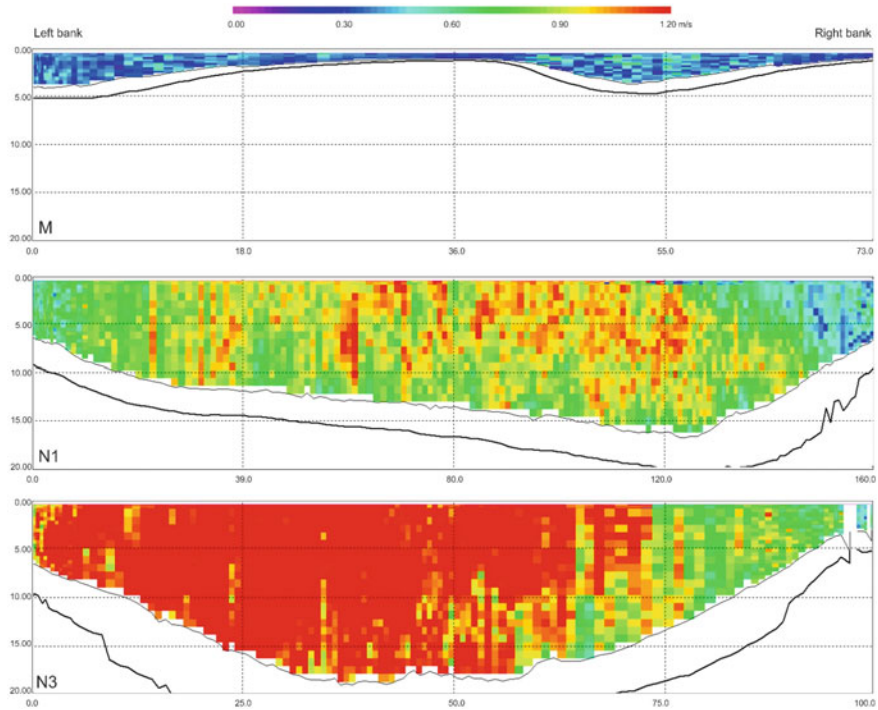

Fig. 10 Distribution of local velocities magnitude within cross-sections measured with the ADCP at the downstream confluence (profiles N1 and N3) and at the apex (profile M) of the former meander M3 in June 2017

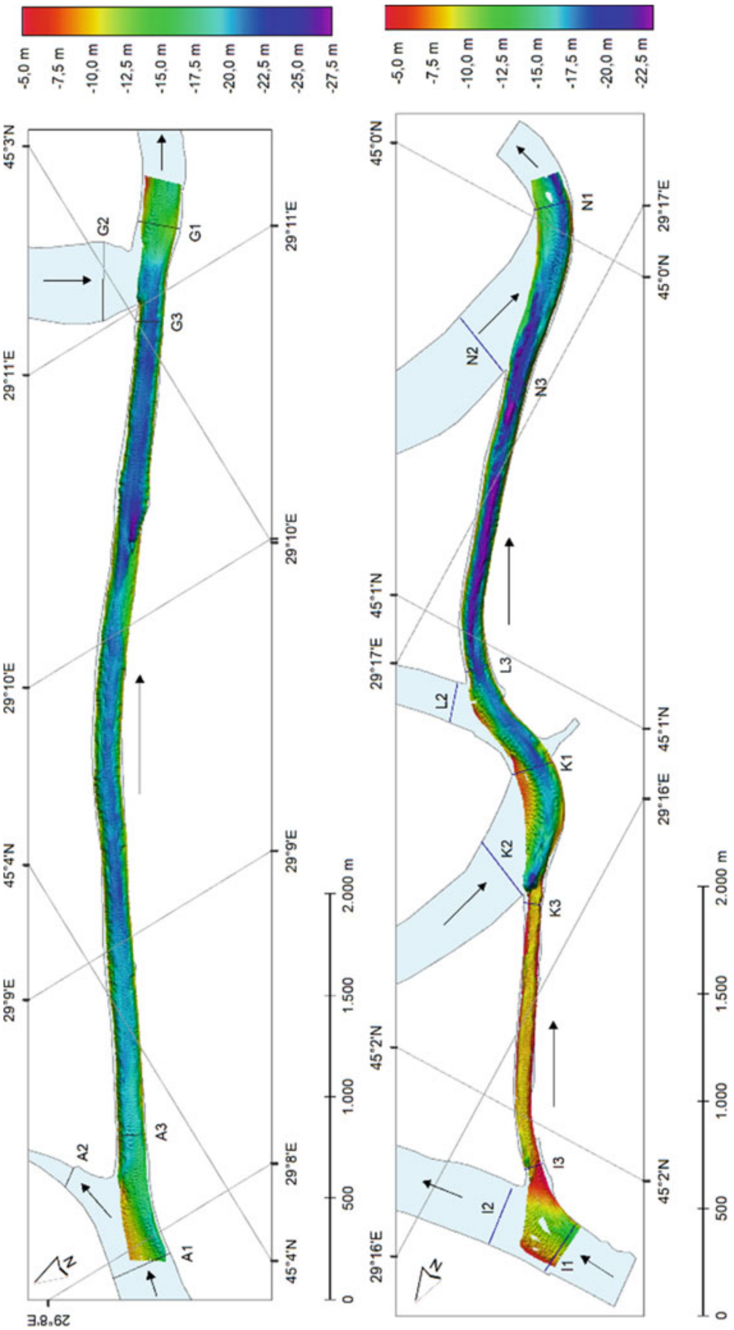

Fig. 11 Morphology of the artificial canals of the M1, M2, and M3 meanders in September 2016

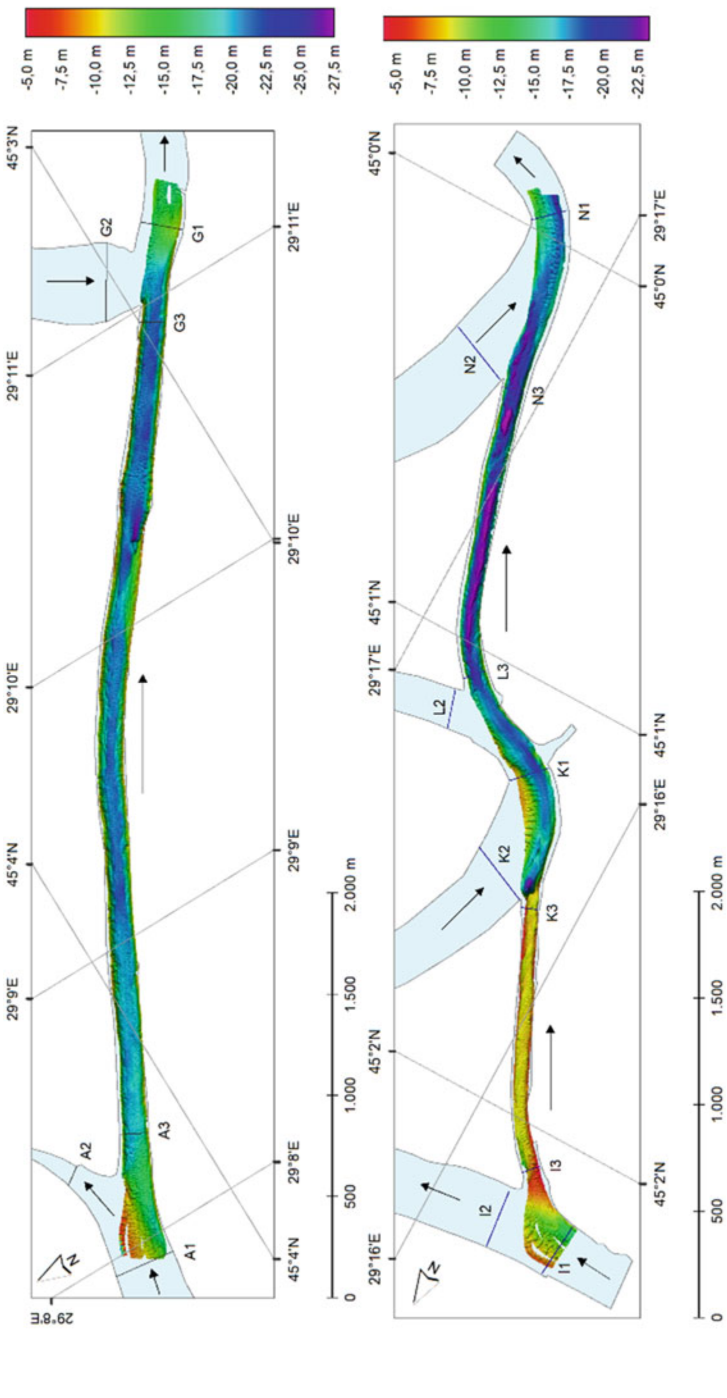

Fig. 12 Morphology of the artificial canals of the M1, M2, and M3 meanders in June 2017

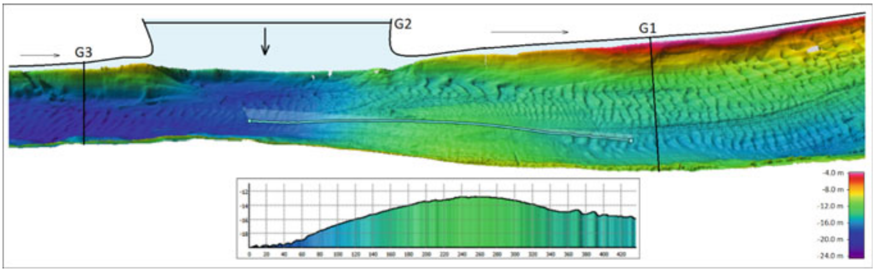

Fig. 13 Large dune situated at the confluence of M1 cut-off

$$Qs = SSC \cdot v \cdot A$$

where Qs is the suspended sediment discharge ($kg \cdot s^{-1}$), SSC is the mean concentration of suspended sediment for the considered section ($mg \cdot l^{-1}$), A is the area of the section (m^2), and v is the average water velocity per cross-section ($m \cdot s^{-1}$).

The concentrations of suspended sediments (*SSC*) measured on the investigated sections range between 10.0 and 38.2 mg l^{-1}, in September 2016, and between 5.0 and 24.1 mg l^{-1}, in June 2017 (Fig. 14 and 15). These values are very low compared to values of the same type of other large rivers: for the Mekong (Thailand) average values of 962 mg l^{-1}, for Mississippi (USA) 849 mg l^{-1}, and even 8240 mg l^{-1} for Rio Grande (USA) [87].

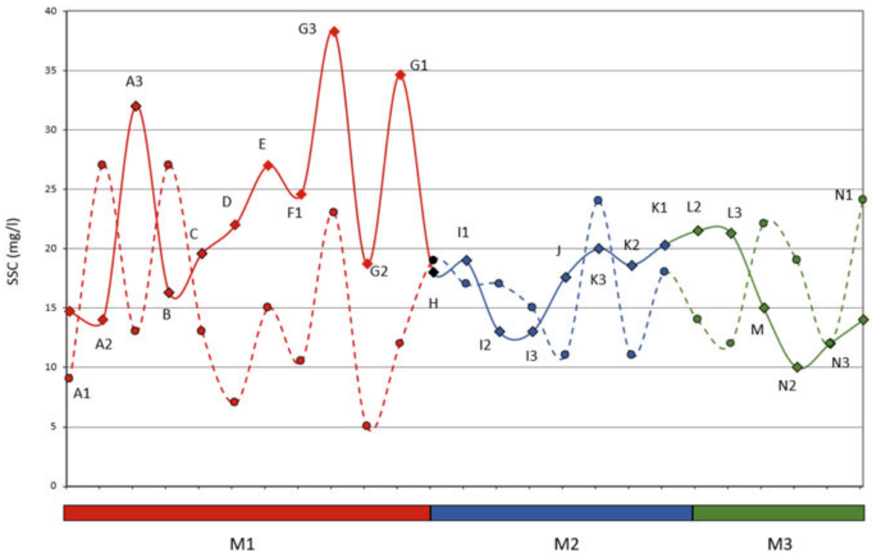

Fig. 14 SSC (mg/l) mean values within cross-sections of the meanders M1, M2, and M3 in September 2016 (continuous line) and June 2017 (dashed line)

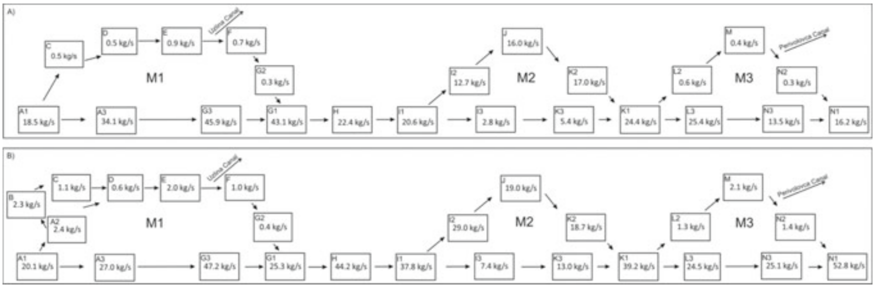

Fig. 15 A box model for SS fluxes by sections of M1, M2, and M3 meanders in September 2016 (A) and June 2017 (B)

At the entrance to the studied meanders area of the St. George distributary the suspended sediment discharge was approximately 18.5 kg·s^{-1} in September 2016 and, 20.1 kg·s^{-1}, in June 2017 (A1). Subsequently, at the exit of the three meanders system the suspended sedimentary discharge was approximately 16.2 kg·s^{-1}, in September 2016, and 52.8 kg·s^{-1} in June 2017 (N1). The difference is not significant in September 2016 at low discharge, but in June 2017, the sediment flux increases by 32.7 kg·s^{-1} (N1) at high water discharge. Along the three meanders accumulation of sediments and erosions of the riverbed occur locally as follows:

1. On M1, in September 2016, from the sedimentary discharge of 18.5 kg·s^{-1} at the upstream bifurcation (cross-section A1), a very small part, of 0.5 kg·s^{-1}, enter through the former meander (in cross-sections C and D). On the cut-off channel (between A3 and G3) the sedimentary flow in suspension is increased (from 34.1 kg·s^{-1} and 45.9 kg·s^{-1} on profiles A3 and G3). On the meander natural course, the suspended sediment discharge becomes lower (0.9 kg·s^{-1} on E, 0.3 kg·s^{-1} on G2) until the confluence. At the exit of the meander, the discharge of 43.1 kg·s^{-1} on cross-section G1 is settled down immediately downstream forming a large dune. In June 2017, the suspended sediments discharge was along the cut-off canal 20.1 kg·s^{-1} on A1 and 47.2 kg·s^{-1} on G3. In the meander natural course, the suspended sediment load progressively decreases from 2.4 kg·s^{-1} on A2 to 0.4 kg·s^{-1} on G2, indicating a strong aggradation process within the channel.
2. On M2, most of the suspended sedimentary discharge is transported by the former meander (approx. 59% in September 2016 and 65% in June 2017). Downstream (profile K1) the sum of the sedimentary fluxes K3 + K2 is higher than the load on the cross-section I1 for both sets of measurements.
3. On M3 the distribution of the sedimentary fluxes is similar to M1, the suspended sediments discharge passing through the cut-off canal is between 98–99% of the total discharge of the distributary in both measurement sets. In June 2017, at a high water level, the output sedimentary discharge N1 (52.8 kg·s^{-1}) is significantly greater than the input discharge K1 (39.2 kg·s^{-1}). This difference shows a sedimentary supply of 13 kg·s^{-1} from the banks or bed erosion in the confluence area.

The role of cut-off canals in the distribution of sedimentary fluxes is a very important one. To an even greater extent, the angle between the natural course and the cut-off canal plays a significant role: at sharper angles (below 40–45°) the water and sediments discharge on the natural course is taken over almost entirely by the cut-off canal, while at angles greater than 45° only a small part of the total discharge on the distributary will be captured by the cut-off canal. This situation is found in the studied meanders: at M1 and M3, where the angles between the natural course and the cut-off canals (the diversion angles) are 22° and 23–25°, respectively, the cut-off canals take over 95% of the total discharge while M2, where the bifurcation angles are over 55° the main flow and water and sediment continues to flow on the natural course of the meander and only 12–23% is directed to the cut-off canal.

4.4 *Grain Size of Bed Sediments*

The grain size of bed sediments sampled in September 2016 has been analysed by [74]. The authors found that the bottom sediments of the main natural channel are composed mostly of sand (medium sand, 59–73% on profiles A1, G1, H, I1, and K1, and coarse sand, 78% on N1) with values of the median parameter ranging between 0.196 and 0.680 mm. Therefore, the sorting is relatively good ($0.6 < \sigma i > 0.75$) (Fig. 16). In the M1 and M3 meanders, the bottom sediments of the artificial canals (profiles A3, G3, and I3) are formed of medium and fine sand with median values ranging between 0.298 and 0.321 mm, indicating a relatively good sorting and positive asymmetry. On the profiles K3, L3, and N3, the clayey silt sediments with high clay percentages are present. The *in situ* analyse describes those sediments such as compact material, possible from the bed substrate [74]. On the former meanders of M1 and M3 (on the profiles A2, B, C, D, E, F, G2, L2, M, N, and N2) the sediments are fine and very fine (clayey silt) with weak and very weak sorting. Along M2, the sediments are formed by coarse, medium, and fine sand (median between 0.286 and 0.302 mm). The relationship between the standard deviation (σi) and the median grain size is shown in Fig. 16; most of the fine sediments from M1 and M3 former meanders are poorly sorted ($0.15 < \sigma i > 2.35$) [74].

In June 2017, the sediments of the main natural channel are formed of sand (medium sand, 54–67% on profiles A1, G1, H, K1, and N1, and fine sand, 61% on I1); the median is situated between 0.194 and 0.350 mm with relatively good sorting ($0.6 < \sigma i > 0.8$) (Fig. 16). The sediments of the artificial canals (profiles A3, G3, and I3) are composed of medium sand (the median between 0.204 and 0.268 mm), with good sorting and positive asymmetry. On the profiles K3 and N3, the sediments are formed from clayey silt with high clay content. Along the former meanders, samples from profiles situated closed to the bifurcations (e.g., A2, B, I2, and L2) are formed mainly of fine sand (between 53 and 63%). The sediments of the M1 are very fine (clayey silt) with weak and very weak sorting ($1.81 < \sigma i > 2.08$).

The comparative analysis of the percentage values of the particle size composition between the two sets of samples shows small distinct changes in the sediment's

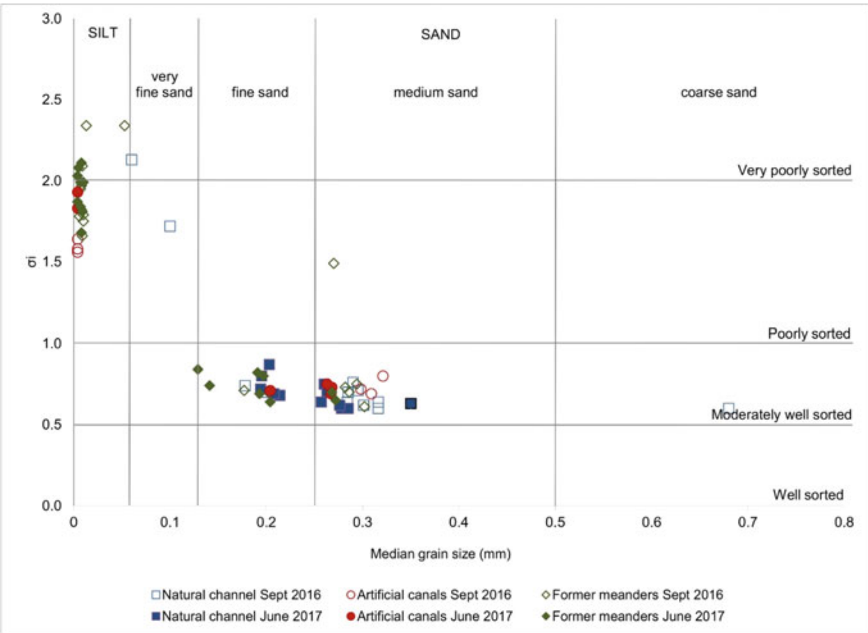

Fig. 16 Grain size distribution diagram: σi = f(M) in September 2016 and June 2017

characteristics. In most cases, the differences between the percentage values for samples collected from approximately the same points in the two campaigns are smaller than the working error of the particle size analysis (the working error of granulometric analyses is a maximum of 5%). In addition to the working error of the laboratory, which is below 2%, errors may occur in positioning the sample's locations in both field campaigns. Differences in the percentages of less than 3% clay particle from sands found in several pairs of samples (samples collected in 2016 and 2017) cannot be taken into account given the abovementioned errors. There are several cases when the granulometry of the sediments collected in June 2017 differs from that of September 2016. These differences are likely the result of errors due to location positioning (sediment granulometry differs depending on the position in the channel) or different hydrodynamic conditions (difference of the water level).

4.5 Long Term Evolution

The first hydrological and bathymetrical impact studies for the Mahmudia (M1) and Upper Dunavăţ and Lower Dunavăţ (Perivolovca) (M3) meanders have been performed by [67], who carried out a sequence of bathymetric measurements during

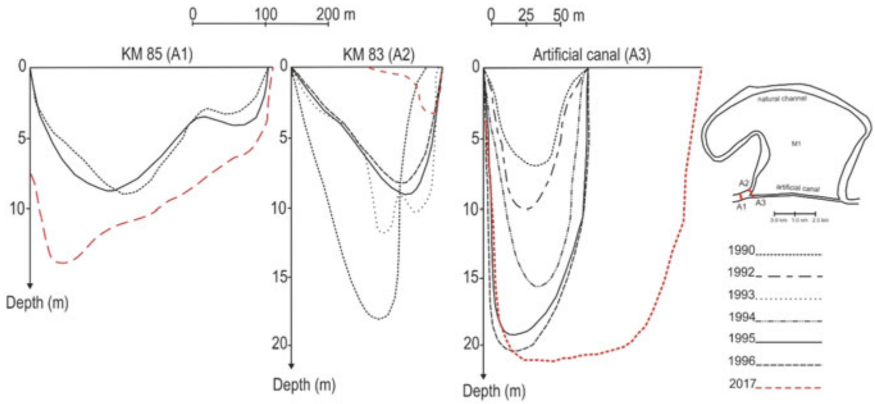

Fig. 17 River-bed evolution (1990–2017) in the Mahmudia modified system *(after Popa, 1997)*

six years immediately after the building of the cut-off canals. The depth measurements at the bifurcation of the Mahmudia meander (M1) (Fig. 17) show that the channel morphology changed continuously during the studied period (1990–1996). Intense aggradation of the meander natural course (aggradation rates up to 11 m, i.e., 1.8 m·y^{-1}) and strong erosion processes of the cut-off canal (deepening rates up to 13 m, i.e., 2.1 m·y^{-1}) have been identified [67].

Later [69] have analysed the behavior of the meander M1 and its cut-off canal in 2006, during the 100-year recurrent flood. The significant increase of water velocity and SSC in the cut-off canal was observed determining very active erosion processes, while the water and sediment fluxes through the meander natural course were greatly reduced, with a very fast clogging of the channel (decrease of hydraulic energy, depth reduction and formation of islands, immediately fixed by the vegetation, especially by forests on banks).

Extending the calculation of the aggradation/degradation rates to our measurements from 2017, we found that, between 1990 and 2017, the natural channel upstream the bifurcation (A1) was eroded with a rate of 1.17 m·y^{-1}. For the same period, significant narrowing of the channel and important infilling processes were observed on the meander natural course (A2), with rates of 0.55 m·y^{-1}.

The cut-off canal evolved completely in a different way. During the first 6 years after its excavation, a very strong erosion process was recorded in the cut-off canal. The canal deepened from 7.0–7.5 m (depth provided by the execution project) in 1990, to about 20 m in 1996, its width remaining almost unchanged (about 75 m). In the next 20 years, however, there was no significant deepening of the canal (in 2017 the maximum depth was 21–22 m, relatives depths), instead, the erosion worked laterally causing a significant widening of the canal (during 1990–1996 period—the canal width was about 75 m, in 2017—almost 150 m). The limitation of the canal deepening is probably due to a more compact, more resistant to erosion, substrate.

Using the imagery analyses [71] explained that before the St. George menders cut-off programme, between 1970 and 1984, the evolution of meanders was marked by generally very slow changes, with sometimes local enlargements of the channel, but after the cut-offs, that started in 1984, the narrowing of the channels by banks accretion and channel aggradations within the rectified meanders became dominant processes.

Based on the ADCP measurements, the same authors [71] confirmed the importance of the cut-off canals on the geomorphologic and sedimentary evolution of the three meanders. After the artificial works, the three studied meanders showed different responses: on M1, the water flow acceleration in the cut-off canal produced incision processes; consequently through the meander natural course the water and sediment fluxes were reduced. Meanders M2 and M3 have different behaviour; their evolution is depending on the angle of bifurcation between the natural course and the cut-off canal and the free water surface slope increase.

After a decade, (our measurements from September 2016 and June 2017) the three meanders register important changes in hydro-morphological and sedimentological behavior. The natural course of M1 undergoes very visible infilling processes related to the decrease in hydraulic energy—the water and solid fluxes have been significantly reduced. During this time the cut-off canal of M1 was continuously strongly eroded, the depth increased from 7–8 m at the beginning (in 1988 when the cut-off was completely operational) up to 27 m, and the width enlarged from almost 75 m to over 110 m in 2017.

On M2, the natural course remained the main water and sediment pass-way, mainly due to the high value of the bifurcation angle between the natural course and the cut-off canal (over 55°); this angle makes the flow of water and sediment continue to be directed on the natural course and only about 12–23% to be taken by the cut-off canal.

The most important changes have been recorded in the repartition of the water and sediment fluxes along M3, with significant consequences on hydro-morphology and sedimentology of the natural course: in 2006 the water fluxes were almost equally distributed between the meander natural course and the cut-off canal, while, in 2017, the natural course (L2) received only 3–4% of the total flow, with significantly reduced velocities (an average of 0.34 $m \cdot s^{-1}$ in the cross-section L2, close to the bifurcation, with progressive decrease up to 0.16 $m \cdot s^{-1}$ in N2).

This development is consistent with most of the bibliographic data. [88, 89] describes two temporal phases in the hydro-morphological response of meanders channels versus cut-offs: first, an immediate response that appears just immediately after the rectification, then a subsequent response that sets in gradual and permanent changes over a longer period. Using GIS analyses [57] has identified these two phases in the evolution of St. George's natural course, especially within the study sector: the immediate response is noticeable from the end of the 1980s. The second phase, after 1990, corresponds to a continuous change of the natural course and the sedimentation on the banks.

Kiss et al. [5] and Amissah et al. [90] confirm the rapid response of the Tisza to the cut-offs by bed aggradation, accretion of the banks, progradation of the meanders point bars. On the Wales [91] show that the meander rectification facilitates the progress of aggradation, the reduction of the mobility of the meanders, and the widening of the bifurcations and confluences of natural channels and the cut-off canals. Contrary [92] describes an increase in the sinuosity of the Bollin (Cheshire) River after rectification works. Similarly [93] reports for the Sacramento River, where the increase in sinuosity is accompanied by a reduction in the width of the channel. For the Mississippi River [25] show that the rectification of meanders determined the reduction of water levels (by 0.6 to 4.7 m) and an increase of the water-free slope. Nevertheless, there are also opinions [94], that the meanders cut-off introduces only temporary disturbances to the river system.

According to the studies performed, the St. George distributary of the Danube Delta is very sensitive to the meanders cut-off programme, with a fast response in increasing its total water and sediment discharges and in the changes of hydro-morphological and sedimentological processes within the rectified meanders.

5 Conclusions

In all river systems, meander cut-off programmes have an extremely important environmental impact generating changes especially in the hydrological and sedimentological status of the rivers. Within deltas/estuaries, the impact also extends to changes in water and sediment circulation towards or from the inter-distributary depressions. The hydrological changes are mainly due to the shortening of the river's natural courses length, which means increase in the water-free surface slope and therefore increases in the water flow velocity and of its capacity of sediment scouring and transport. The increase of the flow velocity and its energetic capacity are recorded within the cut-off canals, while the natural courses of the rectified meanders are almost abandoned and important clogging phenomena are noticed.

The impact of the cut-off canals depends on the increase of the water free surface slope generated by the respective canal (the course shortening resulting from the meander cut-off), as well as on the bifurcation angle (the angle between the natural course and the cut-off canal, at its beginning). When this angle is less than 30–40°, most of the river water and sediments flow is taken over by the cut-off canal, while the angle is greater than 45–50°, only a small part of the discharge is directed to the cut-off canal. In time, however, even in these conditions in which the inertial energy of the current in the river is directed towards the natural river course, the modification of the water free surface slope will determine the gradual increase of the water and sediment flows through the cut-off canal.

The conclusions set out above are illustrated by the situation in the Danube Delta, where the St. George distributary's free meanders were rectified between 1981–1994, which led to important changes in the environmental conditions delta. The meander's rectification led to the shortening of the natural course by some 32 km and implicitly to the increase of the free water slope and the water and sediment flow velocity. The results of the present study refer to the situation within the first three meanders of the six free ones of the distributary. The most dramatic situation is on M1 and M3, where the cut-off canals take over 85–90% of the water and sediment flows of the arm, while the natural courses of the rectified meanders suffer an intense clogging, with the almost complete stopping of the water circulation on them. The meander M2 behaves differently because the bifurcation angle of the cut-off canal is higher than 55° and it takes only 13–23% of the total discharge which is mostly directed towards the natural course of the meander.

The chapter also presents information on the characteristics and dynamics of sediments transported by the river reflected in the morphology of the riverbed.

6 Recommendations

In most of the world's river systems, important hydro-technical works have been carried out, often without knowing in detail what environmental impact they will have. These effects can be amplified to the point of ecological disasters by overlapping modifications caused by global climate change.

Advanced knowledge and understanding of the causes of environmental changes in river systems, especially in deltas/estuaries, is the only possibility to achieve their scientifically correct sustainable management. It is, therefore, necessary to establish complex long-term multidisciplinary research programmes for understanding all-natural processes that control environmental systems in the new conditions of continuous climate change and the increased impact of human interventions. Only the multidisciplinary approach of these studies (hydrology, sedimentology, geomorphology, biology, geophysics, meteorology, oceanology, etc.), the use of the most modern techniques and study methodologies, as well as the follow-up of these processes for long periods will ensure their understanding for taking adequate and effective and sustainable environmental protection measures.

Acknowledgements The research was fouded by the Ministry of Research, Innovation and Digitization Core Program, Projects PN16450503 (Contract no. 37N/2016) and PN19200401 (Contract no. 13N/08.02.2019) and Project AMBIACVA (Contract 23PFE/30.12.2021).

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