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Invited Research Article

Maintenance of large deltas through channelization: Nature vs. humans in the Danube delta

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ABSTRACT

Over the last half century, while the total sediment load of the Danube dramatically decreased due to dam construction on tributaries and its main stem, a grand experiment was inadvertently run in the Danube delta: the construction of a dense network of canals, which almost tripled the water discharge toward the interior of the delta plain. We use core-based and chart-based sedimentation rates and patterns to explore the delta transition from the natural to an anthropogenic regime, to understand the effects of far-field damming and near-field channelization, and to construct a conceptual model for delta development as a function sediment partition between the delta plain and the delta coastal fringe. We show that sediment fluxes increased to the delta plain due to channelization counteracting sea level rise. In turn, the delta coastal fringe was most impacted by the Danube's sediment load collapse. Furthermore, we suggest that morphodynamic feedbacks at the river mouth are crucial in trapping sediment near the coast and constructing wave-dominated deltas or lobes. Finally, we suggest that increased channelization that mimics and enhances natural processes may provide a simple solution for keeping other delta plains above sea level and that abandonment of wave-dominated lobes may be the most long term efficient solution for protecting the internal fluvial regions of deltas and provide new coastal growth downcoast.

1. Introduction

River deltas are constructed with surplus fluvial sediment that is not washed away by waves and currents or drowned by the sea. The waterlogged, low gradient deltaic landscapes favor development of marshes and mangroves, which in turn, contribute organic materials to the delta. In natural conditions, deltas are dynamic systems that adapt to changes in boundary conditions by advancing, retreating, switching, aggrading, and/or drowning. However, most modern deltas are constrained in place by societal needs such as protecting residents, resources, and infrastructure or preserving biodiversity and ecosystem services. Human activities over the last century have inadvertently led to conditions that are unfavorable for deltas (Ericson et al., 2006; Syvitski et al., 2009). New sediment input has been severely curtailed by trapping behind river dams. Distribution of the remaining sediment load across deltas or along their shores has been altered by engineering works. And accelerating eustatic sea level rise combined with anthropogenic subsidence favors marine flooding that surpasses the normal rate of sediment accumulation, leading in time to permanent drowning of extensive regions of the delta plains. Restoration is envisioned for extensively altered deltas (e.g., Day et al., 2007; Kim et al., 2009; Allison and Meselhe, 2010; Paola et al., 2011), but in these hostile conditions virtually all deltas are becoming unstable and require strategies for maintenance.

Availability of sediments is the first order concern for delta maintenance. Sediment budgets are, however, poorly constrained for most deltas (Blum and Roberts, 2009 and references therein). We know that fluvial sediments feed the delta plain (topset) and the nearshore delta front zone (foreset) contributing to aggradation and progradation respectively, but only limited quantitative information exists on the laws governing this sediment partition (Paola et al., 2011 and references therein). Except for deltas built in protective embayments (e.g., Stouthamer et al., 2011), the trapping efficiency appears remarkably small as over 50% of the total load may escape to the shelf and beyond (Kim et al., 2009; Liu et al., 2009). Therefore, a key strategy for delta maintenance is a deliberate and rational sediment management that would

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optimize the trapping efficiency on the delta plain (e.g., Day et al., 2007; Kim et al., 2009; Allison and Meselhe, 2010; Paola et al., 2011) and along the delta coast. Here we look at how fluvial sediments delivered to the wave-dominated Danube delta changed in natural vs. anthropogenic conditions on both delta plain and delta front and the examine how similar changes may affect maintenance of deltas in general and wave-dominated deltas in particular.

2. Background

2.1. Natural morphology and dynamics

The Danube delta, built in the northwestern Black Sea over the last ~9000 years (Giosan et al., 2009), comprises of two distinct morphological regions (Antipa, 1915). The internal "fluvial delta" was constructed inside the former Danube Bay, whereas the external "marine delta" developed into the Black Sea proper once this paleo-bay was filled (Fig. 1). The modern delta plain preserves surface morphological elements as old as ~5500 years indicating that sea level did not vary much since then and that subsidence has been minimal when considered at the scale of the whole delta (Giosan et al., 2006). The fluvial delta is an amalgamation of river-dominated bayhead and lacustrine lobes characterized by networks of successively branching channels and numerous lakes (Fig. 1). Wave-dominated lobes, characterized by beach ridge and barrier plains composed of alongshore-oriented sand ridges, are typical for the marine delta (Fig. 1). Although the youngest region of the marine delta, Chilia III, started as a river-dominated lobe, it has come under wave-dominance in the first half of 20th century when sediment delivered by Chilia branch became insufficient relative to its size (Giosan et al., 2005). Much of the late development of the delta may be due to expansion of deforestation in the drainage basin in the last 1000 years (Giosan et al., 2012) leading to an overextended Danube delta.

The high density of the fossil and active channel network (Fig. 1) suggests that after construction, the natural delta plain was fed by fluvial sediments through overbank flooding and avulsion in the fluvial sector, but primarily via minor overbank flooding in the marine sector. In the latter waves have tended to suppress avulsion and, thus, channel development (Bhattacharya and Giosan, 2003; Swenson, 2005). The fluvial sediment delivery to the internal delta was probably relatively small compared to the sediment delivered to the coast even with secondary channels present there. For example, Antipa (1915) described the internal delta after his comprehensive campaign of mapping it at the beginning of the last century as a "vast shallow lake" covered by floating reed islands and with marshes along its edges. Even today hundreds of lakes dot the fluvial delta (Giosan et al., 2005). Antipa's "vast lake" was bounded by the high banks of the three large Danube distributaries (i.e., the Chilia, Sulina, and St. George from north to south) and the sand ridges of the marine delta, and internally segmented by the

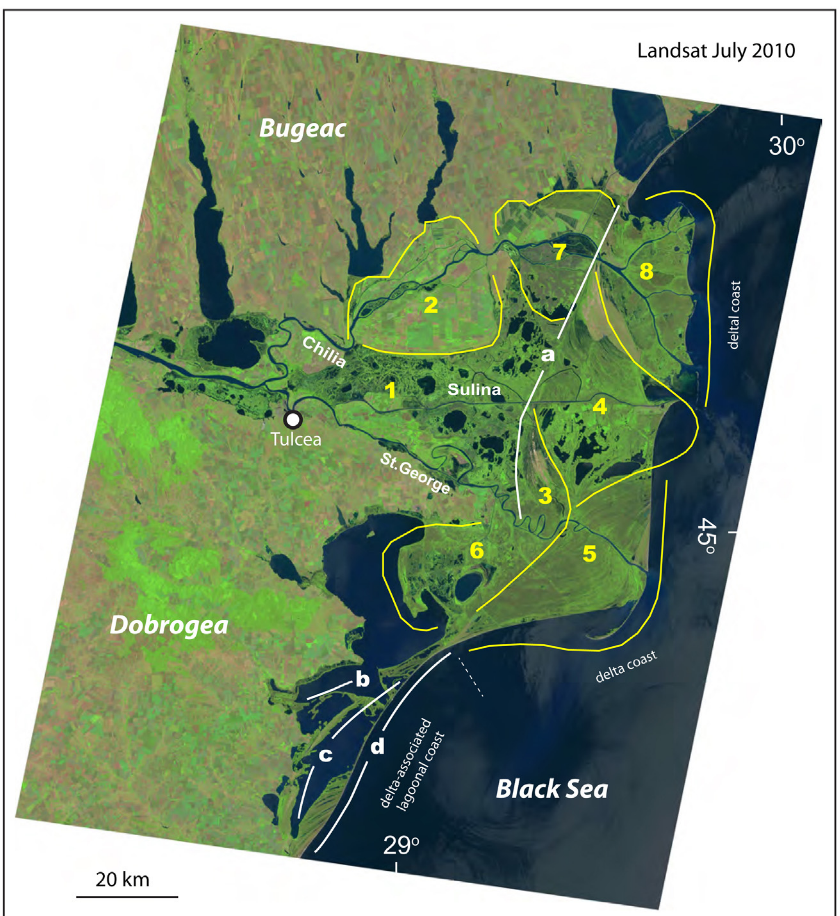

Fig. 1. Danube delta geography and its evolution phases. Yellow lines delineate delta lobes in the order of their build-up (Giosan et al., 2005, 2006, 2012): (1) Tulcea, (2) Chilia III, (3) St. George I, (4) Sulina, (5) St. George II, (6) Dunavatz, (7) Chilia II, and (8) Chilia III. White lines delineate the trends for baymouth barriers systems associated with Danube delta (Giosan et al., 2005, 2006): (a) Danube Bay barrier system, (b) Zmeica barrier system, (c) Lupilor barrier system, and (d) Chituc barrier system. The Danube Bay barrier system separates the internal delta (i.e., fluvial) from the external delta (i.e., open marine deltaic lobes). Note the dominance of channels and lakes in the internal delta vs. quasi-shore-parallel linear sand ridges and dunes in the external delta.

minor levees of some more prominent secondary channels. Most of these secondary channels were however partially abandoned and the few larger ones remaining open all along their course (Vidraşcu, 1911) were delivering negligible amounts of freshwater leading to hypoxia in the summer (Antipa, 1941). With only localized and minor overbank flooding, delta plain development on the marine sector was in turn dominated by alongshore marine redistribution of sediment and coastal progradation via successive coastal sand ridge development (Giosan et al., 2005, 2006).

2.2. Human impacts

Human intervention in the Danube delta began in the second half of the 19th century and affected the three major distributaries of the river in different degrees. Initially, protective jetties were built and successively extended at the Sulina mouth and the corresponding branch was transformed into a shipping channel by shortening and dredging (Fig. 2a; Rosetti and Rey, 1931). After World War II, meander cuts and other engineering works on the other major distributaries also slightly changed the water and, by extension, the sediment partition among them. The main net effect was that the Chilia branch lost ~10% of discharge (Bondar and Panin, 2001), primarily to the Sulina channel. Polder construction for agriculture (Fig. 2a) expanded until 1990 to over 950 km^2 (over 25% of the ca. 3400 km^2 of the delta proper) but restoration of these polders has started and will eventually recover ca. 600 km^2 (Staras, 2000; Schneider, 2010).

The most extensive and persistent engineering activity in the delta was the cutting and dredging of shallow, narrow canals. Because the number of secondary channels bringing freshwater to deltaic lakes and brackish lagoons south of the delta was limited and this affected fisheries, several canals were dug before 1940s to aid fishing (Fig. 2a; Antipa, 1941). After WWII, the number of canals increased drastically for industrial scale fishing, fish-farming and reed harvesting (Fig. 2a; e.g., Oosterberg and Bogdan, 2000). Most of these canals were dug to shallow depths (i.e., ca. 1–2 m) and were kept open by periodic dredging. Compared to the pre-WWII period, the length of internal channels and canals doubled from 1743 km to 3496 km (Gastescu et al., 1983). Following a slack phase after the fall of the Communist economy in Romania beginning in 1989, canal dredging is now primarily employed to maintain access for tourist boats into the interior of the delta.

2.3. Water and sediment fluxes

The exchange of water between the main distributaries and the delta plain more than tripled from 167 m^3/s before 1900 to 620 m^3/s between 1980 and 1989 (Bondar, 1994) as a result of canal cutting. The successive relative increases in water transiting the interior of the delta plain correspond to 3.0 and 11.3% respectively for the annual average Danube discharges of 5530 and 5468 m^3/s respectively (GRDC, 2010). However, in the same time, the full sediment load entering the delta has drastically diminished from ca. 70 Mt/yr to ca. 25 Mt/yr after the intensive damming of the Danube and its tributaries in the second half of the 20th century (McCarney-Castle et al., 2012 and references therein). The expected average potential sediment deposition on the delta plain can be roughly estimated using these water discharge and sediment load measurements for the Danube. It is interesting to note that the increase in water discharge transiting the interior of the delta have combined with the decrease in sediment load due to damming to keep sediment load directed toward the delta plain quite constant with ~2.1 MT/yr for the Danube natural system load at the delta of ~70 MT/yr and ~2.5 MT/yr for the anthropogenic system when the load decreased to ~25 MT/yr. These numbers highlight the fact that due to the increase in density of human-dug canals sediment trapping on the delta plain has become a significant part of the present sediment budget of the delta (i.e., >10%). In the same time, these numbers suggest that the main impact of the increasing fluvial sediment deficit would be expected at the coast.

If we assume that sediments that enter the interior of the delta from the main distributaries, either as overbank flows or via the narrow and shallow secondary canal network, do not escape back

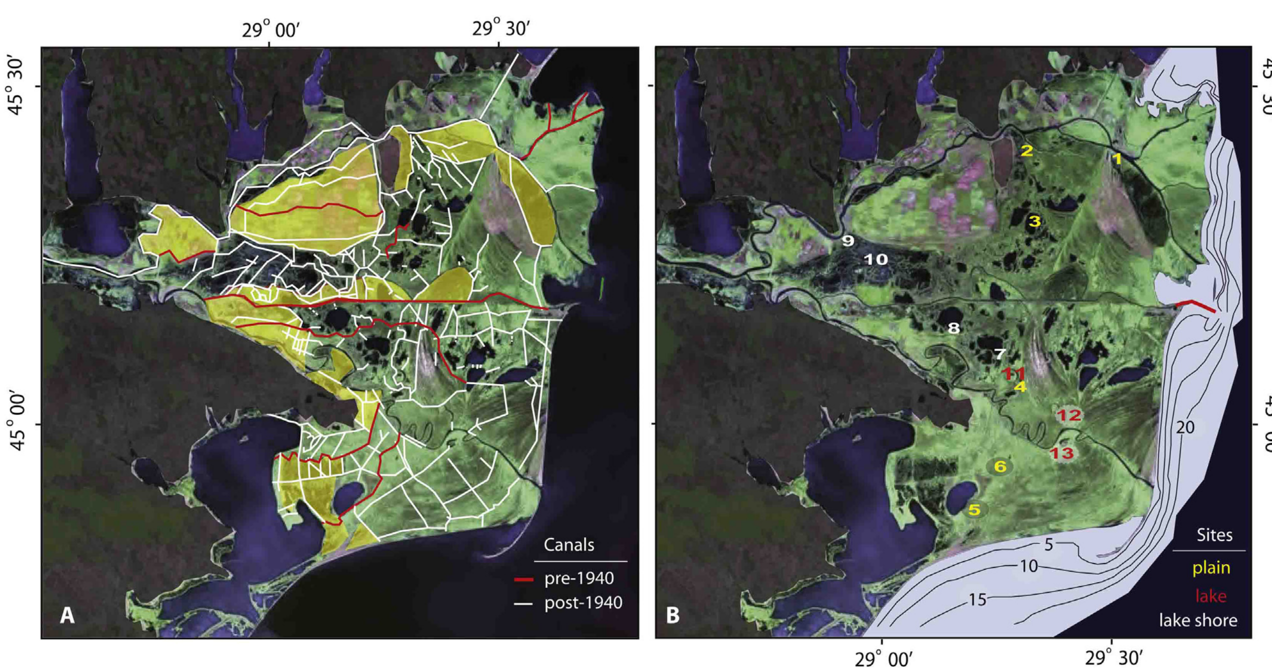

Fig. 2. (A) A synthetic look at large-scale direct human intervention in the Danube delta. Canals dug within the delta are shown for two different phases of channelization: pre- and post-WWII. The course for the Chilia-Bastroe Canal (under construction) is also shown. Areas reclaimed for agriculture at the end of 20th century are indicated by a yellow mask. (B) Cores studied from depositional environments ranging from proximal to distal relative to the fluvial sediment source including delta plain marshes, lake shore marshes and lakes. The bathymetric coverage for the Danube delta nearshore region used in this study is a shown with depth contours.

Table 1
Cores studied in the internal (fluvial) part of the Danube delta.

Core	Location (*Lobe*)	Depositional environment	Latitude	Longitude
KP11	Periprava (*Chilia III*)	Delta plain	45°23′ 26.5236″ N	29°34′ 22.2025″ E
KP2	ChiliaVeche (*Chilia II*)	Delta plain	45°25′ 6.2878″ N	29°21′ 37.0726″ E
KP3	Matita (*Tulcea*/*Chilia II*)	Delta plain	45°22′ 58.3499″ N	29°31′ 13.9977″ E
P1	Perivolovca (*Tulcea*)	Delta plain	45°02′ 27.4896″ N	29°20′ 26.5910″ E
D3	Dranov (*Dunavat*)	Delta plain	44°51′ 28.4128″ N	29°12′ 55.8153″ E
D2	Dranov Canal (*Dunavat*)	Delta plain	44°55′ 37.1255″ N	29°16′ 22.5829″ E
FO1	Fortuna (*Tulcea*)	Lake shore	45°19′ 11.6918″ N	29°26′ 7.2078″ E
GO1	Gorgova (*Tulcea*)	Lake shore	45°07′ 31.1130″ N	29°11′ 49.4182″ E
HO1	Hontu (*Tulcea*)	Lake shore	45°15′ 41.6598″ N	28°55′ 47.7601″ E
NE1	Nebunu (*Tulcea*)	Lake shore	45°14′ 45.8540″ N	29°00′ 55.2225″ E
G1	Gorgostel (*Tulcea*)	Lake	45°03′ 29.8860″ N	29°19′ 46.0410″ E
E1	Erenciuc (*Sulina?*)	Lake	44°59′ 11.7012″ N	29°25′ 45.9752″ E
B1	Belciug (*St. George II*)	Lake	44°56′ 56.9849″ N	29°25′ 46.8298″ E

into the main distributaries, the sediment trapped in the interior of the delta can be estimated. This tenet is a reasonable one if we take into account almost all branches of the canal network end in or cross lakes that act as sediment traps. Making the supplementary assumption that most, if not all, of this sediment feeds the internal fluvial delta rather than the marine delta, because canal density is insignificant in the latter, we estimate the average sediment flux changed from 0.07 in natural conditions to 0.09–0.12 g/cm^2 today when distributed uniformly across for an area the entire internal delta plain (~2800 km^2 or ~2000 km^2 without polders). The figures would be somewhat smaller when consider the losses to areas of the marine delta plain that do have some canals. However, these numbers ignore organic sedimentation that is expected to be significant in the internal delta. The flux estimates above translate into sedimentation rates of 0.5–0.8 mm/yr if we use a dry density of 1.5 g/cm^3 for water saturated mixed sand and mud with 40% porosity (Giosan et al., 2012).

In natural conditions, most of the internal delta plain was submerged with the exception of the levees of major and minor distributaries suggesting a sediment starved environment (Antipa, 1915). In anthropogenic conditions, the situation is probably similar with sediments rather than being spread evenly across the delta, accumulating close to the secondary channel network or in lakes fed by this network. But are these figures realistic when compared to directly measured rates across various depositional environment of the delta plain? And because the changes due to damming are expected to have affected primarily the Danube delta coastal fringe where the bulk of the Danube's sediment load has always been directed, how was this drastic decrease of sediment discharge felt at the coast? How these transformations of the sedimentary dynamics attributed to anthropogenic actions combine to affect the Danube delta as a whole is poorly known and comprises the main topic of our study.

3. Methods

Sedimentation on the delta plain was examined in sediment cores collected from all internal deltaic lobes as well as fluvial-fed sectors of the external marine lobes. Thus our discussion on delta plain sedimentation will generally be restricted to the internal and fluvially dominated delta plain, which start at the apex of Danube delta where the river splits into the Tulcea and Chilia branches and comprises of the Tulcea, Dunavatz, and Chilia I, II, and III lobes (Fig. 1). The cores cover depositional environments typical for Danube delta ranging from proximal to distal relative to the fluvial sediment source including delta plain marshes, delta plain lakes and lake shore marshes (Fig. 2b; Table 1). Marsh cores were collected in 0.5 m increments with thin wall gouge augers to minimize compaction. A modified thin wall Livingstone corer was used to collect lake cores from the deepest areas of three oxbow lakes.

Bulk densities were measured on samples of known volume (Tables 2 and 3). A Canberra GL2020RS low-energy Germanium gamma well detector measured the activity of ^{137}Cs at intervals ranging from 1 cm to 10 cm until the level of no activity was consistently documented. Sedimentation rates were estimated based on the initial rise (~1954 A.D.) and subsequent peaks in ^{137}Cs activity associated with the moratorium on atmospheric nuclear weapons testing (~1963 A.D.) and the Chernobyl nuclear accident (1986 A.D.) that is detectable in many European marshes (e.g., Callaway et al., 1996). The use of ^{137}Cs is well established as a dating method in the Danube delta and the Black Sea (Winkels et al., 1998; Duliu et al., 2000; Gulin et al., 2002; Aycik et al., 2004).

Table 2
Modern sediment fluxes to the internal (fluvial) part of the Danube delta.

Core	Time horizon depth			Bulk dry density			Organic matter		Sedimentation rate			Bulk flux			Siliciclastic flux	
	1954 (cm)	1963 (cm)	1986 (cm)	1954 (g/cm^3)	1963 (g/cm^3)	1986 (g/cm^3)	1954–1986 (%)	1986–2008 (%)	1954 (cm/yr)	1963 (cm/yr)	1986 (cm/yr)	1954 (g/cm^2)	1963 (g/cm^2)	1986 (g/cm^2)	1954 (g/cm^2)	1986 (g/cm^2)
KP11	38.5		6.5	0.7		0.4	10	15	0.71		0.3	0.5		0.12	0.45	0.1
KP2	55.5			0.8			8		1.03			0.82			0.76	
KP3	35.5		11.5	0.8		0.6	19	37	0.66		0.52	0.53		0.31	0.43	0.2
P1	102.5		25.5	0.3		0.2	15	23	1.9		1.16	0.57		0.23	0.48	0.18
D3	35.5	25.5	10.5	0.7	0.6	0.5	6	14	0.66	0.57	0.48	0.46	0.34	0.24	0.43	0.21
D2	59.5	49.5	6.5	0.6	0.6	0.6	12	15	1.1	1.1	0.3	0.66	0.66	0.18	0.58	0.15
FO1	45.5	35.5	15.5	0.4	0.4	0.4	43	43	0.84	0.79	0.7	0.34	0.32	0.28	0.19	0.16
GO1	51.5		21.5	0.5		0.4	10	10	0.95		0.98	0.48		0.39	0.43	0.35
HO1	27	21.5	6	0.4	0.4	0.4	10	7	0.5	0.48	0.27	0.2	0.19	0.11	0.18	0.1
NE1	45.5	41.5	11.5	0.5	0.5	0.5	11	24	0.84	0.92	0.52	0.42	0.46	0.26	0.37	0.2
G1	23		7	0.8		0.8	22	22	0.43		0.32	0.34		0.25	0.27	0.2
E1	51	27	7	0.6	0.5	0.4	23	30	0.94	0.6	0.32	0.52	0.31	0.14	0.4	0.1
B1	7			1.4			15		0.13			0.18			0.15	

Table 3
Radiocarbon dates and millennial sediment fluxes to the internal (fluvial) part of the Danube delta.

Core	Depth (cm)	Lab No.	Material	Condition	14C age (years BP)	Error (years)	Cal. age (years)	Sed. rate (cm/yr)	Density (g/cm^3)	Bulk flux (g/cm^2)
KP2	190	OS-57606	*Cardium* sp.	Articulated	1340	30	673–930	0.14–0.20	1.66	0.23–0.33
P1	265	OS-64644	Peat	*In situ*	2670	55	2718–2920	0.06	0.68	0.04
D3	526	OS-64644	Peat	*In situ*	3120	35	3254–3441	0.14–0.15	1.34	0.19–0.20
D2	398	OS-64623	Peat	*In situ*	3620	45	3891–4148	0.08–0.09	1.36	0.11–0.12
FO1	367	OS-64624	Peat	*In situ*	3270	40	3395–3606	0.09	1.54	0.15
GO1	819	OS-64803	Peat	*In situ*	4010	80	4243–4814	0.16–0.18	1.26	0.20–0.23
NE1	544	OS-69054	Peat	*In situ*	5190	40	5773–6172	0.09	1.58	0.13–0.14

Average organic matter content was measured using the loss-on-ignition method (Dean, 1974) on mixed samples representative for intervals used for the sedimentation rate analyses. Sediment fluxes were then calculated using ^{137}Cs-based sedimentation rates for bulk and siliciclastic sediments using the raw and organic matter-corrected dry bulk densities (Table 2).

AMS radiocarbon dates were used to estimate long term net sediment fluxes at millennial time scales (Table 3) since the Black Sea level stabilized ~5500 years ago (Giosan et al., 2006). Dating was performed on vegetal macrofossils from peat levels or *in situ* articulated shells recovered deeper in our cores. Fluxes were calculated using calibrated radiocarbon-based sedimentation rates and average bulk densities for each core. These long term accretion rates and derived fluxes represent the net average sedimentation rates at a fixed point within the delta regardless of the dynamics of the deltaic depositional environments at that point. Thus, the recent dynamics of these environments may appear relatively sluggish due to the mere fact that the last century is a short period of time compared to the last ~5500 years. However, at millennial time scales significant changes in the sedimentary environment at any point of the delta plain can be expected primarily through avulsion, lateral channel erosion and deposition, and lake infilling. Sediment capturing on the delta plain via human engineering solutions is therefore expected to be *ab initio* more effective than sediment trapping under a natural regime due to a shorter and cumulatively less dynamic history.

Changes in morphology at the coast and on the shelf in front of Danube delta in natural (i.e., second half of the 19th century) vs. anthropogenic conditions (i.e., late 20th to beginning of the 21st century) were explored within a GIS environment. We analyzed bathymetric changes using historic and modern charts and, in part, our new survey data. The charts were georeferenced using common landmarks verified in the field by GPS measurements (Constantinescu et al., 2010) and reprojected using the UTM/WGS84, Zone 35N projection. The depth values from English maps that were initially expressed in feet and fathoms were converted into meters. Because the spatial extent for the charts was not similar for all the documents therefore, volumetric comparisons were made only for the common overlapping areas. DEMs were constructed for each survey with the spatial resolution of 20 m followed by their difference expressed in meters for each interval leading to maps of morphological change (in cm/yr) by dividing bathymetric differences by the number of years for each time interval.

The oldest chart used (British Admiralty, 1861) is based on the single survey of 1856 under the supervision of Captain Spratt, whereas the 1898 chart (Ionescu-Johnson, 1956) used their own survey data but also surveys of the European Commission for Danube since 1871. For the anthropogenic interval, we compared the 1975 chart (SGH, 1975) with our own survey data of 2008 for the Romanian coast completed by a 1999 chart for the Ukrainian coast of the Chilia lobe (DHM, 2001). The 2008 survey was performed from Sulina mouth to Cape Midia on 60 transversal profiles down to 20 m water depth using Garmin GPS Sounder 235. The charts from 1898, 1975, and 1999 are updated compilations of the bathymetry rather than single surveys and this precludes precise quantitative estimates for morphologic changes. Because of this uncertainty, we only discuss change patterns for regions where either the accretion or erosion rates reach or pass 5 cm/yr (or >0.75 m change between successive charts). However, these comparisons still allow us to qualitatively assess large scale sedimentation patterns and to evaluate first order changes for shelf deposition and erosion. Using these volumetric changes and a dry density of 1.5 g/cm^3 for water saturated mixed sand and mud with 40% porosity (Giosan et al., 2012), we estimated the minimal deposition and erosion along the deltaic fringe zone for both the 1856–1871/1897 and 1975–1999/2008 time intervals.

We also analyzed the evolving patterns of shoreline change along the Danube delta coast on 177 cross profiles during the transition from natural to anthropogenic conditions using the single surveys of 1856 (British Admiralty, 1861) and 1894 (CED, 1902) and shoreline changes between 1975/1979 and 2006 (SGH, 1975; Vespremeanu-Stroe et al., 2007). Automatic extraction of rates was performed using the Digital Shoreline Analysis System (Thieler et al., 2009).

4. Results

4.1. Delta plain sedimentation

Recent sedimentation rates at all our locations have been above or close the local relative sea level rise of ~3 mm/yr (Table 2) when both siliciclastic and organic components are considered. However, millennial scale sedimentation rates (Table 3) are all below these recent rates with the lowest values at sites within the interior of the delta far from the main distributaries, such as lakes Fortuna (FO1) and Nebunu (NE1) or natural channels Perivolovca (P1) or Dranov Canal (along the former natural channel Cernetz; D2). The corresponding siliciclastic fluxes (Tables 2 and 3 and Fig. 3) are between 1.5 and 8 times higher than the expected flux of 0.09–0.12 g/cm^2 calculated by us using the available estimates for water flux transiting the interior of the delta (*vide supra*). This holds true for all depositional environments (Table 1 and Figs. 2 and 3) and for all time intervals investigated. The larger than expected fluxes suggest that either a sampling design bias toward locations proximal to the sediment source (i.e., channels), turbid waters trapping inside the delta more than 10% of the sediment transported in suspension by the Danube or a combination of both. In this context, we note that any location in the delta is relatively proximal to a channel due to the high density of the channel network and that the siliciclastic flux in the most distal lake cored by us (Belciug) is still above the expected 0.09–0.12 g/cm^2. However, even if any bias was introduced by sampling, the pattern of increased deposition near channels would mimic well the natural deposition pattern (Antipa, 1915).

The largest overall siliciclastic fluxes correspond to the post-WWII period (1954-present) with an average of 0.4 g/cm^2. When only the post-damming interval is considered, siliciciclastic fluxes

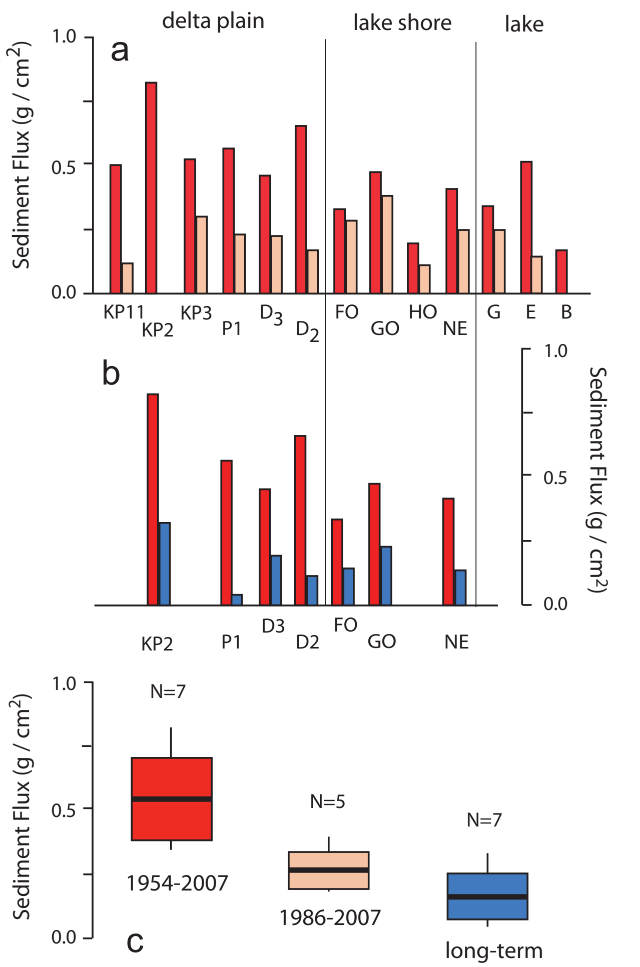

Fig. 3. Bulk sediment fluxes to various depositional environments of the internal delta: (a) modern fluxes post WWII (1954; dark red) and post-Iron Gate damming (1986; light red); (b) modern (post WWII; dark red) vs. millennial scale fluxes (blue); (c) box-and-whisker plots for sediment fluxes (post-WWII, post-Iron Gate damming, and millennial) with mean, standard deviation, minima and maxima shown.

fall back to values not much higher than those measured for the long term, millennial time scales: 0.23 vs. 0.14–0.17 g/cm^2 respectively. Post-WWII fluxes to locations on the delta plain near distributaries, secondary channels or canals were generally higher than fluxes toward lakes, either from cores collected at their shores or within the lake proper (Fig. 3), but this apparent relationship collapses in the most recent, post-damming period. And while large reductions in fluxes occurred at the delta plain marsh sites between these two recent intervals, at locations associated with lakes, the decrease in fluxes is less dramatic (Fig. 3). These two observations combined suggest that there is a similar amount of sediment reaching the lakes, but that coarser sediment settling faster near canals may have decreased in quantity. The lowest sediment fluxes for the entire dataset was measured in the most isolated lakes like Belciug, an oxbow lake, and Hontzu Lake, even if both are located relatively close to major distributaries (i.e., St. George and Chilia respectively).

4.2. Nearshore sedimentation

Our analysis of historical bathymetry between 1856 and 1871/1897 clearly shows that in natural conditions two depocenters were present along the Danube delta coast and they were located close the mouths of the largest Danube distributaries: the Chilia and the St. George. The Chilia distributary, which at the time transported ca. 70% of the total Danube sediment load, was able to construct a river dominated lobe (Fig. 4a) on the shallow and relatively wave-protected region of the shelf that fronted its mouths (Giosan et al., 2005). Sediment accumulation led to a uniformly ~20 m thick delta front advance in a quasi-radial pattern, all around the lobe's coast. Sedimentation rates reached in places values higher than 50 cm/yr especially at Chilia's northern and central secondary mouths.

The second depocenter belonged to the other active delta lobe, St. George II, which exhibited a wide shallow platform fronting its mouth with an incipient emergent barrier island that was already visible in 1897 (Fig. 4a). Such a platform was conspicuously missing in front of the Chilia lobe. The main St. George depocenter on the delta front was deeper than at Chilia (to ~−30 m isobath) and was almost entirely offset downdrift of the river mouth but deposition similarly took place in a radial pattern around the delta platform. The accumulation rates were even higher than for the Chilia depocenter (up to 70–80 cm/yr) even if the feeding distributary, the St. George, was transporting at the time only ~20% of the total sediment load of the Danube. This suggests that the St. George depocenter was an effective temporary sediment trap rather than a point of continuous sediment redistribution toward the rest of the lobe's coast.

The nearshore zone between the Chilia lobe and St. George mouth, corresponding largely to the partially abandoned Sulina lobe, was erosional all along (Fig. 4a) to the closure depth (i.e., ~5 m in wave protected regions and ~10 m on unprotected stretches of the shoreline – Giosan et al., 1999) and even deeper toward the south. The third distributary of the Danube, the Sulina branch, discharging less than 10% of the Danube's sediment load, could not maintain its own depocenter. However, together with the Chilia plume, Sulina probably contributed sediment to the stable distal offshore region (>5 m depth) in front of its mouth (Fig. 4a). Further downdrift, the nearshore zone to Perisor, outside the frontal St. George depocenter, was stable to accreting, protected from the most energetic waves coming from the northeast and east by the St. George lobe itself (Fig. 4a; Giosan, 1998).

During the anthropogenic interval between 1975 and 1999/2008, the natural pattern of morphologic change with accumulation at active lobes and mild erosion/stability in non-active stretches of the nearshore has almost completely disappeared (Fig. 4b and d). The Chilia lobe became wave-dominated in this anthropogenic period showing some similarities to the natural St. George lobe regime. Delta front progradation became limited to largest mouths and a submerged platform developed in front of the Old Stambul asymmetric sub-lobe on which a barrier island emerged (i.e., the Musura Island developed since the 1980s; Giosan et al., 2006). Aiding these morphological processes at the Old Stambul mouth, the continuous extension of the Sulina jetties blocked the southward longshore drift trapping sediment upcoast. The same jetties induced deposition and shoreline progradation in their wave shadow downcoast, south of the Sulina mouth (Giosan et al., 1999), constructing a purely anthropogenic, local depocenter.

During the anthropogenic interval, the St. George lobe started to exhibit incipient but clear signs of abandonment (Giosan, 1998; Dan et al., 2009, 2011; Constantinescu et al., in preparation). Erosion of the delta front has become generalized down to 20–25 m water depth, reaching values over 50 cm/yr in places. The Sacalin barrier island (Fig. 4d) has continued to elongate and roll over and became a spit in the 1970s by connecting with its northern end to the delta plain. During its lifetime, the barrier has effectively transferred eroded sediments downcoast toward its southern tip (Giosan et al., 2005), the only zone where the delta

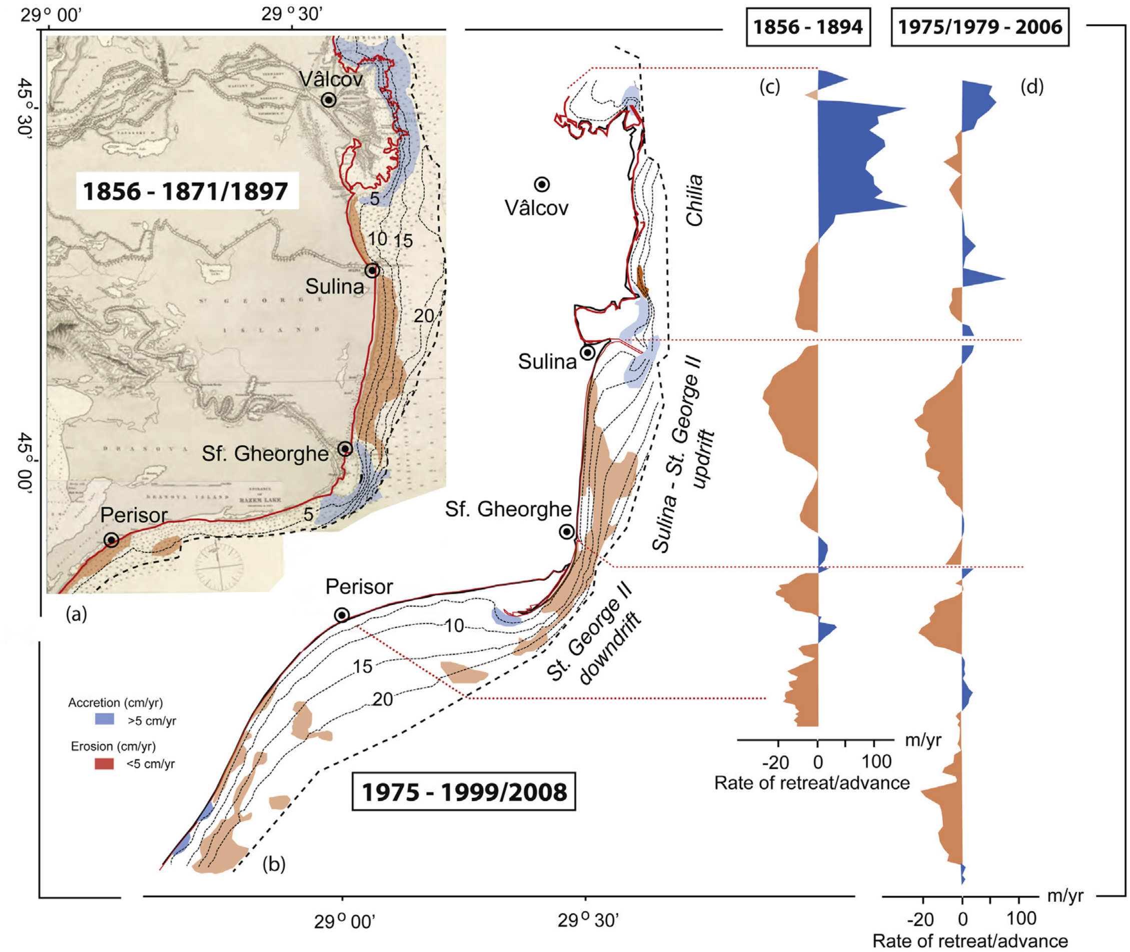

Fig. 4. Dynamics of the shoreline and nearshore region off Danube delta coast and associated lagoon coast (see Section 3 for details). (a) Nearshore changes in natural conditions. Captain Spratt's map of 1856 (British Admiralty, 1861) is used as background and the shoreline in red is from 1894. (b) Nearshore changes in the anthropogenic regime. The subpanel is translated right and down for visualization purposes. The shoreline in black is 1975/1979 and the one in red is 2005. (c) Shoreline change rates in natural conditions. (d) Shoreline change rates in anthropogenic conditions. Note the difference in scale for shoreline retreat vs. advance in both (c) and (d).

front remained locally depositional at St. George's mouth. The sheltered zone downcoast of Sacalin Island remained stable to mildly erosional. For the anthropogenic time interval, the available bathymetric data extends also downcoast beyond Perisor where the nearshore slowly transitions into a largely erosional regime (Fig. 4b).

Overall, based on the bathymetric changes discussed above, we estimated that the minimal deposition for the delta fringe zone was on the order of 60 MT/yr in natural conditions between 1856 and 1871/1897. In contrast the same parameter for the 1975–1999/2008 was only ~25 MT/yr. Both these values are surprisingly close to what the Danube has actually delivered to the Black Sea during these intervals (i.e., ~70 and 25 MT/yr). However, the erosion estimated over the same intervals was ~30 MT/yr and 120 MT/yr (!) respectively indicating significant loss of sediment. Both accretion and erosion were calculated over the same alongshore span for both time intervals (i.e., Chilia, Sulina-St. George II updrift and downdrift in Fig. 4) assuming that in both cases the bathymetric data extended far enough offshore so that morphologic changes became insignificant beyond that limit.

4.3. Shoreline changes

The large scale pattern of coastal changes during the natural regime is generally supported by their contemporary nearshore changes. The Chilia lobe shoreline changes faithfully reproduced the nearshore behavior with generalized progradation in natural conditions (Fig. 4c) at rates up to 120 m/yr! Between Sulina and St. George, the shore was largely erosional at rates up to 30 m/yr (Fig. 4c) showing progradation only immediately updrift of the St. George mouth (Fig. 4c) suggesting that blockage of the longshore drift led to very local beach ridge development (Bhattacharya and Giosan, 2003). Downdrift of the St. George mouth behind the delta platform, the coast exhibited successive stretches of minor erosion and deposition. Further downdrift, the coast to Perisor was decoupled in behavior from the stability of its nearshore zone acting largely erosional with retreat rates up to 20 m/yr (Fig. 4c).

During the anthropogenic interval, the Chilia lobe shoreline changes are similar to their nearshore counterparts with local progradation at some secondary mouths (Fig. 4d). The lobe was already showing signs of erosion by the 1940s (Giosan et al., 2005) as the yet undiminished total sediment load to became insufficient for supporting the generalized progradation of its expanding delta front. Localized progradation (Fig. 4b) occurred only where the net wave-driven longshore transport was either minimized (i.e., the northernmost mouth, Ochakov; Giosan et al., 2005) or oriented in the same general direction as the prograding mouth (i.e., the southernmost mouth, the Old Stambul; Giosan et al., 2005). In contrast, in front of all mouths oriented eastward where the longshore transport rate was at a maximum, the delta front became mildly erosional or remained stable. South of Chilia, the shoreline primarily remained erosive to the St. George mouth

(Fig. 4b) as well as along the Sacalin Island. Minor progradation occurred in the shadow of the Sulina jetties, both north and south, and near the St. George mouth.

The sheltered zone downcoast of Sacalin Island became largely progradational during the anthropogenic interval probably because of the additional sheltering afforded by the ever-elongating Sacalin Island (Giosan et al., 1999). The shoreline for the distal coastal sector south of Perisor, composed of baymouth barriers fronting the lagoons south of the delta (Fig. 1), followed a similar trend from stable to weakly retrogradational. One exception is the southernmost sector near Cape Midia where convergence of the longshore drift behind the harbor jetties of Midia Port (Giosan et al., 1999) led to mild progradation (Fig. 4d).

5. Discussion

5.1. Natural vs. anthropogenic regimes in the Danube delta

Our new data and observations paint a cautiously optimistic view for the recent sedimentation regime on the delta plain, but also make it clear that the brunt of the dramatic Danube sediment load reduction over the last half century has been felt by the delta fringe zone from the delta front to the shore. The delta plain can act as an effective trap as long as sediment is redirected toward it from large distributaries even in conditions of reduced sediment load typical for post-damming era. However, the reduction of sediment at the coast appears to be irreparable in the short run.

On the optimistic side, because in natural conditions the delta plain was a sediment starved environment (Antipa, 1915), the canal network dug over the last ~70 years on the delta plain has increased sediment delivery and maintained, at least locally, sedimentation rates above their contemporary sea level rise rate. Furthermore, overbank sediment transfer to the plain seems to have been more effective nearby these small canals than close to large natural distributaries of the river that are flanked by relatively high natural levees. Fluxes of siliciclastics have decreased during the post-damming interval suggesting that the sediment-tapping efficiency of such shallow network of canals that sample only the cleanest waters and finest sediments from the upper part of water column is affected by Danube's general decrease in sediment load. This downward trend may have been somewhat attenuated very recently by an increase in extreme floods (i.e., 2005, 2006 and 2010), which should increase the sediment concentration in whole water column (e.g., Nittrouer et al., 2012). However, steady continuation of this flood trend is quite uncertain as discharges at the delta appear to be variable as modulated by the multidecadal North Atlantic Oscillation (NAO; Râmbu et al., 2002). In fact, modeling studies suggest increases in hydrologic drought rather than intensification of floods for the Danube (e.g., van Vliet et al., 2013).

Overall, the bulk sediment flux to the delta plain is larger in the anthropogenic era than the millennial net flux, not only because the sediment feed is augmented by the canal network, but also because of erosional events lead to lower sedimentation rates with time (i.e., the so-called Sadler effect - Sadler, 1981), as well as organic sediment degradation and compaction (e.g., Day et al., 1995) are minimal at these shorter time scales. There are no comprehensive studies to our knowledge to look at how organic sedimentation fared as the delta transitioned from natural to anthropogenic conditions. Both long term and recent data support the idea that siliciclastic fluxes are, as expected, maximal near channels, be they natural distributaries or canals, and minimal in distal depositional environments of the delta plain such as isolated lakes. However, the transfer of primarily fine sediments via shallow canals may in time lead to preferential deposition in the lakes of the delta plain that act as settling basins and sediment traps.

Even when the bulk of Danube's sediment reached the Black Sea in natural conditions, there was not enough new fluvial material to maintain the entire delta coast. New lobes developed while other lobes were abandoned. Indeed, the partition of Danube's sediment from was heavily favorable in natural conditions to feeding the deltaic coastal fringe (i.e., ~2% to the delta plain vs. 98% to the coast). However, further partition of the fluvial sediment reaching the coast heavily favored one distributary over the others (i.e., the Chilia; ~70%). Consequently, the two active delta lobes of St. George II and Chilia III were built contemporaneously but not only the morphologies of these lobes were strikingly different (i.e., typical river dominated for Chilia and wave-dominated for St. George; Fig. 2) but also their morphodynamics was vastly dissimilar reflecting sediment availability and wave climate (Fig. 3).

The second major distributary, the St. George, although transporting only ~20% of the fluvial sediment load, was able to maintain progradation close to the mouth on a subaqueous quasi-radial "lobelet" asymmetrically offset downcoast. Remarkably, this lobelet was far smaller than the whole St. George lobe. However, it had an areal extent half the size of the Chilia lobe at one third its fluvial sediment feed and was even closer in volume to the Chilia lobe because of its greater thickness. To attain this high level of storage, morphodynamics at the St. George mouth must have included a series of efficient feedback loops to trap sediments near the river mouth even under extreme conditions of wave driven longshore sand transport (i.e., potential rates reaching over 1 million cubic meters per year at St. George mouth; *vide infra* and see Giosan et al., 1999). Periodic release of sediment stored at the mouth along emergent elongating downdrift barriers such as Sacalin Island (Giosan et al., 2005, 2006) probably transfers sediment to the rest of lobe's coast.

In between the two major river mouth depocenters at Chilia and St. George, the old moribund lobe of Sulina eroded away, cannibalizing old ridges and rotating the coast counter-clockwise (as noted early by Brătescu, 1922). South of the St. George mouth, the coast was sheltered morphologically by the delta upcoast and thus stable. One net result of this differential behavior was the slow rotation of the entire current St. George lobe about its original outlet with the reduction in size of the updrift half and concurrent expansion of the downdrift half. Trapping of sediment near the St. George mouth was previously explained by subtle positive feedbacks such as the shoaling effect of the delta platform and the groin effects exerted by the river plume, updrift subaqueous levee (Giosan et al., 2005; Giosan, 2007) and the St. George deltaic lobe itself (Ashton and Giosan, 2011). Thus, the main long term depocenter for asymmetric delta lobes such as the St. George is also asymmetrically placed downcoast (Giosan et al., 2009), while the updrift half is built with sand eroded from along the coast and blocked at the river mouth (Giosan, 1998; Bhattacharya and Giosan, 2003).

Going south of the St. George lobe coast, but still in its wave shadow, the coast is stable today as it was in the past in natural conditions, being shielded from the energetic NE and E waves. Sand released by the erosion of paleo-lobes such as St George I or Sulina (Fig. 1) periodically transferred sand downcoast to construct baymouth barriers and forming the Razelm, Sinoe and Zmeica lagoons (Giosan et al., 2006). If left to natural forces, such a large scale alongshore sediment transfer may begin as soon as the St. George II lobe is *de facto* abandoned (Constantinescu et al., in preparation), once Sacalin Island will attach to the shore with its southern tip or will drown in place.

For all periods considered in this study, the shoreline behavior generally mirrored and was therefore diagnostic for nearshore morphological changes. One exception has been the region downcoast of the St. George mouth where wave sheltering by the updrift delta coast and changes in coastal orientation led to the development of a more complex series of longshore transport cells and an alternation of progradation and retreat sectors. Also several other local mechanisms may be acting to reduce the erosion rates locally along the coast. For example, erosion appears to be minimal along the coast of the Chilia lobe where a series of secondary distributaries still debouche small amounts of sediment. Controlled by the post-damming decrease in fluvial sediment, the sectors of the coast with natural deltaic progradation have shrunk drastically to the two largest secondary mouths of the Chilia distributaries that have become themselves wave dominated. The coast at the St. George mouth has been quite stable probably due to groin-type effects of the river plume and the mouth subaqueous bars and levees (Giosan, 2007). However, the dramatic increase in nearshore erosion for the anthropogenic period was in large part due to the *de facto* abandonment of the St. George lobe (Constantinescu et al., in preparation). Minor depocenters along the coast are not now the result of delta front development *per se*, but reflect either redirecting of eroded sediments offshore by the Sacalin barrier or trapping near large scale jetties.

All in all, the dynamics of the Danube delta coastal fringe clearly shows that the natural pattern of delta coast evolution was a carefully balanced act of deposition and erosion rather than a uniform progradation of the shoreline. And this was aided not only by brute, direct fluvial sediment unloading at the coast but also by more subtle morphodynamic sediment trapping mechanisms. Still the overall budget of the deltaic coastal fringe was in deficit loosing sediment alongshore and offshore. When we take into account the long term history of the Danube delta in addition to insights gained in the current study, we can develop a novel conceptual understanding of its evolution as a function sediment partition between the delta plain and the delta coastal fringe as well as between major and minor distributaries. First, coastal progradation has always been favored relative to delta plain aggradation (Giosan et al., 2009) and was supported by both the quasi-stable sea level in the Black Sea since the mid Holocene (Giosan et al., 2006) and the drastic increase in discharge over the last 1000–2000 years (Giosan et al., 2012). Second, delta fringe depocenters supporting delta lobe development are associated only with the mouths of major distributaries, but their volume is influenced by both sediment discharge and mouth morphodynamics. Lobes develop and are maintained not only via repartitioning most of the sediment load to a single distributary but also by trapping of fluvial and marine sediments at the wave-dominated mouths of small discharge distributaries and periodically releasing them downcoast (Giosan et al., 2005). In this way, multiple lobes with different morphologies can coexist, abandonment of wave-dominated lobes is delayed and, by extension, the intensity of coastal erosion is minimized.

5.2. Implications for future maintenance of large deltas

River delta restoration as defined by Paola et al. (2011) "*involves diverting sediment and water from major channels into adjoining drowned areas, where the sediment can build new land and provide a platform for regenerating wetland ecosystems*." Such strategies are being currently discussed for partial restoration of the Mississippi delta, because the fluvial sediment load there is already lower than what is necessary to offset the already lost land (Turner, 1997; Blum and Roberts, 2009, 2012). The decline in fluvial sediment load on the Mississippi combined with the isolation of the delta plain by artificial levees and enhanced subsidence have led to enormous losses of wetland, but capture of some fluvial sediment that is now lost at sea (e.g., Falcini et al., 2012) is envisioned via controlled river releases during floods and/or diversions (Day et al., 1995, 2009, 2012; Nittrouer et al., 2012). Strategies are designed to maximize the capture of bedload, which is the primary material for new land build up (Allison and Meselhe, 2010; Nittrouer et al., 2012) and they include deep outlet channels and diversions after meander bends where lift-off of bed sand increases. Mass balance modeling for the Mississippi delta indicates that between a fourth and a half of the estimated land loss could be counteracted by capturing the available fluvial sediment load (Kim et al., 2009).

Sand is indeed needed to nucleate new land in submerged environments, but enhancing the input of fine sediments to deltaic wetlands should in principle be an efficient way to maintain the delta plain that is largely above sea level because fine suspended sediments make up the great bulk of the sediment load in large rivers (e.g., 98–95%; Milliman and Farnsworth, 2011). Our data quantifying the effects of the large scale channelization in the Danube delta suggests that shallow canals have been quite effective in capturing sediment on the delta plain even if they catch only the cleanest upper part of Danube's flow. Delivery of sediment through such canal networks thus mimics and enhances the yearly flood sediment pulses (Day et al., 1995, 2011) at a rate that is similar to the fast growing juvenile stages of fluvial dominated deltas (e.g., Jerolmack, 2009) when channel density is at maximum. Careful design of the depth and cross-section for such canal networks should be able to optimize the amount of fines trapped on the plain to counteract the upstream decline in sediment load and/or changes in flood regime. However, the question is if enough sediment exists now in the Danube to counteract sea level rise? Based on our analysis, the 10% of the present Danube load (i.e., 2.5 MT/yr) transiting the interior of the delta needs to be increased 4–8 times to fully maintain accretion in the internal Danube delta (i.e., $\sim$2000 km^2 without considering the polder regions and ignoring the coastal region) at rates higher or equal to the present sea level rise of 3 mm/yr (Cazenave et al., 2002). However, the effective need of fluvial sediment for the internal delta plain could be significantly lower when organic sedimentation is taken into account (Reed, 1995; Kirwan and Temmerman, 2009; Lorenzo-Trueba et al., 2012).

Some similar positive results come from channelization on the small agricultural delta of the Ebro, where canals for rice cultivation have captured suspended sediments at rates keeping up or above the contemporary sea level rise (Ibáñez et al., 2010; Day et al., 2011) or from localized experiments in large deltas such as the Ganges-Brahmaputra (Sengupta, 2009). Although we are not aware of comprehensive studies on this topic, dense channelization has occurred in many deltas around the world (e.g., Nile, Mekong, Red River to name a few) and they may have had similar effects on delta plain accretion. For example, it is known that the intricate canal network for irrigation on the Nile delta captures almost all sediments coming down the Nile after the Aswan Dam (Stanley and Warne, 1998). And on the Mississippi, upstream diversions (e.g., Blum and Roberts, 2009) would be directed toward delta plain maintenance by augmenting accretion rather than primarily build land anew as proposed for the lower Mississippi delta plain. However, cutting of canals by the oil industry on the Mississippi delta plain without a regular infusion of suspended sediments from the river has had instead destructive effects on the marshes of that delta (e.g., Turner, 1997).

While ecological analysis is beyond the scope of the present work, it is clear that the ecological effects of channelization must be carefully considered (Day et al., 2007). Although the lakes in the Danube delta probably went into seasonal hypoxia even in natural conditions (Antipa, 1941), increases in nutrients, pollution and sediment transferred to the delta plain have been cited as a reasons for habitat and ecosystem changes as well as eutrophication and marsh expansion at the expense of lakes (e.g., Oosterberg and Bogdan, 2000). In the Mississippi delta, nutrient excess delivered via diversions to freshwater marshes have been blamed for their apparent vulnerability to hurricanes (e.g., Kearney et al., 2011). For successful schemes of channelization, a comprehensive adaptive management plan for water, sediment and nutrients would be needed to protect the ecological characteristics in addition of maintaining the physical appearance of the delta plain.

If increases in the sediment trapped on the fluvial delta plain may aid to balance the effects of sea level rise, a similar approach for the external, marine delta plain would completely change the landscape of that region. Composed of fossilized sandy beach and barrier ridges that receive little new sand once encased on the delta plain, the marine delta would be transformed by channelization into an environment akin to the fluvial delta with lakes and marshes. In the absence of other solutions, such as hard protection dikes and short of abandonment, channelization could potentially raise the ground locally on these strandplains and barrier plains. Instead, with no new sediment input, the marine delta would in time result in its partial drowning; sand ridge sets of higher relief will transform into barrier systems and thus, with water on both sides, become dynamic again rather than being fossilized on the delta plain. This will provide in turn some protection to the remaining mainland delta coast because dynamic barrier systems with sand sources nearby (i.e., the delta lobes themselves) are free to adjust to dynamic sea level and wave conditions by overwash, foredune construction, and roll over. However, it is clear that the most vulnerable part of the Danube delta is the deltaic coastal fringe where most of sediment deficit is felt.

In order to tackle erosion along the delta coast, a series of large scale diversion solutions have been proposed since the early 20th century (see e.g., compilation by Petrescu, 1957). However, the entire Danube currently debouches only about half the amount of sediment that Chilia distributary used to deliver annually to construct its lobe in pre-damming era! Our study suggests instead that small but dense diversions similar to the natural Chilia secondary channels, thus another type of channelization mimicking natural processes, may minimize erosion in the nearshore. Hard structures such as breakwaters and groins that curtail offshore and alongshore sediment loss may also provide some temporary, if imperfect, relief. However, waves along the coast of Danube delta are a very efficient and relentless sediment redistribution machine, and in the long run erosion will remain a problem. Erosion of moribund lobes, such as it appears to be the case with the current St. George lobe, can provide enough sand if it is abandoned. Reworking of the St. George could feed for centuries the downdrift coast, which could even become progradational (see previous baymouth barriers and strandplains in that region in Fig. 1 and details about their development in Giosan et al. (2006). Similar long term redistribution solutions requiring no direct intervention of humans beyond the partial abandonment of some delta regions can also be envisioned for other wave-dominated deltas around the world and even for the current Balize lobe of the Mississippi.

6. Conclusions

Our sediment flux investigations for the Danube delta included core-based sedimentation rates for depositional environments of the fluvial part of the delta plain and chart-based sedimentation rates estimates for the deltaic coastal fringe. They provide a coherent large-scale analysis of the transition that Danube delta experienced from a natural to a human-controlled landscape. One major conclusion of our study may be applicable to other deltas: even if far-field anthropogenic controls such as dams are dominantly controlling how much sediment is reaching a delta, the trapping capacity of delta plains is so small in natural conditions that a slight tipping of the sediment partition balance toward the plain and away from the coastal fringe can significantly increase sedimentation rates to compete with the global acceleration of the sea level rise.

We also provide a comprehensive view on the natural evolution for the Danube delta coast leading to new conceptual ideas on how wave-dominated deltas or lobes develop and then decay. Although a majority of fluvial sediment reaches the coast, at some point in a delta's life the finite character of that sediment source would become limiting. After that new lobe development would be contemporary with another lobe being abandoned. In those conditions, we highlight the crucial role that morphodynamic feedbacks at the river mouth play in trapping sediment near the coast, thus, complementing the fluvial sedimentary input. Wave reworking during abandonment of such wave-dominated deltas or lobes would provide sediment downcoast but also result in the creation of transient barrier island/spit systems.

On the practical side, we suggest that a near-field engineering approach such as increased channelization may provide a simple solution that mimics and enhances natural processes, i.e., construction of a delta distributary network maximizing annual fluvial flooding, delta plain accretion, and minimization of delta coast erosion. However, the large deficit induced by damming affects the coastal fringe dramatically. Although the rates of erosion at human-relevant scale (i.e., decades) are relatively small compared to the scale of large deltas, in other deltas than Danube's where infrastructure and/or population near the coast are substantial, hard engineering protection structures may be inevitable to slow down the coastal retreat. If soft solutions are to be chosen, abandoning moribund delta lobes to erosion can certainly provide sediment that would stabilize and maybe even lead to growth on the coast adjacent to them. Drowning of paleo-sand ridge sets and their transformation into barrier systems can provide additional though temporary protection to the remaining inland delta plain.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ancene.2013.09.001.

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