Hydromorphological balance of the Danube River Channel on the Sector between Bazias (km 1072.2) and Danube Delta Inlet (km 80.5)

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ABSTRACT.

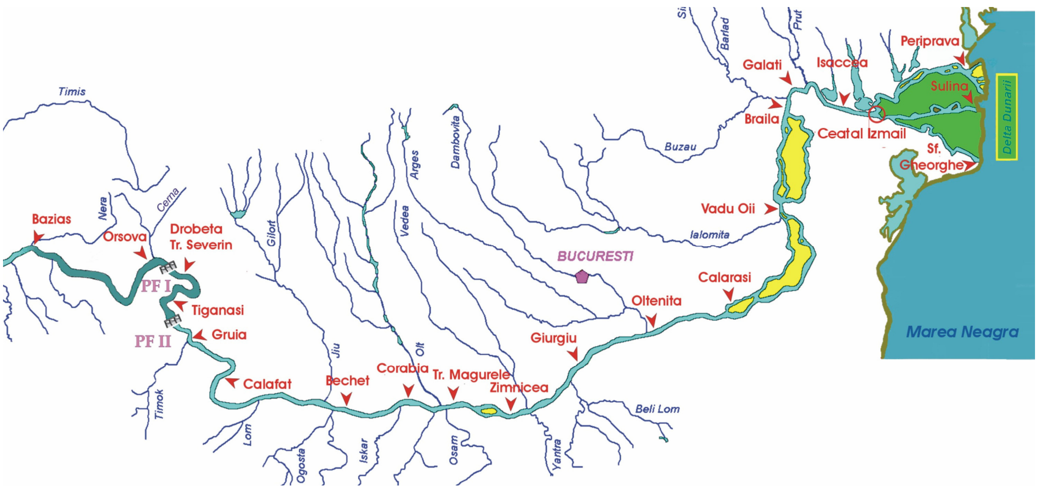
Lower part of Danube River is strongly affected by erosion. A lack of protection of the side banks is the main cause for the formation of the sand bars. These bars can have a negative impact on the navigation safety, especially at the low water levels.
The main objective of this work is to investigate the erosion of the river banks on the lower part of Danube River (Bazias km 1072 – Danube Delta km 80). The water and sediment discharge along with morphologic changes of the river bed are presented.

Key words: hydromorfologic balance, water discharge, suspended sediment, Danube channel, sandbars, hydromorphologic processes.

1. Introduction.

The lower part of the Danube River and the Danube Delta (over 1300 km length) are situated in Romania. These two parts of the same system are used by Romania and riparian states for transportation, energy, irrigation and industry. Due to the economic potential the Danube River was investigated since the middle of the XIXth century. The recorded data were used for a better understanding of the processes affecting the water discharge and the river bed evolution.

Figure 1. Romanian gauges on the Danube River Sector between Bazias (km 1072.2) and Danube Delta.



The Romanian Hydrologic Survey measured the water levels in more than 20 cross sections and 22 permanent points (figure 1). The data recorded by the former Austro-Hungarian Empire and European Commission of the Danube were analyzed extending the survey time span to year 1840.

2. Engineering works influencing the water and sediment discharge on the Danube River.

Along the lower Danube River the engineering works influence the water and sediment discharge regime in the modern time (after the Second World War):

- An embankment of the river (more than 700 km) was built between 1948 and 1985. Two important barrages were erected on the Danube River in 1971 Iron Gates I (km 943) and Iron Gates II (km 863) in 1984.
- Other engineering works for irrigation, navigation and shipyards.

3. The balance of average water discharges

The balance of average water discharges on the lower Danube between 1840 and 2006 was computed using the multiannual average discharge in 17 representative sections (table 1).

Table 1. Multiannual average water discharge (m^3/s) on the lower Danube (1840-2006).

River	Distance (km)	Tributary	Tributary	Balance	Recorded
		right	left	Danube	Danube
Danube at Bazias	1072.2				5566
Danube at Orsova	957				5571
River Cerna	953.5		14.2		
Danube at Turnu Severin	931			5585.2	5555
Danube at Gruia	858			5585.2	5584
River Timok	845.4	40			
Danube at Calafat	786.9			5625.2	5630
River Arcear	769.6	-			
River Lom	741.7	10			
River Tibar	716	-			
River Jiu	691.6		86.1		
River Ogosta	684.5	20			
Danube at Bechet	678.7			5741.3	5746
River Iscar	636.9	55			
Danube at Corabia	624.2			5796.3	5812
River Vit	609.4	15			
River Olt	604.1		172.8		
River Osam	599.9	20			
Danube at Turnu Magurele	596.3			6004.1	6002
Danube at Zimnicea	553.2			6004.1	6000
River Vedea	540		7.1		

River Iantra	536.7	40			
Danube at Giurgiu	493.1			6051.2	6051
River Arges	432.1		48.4		
Danube at Oltenita	430			6099.6	6103
Danube at Chiciu Calarasi	379.6			6099.6	6164
River Ialomita	243.9		43.5		
Danube at Vadu Oii	238			6134.1	6156
Danube at Braila	167			6143.1	6157
River Siret	155.2		217		
Danube at Grindu	141.3			6360.1	6366
River Prut	134.3		96.7		
Danube at Isaccea	101			6456.8	6474
Danube River – Danube Delta limit	80.5			6456.8	6471
Sum		200	685.8		

Based on observations and measurements the multiannual average water discharge was computed (table 2) for the following periods:

- 1840-1900, natural river bed, no engineering works;
- 1901-1930, starting of the river embankment;
- *1931-1970,* the river embankment almost finished;
- *1970-1984,* the river embankment finished and the construction of Iron Gates I ;
- *1985-2006,* the river embankment finished and the construction of Iron Gates I and II.

The data presented in table 1 are plotted in the figure 2.

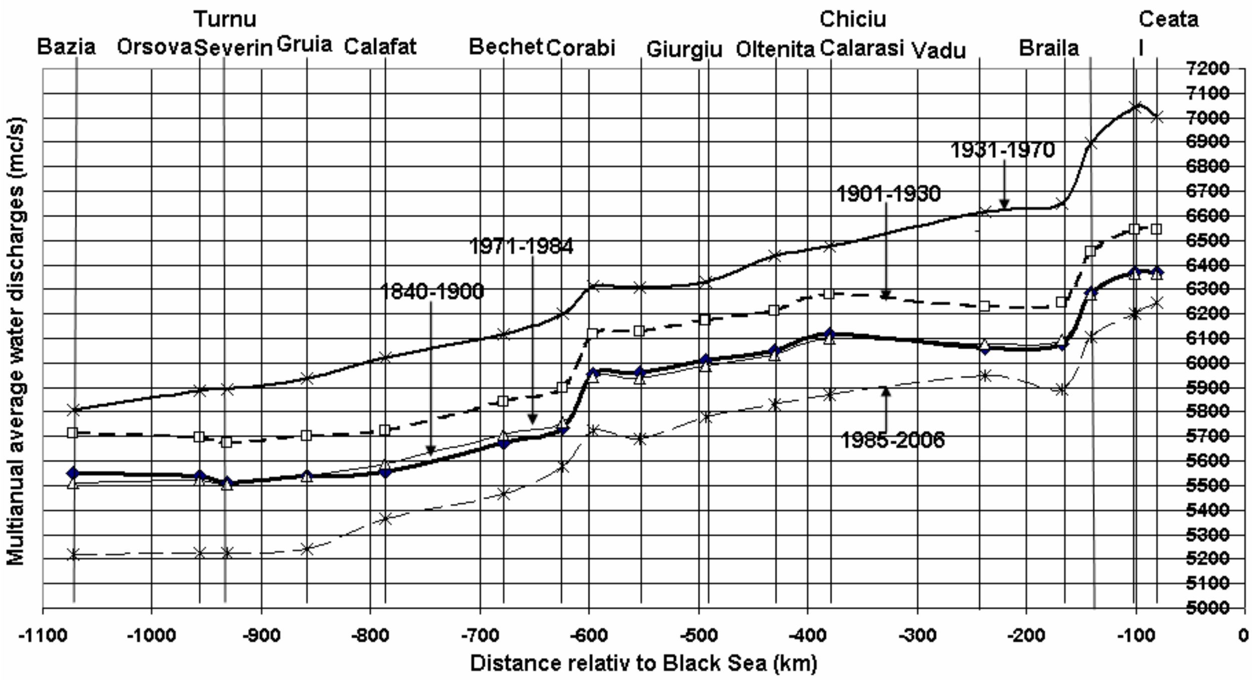
Table 2.
The multiannual average water discharge (m^3/s) in 17 representative hydrometric sections along of lower Danube.

No.	Hydrometric sections	Distance km	1840-1900	1901-1930	1931-1970	1971-1984	1985-2005
1	Bazias	-1072.1	5551	5712	5509	5810	5219
2	Orsova	-957	5537	5697	5521	5889	5225
3	Drobeta Turnu Severin	-931.1	5513	5672	5508	5895	5222
4	Gruia	-858	5541	5701	5540	5938	5239
5	Calafat	-786.9	5558	5722	5590	6019	5365
6	Bechet	-678.7	5676	5843	5709	6119	5466
7	Corabia	-624.2	5736	5899	5758	6199	5577
8	Turnu Magurele	-596.3	5952	6119	5940	6313	5726
9	Zimnicea	-553.2	5959	6126	5939	6310	5688
10	Giurgiu	-493.1	6008	6173	5986	6329	5780
11	Oltenita	-430	6050	6214	6034	6435	5830
12	Chiciu Calarasi	-379.6	6117	6281	6101	6479	5870
13	Vadu Oii	-238	6059	6227	6076	6619	5950
14	Braila	-167	6077	6244	6094	6650	5891
15	Grindu	-141.3	6283	6454	6278	6898	6106
16	Isaccea	-101	6370	6544	6366	7044	6199
17	Ceatal Ismail	-80.5	6370	6541	6361	7005	6245

From the data presented in table 1 it can be noticed a good correlation between the multiannual average water discharge of the Danube River and the summation of the multiannual average water discharge of the tributaries.
Table 2 and figure 2 show the constant increase of the water discharge in the period 1840-2006, with slight decrease trend at Bazias (km 1072) and increase trend at the beginning of the Danube Delta (km 80).
The trends for the water discharge at Bazias and Ceatal Ismail in the period 1931-2000:

Hydrometric section	Average 1840-2006	Trend
Bazias	5566 m^3/s	-0.951 $m^3/s/year$
Ceatal Ismail	6471 m^3/s	1.17 $m^3/s/year$

Figure 2.
Variation of the multiannual average water discharge along lower Danube on 1840-1900, 1901-1930, 1931-1970, 1971-1984 and 1985-2006 intervals.



4. Sediments discharge balance.

The average discharge sediment balance on the lower Danube (1840-2006), computed in 17 representative hydrometric sections is presented in **table 3**.

Table 3.
The multiannual average suspended sediment discharge of the lower Danube sediment discharges (kg/s) between 1840 and 2006.

River	Distance (km)	Tributary	Tributary	Balance	Recorded
		right	left	Danube	Danube
Danube at Bazias	1072.2				988
Danube at Orsova	957				997

River Cerna	953.5		3.62		
Danube at Turnu Severin	931			1000.6	925
Danube at Gruia	858			1000.6	1087
River Timok	845.4	13.6			
Danube at Calafat	786.9			1014.2	1364
River Arcear	769.6	-			
River Lom	741.7	3.4			
River Tibar	716	-			
River Jiu	691.6		115.5		
River Ogosta	684.5	10.64			
Danube at Bechet	678.7			1143.8	1330
River Iscar	636.9	26.67			
Danube at Corabia	624.2			1170.5	954
River Vit	609.4	5.7			
River Olt	604.1		161.1		
River Osam	599.9	7.76			
Danube at Turnu Magurele	596.3			1345	1327
Danube at Zimnicea	553.2			1345	1237
River Vedea	540		13.4		
River Iantra	536.7	33.65			
Danube at Giurgiu	493.1			1392	1359
River Arges	432.1		56.2		
Danube at Oltenita	430			1448.2	1349
Danube at Chiciu Calarasi	379.6			1448.2	1565
River Ialomita	243.9		113.4		
Danube at Vadu Oii	238			1561.6	1485
Danube at Braila	167			1561.6	1503
River Siret	155.2		311.5		
Danube at Grindu	141.3			1843.1	1495
River Prut	134.3		41.7		
Danube at Isaccea	101			1914.8	1734
Danube at the beginning of Delta Delta	80.5			1914.8	1619
Sum		101.4	816.42		

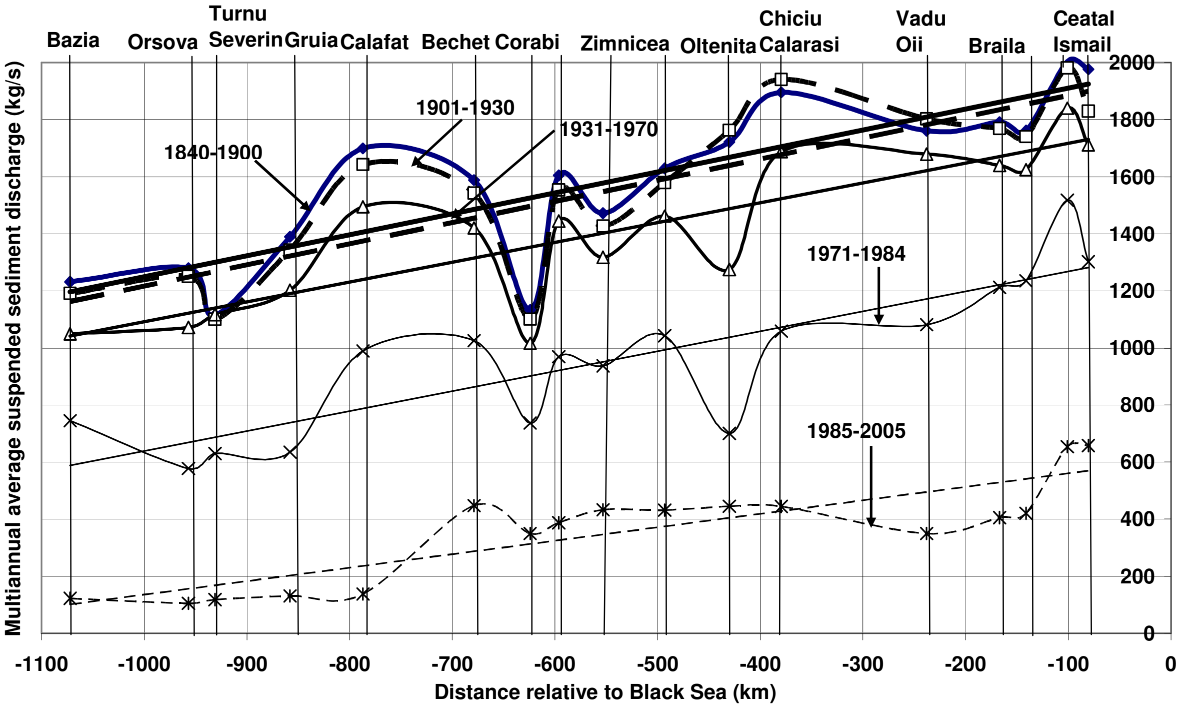
From the data presented in table 3 it can be noticed a good correlation between the multiannual average suspended sediment discharge of the Danube River and the summation of the multiannual average suspended sediment discharge of its tributaries. To highlight the trend of the average suspended sediment discharge the multiannual values were computed in the same hydrometric sections and at the same time (table 4).

Table 4.
The multiannual average suspended sediment discharge on the lower Danube (kg/s) in 17 hydrometric sections for the periods 1840-1900, 1901-1930, 1931-1970, 1971-1984 and 1985-2006.

No.	Hydrometric sections	Distance Km	1840-1900	1901-1930	1931-1970	1971-1984	1985-2006
1	Bazias	1072.2	1232	1191	1049	752	154
2	Orsova	-957	1280	1251	1072	582	126
3	Drobeta Turnu Severin	-931.1	1116	1100	1117	618	142
4	Gruia	-858	1390	1343	1202	635	135
5	Calafat	-786.9	1699	1643	1495	989	190
6	Bechet	-678.7	1588	1542	1421	1026	457
7	Corabia	-624.2	1134	1101	1016	741	354
8	Turnu Magurele	-596.3	1605	1554	1445	969	393
9	Zimnicea	-553.2	1472	1428	1317	971	440
10	Giurgiu	-493.1	1630	1579	1462	1043	434
11	Oltenita	-430	1722	1763	1275	701	453
12	Chiciu Calarasi	-379.6	1896	1941	1690	1005	454
13	Vadu Oii	-238	1761	1803	1680	1082	356
14	Braila	-167	1791	1769	1638	1170	433
15	Grindu	-141.3	1762	1741	1623	1236	425
16	Isaccea	-101	2004	1982	1840	1526	672
17	Ceatal Ismail	-80.5	1958	1808	1689	1249	650

Table 4 and figure 3 show that the coarse sediment discharge, between 1840 and 2006, did not have a constant increase. The conclusion is that the hydromorphologic processes in present time (1971-2006) are different from those in the past (1840-1970).

Figure 3.
Variation of the multiannual average sediment discharges on the lower Danube in the periods 1840-1900, 1901-1930, 1931-1970, 1971-1984 and 1985-2006.



The decreasing trend of the multiannual average sediment discharges on the lower Danube is presented in **figure 4.**

Figure 4.
Chronological graphs of the multiannual average suspended sediment discharges on the lower Danube in 17 hydrometrical sections between 1840 and 2006.

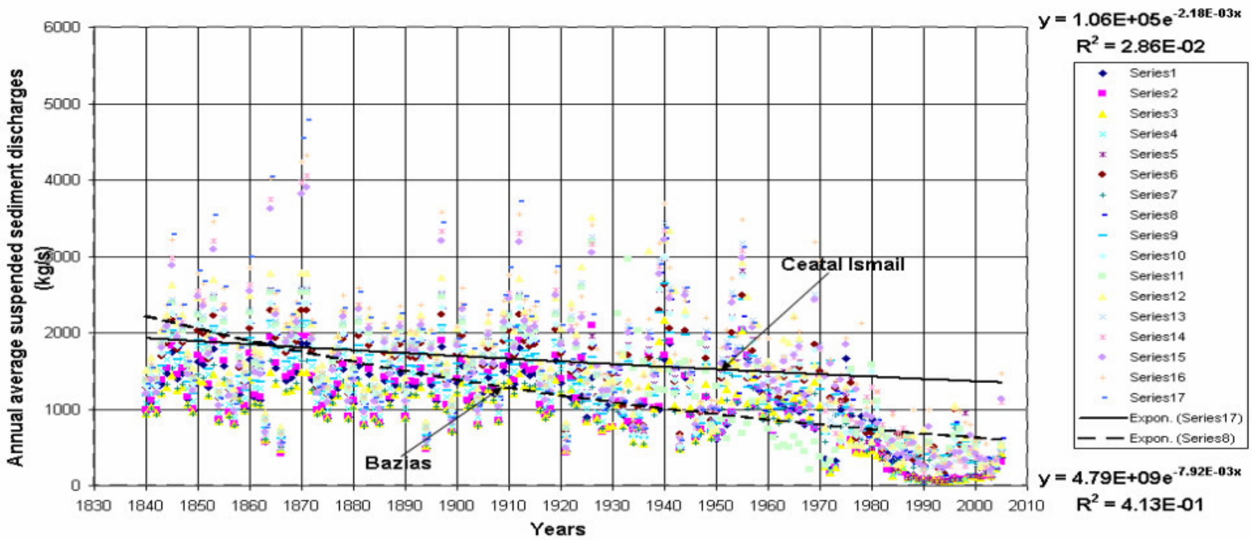
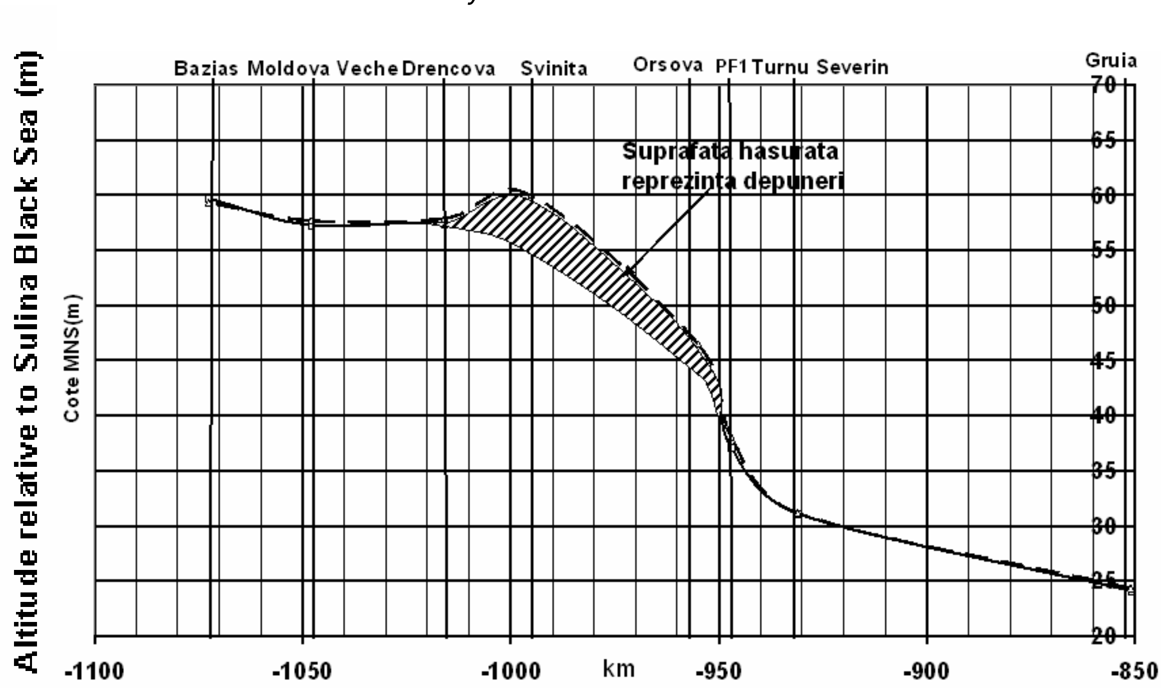


Figure 4 show a decreasing trend for the multiannual average sediment discharges on the lower Danube starting with 1965. The construction of the two barrages Iron Gates I and II enhanced the decreasing trend of the sediment discharge due to the deposition of the sediment behind the barrages.

Figure 5.
Variation of the river bed elevation for the Iron Gates lakes. Solid line corresponds to the river bed elevation in 1971 and the dashed line to year 2005.



Distances relative to Black Sea (km)

A quantity of 393 mil. tons of sediment was discharge in Iron Gates I lake between 1971 and 2005. 34% from this quantity (meaning 133 mil. t) was deposited. The deposition rate was higher between 1971-1975, reaching 39%. The sediments were deposited especially in the area between km 1016 and km 943, reaching 5 m thickness at km 995. The grain-size of the deposited sediments varies between 0.08 and 0.001 mm, with a mean diameter (d_{50}) of 0.025 mm.

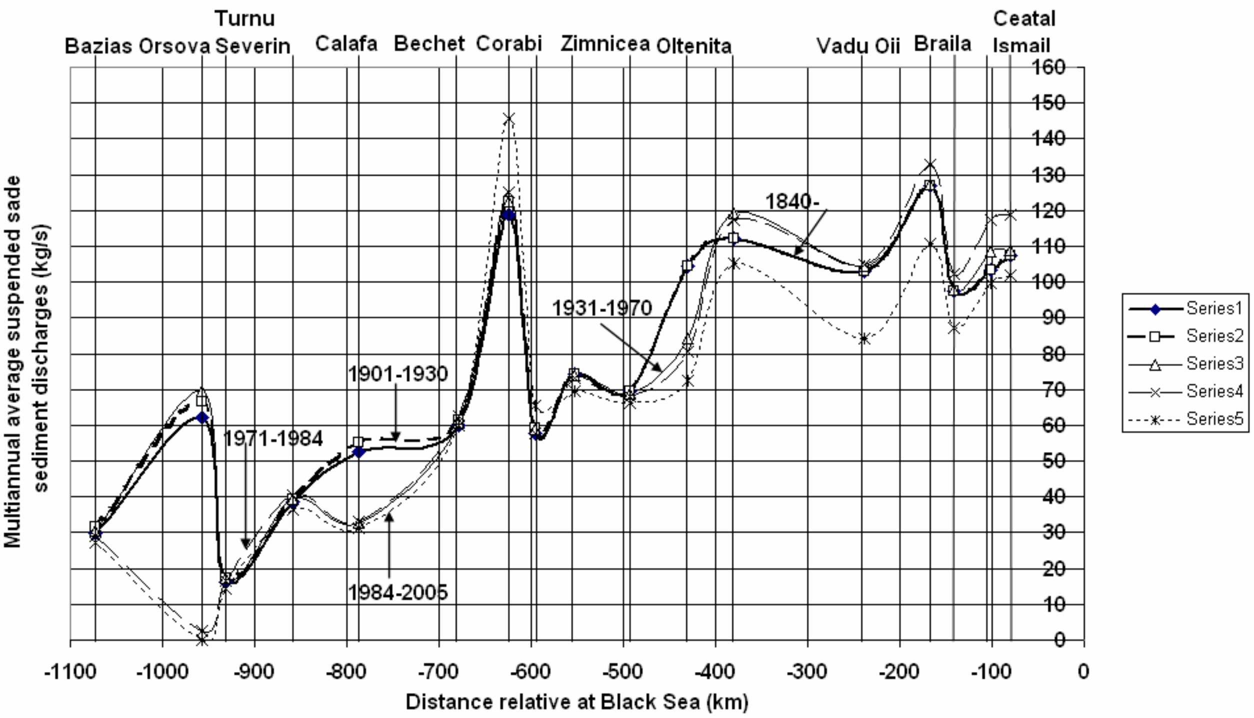
The sediments with a diameter over 0.08 mm are the most important for the hydromorphologic processes affecting the river bed. The general sediment discharge on the lower Danube was investigated by measuring separately the discharge of coarse and fine sediments. The coarse sediment discharge is proportional with the kinetic energy of the water current. At low waters, when the velocity of the water current drops below a critical level the transport of the coarse sediment ceased. The critical level is a function of the water depth and sediment grain size.
In table 5 and figure 5 the multiannual average coarse sediment discharges are presented.

Table 5.
The multiannual average sediment discharges on the lower Danube at 17 hydrometric sections for the intervals 1840-1900, 1901-1930, 1931-1970, 1971-1984 and 1985-2006.

No.	Hydrometric sections	Distances (km)	1840-1900	1901-1930	1931-1970	1971-1984	1985-2006
1	Bazias	-1072.2	29.7	32	31	29	27
2	Orsova	-957	62.0	67	70	3	0
3	Turnu Severin	-931.1	16.3	17	17	17	14
4	Gruia	-858	38.5	39	39	40	36
5	Calafat	-786.9	52.7	55	33	33	31

6	Bechet	-678.7	59.8	61	61	63	60
7	Corabia	-624.2	118.8	123	122	125	146
8	Turnu Magurele	-596.3	57.7	59	59	58	66
9	Zimnicea	-553.2	74.3	74.3	73.8	73.2	69.5
10	Giurgiu	-493.1	69.4	69.4	68.7	68.2	66.1
11	Oltenita	-430	104.6	104.6	84.1	80.7	72.6
12	Chiciu Calarasi	-379.6	112.1	112.1	119.0	117.4	105.0
13	Vadu Oii	-238	103.2	103.2	104.6	104.7	84.3
14	Braila	-167	126.8	126.8	127.1	132.7	110.9
15	Grindu	-141.3	97.5	97.5	98.0	102.4	87.1
16	Isaccea	-101	103.4	103.4	108.7	117.4	99.8
17	Ceatal Ismail	-80.5	107.4	107.4	108.9	118.9	102.0

Figure 6.
The multiannual average coarse suspended sediment discharges on the lower Danube for the intervals 1840-1900, 1901-1930, 1931-1970, 1971-1984 and 1985-2006.



Between 1971 and 2006 the Iron Gates I lack has retained a sediment quantity about 836,276 t/yr between Bazias section (km 1072) and Orsova section (km 957), which means about 88 % from sand sediment transported through Bazias section.
It can be noticed that despite the decreasing trend of the sediment discharges, the coarse sediment discharges remained constant in time. Downstream from Iron Gates lakes the river regains much of the sediment due to erosion and contribution of the tributaries.
The grain size of the coarse suspended sediments varies between 0.1 and 0.5 mm, with a mean size of 0.2 mm. The sediments of the bottom layer have a grain size ranging between 0.08 and 3 mm.

5. The characteristics of morphologic regime.

The research regarding the morphology consists, mainly, in mapping of the river bed at various times and measurements of the water and sediment discharge at a number of cross sections.
The major part of the data regarding the morphology of the river bed was collected by National Navigation Authority. These maps have various scales (1/2500, 1/5000 and 1/10000) and their system of coordinates it is not part of any international system. The precision of the distances and depths is around 1%.
In order to investigate the morphological regime of the river bed data recorded between 1909 and 1992 were used. Table 6 shows the main results.

Table 6.
The morphometric average data (width and talveg depth) of the lower Danube channel (sector Iron Gates II) for 1909, 1962 and 1988.

Morphometric	**The years with bathimetric elevations**			**Annual**
elements	**1909**	**1962**	**1988**	**variation**
Sector between km 860 and km 80 (length 780 km)				
• Water surface A(km^2)	630.9	634.7	683.0	0.573
• Average width Bmed(m)	809	814	876	0.737
• Average depth hmed(m)	13.1	8.0	7.4	-0.076
• Vulnerable length(km)	120	138	244	1.390
Sector between km 860 and km 375 (length 485 km)				
• Water surface A(km^2)	438.6	438.6	484.8	.499
• Average width Bmed(m)	904	904	1000	1.04
• Average depth hmed(m)	11.1	6.4	6.0	-0.07
• Vulnerable length(km)	111	120	219	1.185
Sector between km 375 and km 240 (length135 km)				
• Water surface A(km^2)	95.5	100.3	93.3	-0.0104
• Average width Bmed(m)	707	743	691	-0.073
• Average depth hmed(m)	12.6	7.8	6.9	-0.075
• Vulnerable length(km)	8.6	12	18	0.111
Sector between km 240 and km 169 (length 71 km)				
• Water surface A(km^2)	32.2	33.2	39.6	0.083
• Average width Bmed(m)	453	468	558	1.175
• Average depth hmed(m)	20.1	11.1	10.6	-0.127
• Vulnerable length(km)	0	0	0	0
Sector between km 169 and km 80 (length 89 km)				
• Water surface A(km^2)	59.0	62.2	65.4	0.078
• Average width Bmed(m)	663	699	735	0.877
• Average depth hmed(m)	20.0	15.1	13.4	-0.085
• Vulnerable length(km)	0	6	8	0.103

NOTE: The vulnerable length refers to sectors where the width of the channel is larger of 1000 m.

The conclusions of this work are:
- Downstream of Iron Gates I and II barrages the river bed is affected by erosion.
- The erosion causes channel widening.
- The average of unique channel widening was about 1.0 m/yr in 1992.
- The decreasing of channel depths due to sediment deposition in many sectors.
- The average of channel depths was about 8.0 cm/yr in 1992.
- Formation of sandbars and islands led to a channel ramification.
- The morphologic equilibrium of the river bed on the lower Danube stops when the water discharge drops bellow 2.8 m^3/s.
- In order to keep the morphologic equilibrium of the river bed B <= 146·h; where B is the channel width and h is the channel depth.
- The vulnerable channel length increase from 120 km in 1909 to 244 km in 1988.
- The number of navigation critical points increase from 26 in 1967 at 62 in 1990.
- The annual periods with low waters (< 2.5 m) in critical points increase up to 50 days.
- The number of islands on the sector Turnu Severin - Chiciu-Calarasi increase from 93 in 1934 (283 km total length) to 135 in 1992 (353 total length).
- The safety of navigation is strongly influenced by the processes previous describe and there is an urgent need to stop or diminish the effects of the hydromorphological processes.

The data published by Danube Commission indicate a volume of coarse sediments dredged from the river bed of 2,493,114 m^3/yr, between 1961 and 1990. Part of this volume (not known) was used for the construction purposes.

Bibliography

1. C.Bondar.,I.State.,D.Cernea.,E.Harabagiu.(1991).
Water flow and sediment transport of the Danube at its outlet into the Black Sea.Meteorology and Hydrology.Vol.21.ISSN 1015-3640.p.21-25.Bucuresti.
2. Bondar C.(1992)
Trend and cyclicity of anual Danube discharge at Danube Delta input.
XVI Konferenz der Donaulander uber hydrologische verhersagen und hydrologische-wasserwirtschaftliche Grundlagen,l8-22, mai, Kelheim, Bundesrepublik Deutchland, p.32l-326.
3. Bondar C.(1993), joint author.
Die Donau und ihr Einzugagebiet-Eine hydrologische Monographie Folgeband I.Schwebstoff- und Geschieberegime der Donau.Regionale Zusammenarbeit der Donaulander im Rahmen das Internationaen Hydrologischen der UNESCO.
4. Bondar C., Carmen Buta, Harabagiu Elena.(1994)
Variation and trend of the water,sediment and salt runoff for the Danube river,at the inlet in our country,during the period 1840-1992.
XVII Conference of the Danube Countries on Hydrological Forecasting and Hydrological Bases of Water Management. Budapest,5-9 September, p.671-676.
5. Bondar C.(1996), joint author.
Die Donau und ihr Einzugagebiet-Eine hydrologische Monographie Folgeband I. Die furten der Donau. Regionale Zusammenarbeit der Donaulander im Rahmen das Internationaen Hydrologischen der UNESCO.
6. Bondar C.(1996)
Certain characteristics of the Anthropic Influences upon Water Sediment and Salt Runoff on The Danube in The Romanian Border Reach.
XVIII Conference of the Danube Countries on Hydrological Forecasting and hydrological Bases of Water Management.Volume 19/1, p.Al91-Al98, Graz, August, Austria.
7. Bondar C., Blendea V.(2000)
Water and Sediment Transport by The Danube into the Black Sea during 1840-1995.

IOC Workshop Report No. 145, p.85-63, Paris, January, 2000.
8. Bondar C. (2000)
Hydromorphological processes on the lower Danube riverbed.
Romanian Society of Geophysics. International Geophysical conference and exposition, Bucharest 2000, p.428-431.
9. Bondar C.(2000)
The physical degradation of the Danube riverbed in the low reaches.
3 rd INTERNATIONAL CONFERENCE of Balkan Environmental Association (B.E.N.A.)
TRANSBOUNDARY POLLUTION, abstract, II.57, p.142-143, 23-26 November.
Bucharest - Romanian.
10. Bondar C., Modev S., Sava S.C.(2002)
The State of the Danube riverbed along the Romanian-Bulgarian border.
XXIst CONFERENCE OF THE DANUBE COUNTRIES on the Hydrological Forecasting and Hydrological Bases of Water Management. CONFERENCE ABSTRACTS, Bucharest-Romania, 2-6, September.
11. Behr O., Gutknecht D., Modev S., Bondar C.(1999)
First international study on the morphological changes of the Danube river down-stream.
Anniversary scientific Conference, 50 years, Faculty of Hydrotechnics, p I.1-I.10, Sofia, 6-8 october 1999.
12. Behr O., Gutknecht D., Modev S., Bondar C., Prohaska S.(2000)
Danube river morphology: A common initiative was taken. Considerable Changes in Danube river bed and bank morphology have produced serious effects on water management activities.
DANUBE WATCH EDITORIAL, Welcome, no.1/2000, Vienna.
13. Goda.L.(1996).
Die Donau ihr Einzugsgebiet-Eine hydrologische Monographie, Folgeband I.Die Furten de Donau.
Regionale Zusammenarbeit der Donaulander inm Rahmen das Internationalen Hydrologischen Programmes der UNESCO.Budapest.
14. Mladenov.N.(1978).
Virhu hidrologichnia rejima na reka Dunav mejdu 845-iia i 375-iia rechen kilometir.
Limnologia na bilgarskia sektor na r.Dunav.
Bilgarska akademia na naukite.Sofia,p.29-60.
15. Petrescu.A.(1974).
Exploatarea Sistemului hidroenergetic si de navigatie Portile de Fier 1.
Hidrotehnica,vol.19,nr.7/1974,Bucuresti,p.320-324.
16. Pechinov.D.(1978).
Plavaschi nanosi v bilgarskia sektor na reka Dunav. Limnologia na bilgarskia sektor na r.Dunav.
Bilgarska akademia na naukite.Sofia,p.61-78.
18. Rakoczi.L.(1993).
Die Donau ihr Einzugsgebiet-Eine hydrologische Monographie, Folgeband I.Schwebstoff-und Geschieberegime der Donau.
Regionale Zusammenarbeit der Donaulander inm Rahmen das Internationalen Hydrologischen Programmes der UNESCO.Budapest.
19. RAZVAN.E. si VOJINOVIC.M.(1971).
Studii de hidraulica pentru Sistemul hidroenergetic si de navigatie Portile de Fier 1.ICPGA,Bucuresti-Belgrad,p.1-278.
20. Stanescu V. si colab.(1967)
Dunarea intre Bazias si Ceatal Izmail.Monografie Hidrologica.
Bucuresti,p.1-369.Poligrafia "13 Decembrie 1918".
21. * * *(1972).
System Hydro-energetique et navigable Derdap(Les Portes de Fer).
Export-Press,Beograd-Francuska 27,p.1-150.
22. * * *(1979)

Donaukmmission: Empfchlungen fur die hydrometeorologischen Dienste an der Donau.