SEDIMENT TRANSPORT ON THE DANUBE RIVER IN THE ROMANIAN BORDER AREA – CHARACTERISTICS

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Abstract. The beginnings of knowledge on the Danube River are lost in the historical past of Europe. The first information on the Danube is of a hydrographic nature, also referring to the elaboration of maps by the Austro-Hungarian Empire. A brief overview of the catchment area, with its orographic, geologic, climatic and hydrographic characteristics, reveals the conditions of water flow and sediment formation on the Danube. In 1838, the Austro-Hungarian authorities set up the first level gauge in the Romanian border sector (at Orşova) to measure water levels on the Danube. In the following years, water flow and sediment measurements began, further completed by the Romanian state after the 1877 War of Independence. Based on past measurements and on those gathered so far, enabled reconstituting the water level and sediment flow regime until 1840, presented in this paper. Special attention has been paid to coarse alluvial transport, dragged and in suspension. Analysing the interaction between water current and physical structure of the riverbed, yielded the empirical functions of hydro-morphological stability of the Danube riverbed and the empirical functions of dragged and suspended coarse sediment transport. The average specific discharge by sections of dragged coarse sediment and the average concentrations by sections of coarse sediment in suspension depend linearly on the average specific water discharge. Based on the empirical functions of coarse alluvial transport, which result from the processing of measurement data, led to determining the daily discharge of coarse sediment, dragged and in suspension, on the Romanian sector of the Danube between 1840 and 2012. Calculations yielded the multiannual average values and the maximum annual values of dragged and suspended coarse sediment discharge at the hydrometrical sections downstream of the Iron Gate. Here are the synthetic data: multiannual average values of dragged coarse sediment discharge vary between 14.6 kg/s at Gruia and 5.6 kg/s at Ceatal Ismail; maximum values of dragged coarse sediment discharge vary between 23.9 kg/s at Zimnicea and 47.9 kg/s at Grindu; multiannual average values of suspended coarse sediment discharge vary between 54.1 kg/s at Zimnicea and 130.1 kg/s at Ceatal Ismail; maximum values of coarse sediment discharge vary between 400 kg/s at Corabia and 2048 kg/s at Ceatal Ismail.

1. INTRODUCTION

A knowledge of the Danube River goes back to Europe's historical past. The first scientific information speak about hydrographic aspects and the elaboration of maps by the Astro-Hungarian Empire. Thus, in 1838, the first hydrometric rod was planted by the emperial authority at Orşova to measure the Danube water levels (13). As of 1857, the former European Commission of the Danube initiated measurements on water and alluvia discharge in the Danube Delta, completed by the Romanian State after the 1877 War of Independence.

On the basis of these past measurements and of others gathered up to-date, the water level and sediment discharge regime could be assessed (up to 1840), with highlight on dissolved and suspended coarse alluvia transport, an issue never tackled before (5).

Empirical functions were obtained by analysing the interaction between the water current and the channel physical structure. These functions were used to establish the hydromorphological stability of

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the Danube channel and of the dislodged and suspended sediment load. The results have shown that the mean specific discharge of coarse alluvia by sectors and the mean concentrations of coarse suspended sediment by sections are lineary dependent on mean sectional water discharge.

The empiric functions of coarse sediment transport, assessed by the processing of data-sets measurements, led to establishing the daily discharge of dislodged and suspended coarse sediments in the Romanian Danube sector over the 1840–2012 interval.

2. THE FORMATION OF WATER AND SEDIMENT DISCHARGE ON THE DANUBE RIVER

2.1. The Danube drainage basin

The Danube drains its waters from an 817,028 km^2 hydrographic basin which covers about 11% of Europe’s surface-area. Depending on the course of the Danube channel, the basin shape is asymmetric, with 56% of its surface lying on the left bank and 44% on the right bank.

Out of the whole Danube basin area, 36% are covered with mountains: very tall (over 4,000 m in the Alps), and tall (1,000–2,000 m in the Carpathians, the Balkans and the Dinaric Alps); 64% represent medium-high and low areas (tablelands, hills and plains). Orographically speaking, the Danube basin contains three sub-basins: upper, middle and lower, average basin altitude is 475 m.

The geological structure of the Danube drainage basin consists of eruptive, sedimentary (limestone) and metamorphic rocks. The basin soil structure is formed of clays and loess combined with chernozems on which a vegetation of meadows, crops and various types of forest lands has developed.

In terms of physical-geographical conditions (position, relief and vegetation), a specific continental-temperate climate has developed in the course of time, its characteristic parametric values are given below:

- The annual mean air temperature stands between 8°C in the upper part of the basin and 12°C in its lower part; absolute air extremes of +37°C in summer and –36°C in winter. Values of +43° and of –33°C are recorded in the plain-area of the Lower Danube sector.
- A major climatic factor of the Danube basin, namely precipitation, is basically involved in the formation of water discharge and the River’s water-regime. In view of the diversity of atmospheric circulation and of landform-types within the Basin area, precipitation are unevenly distributed. Thus, in the lowlands, the annual mean stands at some 400–600 mm, with 800–1,200 mm in the Carpathians and 1,800–2,500 and over in the Alps. Highest amounts fall in spring and summer, lowest ones in autumn and winter. The snow layer is usually 20–30 cm thick in the plains and tablelands, and about 1.5–2 m in the mountains. In harsh winters, the snow layer can be several metres thick (e.g. in the years 1953–1954 and 2012).
- Apart from precipitation, evaporation and evapo-transpiration register pretty high values, the latter ranging from 450 mm and 650 mm/year in the low areas of the upper part of the basin, down to 100 mmm/year with the decrease of altitude. A similar situation occurs in the middle part of the basin, where mean values reach 500 mm/year. In the lower part of the basin evapotranspiration increases up to a mean value of some 400 mm/year at the Danube mouth to the Black Sea.

2.2. The Danube Basin drainage network

The relief, geology, soil, vegetation and climate of the Danube drainage basin have shaped a relatively dense hydrographic network of valleys, brooks, rivers and lakes drained by its channel. The Danube-drained network of over 120 tributaries by the is unevenly distributed in the three sectors of this hydrographic basin.

In its upper part (131,338 km^2), the Danube tributaries (Iller, Lech, Altmuhl, Naab, Regen, Isar, Inn, Traun, Enns, Kamp and Morava Ceha) spring from the permafrost mountains. The main tributaries of the middle part (444,894 km^2) are Raab, Vah, Hron, Drava, Sava, Tisa, Veliko Morava, as well as smaller watercourses. The lower part (240,796 km^2) receives the Timok, Jiu, Iskar, Olt, Iantra, Vedea, Argeş, Ialomiţa, Siret, Pruth and several less important tributaries.

A common feature of the Danube tributaries is their rapid flow in the mountain area they spring from, with rates slowing down in the hillsides and plains where channels are lined with broad, high-water floodable meadows.

3. THE DANUBE CHANNEL

The Danube channel follows the route of an old drainage basin depression, formed at the beginning of the Quaternary and crossing Europe from West to East through the territories of twelve countries: Germany, Austria, Slovakia, Croatia, Hungary, Serbia, Romania, Bulgaria, the Republic of Moldova and Ukraine. The Danube springs from the South-Eastern slope of the Black Forest Mts (in Germany), the source of the rivers Brege (1,000 m alt.) and Brigah (1,1125 m alt.). The Danube channel, which covers some 2,875 km from source to mouth (at the Black Sea) is formed by the unification of the two streams (Brege, 48.5 km and Brigah, 42.6 km) in front of Donauessingen settlement (676 m alt.).

- **The Upper Danube sector**

The Danube channel (970 km long) covers a distance of some 970 km from its sources (km 2,875) to Devin (km 1,880); at the end of this course the drainage basin reaches 131,338 km^2 (in the Bratislava section at km 1,868.8). This Danube channel sector is typically mountainous, with a narrow, meandering valley deeply cut into the rocks, water flowing at great speed.

- **The Middle Danube sector**

This sector stretches out along some 959 km between Devin (km 1,880) and Turnu Severin harbour (km 931) the drainage basin finally having a 578,300 km^2. But for the Carpathian Mts. Defile (from Baziaş km 1,073 to Gura Văii km 942), this sector is typically lowland.

With a view to improving navigation and energy production, the Middle Danube sector was provided with a dam, locks and water-power plants located in the Carpathian Defile (the so-called Iron Gate Hydropower and Navigation System), built between 1964 and 1971. The influence of the newly-formed storage-lake stretches out up to Belgrade (km 1,172).

- **The Lower Danube sector**

The Lower Danube channel goes from downstream of Turnu Severin harbour (km 931) to the mouth of the Danube Delta (at Ceatal Ismail, km 79.64); the drainage basin area has 807,000 km^2. In this lowland sector, the channel is 300–1,300 m wide, over 1.5 m minimum depth, with up to 28 km-wide floodplains.

The overall Danube Floodplain area in the Romanian border sector covers 680,000 ha, out of which some 419,820 ha are dyked along 1,158 km to prevent overflows.

The water-table slope and the water current velocity are of 4.5 cm/km and 2.5 km/hr respectively, on average. Except for the upstream sector, where the Iron Gate 2 Energy and Navigation System was built (km 863) and a storage-lake formed between km 942.8 and km 863, the channel is not regulated. Numerous holms and secondary arms developed downstream.

The Danube and the Danube Delta, displaying over 1,300 km of channels, and a 1.30 km-long sea coast, lie within Romania's natural borders.

The three hydrographic elements represent natural resources used by Romania and its riparian neighbour countries for navigation, energy, and as a source of water for agriculture, industry, urbanism and tourism.

- **The Danube Delta**

In-between the main arms and outside them, the Danube Delta area totals 4,200 km^2 (out of which 880 km2 lie on Ukrainian territory and 3,370 km^2 on Romanian territory) there are several water zones, among which Chilia-Sulina between the arms of Chilia, Tulcea and Sulina; Sulina-Sfântu Gheorghe between the arms of Sulina and Sfântu Gheorghe; Sfântu Gheorghe-Razelm, in the south, in-between the last two arms where one finds two zones: 1) the Razelm-Sinoe Complex and 2) the Ialpug-Catlabug-Chitai Lake Complex north of Chilia Arm on Ukrainian territory.

3.1. Characteristics of the Lower Danube water regime

3.1.1. Water discharge

- **Water flows. Trends.**

Data on water flows and levels (1840–2011) [7] are given in Table 1.

Water flow-time variation trends are illustrated in Fig. 1 graphs of water discharge multi-annual mean values at Orşova and Ceatal Ismail (1840–2013). The findings reveal that, after a lapse of some 75 years, values remained stable at ca 5,550 m^3/s at Orşova and ca 6,500 m^3/s at Ceatal Ismail.

In the Lower Danube, between Orşova and the river inflow to the Danube at Ceatal Ismail (km 80), the Danube tributaries contribute to a water-flow of some 890 m^3/s. Due to water drainage from the upstream, as well as from the Romanian sector, water levels at the Delta mouth average some 6,550 m^3/s, a daily maximum (2,187 m^3/s) and minimum (1,303 m^3/s having been registered on July 2, 1897 and on December 31, 1855, respectively.

The average water-flow at the mouths of the Danube arms to the Black Sea is 5,990 m^3/s. the difference of 560 m^3/s between the two values comes from water penetrations into the Delta, losses through evaporation and inflows to the Black Sea by other routes than the mouths of the Danube arms. Water flows tend to increase with time, annual maxima by ca 4.5 m3/s; average and minimum values by 4 m^3/s and 3.1 m^3/s, respectively.

Table 1

Characteristic multi-annual variables of the Danube water-flow (1840–2012)

No	Metering section	Position (km)	Maximum flow				Average flow	Minimum flow			
			Qmax m^3/s	Year	Month	Day		Qmin m^3/s	Year	Month	Day
1	Baziaş	1,072.4	15,800	2006	4	16	5,551	1,015	1901	1	13
2	Moldova Veche	1,048.7	15,880	2006	4	16	5,554	1,002	1858	2	23
3	Drencova	1,016.4	15,931	2006	4	16	5,554	1,003	1901	1	13
4	Şviniţa	995	15,877	2006	4	16	5,557	1,060	1985	10	6
5	Orşova	957.4	15,947	2006	4	16	5,574	1,060	1985	10	6
6	Drobeta-Turnu Severin	932	15,758	2006	4	16	5,585	1,103	1985	10	6
7	Gruia	856.5	15,758	2006	4	16	5,592	1,103	1985	10	6
8	Calafat	786.9	15,916	2006	4	16	5,636	1,009	1858	2	3
9	Bechet	678.7	16,169	2006	4	16	5,724	1,019	1864	2	23
10	Corabia	624.2	16,185	2006	4	16	5,731	1,022	1864	1	13
11	Turnu Măgurele	596.3	16,885	2006	4	16	5,932	1,152	1684	1	13
12	Zimnicea	553.2	16,919	2006	4	16	5,991	1,010	1858	1	15
13	Giurgiu	493.1	17,000	2006	4	16	6,011	1,030	1858	1	15
14	Olteniţa	429.8	17,303	2006	4	16	6,077	1,060	1858	1	15
15	Chichiu-Călăraşi	379.6	17,303	2006	4	16	6,107	1,041	1920	12	8
16	Călăraşi-Borcea Arm	94.5	3,203	1845	5	2	946	132	1985	10	6
17	Izvoarele	348.6	15,751	2006	4	16	5,148	839	1858	1	15
18	Bala Arm	8	9,516	2006	4	16	2,462	302	1858	2	26

Table 1 (continues)

19	Vlădeni Borcea Arm	1	11,120	2006	4	16	3,431	538	1858	2	26
20	Hârşova	248	7,846	1845	8	2	2,715	460	1985	10	6
21	Vadu Oii	238	17,372	2006	4	16	6,130	1,100	1864	2	1
22	Bălaia-Vâlciu Arm	1	3,739	2006	4	16	1,324	237	1864	2	1
23	Gropeni-Cremenea Arm	197.5	11,740	2006	4	16	4,164	745	1864	2	1
24	Smârdan-Măcin Arm	4.5	1,893	2006	4	16	665	118	1864	2	1
25	Brăila	167	17,525	2006	1	6	6,149	1,100	1864	2	1
26	Grindu	141.3	21,347	1897	7	2	6,410	1,446	1855	12	30
27	Isaccea	100.2	21,864	1897	7	2	6,516	1,303	1855	12	30
28	Ceatal Ismail Danube	80.5	21,867	1897	7	2	6,516	1,303	1855	12	30

Water discharge variation over longer time-intervals, as well as within one and the same year is influenced by the time-variation of climatic factors (atmospheric circulation, precipitations temperature, etc., ending up a short climatic cycle) within the Danube basin which generate the water flows.

Thus, once every 10 years, annual discharges may increase or diminish by some 25% versus the long-time multi-annual mean. Once every 100 year, water discharge is over 52% higher or 36% lower than the multi-annual mean.

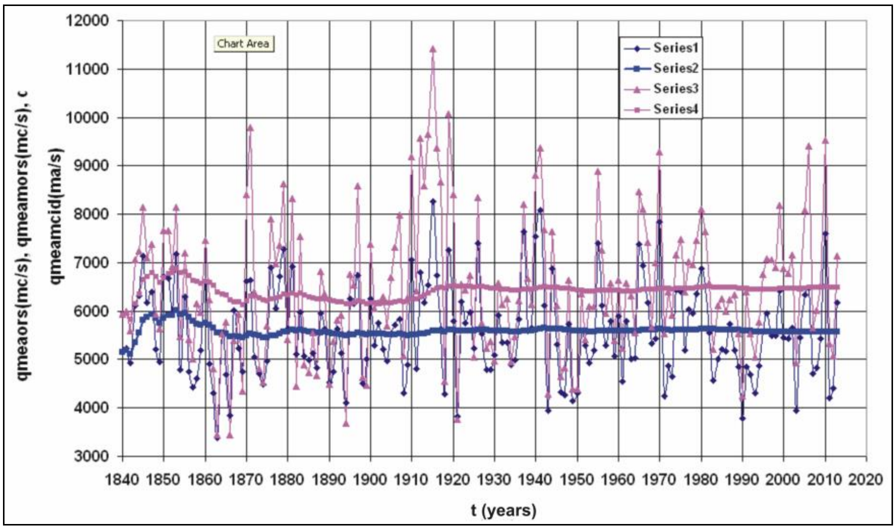

Fig. 1 – Danube water discharge, time-variation graphs of average annual and multi-annual flows (1.3 and 2.4, respectively) at Orşova (1.2) and Ceatal Ismail (3.4) over 1840–2013.

Water discharge within the annual hydrological cycles is unevenly distributed in time, with mounthly flows possibly oscilating by some +38% in May–June and –36% in September. In years with very great or very small water deviations from the long-time multi-annual mean of daily discharges, maximum and minimum values may reach 137%, and –75%, respectively.

- **Levels. Trends.**

Systematic Danube-level measurements go back to the 19th century, having been made first at Linz (1821), then in Bratislava and Budapest (1823), Ingolstadt (1827), Orşova (1839), Bezdan (1856), Sulina (1857), Tulcea (1858), Ruse (1898) and Ismail (1920).

In the upper Danube drainage basin, highest annual level variation amplitudes occurred in the warming season (March–June), with lowest ones in the cooling interval (September–October).

Table 2

Multi-annual characteristic variables of the Danube water level (1840–2011)

No	Metering station	Position (km)	Maximul level				Average level	Minimum discharge			
			Hmax cm	Year	Month	Day		Hmin cm	Year	Month	Day
1	Baziaş	1,072.5	820	2006	4	14	323	–117	1858	1	16
2	Moldova Veche	1,048.9	880	2004	11	14	343	–127	1866	1	11
3	Drencova	1,016.2	1,034	2004	8	3	372	–100	1866	1	11
4	Şviniţa	994.8	2,038	1995	8	21	646	–7	1866	1	11
5	Orşova	953.3	2,725	1996	12	24	799	–58	1866	1	11
6	Drobeta-Turnu Severin	931	981	1991	1	13	342	–122	1866	1	11
7	Gruia	851	898	2006	4	20	295	–196	1985	1	17
8	Calafat	794.6	861	2006	4	23	292	–124	1866	1	12
9	Bechet	679	871	1896	4	18	299	–117	1866	1	12
10	Corabia	625.5	882	1895	4	18	277	–138	2003	9	7
11	Turnu Măgurele	597	790	2006	4	24	252	–105	1866	1	12
12	Zimnicea	553.5	864	1895	4	10	297	–122	1868	1	12
13	Giurgiu	492.8	842	1895	4	18	287	–144	2003	9	8
14	Olteniţa	429.7	886	1895	4	18	285	–135	1866	1	14
15	Călăraşi-Borcea Arm	94.5	785	1895	4	18	246	–150	1866	1	15
16	Cernavodă	298.3	757	1895	4	18	244	–237	2003	9	10
17	Hârşova	252	764	2006	4	25	286	–136	1858	3	12
20	Brăila	169.4	701	2010	7	6	281	–86	1858	1	25
21	Isaccea	103.7	537	2010	7	6	217	–48	1921	10	31
22	Tulcea Tulcea Arm	71.6	458	1897	7	2	165	–45	1921	10	11
23	Sulina-Sulina Arm	0.0	137	2006	5	2	45	–36	1921	1	25

Water level and water discharge regimes are closely connected. Figure 2 diagram shows average water discharge variations of 0–16,000 m^3/sec. alongside the Romanian sector of the Danube over the 1980–2010 interval. Flooding episodes on the Danube may last for several months even, e.g. in the years 1897, 1940, 1970, 1980, 2006 and 2010. Both historical and current measurements data attest to high flooding events in 1501, 1838, 1890, 1897, 1899, 1924, 1926, 1937, 1940, 1942, 1944, 1954, 1956, 1970, 1980, 2006 and 2010, producing material damage and casualties.

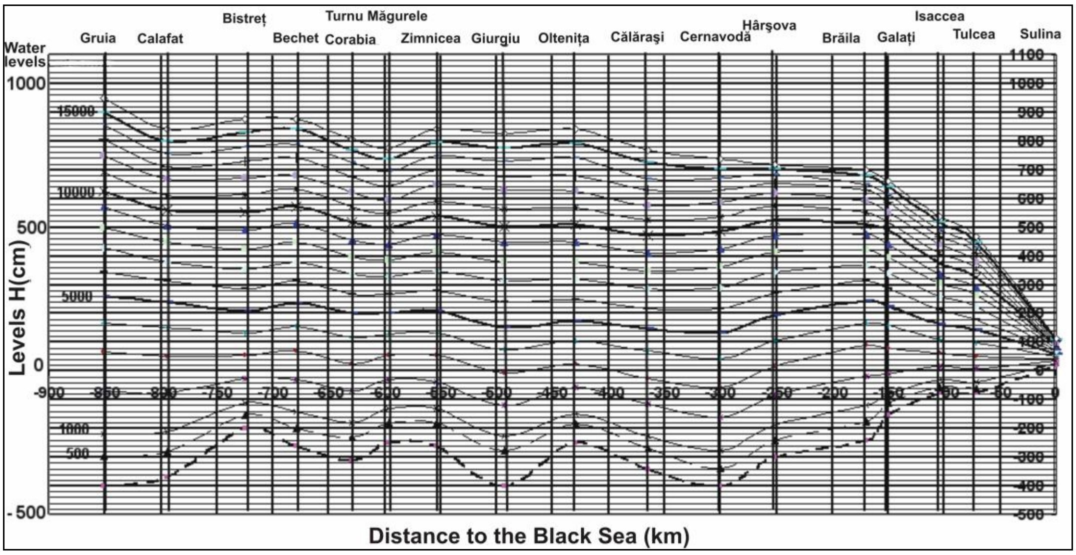

Fig. 2 – Water-table level variations along the Romanian sector of the Danube corresponding to 0–16,000 m^3/s water discharges (mean values over 1980–2010).

Insofar as time level variation trends are concerned statistical data for the 1840–2010 interval show an annual level increase of 0.11 cm, 0.176 cm, and 0.109 cm at Călăraşi, Galaţi and Tulcea, and a temporal decrease trend of –0.368 cm at Cernavodă.

3.1.2. Sediment discharge

- **The nature and granulometry of sediments.**

The earth particles entrained by water and drained from the Danube hydrographic basin reach the mainstream in the form of sediment (alluvia). Sediment particles consist mainly of silica (specific porosity ca 1.65 kg/dm^3). Grain varies between bolders and clays. In the Lower Danube sector, the sediment granulometric composition consists of coarse sand and clay fractions. In terms of grain size, there are two categories of sediment, with different behaviour (laminar or turbulent) when falling into a mildly flowing water.

Grain fraction smaller than 0.063 mm display a turbulent behaviour when falling into mildly flowing water, being carried only in suspension under the influence of water current turbulence.

The laminar behaviour is specific to smaller grain fractions. If larger than 0.063 mm, they display a turbulent behaviour when falling into mildly flowing water and are carried by the water current by dislodging and in suspension. Dislodging the sediment on the channel-bed, or lifting it in suspension occurs when the water current velocity exceeds a certain limit, the so-called critical velocity of dislodging of sediment. Mean diametric values in measured years are given in Table 3.

Table 3

Mean values of water flows (Q), total discharge of suspended (Rs) and dislodged (Rg) sediments, alos of suspended (d50s) and dislodged (d20g) sediment particles corresponding to 50% of the granulometric composition in measurement years on the Danube

Metering sections	Measured years	Position	Q	Rs	d50s	Rg	d50g
		Km	mc/s	kg/s	mm	kg/s	mm
Baziaș	1971–1998	1,072.4	5,656	516	0.022	0.70	0.285
Moldova Veche	1973–1998	1,048.7	5,562	356	0.022	0.510	0.281
Drencova	1971–1997	1,016.4	5,559	341	0.022	0.433	0.282
Șvinița	1972–1998	995	5,414	402	0.022	0.991	0.020
Orşova	1971–1998	957.4	5,511	464	0.022	0.222	0.107
Drobeta-Turnu Severin	1969–1997	632	6,051	309	0.023	1.25	0.453
Gruia	1969–1995	856.5	5,673	354	0.024	9.37	0.462
Calafat	1969–1995	786.9	5,749	399	0.025	1.04	0.428
Bechet	1969–1995	678.7	6,202	522	0.025	11.69	0.297
Turnu Măgurele	1970–1985	596.3	6,503	1,474	0.026	14.96	0.302
Zimnicea	1972–1995	553.2	6,025	999	0.027	14.57	0.243
Giurgiu	1970–1995	493.1	6,198	991	0.023	16.12	0.247
Oltenița	1969–1985	429.8	6,641	1,368	0.025	13.17	0.294
Chiciu-Călărași	1970–1985	379.6	6,713	1,434	0.024	14.83	0.261
Vadu Oii	1969–1995	238	6,738	1,202	0.020	5.89	0.245
Brăila	1971–1995	167	6,776	1,134	0.021	4.03	0.185
Grindu	1969–1985	141.3	7,428	1,703	0.022	7.60	0.181
Ceatal Ismail	1969–1995	80.5	7,123.741	1,534.169	0.020	3.50	0.155

where Q = Suspended sediment measurements yielded mean water discharge;
Rs = suspended sediment measurements yielded mean alluvia suspended discharge;
Rg = dislodged sediment measurements yielded mean dislodged alluvia discharge.

- **Hydraulic lifting of sediment in suspension.**

Channel-bed sediments are water-flow moved by hydrodynamic pressure and by friction. Another interaction between the water current and the sediment grains entailed by it is the action of the vertical components of pulsating velocities within the water current and the water falling velocity of the respective grains.

Water measurements on the Danube have revealed that the mean value of the pulsating velocity vertical component v_p(cm/s) is expressed by the empirical function (1) [3].

$$v_p = 6.76 * q_m / h_m^{0.961} \qquad (1)$$

where q_m(sqm/s) is the mean specific water discharge value.

On the other hand, the average sediment grains water fall velocity (w), called sinking velocity, is defined by functions dependent on grain-size (d) and water temperature (θ) [6]. With grain-size (d) of 0.1-0.6 mm, sinking velocity w (cm/s) is given by Zegjda's relation:

$$w = d * g^{2/3} / (5* \zeta^{1/3}) * (\rho_s/\rho - 1)^{2/3} \qquad (2)$$

where g = gravitation acceleration, ζ = water temperature-dependent kinematic viscosity coefficient (θ) (relation 3) and ρ_s/ρ, expressing the relation between solid density (ρ_s) and water density (ρ) equal with ca 1.65.

$$\zeta(cm^2/s) = 0.000001775 / (1 + 0.0337 * \theta + 0.00022 * \theta^2) \qquad (3)$$

For grains smaller than 0.06 mmm, the sediment water fall velocity is given by relation (4):

$$w = g * d^2 / (18* \zeta) * (\rho_s/\rho - 1) \qquad (4)$$

Whenever up $v_p >= w$, channel-bed silts are dislodged or turbulent suspended in the channel water current.

This is exemplified by checking the relation between water fall velocity w grains of 0.063 mm in diametre and the vertical component of vp pulsating current for the 11° mean Danube water temperature. In the case of 0.063 mm particles and 11° water temperature (eq. 2) w grain fall velocity = 2.8 mm/s. On the other hand, relation (1) shows that with minimum 0.2 m/s, average velocity in the Danube channel, pulsating vertical velocity is 13.5 mm/s. Hence, five particles smaller than 0.063 mm in diametre are maintained and carried exclusively in suspension by very mild Danube currents without being involved in channel-bed morphological processes. Therefore, it is only coarse sediments that take part in channel-bed hydromorphological processes.

- **Sediment water transport in the Romanian Danube sector**

Under the action of the water flow, solid sediments are detached from the channel walls by erosion produced by the current, by waves and by ice. Another category of solid particles in the Danube channel are brought by the tributaries that flow on the river drainage-basin slopes.

The type of water current-entailed movement is grain-size dependent. Under water-current action, sediment behaviour is grain-size dependent. Measurements made on the Danube have shown that sediments are being moved either by dislodging or in suspension.

Smaller than 0.063 mm grains, the so-called fine sediments, are moved solely in suspension, irrespective of the water current velocity.

Larger than 0.063 mm grains, the so-called coarse sediments, are moved by dislodging, or in suspension, depending on the water current velocity.

The different entailment in movement of fine and coarse sediments is due to the distinct hydraulic behaviour of solid particles deposition in water.

The Danube transport of coarse sediment begins when the water current velocity exceeds a certain critical value. The critical value of the dislodged coarse sediment and of the suspended coarse sediment entailed in movement is distinctively different. Thus, the different behaviour to the water current action makes the coarse sediment transport regime dependent on water current energy, whereas fine sediment discharge depends on natural factors outside the channel, such as precipitation.

Present-day assessment of (fine and coarse) sediment transport on the Danube

The transport of sediments is quantified by measuring the discharge of alluvia. Systematic measurements of water and alluvia flow-rates on the Danube are made by the Romanian Waters National Administration, the results being stored in the hydrographical data-base of the National Institute of Hydrology and Water Management. Processing these data yielded a series of characteristics regarding Danube suspended and dislodged sediments.

Two monographic hydrological works were elaborated at the Institute of Hydrotechnical Studies and Research of the State Committee for Waters between 1960 and 1967. The first, published in Romanian and Russian (1963), dealt with the Danube Delta (coordinator Eng. C. Diaconu, Ph.D.); the second (1967), covered the Danube course between Baziaş and its inflow to the Delta (coordinator: Eng. V. Stănescu, Ph.D.).

Between 1975 and 1985, a regional collaboration among the riparian countries of the Danube drainage basin, started under the UNESCO International Hydrological Programme (IHP), resulted in the elaboration (1988) of a *Monograph of the Danube Drainage Basin* (published in English, German, French and Russian). This monographic work describes the River's water regime from source-area to discharge into the Black Sea.

The hydrological Monograph of the Danube Delta provides data on sediment and water discharges at the river inflow to the Delta:

- Multi-annual average water flow-rate (1921–1960) = 6,290 m^3/s; maximum and minimum water flow values = 14,050 m^3/s, and 1,350 m^3/s, respectively.
- Multi-annual average suspended sediment discharge (1921–1960) 2,140 kg/s; 5,150 kg/s (1941) and 628 kg/s (1921), respectively;
- Suspended sediment granulometry of fractions between 0.002 mm and 1 mm is dominated by smaller than 0.1 mm particles.
- Dislodged sediment discharge (grain-size 0.08 and 0.6 mm) is at most 5–6% of the suspended sediment one.

Hydrological Monograph data on the Danube water and sediment discharge rates (1921–1962) between Baziaş and the river inflow to the Danube Delta, cheched at three metering stations: Orşova, Olteniţa and the Danube inflow to the Delta:

- Multi-annual average water flow-rate: 5,950 m^3/s at Orşova, 6,000 m^3/s at Olteniţa and 6,220 m^3/s at the Danube inflow to the Delta.
- Multi-annual average suspended sediment discharge: 1,110 kg/s at Orşova, 1,765 kg/s at Olteniţa, 1,800 kg/s at Brăila, and 2,110 kg/s at the Danube inflow to the Delta.
- Dislodged sediment discharge: ca 1.5% of the suspended sediment discharge. No information on sediment granulometry.

Monograph data on the Danube water and sediment discharge at four metering station in the Romanian border sector:

- Water flow-rates: Orşova 5,699 m^3/s; Zimnicea 6,150 m^3/s; Vadu Oii 6,216 m^3/s and at the Danube inflow to the Delta 6,550 m^3/s.
- Multi-annual average sediment discharge (1930–1990): Orşova 816 kg/s; Zimnicea 1,102 kg/s; Vadu Oii 1,356 kg/s and the Danube inflow to the Delta: l,457 kg/s.
- Suspended sediment granulometry: average grain-size particles measured at Turnu Severin: 0.0251 mm and at the Danube inflow to the Delta: 0.0212 mm.

- Multi-annual average discharged sediments (1930–1990) Orşova: 2.55 kg/s; Zimnicea 14.9 kg/s; Vadu Oii 4.32 kg/s and the Danube inflow to the Delta 2.21 kg/s. The average grain-size was 0.444 mm at Turnu Severin and 0.145 mm at the Danube inflow to the Delta.

Other in-depth information on the sediment transport of fine alluvia, on the one hand and of coarse alluvia, on the other, were partly published, yet without a characterisation of their regime. It is more than 50 years since Romanian specialist bodies have made a complex study of the Danube and its Delta water regime. An update of this issue is given furthermore.

Looking back at past data (down to 1840) on the overall (fine and coarse) sediment discharge has largely contributed to a better knowledge of their regime in the Romanian sector of the Danube (Table 4).

The time-variation graphs (1840–2012) of overall sediment discharge at the Baziaş, Gruia and Ceatl Ismail metering sections are given on Figure 3.

Table 4

Characteristic values (1940–2012) of the multi-annual average water flows Q (mean) and the annual average maxima (Rmaa), multi-annual average (Rmeam) and annual minima (Rmia) of total (fine and coarse) sediments at the metering sections placed alongside the Romanian sector of the Danube

No	**Metering stations**	**Position (km)**	**Qmeam** m^3/s	**Rmaa** kg/s	**Rmeam** kg/s	**Rmia** kg/s
1	Baziaş	1,072.4	5,558	2,022	829	61
2	Moldova Veche	1,048.7	5,552	2,020	837	57
3	Drencova	1,016.4	5,563	2,023	832	14
4	Şviniţa	995	5,570	2,025	825	54
5	Orşova	957.4	5,568	2,045	822	53
6	Drobeta-Turnu Severin	632	5,587	2,165	845	54
7	Gruia	856.5	5,656	2,661	858	47
8	Calafat	786.9	5,655	2,978	1,080	57
9	Bechet	678.7	5,857	3,079	1,152	157
10	Turnu Măgurele	596.3	5,920	3,225	1,248	126
11	Zimnicea	553.2	5,976	2,631	1,102	150
12	Giurgiu	493.1	6,007	2,989	1,211	141
13	Olteniţa	429.8	6,079	2,962	1,291	170
14	Chiciu-Călăraşi	379.6	6,096	3,624	1,379	172
15	Vadu Oii	238	6,155	4,167	1,425	187
16	Brăila	167	6,181	4,062	1,430	142
17	Grindu	141.3	5,405	4,076	1,659	209
18	Isaccea	100.2	6,509	4,489	1,645	224
19	Ceatal Ismail	80.5	6,495	4,470	1,599	200

3.1.3. A study of coarse sediment transport on the Danube

According to national regulations in effect, measurements of sediment discharge on the Danube have in view suspended and dislodged alluvia as a whole, without any differentiation between fine and coarse sediments.

Since coarse sediment depositions have negative effects on navigation, the National Navigation Body assigned the Water Management Body the task of undertaking special measurements of this phenomenon.

Thus, the then Institute of Meteorology and Hydrology (IMH), benefitting from the material nad technical support of the National Navigation Authority, proceeded to organising a special campaign for water and sediment discharge measurements, headed by Eng. C. Bondar, who also participated in this endeavours; concentrations of fine and coarse sediments were measured separately.

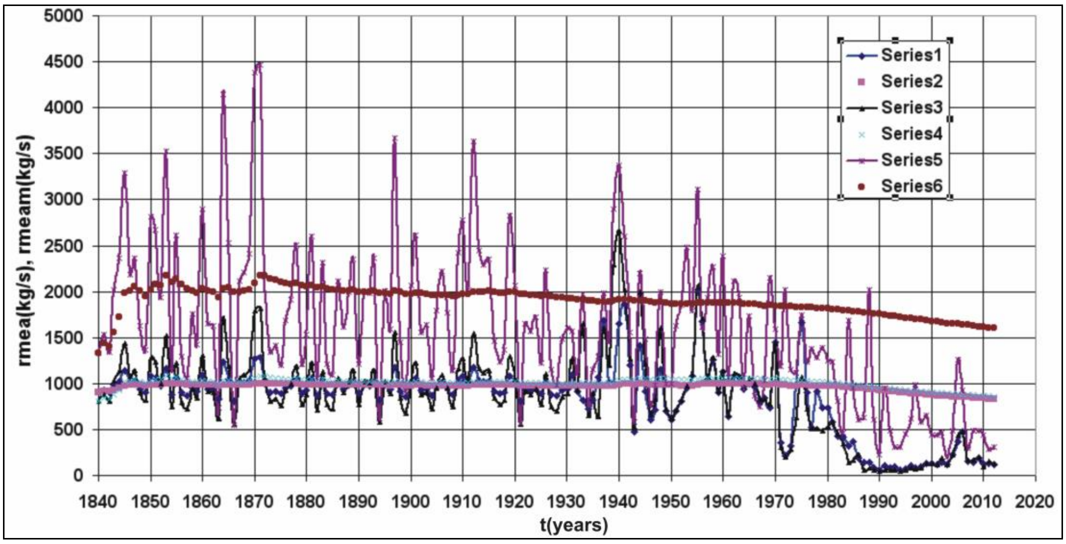

Fig. 3 – Graphical representation of the overall (fine and coarse) sediment discharge on the Danube (1840–2012), annual means (1,3,5) and multi-annual means (2,4,6).

The first such campaigns covered the whole Romanian Danube sector; research vessels were provided by the Navigation Body, and used between 1970 (a high-flood year) and 1975 until IMH would built its own vessel for complex water studies on the Danube, thus continuing the measurement of sediments. The National Institute of Meteorology and Hydrology (NIMH) would use this vessel (called LIPOVA) only until 1997.

Within that time-span, NIMH conducted biannual measurements with the LIPOVA both in high spring waters and in low autumn waters, focussing on water and sediment discharge throughout the Romanian sector on the Danube, inclusive of the Danube Delta arms. A number of ca. 1,070 measurements were made in 34 metering sections.

The data yielded by this special water-and-sediment-discharge measurements were processed, both coarse dislodged sediments and suspended sediments being correlated with specific water discharges in terms of the average channel depth where measurements had been conducted.

The mean specific water flow-rate by section **q** was taken to be the water-flow variable because, as hydrodynamic factor, the specific water flow within a channel represents the water current energy concentration grade/channel width unit. At the same time, the specific water flow-rate is also an indicator of water current turbulence. For the same total water flow-rate in the channel, the specific water flow is inversely dependent on channel length, being lower in the wide channel sections, and higher in narrow ones.

According to measurements and observations, channel depths multi-annual means are directly dependent on the specific water flow multi-annual means. Measurements of coarse sediments have shown that, for the same specific water flow, the transport of coarse sediments depends on average channel depth, since water current velocity is channel-depth dependent.

Proceeding from these findings, the specific average discharge of coarse sediment by section was globally correlated with the average specific water flow-rate by section in terms of average channel depths.

The partial results of distinctively processing past measurements by fine and coarse sediment discharge had been published at the time both in Romania [1] and abroad [4].

In order to complete and get an in-depth knowledge of coarse sediment transport on the Danube, also the other data, gathered from 1,070 measurements made between 1971 and 1997 at 34 metering sections, were used. Furthermore, an improved methodology of measurement data was resorted to.

The mean digital results of measurement processing led to establishing two basic empiric functions of coarse sediment transport:

$$gtm = agt * qm - bgt \qquad (5)$$

$$gsm = ags * qm - bgs \qquad (6)$$

where the average specific water-flows (qm) in the channel sectors is given in mp/s; specific discharge of average coarse sediment / section (gtm) is given in g/m/s and concentration of the average coarse suspended sediment by section (gsm) in g/m^3.

A simple transformation turns the empiric functions (5) and (6) into (7) and (8).

$$gtm = agt * (qm – bgt/agt) \qquad (7)$$

$$gsm = ags * (qm – bgs/ags) \qquad (8)$$

Analysing the structure of the empirical functions (7) and (8), one finds that bgt/agt and bgs/ags relations can be interpreted as critical values of mean specific discharges (qm) where coarse sediment transport begins from, so that,

$$qmcrgt = bgt/agt \qquad (9)$$

$$qmcrgs = bgs/ags \qquad (10)$$

According to relations (9) and (10), the empirical functions (7) and (8) grow into (11) and (12).

$$gtm = agt * (qm – qmcrgt) \qquad (11)$$

$$gsm = ags * (qm – qmcrgs) \qquad (12)$$

The processing of measurement data on dislodged and suspended coarse sediment discharge by the above-mentioned methodology, yielded the empirical functions (14) and (16) of the critical means of water specific flow-rates where coarse sediment transport begins from.

- Dislodged sediment

$$agt =6.497*exp(–0.085*hm) \qquad r = 0.992 \qquad (13)$$

$$bgt = 4.827*hm^0.306 \qquad r = 0.607 \qquad (14)$$

$$qmcrgt = 0.222 * hm ^1.227 \qquad r = 0.996 \qquad (15)$$

- Suspended corse sediment

$$ags = 5.615*exp(–0.0259) \qquad r = 0.979 \qquad (16)$$

$$bgs = 4.281*hm^0.857 \qquad r = 0.996 \qquad (17)$$

$$qmcrgs = 0.517 * hm ^1.147 \qquad r = 0.998 \qquad (18)$$

Hence, channel integral coarse sediment values are given in relations (19) and (20).

$$Gt(kg/s) = agt * (qm – qmcrgt) * B/1000 \qquad (19)$$

$$Gs(kg/s) = qm * ags * (qm – qmcrgs) * B/1000 \qquad (20)$$

where B stands for channel length.

The empirical functions (19) and (20) allow to determine the discharge of dislodged and suspended coarse sediments along the Romanian Danube channel sector, provided that channel morphometry and water flow-rates are known. On the basis of these two functions, two computation programmes were elaborated to assess: 1) the transport capacity of dislodged and suspended coarse sediments and 2) the daily discharge of dislodged and suspended coarse sediments on the Danube metering sections over the 1840–2012 interval.

The results of implementing the first programme are shown in Figures 4 and 5. Looking at the two figures, one may depict the following characteristics of coarse sediment discharge variation at the metering stations, located alongside the Romanian Danube sector, in terms of water flow-rates.

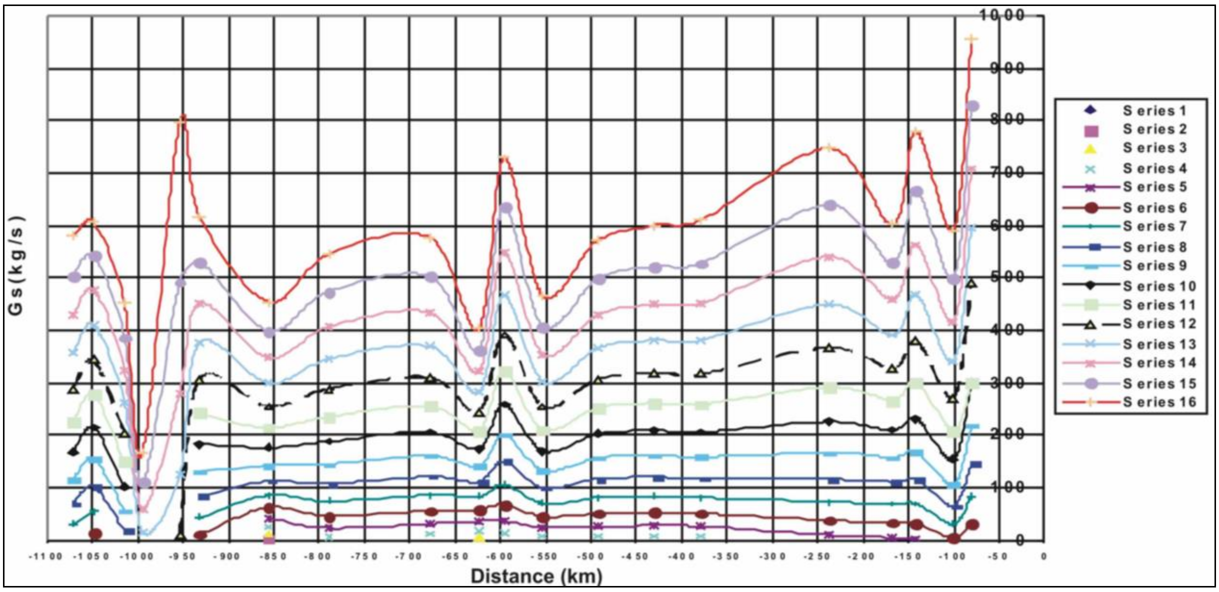

Fig. 4 – Graph of suspended coarse sediment discharge alongside the Romanian Danube sector, water flow-rate between 1,000 (1) m^3/s and 16,000 (16) m^3/s.

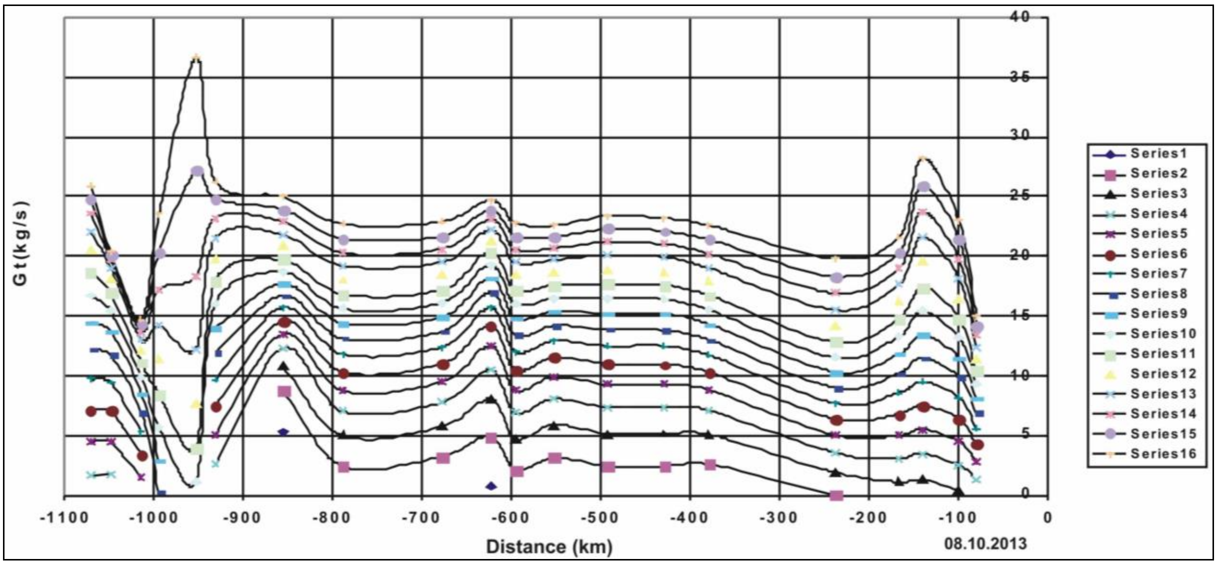

Fig. 5 – Graph of dislodged coarse sediment discharge of alongside the Romanian Danube sector, water flow-rate between 1,000 (1) m^3/s and 16,000 (2) m^3/s.

- Dislodged sediment discharge decreases from up-to-downstream, maximum value ca. 42 kg/s at Orşova metering station, water flow-rate 16,000 m^3/s.
- Suspended coarse sediment discharge increases from up-to-downstream, maximum value ca. 1,080 kg/s at Ceatal Ismail metering section, water flow-rate 16,000 m^3/s.

The results of implementry the second computation programme enabled us to determine, among others, the mean multi-annual and the maximum annual values of dislodged and suspended coarse sediments at the metering sections downstream of the Iron Gate over the 1840–2012 interval (Table 5).

Table 5

The mean multi-annual and the maximum annual values of dislodged and suspended coarse sediments at the metering sections of Danube, 1840–2012

Metering sections	**Dsilodged coarse sediments (kg/s)**		**Suspended coarse sediments(kg/s)**	
	Multi-annual means	**Annual maxima**	**Multi-annual means**	**Annual maxima**
Gruia	14.6	26.6	63.1	474
Calafat	10.2	24.6	54.9	598
Bechet	10.7	24.5	61.1	618
Corabia	13.9	25.1	58.0	400
Turnu Măgurele	10.8	25.5	91.0	891
Zimnicea	11.7	23.9	54.1	454
Giurgiu	11.9	25.6	74.6	694
Olteniţa	11.9	27.2	87.1	837
Chiciu-Călăraşi	11.0	26.2	75.4	775
Vadu Oii	7.1	24.4	72.4	1042
Brăila	7.6	26.1	66.8	842
Grindu	8.9	47.9	84.6	1844
Isaccea	7.8	35.9	57.2	1367
Ceatal Ismail	5.6	20.4	130.1	2048

Characteristic features of:

- Dislodged coarse sediments:
  - Multi-annual value range from 14.6 kg/s at Gruia to 5.6 kg/s at Ceatal Ismail.
  - Maximum value range from 23.9 kg/s at Zimnicea to 47.9 kg/s at Grindu.
- Suspended coarse sediments:
  - Multi-annual mean value range from 54.1 kg/s at Zimnicea to 130.1 kg/s at Ceatal Ismail.
  - Maximum value range from 400 kg/s at Corabia to 2,048 kg/s at Ceatal Ismail.

4. CONCLUSIONS

Proceeding from the fact that the granulometric structure of the Lower Danube sediments contains two main categories of grains, fine grains under 0.063 mm and coarse grains over 0.063 mm, the paper presents the main hydrological characteristics of the overall (fine plus coarse) sediment transport, as well as of dislodged and suspended coarse sediment transport.

Measurements of sediment discharges in the Romanian Danube sector are also analysed. Having in view the hydraulic criterion of sediment lifting in suspension, it follows that the Danube fine alluvia are carried by the water current exclusively in suspension.

Analysing the interaction between the water current and the channel physical structure, the empirical functions of the Danube channel hydromorphological stability and the empirical functions of dislodged and suspended sediment transport could be established.

The findings have revealed that the mean specific discharge by sections of dislodged coarse sediments, and the mean concentrations by sections of suspended coarse sediments are linear-dependent on the mean specific water flow-rates by sections.

On the basis of the empirical functions of coarse sediment transport yielded by processing the data-sets measurements, the daily discharges of dislodged and suspended sediments in the Romanian Danube sector over 1840–2012 were obtained. Further computation yielded the multi-annual means and the annual maxima of dislodged and suspended sediment discharges at the metering sections downstream of the Iron Gate point.

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