SEDIMENT TRANSPORT ON THE ROMANIAN SECTION OF THE DANUBE RIVER

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Abstract. The paper briefly presents the physico-geographical characteristics of the Danube River basin in order to introduce data and considerations on the river water and sediment discharges, focusing on the coarse-grained bed- and suspended loads.

The analysis of interactions between the water flow and the riverbed physical structure allowed to establish the empirical functions of the bed- and suspended coarse-grained sediment load transport. For a given cross-section a linear dependence between the average specific water discharge and the coarse sediment bed-load average specific discharge as well as the mean concentration of the suspended coarse sediment was found.

The coarse-grained sediment transport empirical functions based on a long series data for the period 1965 – 1989 allowed the determination of the daily coarse-grained bed- and suspended sediment discharges along the Romanian Danube River section for an extended period between 1840 and 2012.

The multiannual average values and maximum annual discharges of the bed- and suspended coarse-grained sediment load (d50%>0.063 mm) have been computed for the cross-sections downstream the Iron Gates barrages.

For the coarse-grained bed load:

- The multiannual average values of the bed-load discharge vary from 14.6 kg/s at Gruia (km 856.5) to 5.6 kg/s at Ceatal Ismail (Km 80.5);
- The maximum values of the bed-load discharge vary between 23.9 kg/s at Zimnicea (km 553.23) and 47.9 kg/s at Grindu (km 141.3).
- For the coarse-grained suspended load:
- The multiannual average values of the coarse-grained suspended load discharge vary between 54.1 kg/s at Zimnicea and 130.1 kg/s at Ceatal Ismail;
- The maximum values of the coarse-grained suspended load discharge vary from 400 kg/s at Corabia (km 624.2) to 2048 kg/s at Ceatal Ismail.

Key words: Danube River, catchment basin, transport, sediment, coarse bed-load discharge

1. INTRODUCTION

The beginnings in knowledge about the Danube are lost in the historical past of Europe. The first information about the Danube refers to its hydrography and to the mapping of the region by Austro-Hungarian Empire.

A brief overview of the river catchment area with its orographic, geologic, climatic and hydrographic characteristics will be presented in order to better describe the Danube water runoff and sediment transport.

The first level gauge (stage recorder) on the Romanian section of the Danube was installed by the Austro-Hungarian Empire at Orsova in 1838. The regular measurements of the water and sediment discharges started in 1857 being first performed by the Danube European Commission and then continued by the Romanian State after the Independence War of 1877.

Based on these measurements as well as on the more recent data, a reconstitution of the water level regime and of the water and sediment discharges from 1840 until today has been achieved and is presented in this paper. Special attention was paid to the bed- and suspended- coarse-grained loads, less explored in the past.

Analysing the interaction between the water flow and the physical structure of the riverbed the empirical functions of hydro-morphological stability of the Danube riverbed as well the empirical functions of the bed- and suspended- coarse-grained loads have been established. The average specific discharges of the coarse bed-load and the average concentrations of the coarse-grained suspended-load on a given cross-section depend linearly of the average specific water discharge on the considered cross-section.

Using the empirical functions of the coarse alluvial transport, the daily bed- and suspended- coarse-grained loads discharges on the Romanian section of the Danube for the period 1840 – 2012 have been determined. Processing these data, the multiannual average values and the maximum annual values of the bed- and suspended- coarse-grained loads discharges have been calculated for the hydrometrical cross-sections downstream of the Iron Gate dams. The synthetic data of this processing are shown below:

- For the coarse-grained bed load:
  - The multiannual average values of the coarse bed-load discharge vary from 14.6 kg/s at Gruia (km 856.5) to 5.6 kg/s at Ceatal Ismail (Km 80.5);
  - The maximum values of the coarse bed-load discharge vary between 23.9 kg/s at Zimnicea (km 553.23) and 47.9 kg/s at Grindu (km 141.3).
- For the coarse-grained suspended load;
  - The multiannual average values of the coarse-grained suspended load discharge vary between 54.1 kg/s at Zimnicea and 130.1 kg/s at Ceatal Ismail;
  - The maximum values of the coarse-grained suspended load discharge vary from 400 kg/s at Corabia (km 624.2) to 2048 kg/s at Ceatal Ismail.

2. FORMATION OF THE DANUBE WATER RUNOFF AND SEDIMENTS FLUX

2.1. Danube catchment area

Danube drains its water from a catchment area of 817,028 km^2, occupying about 11% of the European continent. The Danube catchment area is disposed asymmetrically, with about 56% of the area located on the right side and 44% on the left side of the river.

Of the total area of the Danube catchment area, 36% is occupied by mountains with very high (above 4000 m in the Alps) and high (1000-2000 m in the Carpathians, Balkans and the Dinaric mountains) altitudes and 64% is occupied by areas with medium and low altitudes (plateaus, hills and plains). The average altitude of the Danube basin is 475 m (Stănescu, V., 1967**;** Stančik *et al.* 1988). The Danube catchment area is divided into three sub-basins: upper, middle and lower.

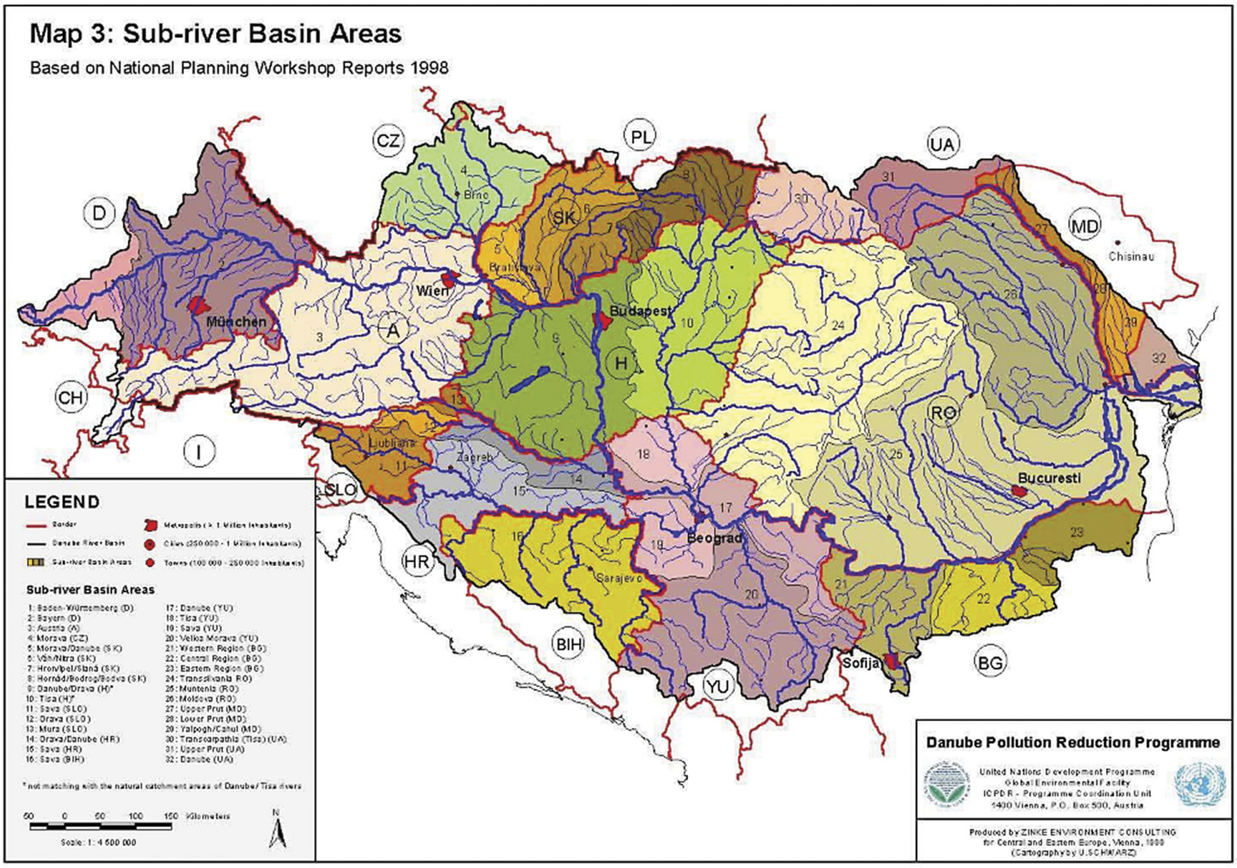

Fig. 1. Map of the Danube catchment basin with sub-basins and the main hydrographic network

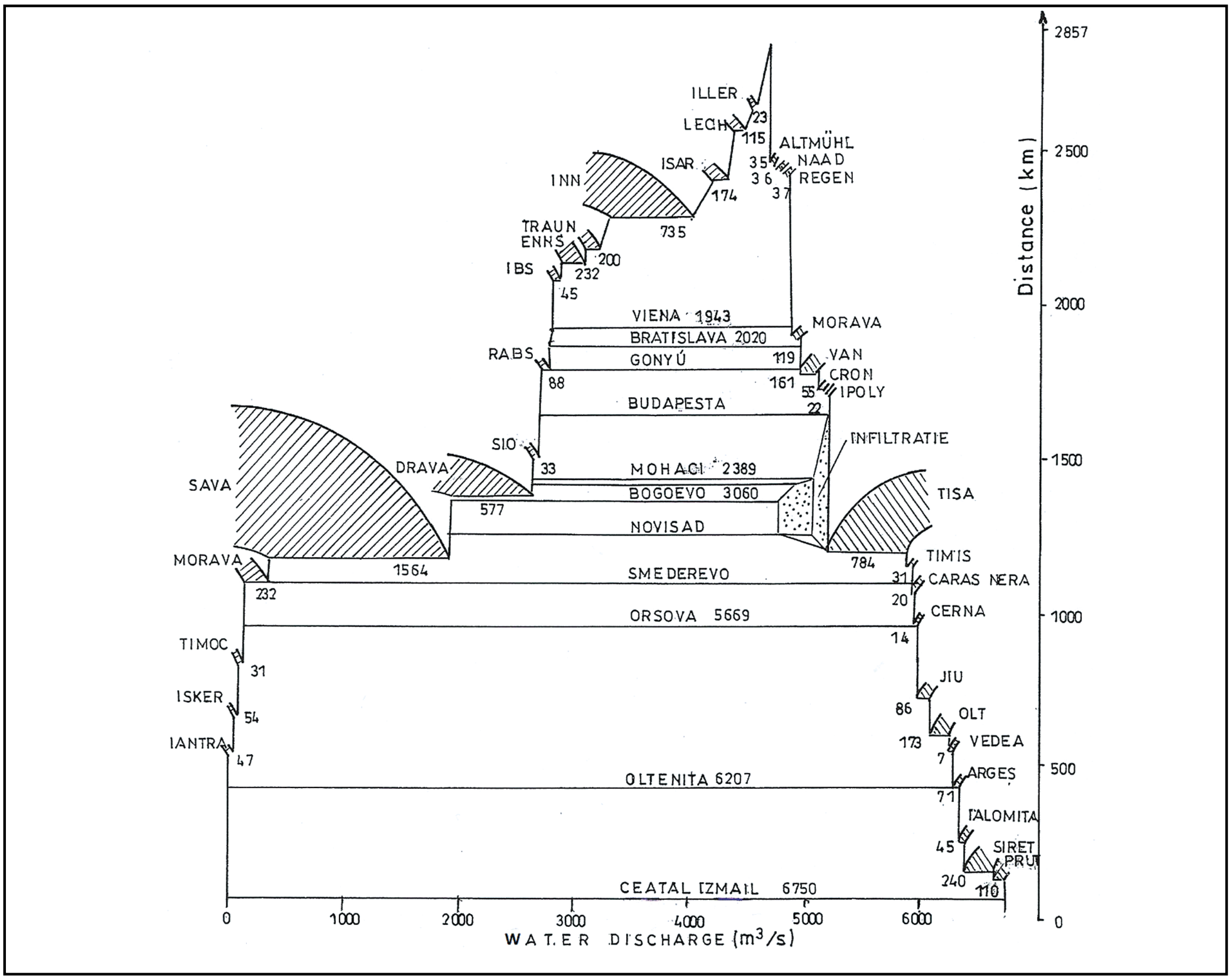

Fig. 2. Scheme of the Danube tributaries multiannual average water supply to the main river course (after Stănescu V, 1967)

The climate in the Danube River basin is temperate-continental, with the mean annual air temperature variying between 8ºC in the upper basin and 12ºC in the lower basin. Absolute extreme temperature of air reaches values of 37º C in summer and - 36º C in winter time, in the upper basin. In the plain of the Lower Danube, absolute extremes are from 43ºC to - 33ºC.

A climatic factor of primary importance for the Danube catchment area is represented by rainfall whose role is crucial for the formation of water flow and hydrological regime of the Danube. The rainfall distribution across the Danube basin is inequable, due to the atmospheric circulation characteristics and relief types. Annual average amount of precipitation in lowland areas is about 400-600 mm, in the Carpathian Mountains about 800-1200 mm and in the Alps from 1800 up to 2500 mm and more. The highest amount of rainfall is recorded in spring and summer and lowest quantities in autumn and winter. The rainfalls on the right side of the Danube catchment area are more abundant than on the left side of the river. Snows fall every year at altitudes above 100 m (Stănescu, V., 1967). The fewer days with snow are found in the lower Danube basin. In the valleys, the snow is present about 20-30 days/year, on the hills about 40-50 days/year, in the Carpathian Mountains about 80 days/year and in the Alps about 180 days/year. The snowfall begins in October and ends in May (in the mountains). The snow cover thickness reaches 20-30 cm within the plains and plateaus, about 1.5-2 m in the mountains. In harsh winters the snow reaches several meters as was the case in the winter of 1953-1954 and in 2012.

An opposite phenomenon to the rainfall is the evaporation and evapotranspiration, which in Danube basin has significant values. Thus, in the lowlands from upper Danube basin, evapotranspiration varies between 450 and 650 mm/year. At higher elevation, the evapotranspiration decreases up to 100 mm/year. The evapotranspiration shows similar characteristics in the middle part of Danube basin, where it is approximately 500 mm/year. In the lower Danube basin, evapotranspiration decreases, reaching an average value of about 400 mm / year close to the Danube mouths zone.

2.2. Hydrographic network of the Danube River basin

The hydrographic network of the Danube basin is relatively dense consisting of over 120 tributaries unevenly distributed in the three sections of the basin (Stănescu, V., 1967; Stančik *et al.* 1988).

In the upper basin, with an area of 131338 km^2, the main tributaries of the Danube are Iller, Lech, Altmühl, Naaba, Regen, Isar, Inn, Traun, Enns, Kamp and Czech Morava, which springs from the mountains with permanent snow. In the middle section of the river basin, with an area of 444894 km^2, the main tributary rivers are Raab, Vah, Hron, Drava, Sava, Tisa, Veliko Morava and others smaller. In the lower basin, with an area of 240796 km^2, the Danube receives the following tributaries: Timok, Jiu, Iskar, Olt, Yantra, Vedea, Arges, Ialomita, Siret, Prut and others of less importance. Danube tributaries have a common characteristic namely: fast currents in the mountains area, then their character gets slower on their course through the hills and plains areas, forming the riverbeds with wide alluvial plains, floodable at high waters.

The hydrographic network of the Danube basin includes also the network of canals that has been built over time. Thus, for linking different hydrographic basins of Europe and creating important inland waterways, between 1836 and 1898 has been built on West Germany territory the first version of the Rhine-Main-Danube canal, about 178 km long and 1.5 m deep. At the end of the twentieth century this canal was upgraded and extended for inland water transport with large ships. Other canals have been built in the past on the Danube River on the former secondary branches in the Pannonian Plain and the western part of Romania.

In Romania, in the second half of the nineteenth century, the Sulina distributary of the Danube Delta was transformed into a maritime canal. The length of this canal is 71.7 km, with a depth over 9 m and width of about 130 m. In 1984 came into operation the Danube-Black Sea Canal, which connects the Danube with the Black Sea (from the Cernavoda port on the Danube to the Constanta Sud-Agigea and Midia ports on the Black Sea. Between 1981 and 1992, the St. George distributary was shortened also by 32.6 km (the initial length 108.8 km) through an important cut-off programme that rectified 6 large mender bends.

The Danube hydrographic network includes also natural lakes and backwaters whose surfaces are sometimes important. These lakes can be mountain lakes, lowland and floodplain lakes and, in the lowest section of the river, lagoon-type ones (local name limans). The main lagoon-type lakes in this Danube lower section are: Brates (72 km^2), Kahul (92 km^2), Ialpuk (152 km^2), Kugurlui (71 km^2), Katalpuk (71 km^2) and Kitai (40 km^2), with depths between 1 and 8 m (Almazov A.A.*et al.*, 1963).

A number of reservoirs for complex goals (energy, improving the navigation, water storage and other uses) have been created in the twentieth century across the Danube basin. Thus in the upper basin there are 24 barrage lakes, other lakes have been built in the middle and lower sections of the Danube. The largest barrage lakes are on the lower Danube at the Iron Gates 1 (km 942.8) and Iron Gate 2 (km 863).

The lakes and ponds are relatively few and small in the Danube floodplain and wetlands in the middle and lower sections. The Danube Delta is the only area from the lower Danube section rich in ponds.

3. THE DANUBE VALLEY

The Danube River starts in Germany, on the South-Eastern flank of the Black Forest Mountains, where the rivers Brege (altitude 1000 m and 48.5 km long) and Brigah (altitude 1125 m and 42.6 km long) have their springs. From the confluence point of these two rivers, near the town of Donauessingen (altitude 676 m), the Danube valley stretches from West to East on territories of 10 countries (Germany, Austria, Slovakia, Hungary, Croatia, Serbia, Romania, Bulgaria, Moldova and Ukraine) on about 2875 km until its mouths zones to the Black Sea (Stănescu, V., 1967; Stančik *et al.* 1988).

The Danube upper section

The upper Danube valley stretches from the confluence of Brege and Brigah rivers (km 2857) to Devin (km 1880) on 970 km. The upper drainage basin until Bratislava section at km 1868.8, is of 131,338 km^2. This section of the Danube is typically mountainous with a narrow and winding valley, deeply carved in rocks in which water flows rapidly.

The Danube middle section

The middle section of the Danube extends from Devin (km 1880) to Drobeta-Turnu Severin port (931 km) on about 959 km; the middle Danube catchment basin is of 578,300 km^2. In this section the valley is typically a lowland one, excepting the gorge crossing the Carpathian Mountains (from Bazias km 1 073 to Gura Vaii km 942). At the downstream exit of the gorge, in 1964 – 1971 period, a large dam with locks has been built (at km 942.8) – the so called hydro electro-power and navigation system Iron Gates I (installed power 2 x 1068 MW). The barrage lake extends on about 130 km, untill Belgrade (1172 km), and has a water volume of 2 830 – 1 350 million m^3 (depending of the water level in the dammed lake).

The Danube lower section

The lower section of the Danube stretches downstream Drobeta-Turnu Severin port (931 km) until the Danube Delta apex (Ceatal Ismail 79.64 km). The surface of the lower Danube catchment area is of 807,000 km^2. The valley crosses plain regions, the river channel width ranges between 300 and 1 300 m, with minimum depths of about 1.5 m and wide floodplains and meadows up to 28 km.

The average slope of the free water surface is about 4.5 cm/km and the average current velocity varies between 2 and 5 km/hour. The riverbed is not regularized, except the upstream part at 863 km, where between 1975 and 1984 was built the hydro electro-power and navigation system Iron Gates II, with a barrage lake between km 863 and km 942.8 of 425–600 million m³ water volume.

Downstream The Iron Gates II dam there are many islets and many secondary branches.

The Danube Delta

The Danube Delta starts at the first river bifurcation (the delta apex at Ceatal Ismail 79.64 km), has three main distributaries (Chilia, Sulina and St. George) and covers a total area of about 5 800 Km². The Danube Delta comprises the following hydrographic units situated between the main branches: the Chilia-Sulina Unit situated between the Chilia and Sulina distributaries, the Sulina-St.George Unit, between the branches of Sulina and St. George, and the St. George-Razelm Unit, in the south, from the St. George branch and including the Razelm Lake, Razelm-Sinoe complex lagoon area. Additionally there is the Ialpug-Catlabug-Chitai lakes area northward the Chilia branch on Ukraine territory.

The Danube River mouths zone

The mouths of the Danube distributaries flowing into the Black Sea form a hydrographically distinct "Danube mouths zone unit" (Diaconu, C., Nichiforov, I. D., 1963). The distributaries of the three main branches are the following:

The northern Chilia branch forms a lobate delta at its mouth zone with many distributaries of which the most important are: Belgorodskii, Ancudinov, Poludenai, Prorva, Gneusev, Potapof, Otnojnai, Pescianai, Bystroe, Vostocinai, Tiganskii, Zavodniskii, Curilskii, Old Stambulsky and Musura. Except the mouth of the Prorva branch, that in the period 1958-1991 was dredged and kept as a maritime waterway for vessels of 3.5 – 5 m draughts, the rest of the Chilia secondary delta distributaries mouths were in natural state. Only recently, since 2004, Ukraine has begun the works to open a new maritime waterway on Bystroe distributary. This new waterway affected in some way the hydrological regime of the secondary delta Chilia, as the Bastroe distributary became the most active of the Chilia delta distributaries network approaching the hydrological parameters of Sulina branch.

The Sulina distributary mouth zone: the Sulina distributary was transformed into a maritime waterway by a large meander belts cut-off programme achieved by the European Danube Commission at the end of the 19th century. The maritime navigation depths at the Sulina mouth were maintained in natural conditions between 1861 and 1892, then, between 1893 and 1923, the navigation depths of 24 feet were maintained by dredging, and since 1924 for maintaining the maritime navigation depths, to the dredging protection dykes that extend into the sea have been added. These dykes have been prolonged yearly reaching the length of 7.8 km in 1978, when the extension was stoped.

At the St. George mouth zone there is a small secondary delta with three distributaries: the main one – the St. George *senso stricto* or Kedriles one, the Seredny, now-a-days almost clogged and the Turetsky distributary flowing into a bay behind a lateral spit Sakhalin. The mouths of these distributaries are in natural state and the water depth at the main branch mouth bar is of about 2.2 m.

3.1. Characteristics of the hydrological regime of the lower Danube

For characterizing the hydrological regime of the Danube River and the Danube Delta, we shall present below the water flow, the water levels and the sediment flow.

3.1.1. Water flow

The water flow is characterized by the water discharge and the water levels.

Water discharge. Trends

The characteristics of the water discharge and the water levels are presented taking into consideration a long-time data series, starting in 1840 until 2012 (Bondar, C., 1970.; Bondar, C., Iordache, G., 2012). The table 1 shows the parameters of the multiannual characteristics of the Danube water discharge for the mentioned period.

The Fig. 3 illustrates the trend of variation in time of the annual average water discharge and of the multiannual average values of water discharge at Orsova (Series 1 and, respectively Series 2) and at Ceatal Ismail (Series 3 and respectively Series 4) between 1840 and 2013. One can observe that in a period of about 75 years, the multiannual average water discharge had stabilized at values of about 5 550 m³/s, at Orsova, and respectively about 6 500 m³/s at Ceatal Ismail.

Taking into consideration the data from Table 1, the Fig. 4 presents the variation of multiannual average water discharge along the Romanian Danube section.

The Danube River on its lower section, between Orsova and the Danube Delta apex, at Ceatal Ismail, receives from the tributaries a water discharge of about 890 m³/s. This discharge added to the discharge coming from the upstream sections of the river give at the Danube Delta apex a multiannual average water discharge of about 6 450 m³/s with a daily maximum of 21,867 m³/s in July 2, 1897 and a daily minimum of 1350 m³/s, produced in October 31, 1921 (Diaconu, C., Nichiforov, I. D., 1963). Figure 2 presents the updated scheme of growth of multiannual average water discharge along the Danube River resulted from the tributaries' additional water supply.

At the Danube mouths zone at the Black Sea, the multiannual average discharge of water is 5 990 m³/s. The difference between the two values at the delta apex and at the mouth zone is 460 m³/s and is due to the water inflow from the river to the Danube Delta interdistributary depressions, evaporation losses and other smaller out-lets discharging the water directly to the Black Sea.

Table 1. The multiannual parameters of the Danube water discharge between 1840 and 2012 at different hydrometrical gauges along the Romanian section of the river.

No	Hydrometrical section	Location (km)	Maximum discharge				Average discharge mc/s	Minimum discharge			
			Qmax mc/s	Year	Month	Day		Qmin mc/s	Year	Month	Day
1	Bazias	1072.4	15800	2006	4	16	5551	1015	1901	1	13
2	Moldova V.	1048.7	15880	2006	4	16	5554	1002	1858	2	23
3	Drencova	1016.4	15931	2006	4	16	5554	1003	1901	1	13
4	Svinita	995	15877	2006	4	16	5557	1060	1985	10	6
5	Orsova	957.4	15947	2006	4	16	5574	1060	1985	10	6
6	Drobeta T.S.	932	15758	2006	4	16	5585	1103	1985	10	6
7	Gruia	856.5	15758	2006	4	16	5592	1103	1985	10	6
8	Calafat	786.9	15916	2006	4	16	5636	1009	1858	2	3
9	Bechet	678.7	16169	2006	4	16	5724	1019	1864	2	23
10	Corabia	624.2	16185	2006	4	16	5731	1022	1864	1	13
11	Turnu Mag.	596.3	16885	2006	4	16	5932	1152	1864	1	13
12	Zimnicea	553.2	16919	2006	4	16	5991	1010	1858	1	15
13	Giurgiu	493.1	17000	2006	4	16	6011	1030	1858	1	15
14	Oltenita	429.8	17303	2006	4	16	6077	1060	1858	1	15
15	Chiciu - Calarasi	379.6	17303	2006	4	16	6107	1041	1920	12	8
16	Calarasi - Borcea branch	94.5	3203	1845	5	2	946	132	1985	10	6
17	Izvoarele	348.6	15751	2006	4	16	5148	839	1858	1	15
18	Bala branch	8	9516	2006	4	16	2462	302	1858	2	26
19	Vladeni - Borcea branch	1	11120	2006	4	16	3431	538	1858	2	26
20	Harsova	248	7846	1845	8	2	2715	460	1985	10	6
21	Vadu Oii	238	17372	2006	4	16	6130	1100	1864	2	1
22	Balaia - Valciu branch	1	3739	2006	4	16	1324	237	1864	2	1
23	Gropeni - Cremenea branch	197.5	11740	2006	4	16	4164	745	1864	2	1
24	Smardan - Macin branch	4.5	1893	2006	4	16	665	118	1864	2	1
25	Braila	167	17525	2006	1	6	6149	1100	1864	2	1
26	Grindu	141.3	21347	1897	7	2	6410	1446	1855	12	30
27	Isaccea	100.2	21864	1897	7	2	6516	1303	1855	12	30
28	Ceatal Ismail Danube	80.5	21867	1897	7	2	6516	1303	1855	12	30

The water discharge shows an increasing trend in time: the annual maximum water discharge increases in time with about 4.5 m^3/s/year, the annual average discharge with about 4 m^3/s/year and the annual minimum discharge with about 3.1 m^3/s/year.

Under the influence of the variation in time of the climatic factors that generate the water flow (atmospheric circulation, precipitations, temperature, etc.) there is a corresponding variation of the water discharge, on large time intervals as well as in each year which close a short climatic cycle. Thus, on the lower Danube section, once every 10 years, may occur increases or decreases by 25% in annual water discharge, compared to the multiannual average. For the same Danube section once in 100 years an increase of water discharge regime by over 52% or a decrease by 36% compared to the multiannual average value may occur.

In the annual hydrological cycles the water flow is unevenly distributed in time, the monthly average water discharge can vary compared to the multiannual average by about +38% in May-June and -36% respectively in September. In the years with very high or very low waters, the deviations from the multiannual long-term average of the daily

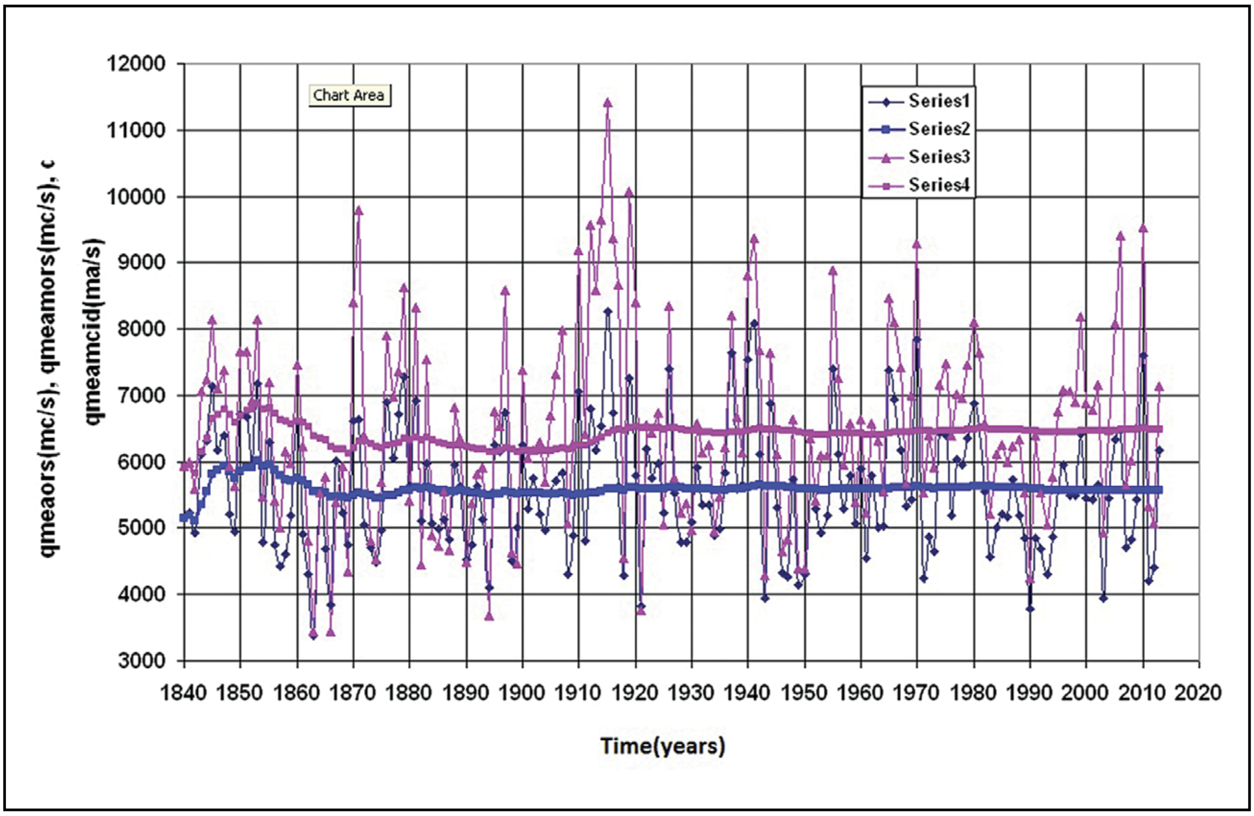

Fig. 3. The variation in time of the Danube annual average water discharge (qmeaors) and of the multiannual average water discharge (qmeamors) at Orsova (Series 1 and respectively 2) and at Ceatal Ismail (Series 3 and respectively 4) between 1840 and 2013

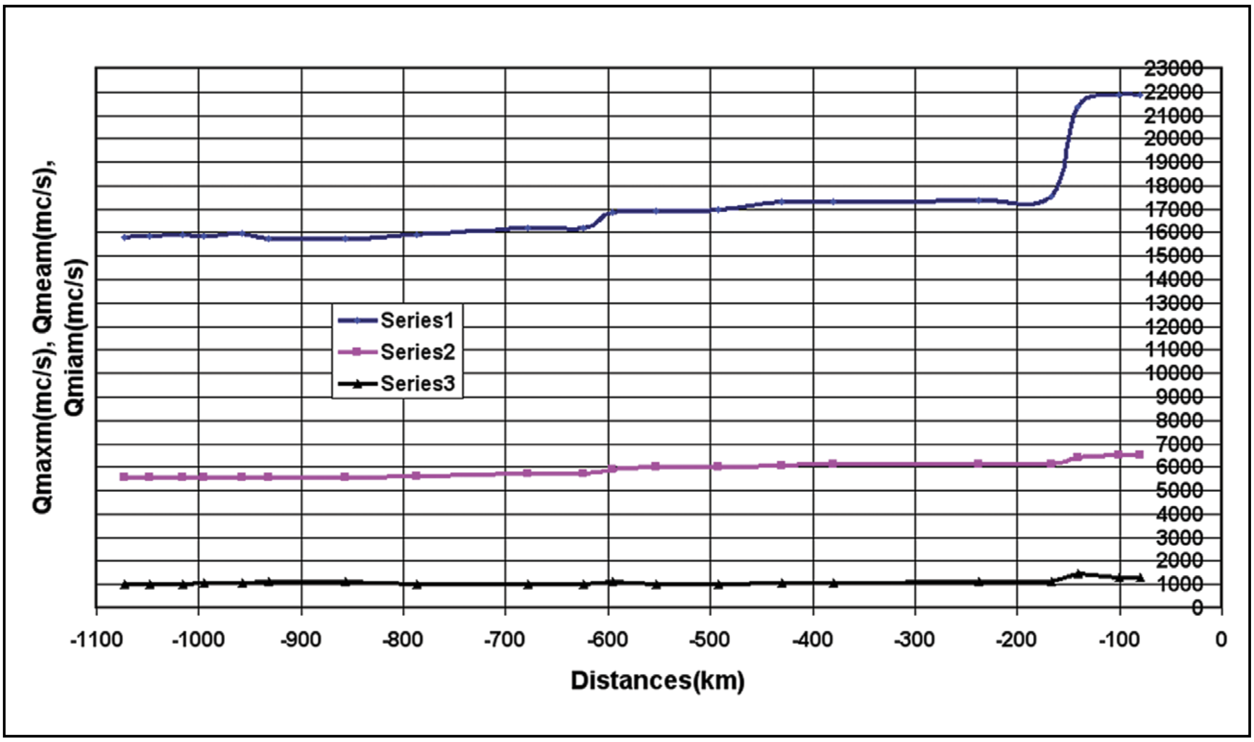

Fig. 4. The variation of characteristic multiannual water discharge: maximum-Qmaxm (Series 1), average-Qmeam (Series 2) and minimum-Qmiam (Series 3) along the Romanian Danube section for the period 1840-2013

water discharge, reach relative values of 137% for maximum discharges and -75% respectively for minimum water discharges.

At the Danube Delta apex, at Ceatal Ismail, in 1987, the distribution of the water discharge among the main delta distributaries was: 57% on the Chilia one and 43% on Tulcea branch and, at the bifurcation of lather, 19% on Sulina distributary and 24% on Saint George branch. In 2010, the distribution of annual average water discharge of Danube on Delta branches was strongly modified: the Chilia distributary - 49%, the Tulcea branch - 51% (20% on Sulina branch and 31% on Saint George branch). The redistribution process of the water discharge of the Danube among the delta main branches continues in detriment of Chilia branch (Bondar, C., Iordache, G., 2012).

3.1.2. Water Levels. Trends

Systematic measurements of the Danube River water levels began in the nineteenth century, first in Linz in 1821, then in 1823 in Bratislava and Budapest, in Ingolstadt in 1827, at Orsova in 1839 at Bezdan in 1856, at Sulina in 1857, in Tulcea in 1858, the Ruse in 1898 and in 1920 at Ismail (Bondar, C., Iordache, G., 2012; Marinov, I., 1977).

The recorded annual amplitude variation of levels in the upper basin of the Danube reaches values up to 14 m. The highest levels occur in the warm season (March-June) and the lowest in the cold season, mainly in the automn (September-October).

The Table 2 shows the multiannual characteristic parameters of the Danube water levels for the period 1840-2013.

The water levels regime is closely linked to the water discharge regime. This is shown in the Figure 5 which expresses the average variation of water levels for the years 1980-2010 along the Romanian Danube section corresponding to water discharges varying between 0 and 16,000 m^3/ s.

The data from Table 2 have been used for analyzing the Danube water levels variation in time. For this purpose, similarly to the water discharge, graphs of variation in time of annual average levels and of multiannual average levels at Orsova and Tulcea between 1840 and 2011 have been drawn (Figure 6). As in the case of water discharge, the levels show

Table 2. Multiannual characteristic parameters of water levels on the Danube, between 1840 and 2011

No.	Hydrometric station	Location (km)	Maximum level				Average level (cm)	Minimum level			
			Hmax (cm)	Year	Month	Day		Hmin (cm)	Year	Month	Day
1	Bazias	1072.5	820	2006	4	14	323	-117	1858	1	16
2	Moldova V.	1048.9	880	2004	11	14	343	-127	1866	1	11
3	Drencova	1016.2	1034	2004	8	3	372	-100	1866	1	11
4	Svinita	994.8	2038	1995	8	21	646	-7	1866	1	11
5	Orsova	953.3	2725	1996	12	24	799	-58	1866	1	11
6	Drobeta T.S.	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 Mag.	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	Oltenita	429.7	886	1895	4	18	285	-135	1866	1	14
15	Calarasi-Borcea branch	94.5	785	1895	4	18	246	-150	1866	1	15
16	Cernavoda	298.3	757	1895	4	18	244	-237	2003	9	10
17	Harsova	252	764	2006	4	25	286	-136	1858	3	12
20	Braila	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	71.6	458	1897	7	2	165	-45	1921	10	11
23	Sulina	0.0	137	2006	5	2	45	-36	1921	1	25

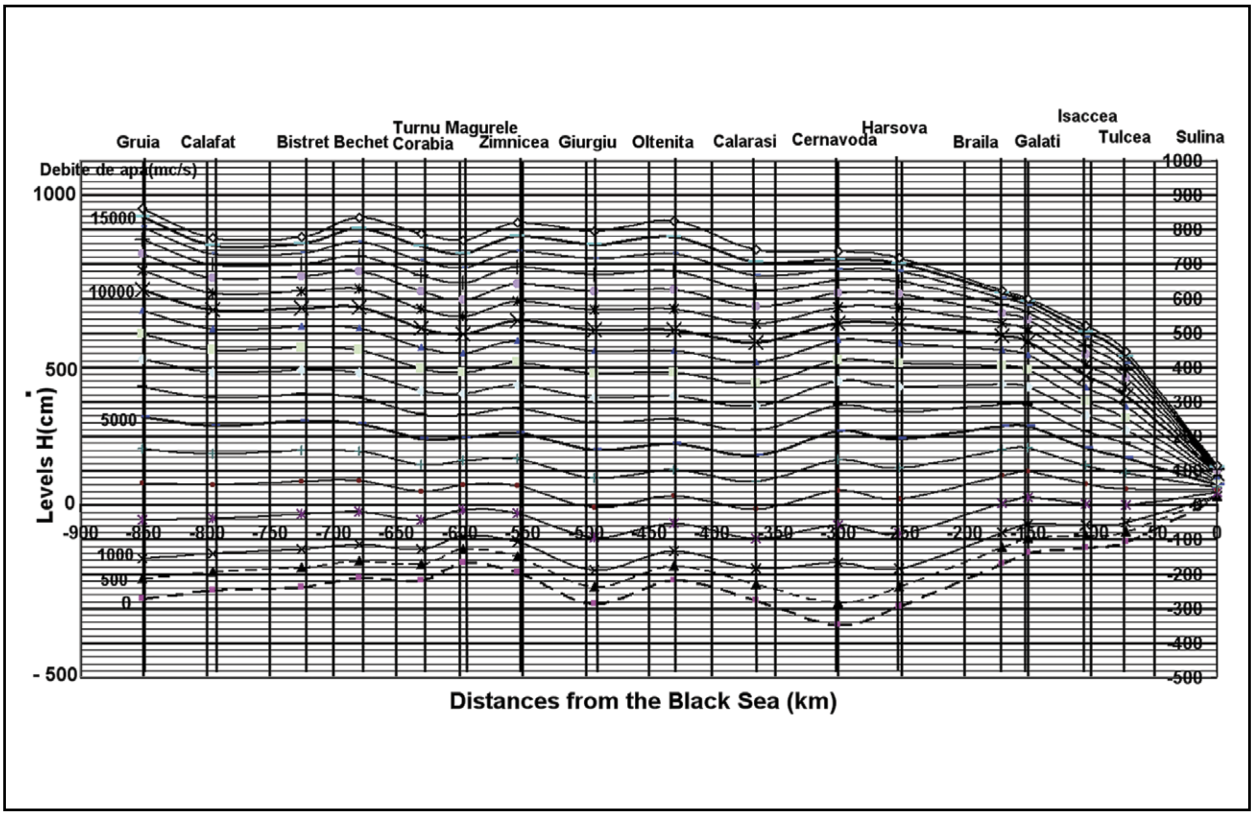

Fig. 5. The water levels variation along the Romanian Danube section corresponding to water discharges between 0 and 16,000 m^3/s (average values for the period 1980-2010)

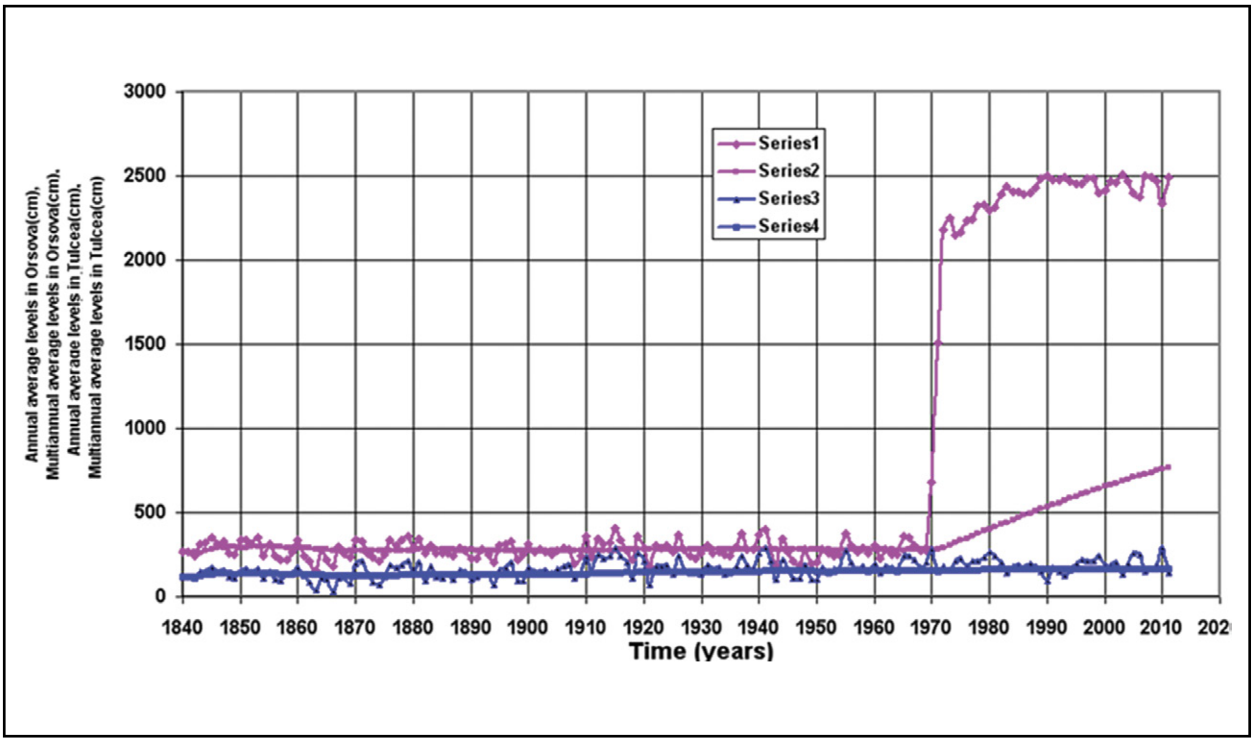

Fig. 6. Variation in time of the annual average (1.1) and multiannual average of the Danube water levels (1.2) at Orsova (Series 1 and respectively Series 2) and Tulcea (Series 3 and respectively Series 4) between 1840 and 2011

the same feature of uniform variation in time, except Orsova hydrometric station where due to the Danube daming at Iron Gate I (km 942.8), the levels have increased considerably after 1973 when the barrage lake was filled.

Downstream the Iron Gate II dam, when the water levels exceed by 40% the average levels, the river banks start to be flooded and the water overflow the lateral levees entering the flood plain.

Danube flood duration is variable, sometimes extending on several months, as was the case in the years 1897, 1940, 1970, 1980, 2006 and 2010. Historical data as well as those resulting from the recent measurement attest the occurrence of the Danube high floods in 1838, 1890, 1897, 1899, 1924, 1926, 1937, 1940, 1942, 1944, 1954, 1956, 1970, 1980, 2006 and 2010, which caused in many cases important damages and even human lifes loss (Bondar, C., 1972; Bondar, C., Iordache, G., 2012).

To privent these disasters, the riparian states have built along the Danube embankments for protecting settlements, economic activities and vast agricultural land from flooding. The limitation of high waters by dykes led to changes in the water levels regime, in the time of occurrence of high levels and also in their amplitude (Rainov, S., *et al.*, 1975).

Statistical data of annual average water levels for the period 1840-2010 at Calarasi, Galati and Tulcea show that there is a positive trend with gradients of 0.11 cm/year, 0.176 cm/year and 0.109 cm/year respectively, while at Cernavoda the trend is negative with a gradient of -0.368 cm/year.

3.1.3. Sediment discharge

Nature and grain size of sediment transported by the river. Trends

The sediment particles are composed mainly of silica with the apparent density of about 1.65 kg/dm^3. The grain size of sediment is diverse, from boulders to clays. In the lower section of the Danube, the granulometric composition of sediments consists from clays to coarse sand (locally with small gravels). Depending of particles size two categories can be distinguished: particles with laminar behaviour in the water flow and ones with turbulent behaviour.

The granulometric fractions consisting of particles smaller than 0.063 mm have a laminar behavior at the fall into the water column at rest and are transported exclusively in suspension under the influence of current turbulence. The fractions consisting of particles of size larger than 0.063 mm have a turbulent behavior at the fall in a water column at rest and are carried by the water current as bedload that moves by dragging, rolling and saltation and partly in suspension. Dragging on the bottom of riverbed or lifting in suspension of fractions with sizes larger than 0.063 mm occurs when the water current speed exceeds a certain limit, being called the critical velocity of entrainment of particulates.

Table 3 shows the average values for different time periods of the Median diameter d50% of the suspended load (d50s) and of the bedload (d50g), together with mean values of water discharge, Qr for suspended load and Qg for bedload, as well as average values of the discharge of suspended load - Rs and of the bedload Rg (Bondar, C., 1975; Bondar, C., State, I., 1977; Bondar, C., Harabagiu, E., 1984).

Table 3 shows the following characteristics of sediment particle size:

- The grain size of suspended load has the median diameter d50% of approximately 0.023 mm;
- The grain size of coarse sediment (bed-load and suspended load) varies between 1 and 0.063 mm, the median diameter d50% being of about 0.185 mm at Braila and of about 0.152 mm at Ceatal Ismail.

The granulometric composition of the bottom sediment along the Romanian Danube section, at the critical shoals for navigation is relatively homogeneous with a slight trend of coarsening over time.

Hydraulic criterion of suspended sediment lifting

The bottom sediments are entrained by the water current through hydrodynamic pressure and friction. Another interaction between the water current and the grains of sediment entrained by the stream is determined by the equilibrium between vertical components of pulsatory velocity of the water current and the falling velocity in water of these grains.

The hydrological measurements on the Danube have shown that the average value of vertical component of pulsatory velocity V_p (cm/s) is expressed by the empirical function (1) (Bondar, C., 1975; Bondar, C., Harabagiu, E., 1984).

$$V_p = 6.76 \times q_m / h_m^{0.961} \qquad (1)$$

where, q_m (mp/s) is the average value of specific water discharge

On the other hand, the average falling velocity in water (w) of the sediment grains, called sinking velocity is defined by functions dependent on grain size (d) and water temperature (θ) [6]. For grains with sizes (d) between 0.1 mm and 0.6 mm, the sinking velocity w (cm/s) is expressed by Zegjda formula.

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

where, g is the gravitational acceleration, and ζ is the coefficient of kinematic viscosity, dependent on the water temperature (θ) by the formula (14):

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

ρs/ρ expresses the ratio between the grains density (ρs) and the water density (ρ) equal to about 1.65.

For granules (d) of less than 0.06 mm the sinking velocity has the expression (4).

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

Table 3. Average sizes of the fine suspended load and of the bedload in hydrometric sections on the Danube, corresponding to d50% of granulometric composition for the years with annual measurements.

Hydrometrical sections	Years	Location	Qr	Rs	d50s	Qg	Rg	d50g
	Units	Km	m³/s	kg/s	mm	m³/s	kg/s	mm
Bazias	1971-1998	1072.4	5656	516	0.022	5656	0.70	0.285
Moldova V	1973-1998	1048.7	5562	356	0.022	5414	0.510	0.281
Drencova	1971-1997	1016.4	5559	341	0.022	5511	0.433	0.282
Svinita	1972-1998	995	5414	402	0.022	5414	0.991	0.020
Orsova	1971-1998	957.4	5511	464	0.022	5511	0.222	0.107
Drobeta T. S.	1969-1997	632	6051	309	0.023	6051	1.25	0.453
Gruia	1969-1995	856.5	5673	354	0.024	5673	9.37	0.462
Calafat	1969-1995	786.9	5749	399	0.025	5656	1.04	0.428
Bechet	1969-1995	678.7	6202	522	0.025	6156	11.69	0.297
Turnu Magurele	1970-1985	596.3	6503	1474	0.026	6333	14.96	0.302
Zimnicea	1972-1995	553.2	6025	999	0.027	6025	14.57	0.243
Giurgiu	1970-1995	493.1	6198	991	0.023	6190	16.12	0.247
Oltenita	1969-1985	429.8	6641	1368	0.025	6641	13.17	0.294
Chiciu Calarasi	1970-1985	379.6	6713	1434	0.024	6713	14.83	0.261
Vadu Oii	1969-1995	238	6738	1202	0.020	6717	5.89	0.245
Braila	1971-1995	167	6776	1134	0.021	6754	4.03	0.185
Grindu	1969-1985	141.3	7428	1703	0.022	7428	7.60	0.181
Ceatal Ismail	1969-1995	80.5	7123.741	1534.169	0.020	7245	3.50	0.155

Qr, Qg, Rs, Rg from table 3, have the following meanings:

- Qr, average water discharge at the measurements of the total (fine and coarse) suspended sediment;
- Qg, average water discharge at the measurements of the bedload;
- Rs, average discharge of suspended load at the date of suspended sediment measurements;
- Rg, average discharge of bed-load at the date of bed-load measurements.

Measurements were performed annually regularly.

When Vp ≥ w, the grains are dragged or turbulently suspended from the bottom by the water current.

Sediment transport hydraulics on the Romanian sector of Danube

The transport of coarse sediment on the Danube starts when the current velocity exceeds a certain critical value. There is a critical velocity for the bedload and another critical velocity for the suspended coarse sediment. Thus, the coarse alluvial transport is dependent of the water current energy.

Current assessment of the total sediment transport on the Danube

Sediment transport is quantified by measurements and calculation of the sediment discharge. These measurements consist of determinig the water discharge and the concentrations of suspended sediment. For the bedload specific measurements have to be done in cross-sections called hydrometric sections. At the same time samples of water, suspended sediments and bedload are collected for grain size analyses.

Systematic measurements of water and sediment discharge on the Danube are made by Romanian Waters National Administration that stores these data in the hydrological database of the National Institute of Hydrology and Water Management. This database was used for determining some characteristics of the Danube suspended load and bedload discharges.

The former Institute of Hydraulic Studies and Research in the coordination of the State Waters Committee, has published two hydrological monographs: one about the Danube Delta (Almazov *et al.*, 1963) in Romanian and Russian languages and the other on the Danube River between Bazias and the Danube Delta apex (Stănescu, V., 1967). Under the auspices of the UNESCO International Hydrological Programme (PHI), in the framework of a regional cooperation of the Danube countries (1975 – 1985), a Monograph of the Danube Basin was published in English, German, French and Russian languages (Stančik *et al.* 1988).

The Hydrological Monograph of the Danube Delta (1963) presents the following data regarding the water and sediment discharges at the entrance in the Danube Delta:

- The multiannual average water discharge for the period 1921-1960 was 6 290 m^3/s, with extreme values of 14,050 m^3/s for maximum water discharge and 1 350 m^3/s for minimum one.
- The multiannual average suspended sediment discharge for the period 1921-1960 was 2 140 kg/s, with 5 150 kg/s as the maximum discharge (in 1941) and 628 kg/s, the minimum one (in 1921).
- The bedload discharge represented no more than 5-6% from the suspended load discharge, consisting of particles with sizes between 0.08 and 0.6 mm.

The Hydrological Monograph of the Danube between Bazias and the Danube Delta apex (1967), shows also data of water and sediment discharge for the period 1921-1962 (meaning that the data refer to the period before damming), in three hydrometric sections Orsova, Oltenita and the Delta apex:

- The multiannual average water discharge at Orsova was 5 950 m^3/s, at Oltenita, 6 000 m^3/s and at the entrance in the Danube Delta, 6 220 m^3/s.
- The multiannual average suspended sediment discharge at Orsova was 1 110 kg/s, at Oltenita, 1 765 kg/s, at Braila, 1 800 kg/s and at the Danube Delta apex, 2 110 kg/s.
- The bedload discharge was of about 1.5% from the suspended sediment discharge.
- There is no information about the sediment grain size.

In the Monograph of the Danube Basin, data on water and sediment discharges on the Lower Danube are presented for four hydrometric sections in the period 1931 – 1970 as follows:

- The water discharge at Orsova (km 954) was 5 699 m^3/s, at Zimnicea (km 553.2), 6 150 m^3/s, at Vadu Oii (km 238), 6 216 m^3/s and at the entrance of the Danube Delta Km (80.5), 6 550 m^3/s.
- The sediment discharge is given for the years 1930-1970, at multiannual average values of 816 kg/s at Orsova (km 954), 1 102 kg/s at Zimnicea (km 553.2), 1 356 kg/s at Vadu Oii (km 238) and 1 457 kg/s at the Delta Danube apex.
- The average grain size of the suspended sediment load was of 0.0251 mm at Turnu Severin (km 931) and 0.0212 mm at the Danube Delta apex.
- For the same period the multiannual average bedload discharge was of 2.55 kg/s at Orsova (km 954), 14.9 kg/s at Zimnicea (km 553.2), 4.32 kg/s at Vadu Oii (km 238) and 2.21 kg/s at the Danube Delta apex. For the bedload sediment, the average grain size was 0.444 mm at Turnu Severin (km 931) and 0.145 mm at the entrance in the Danube Delta.

Other information about the Danube transport of coarse and fine sediment has been partially published but without analysing the flow regime. This paper will present below the needed analysis. For this purpose there were taken into consideration data about total sediment discharge (fine and coarse) on Romanian section of the Danube River from 1840 until 2012. After processing these data the table 4 presents the following characteristic values for the mentioned period: the multiannual averages of water discharge, the annual maximum values, multiannual averages and annual minimum values for the total sediment discharge in different hydrometrical cross-sections along the Romanian Danube River.

3.1.4. The state of knowledge of the coarse grained sediment transport on the Danube

According to national rules in force, the sediment discharge measurements on the Danube refer to suspended- and bed-loads, without differentiating the fine-grained and coarse fractions. At the request of the National Navigation Authority the National Institute of Meteorology and Hydrology (NIMH) has organized special campaigns of water and sediment discharges measurements where the concentrations of suspensions were determined differentiated on fine and coarse fractions.

The campaigns of water and sediment discharges differentiated on fine and coarse fractions on the entire Romanian section of the Danube started in 1970 (at high waters) using the National Navigation Authority vessel and continued until 1975 when NIMH was equipped with a research vessel for complex hydrological measurements on the Danube (R/V Lipova). Using this vessel NIMH conducted biannual campaignes (in spring at high waters and in autumn at low waters) on the Romanian Danube, including the distributaries of the Danube Delta (in 34 hydrometric sections with about 1070 measurement verticals) until 1997. In 1974 when the hydrological stations on the Danube, have been passed under the NIMH administration, they were equipped with bathometers for measuring the bedload and with mini-labs for determining the grain-size of the suspended- and bed-loads. The Danube sediment transport monitoring organised in such a way continued until 1990 when the hydrological stations passed to another administration (Bondar, C., 1975; Bondar, C., State, I., 1977).

Between 2002 and 2006, the National Institute of Hydrology and Water Management had performed bedload measurements in all the hydrological sections of the Danube hydrological stations network where water and sediment discharges were measured.

The data of water and sediment discharges along the Romanian Danube in 1970 (at high waters) have been used and processed for establishing the relationship between the suspended- and bed-loads and the water discharge and the average river depth.

Table 4. The characteristic values for the period 1840-2012 of the multiannual averages of water discharge (Qmeam), and the annual maximum values (Rmaa), the multiannual averages (Rmeam) and annual minimum values (Rmia) for the total sediment discharge in different hydrometrical cross-sections along the Romanian Danube River.

No.	Hydrometric sections	Location Km	Qmeam mc/s	Rmaa kg/s	Rmeam Kg/s	Rmia Kg/s
1	Bazias	1072.4	5558	2022	829	61
2	Moldova V	1048.7	5552	2020	837	57
3	Drencova	1016.4	5563	2023	832	14
4	Svinita	995	5570	2025	825	54
5	Orsova	957.4	5568	2045	822	53
6	Drobeta T S	632	5587	2165	845	54
7	Gruia	856.5	5656	2661	858	47
8	Calafat	786.9	5655	2978	1080	57
9	Bechet	678.7	5857	3079	1152	157
10	Turnu Mag.	596.3	5920	3225	1248	126
11	Zimnicea	553.2	5976	2631	1102	150
12	Giurgiu	493.1	6007	2989	1211	141
13	Oltenita	429.8	6079	2962	1291	170
14	Chiciu Calarasi	379.6	6096	3624	1379	172
15	Vadu Oii	238	6155	4167	1425	187
16	Braila	167	6181	4062	1430	142
17	Grindu	141.3	5405	4076	1659	209
18	Isaccea	100.2	6509	4489	1645	224
19	Ceatal Ismail	80.5	6495	4470	1599	200

Where:

- Qmeam - multiannual average water discharge;
- Rmaa - annual suspended sediment maximum discharge;
- Rmeam - multiannual average of sediment discharge;
- Rmia - annual suspended sediment minimum discharge.

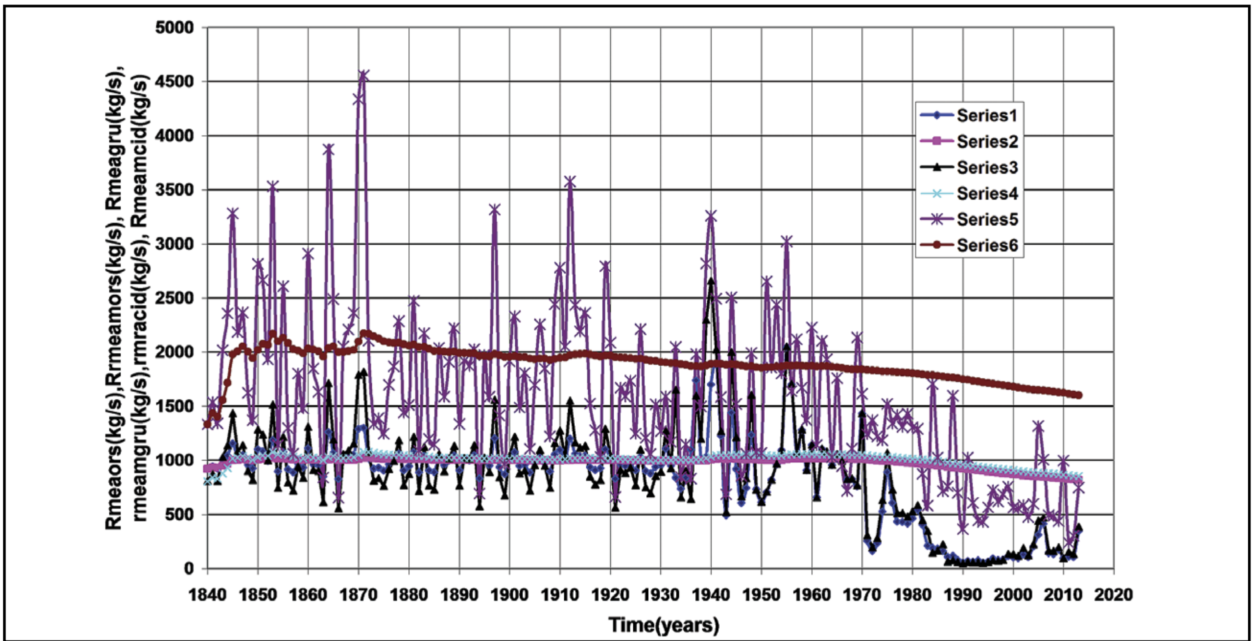

Fig. 7. Graphs of variation in time of the total discharge of sediment (fine and coarse) annual average Rmea(1, 3, 5) and multiannual average Rmeam(2, 4, 6) of the Danube, in hydrometrical sections Bazias (1-2) km 954, Gruia (3-4) km 858 and Ceatal Ismail (5-6) km 80.5 between the years 1840 and 2012.

For characterising the water discharge the specific average water discharge was choosen:

$$q = Q/B;$$

where, Q = total water discharge in the considered section;
B = riverbed width; measurement unit m^2/s;

The specific average water discharge shows the concentration of the water current energy per unit of the riverbed width, beeng also an indicator of water current turbulence. For the same total water discharge in the riverbed, specific water discharge is in an inverse relationship with the riverbed width, consequently when the riverbed is wide, the specific water discharge is lower, compared to the narrow riverbed sections, where the specific water discharge is higher. There is a direct relationship between the multiannual average riverbed depth and the multiannual average specific water discharge. The data show that multiannual average depths in riverbeds and to the multiannual average specific water discharge are interdependent. Also, the measurements showed that for the same specific water discharge, the transport of coarse sediment is dependent on the average depth of the riverbed because the velocity and the enrgy of the water current are dependent on the depth of the riverbed.

The specific coarse sediment discharges averaged for a section and the specific water discharge averaged on the section, were plotted function of the average riverbed depth for the data of 1970 in all the hydrometrical stations along the Romanian Danube. In the Fig. 8 are presented correlation charts for the bedload the in the Fig. 9 for the suspended load.

Partial results of processing the data related to the sediment discharge measurements, differentiated on fine and coarse sediment, made in the past, have been already published (Bondar, C., 1972; Bondar, C., Harabagiu, E., 1984).

For further processing the data from the 1070 measurements made between 1971 and 1997 in 34 hydrometrical sections have been added and the methodology of data processing improved. The empirical functions for the sediment transport on the Danube River have been established by groupping the data regarding the water discharge and the coarse sediment discharge in 7 intervals of average depths (hm), between 5 and 22 m.

The parameters processed from the Table 5 allowed the determination of the empirical functions depending of the average depths of the hydrometric cross-sections where the measurements were performed.

The empirical functions for the parameters of the coarse sediment transport in suspension on the Danube River are:

$qcrgs = 0.517 \times hm^{1.147}$	r = 0.998
$ags = 5.615 \times \exp(-0.0259 \times hm)$	r = 0.979
$bgs = 4.281 \times hm^{0.857}$	r = 0.996

where, ags and bgs are the empirical function parameters of specific coarse sediment transport in suspension, expressed by the function (6), and qcrgs is specific critical water discharge of coarse sediment transport in suspension.

The parameters processed from the Table 6 allowed the determination of the empirical functions depending of the average depths of the hydrometric cross-sections where the measurements were performed.

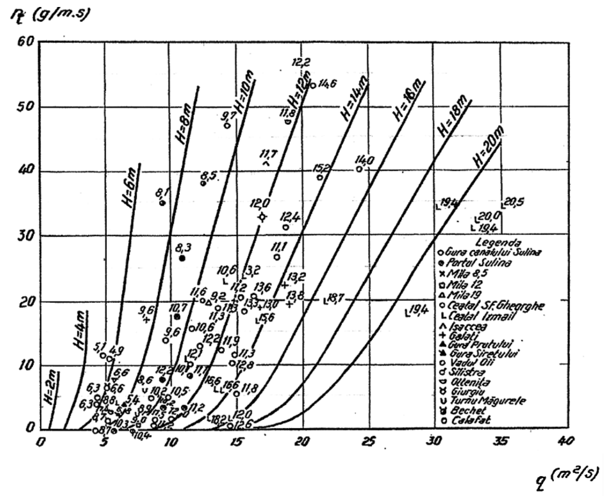

Fig. 8. Correlation between the specific discharge of bedload (rt) and the average specific water discharge (q) in a cross-section, depending on the average riverbed depths, on the Danube River in 1970 (at high waters)

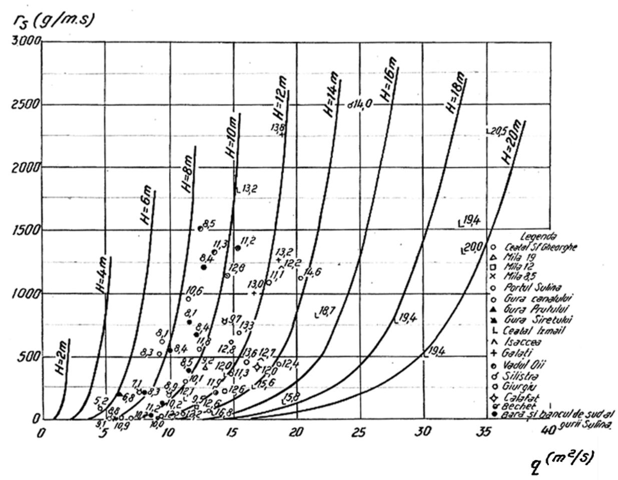

Fig. 9. Correlation between the specific discharge of coarse-grained sediment in suspension (rs) and the average specific water discharge (q) on a cross-section, depending on the average riverbed depths, on the Danube River in 1970 (at high waters)

Table 5. Synthetic data regarding the specific average discharge of coarse sediment in suspension gs (g/cm) measured by NIMH in the hydrometrical cross-sections on the Danube River between 1969 and 1998

gs(g/mc)	Depths hm(m)						
qm(mp/s)	5.87	8.03	9.85	11.99	13.74	15.86	18.8
3.61	0						
5.41		0					
7.05			0				
9.09				0			
10.84					0		
13.05						0	
16.25							9
5	3						
6	10						
6.5							
7							
10	30	20	11				
12		30	20	14			
15		44	33.3	25	17		
20			55	45	39	30	18
25					55	48	36
30						62	50
35							75
The average values of empirical functions parameters of coarse sediment transport in suspension on the Danube River							
Hm(m)	qcrgs(mp/s)			hm(m)	ags	bgs	bgs/ags
5.87	3.95			5.87	4.88	19.29	3.95
8.03	5.49			8.03	4.59	25.21	5.49
9.85	7.24			9.85	4.29	31.08	7.24
11.99	8.87			11.99	4.07	36.10	8.87
13.74	10.66			13.74	3.93	41.91	10.66
15.86	12.51			15.86	3.68	46.02	12.51
18.8	14.58			18.8	3.51	51.13	14.58

Table 6. Synthetic data regarding specific average discharge of the coarse bedload gt (g/m/s) on the Danube River measured by NIMH between 1969 and 1998

gt(g/m/s)	Depths hm(m)						
qm(mp/s)	5.87	8.03	9.85	11.99	13.74	15.86	18.8
1.87	0						
2.79		0					
3.63			0				
4.66				0			
5.55					0		
6.67						0	
8.29							0
5	10						
7	20	14	10				
10	30	22	20	13			
15		40	30	25	19	13	
17			41	32	23	17	13
19				35	28	20	14
25					40	30	20
35							35
The average values of empirical functions parameters for the coarse bedload transport on the Danube							
gt(g/m/s)	qcrgt(mp/s)			hm(m)	agt	bgt	bgt/agt
5.87	1.98			5.87	3.764	7.464	1.98
8.03	2.84			8.03	3.245	9.222	2.84
9.85	3.55			9.85	2.896	10.280	3.55
11.99	4.71			11.99	2.492	11.730	4.71
13.74	5.64			13.74	2.062	11.630	5.64
15.86	6.77			15.86	1.640	11.110	6.77
18.8	7.99			18.8	1.275	10.190	7.99

Table 7. Number of the bedload and suspended loads measurements at different depth intervals

Depths interval (meters)	Average depth (meters)	Number of bedload measurements	Number of coarse sediments in suspension measurements
5-6	5.87	19	21
7-9	8.03	42	48
9-11	9.85	53	58
11-13	11.99	30	36
13-15	13.74	16	31
15-17	15.86	13	9
17-22	18.8	22	17

The empirical functions for the parameters of the coarse bedload transport on the Danube River are:

$qcrgt = 0.222 \times hm^{1.227}$ $\quad$ r = 0.996

$agt = 6.497 \times xp(-0.0851 \times hm)$ $\quad$ r = 0.992

$bgt = 4.827 \times hm^{0.306}$ $\quad$ r = 0.607

where, agt and bgt are empirical function parameters of specific coarse transport of bed load, expressed by function (5), and qcrgs is specific critical water discharge of bed load transport on the bottom of riverbed.

By averaging the data, resulting mean values of specific water discharge (qm), of specific bedload discharge (gtm) and of the average concentrations of coarse sediment in suspension (gsm) are presented in the following table.

For each interval of averaged water depths, the specific water discharge (qm), the values of average specific bedload discharge (gtm) and the values of concentrations of average coarse sediment in suspension (gsm) have been graphically correlated.

The average numerical results of these correlations are shown in the Tables 4 and 5 and in the graphs from Figures 10 and 11. Their analytical expressions have led to determination of two basic empirical functions of coarse sediment transport, which are presented below.

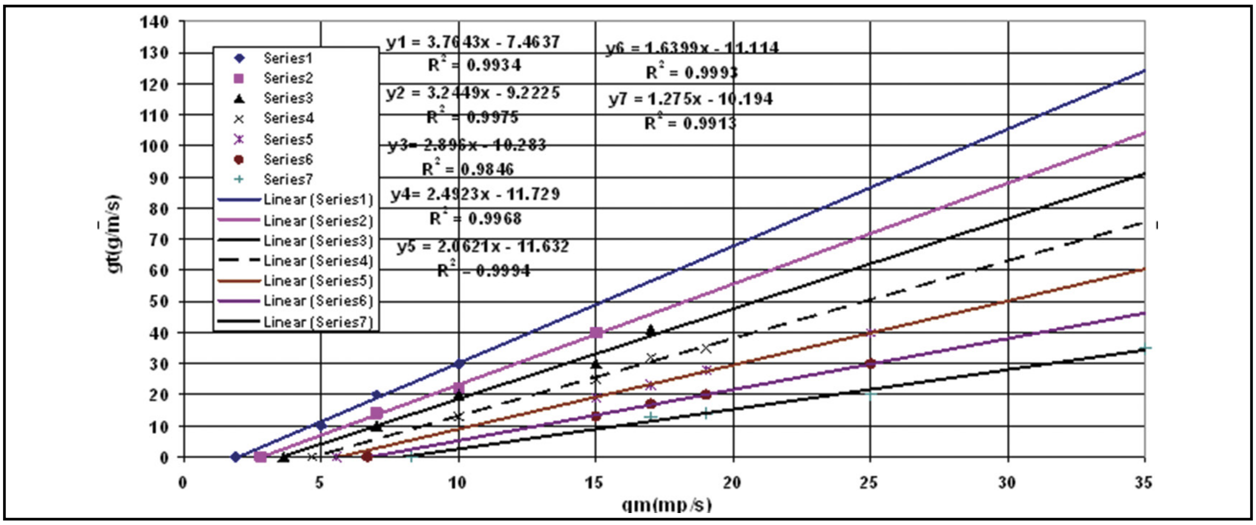

Fig. 10. The graphs of the function gt (qm) dependency on the average depths hm of 5.87 m (1) 8.03 m (2), 9.85 m (3), 12 m (4), 13.74 m (5), 15.86 m (6) and 18.8 m (7) in the hydrometrical sections where the measurements of bedload discharge have been carried out by NIMH between 1965 and 1997

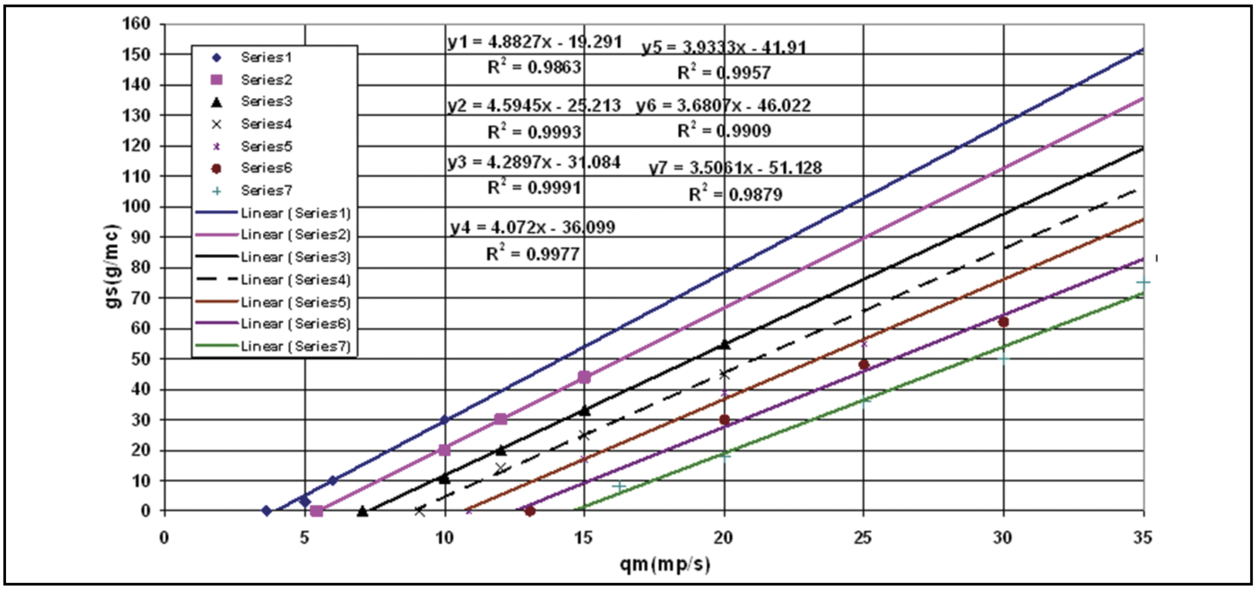

Fig. 11. The graphs of the function gt (qm) dependency on the average depths hm of 5.87 m (1) 8.03 m (2), 9.85 m (3), 12 m (4), 13.74 m (5), 15.86 m (6) and 18.8 m (7) in the hydrometrical sections where measurements of coarse sediment in suspension discharge have been carried out by NIMH between 1965 and 1997

$$gtm = agt \times qm - bgt \quad (5)$$

$$gsm = ags \times qm - bgs \quad (6)$$

where, the average specific water discharge (qm) in the cross-section is expressed in mp/s, the average specific bedload discharge in the considered section (gtm) in g/m/s and the average concentration of coarse sediment in suspension in the same section (gsm) in g/cm.

Through a simple transformation, the empirical functions (5) and (6) become (7) and (8).

$$gtm = agt \times (qm - bgt/agt) \quad (7)$$

$$gsm = ags \times (qm - bgs/ags) \quad (8)$$

The ratios bgt/agt and bgs/ags from the empirical functions (7) and (8) can be interpreted as the critical values of average specific discharge (qm) when starts the coarse sediment transport, consequently,

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

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

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

$$gtm = agt \times (qm - qmcrgt) \quad (11)$$

$$gsm = ags \times (qm - qmcrgs) \quad (12)$$

The parameters' values agt, bgt, ags and bgs are registered toghether with the average depths (hm) at the lower part of the Tables 4 and 5. At the same positions are recorded the empirical functions of those parameters dependency on the average depths (hm).

The processing of the measurements data related to the coarse sediment discharge (bedload and in suspension) led to the empirical functions (14) and (16) of critical average specific water discharge when starts the transport of coarse sediment.

- For the bedload,

$$agt = 6.497 \times \exp(-0.0851 \times hm) \quad (13)$$

$$qmcrgt = 0.222 \times hm^{1.227} \quad (14)$$

- For the coarse sediment in suspension,

$$ags = 5.615 \times \exp(-0.0259 \times hm) \quad (15)$$

$$qmcrgs = 0.605 \times hm^{1.075} \quad (16)$$

Consequently the integral coarse sediment discharge in a cross-section can be expressed by the expressions (17) and (18).

$$Gt(kg/s) = agt \times (qm - qmcrgt) \times B/1000 \quad (17)$$

$$Gs(kg/s) = qm \times ags \times (qm - qmcrgs) \times B/1000 \quad (18)$$

where B is the riverbed width.

Knowing the riverbed morphometry and the water discharge, the empirical functions (17) and (18) allow the determination of the bedload and of the coarse sediment in suspension discharges in any section along the Romanian Danube River. Two computing programmes based on these two functions have been made, one for determining the bedload and the coarse sediment in suspension transport capacity and another one to determine the daily coarse sediment discharge (bedload and in suspension) in the hydrometrical sections along the Danube in the period 1840 - 2012.

The results of the first computing programme are represented in the Figures 12 and 13. They show the following characteristics of the variation of the coarse sediment discharge along the Romanian section of the Danube River, depending on the water discharge (Bondar, C., 1975; Bondar, C., Iordache, G., 2012):

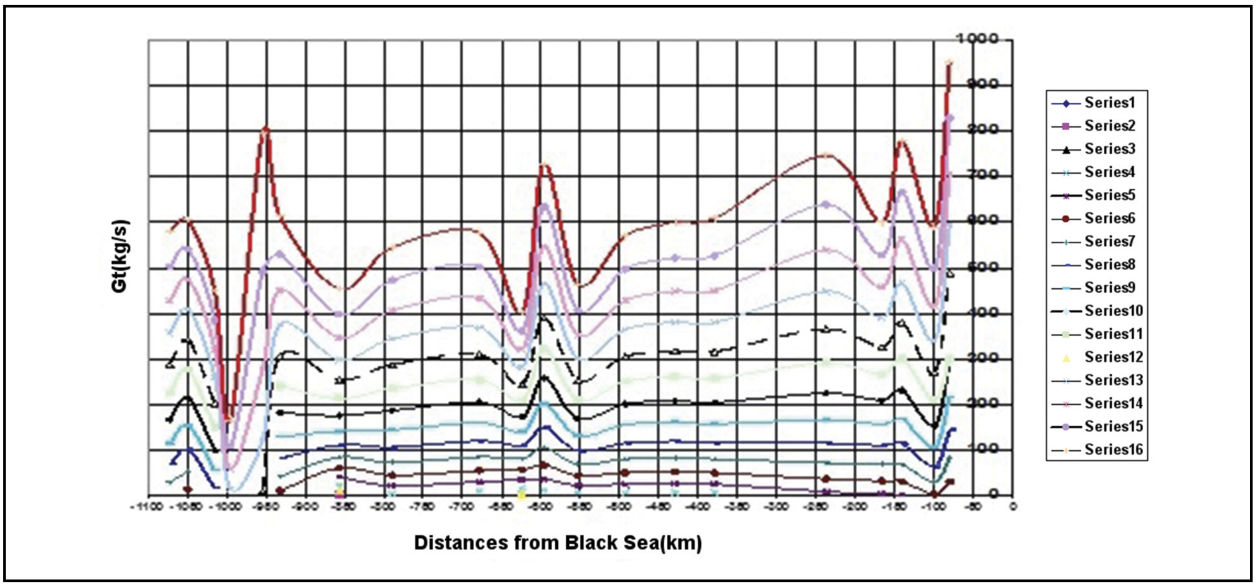

Fig. 12. Graphs of the coarse sediment in suspension discharge (Gs) variation along the Romanian Danube section for water discharges between 1000 (Series 1) and 16000 (Series 16) m^3/s.

- The bedload discharge decrease from upstream to downstream, the maximum value being of about 42 kg/s in the Orsova gauging cross-section at a water discharge of 16,000 m^3/s (data refer to the period before damming) (Figure 13);
- The discharge of coarse sediment in suspension increase from upstream to downstream, the maximum value being about 1080 kg/s at the Ceatal Ismail hydrometric cross-section at a water discharge of 16,000 m^3/s (Figure 12).

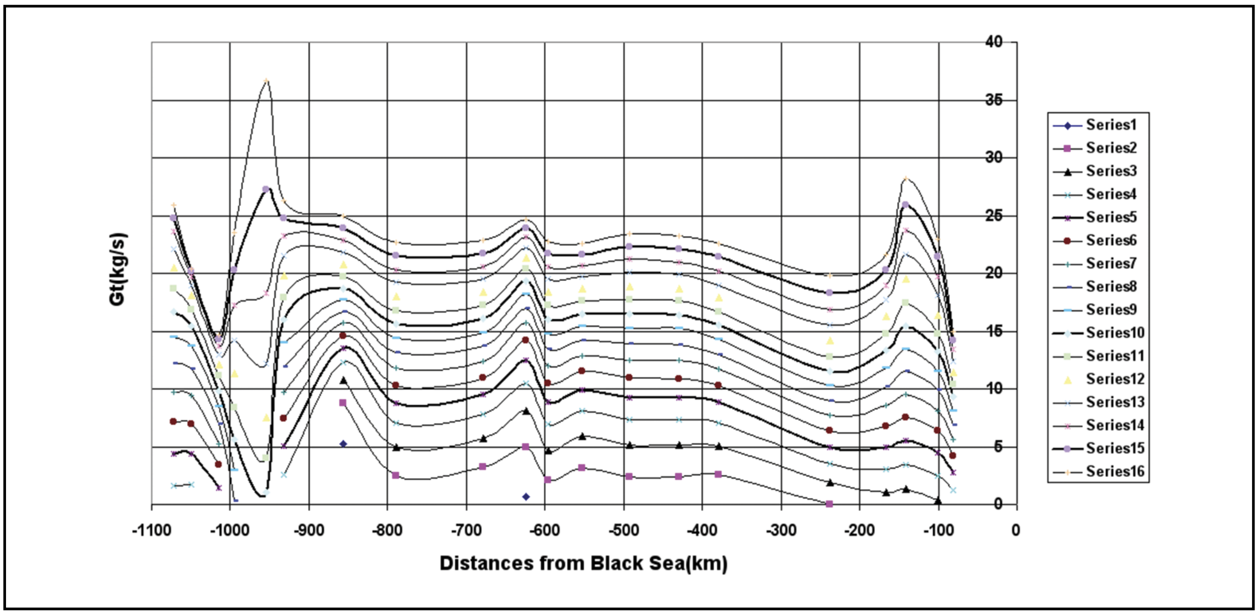

Fig. 13. Graphs of the bedload discharge (Gt) variation along the Romanian Danube section for water discharges between 1000 (Series 1) and 16000 (Series 16) m^3/s.

Table 8. Multiannual average and maximum annual values of bedload discharges and of the coarse sediment in suspension discharges in the hydrometrical cross-sections along the Danube, between 1840 and 2012

Hydrometrical sections	Bedload (kg/s)		Coarse sediment in suspension (kg/s)	
	Multiannual average	Annual maximum	Multiannual average	Annual maximum
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 Magurele	10.8	25.5	91.0	891
Zimnicea	11.7	23.9	54.1	454
Giurgiu	11.9	25.6	74.6	694
Oltenita	11.9	27.2	87.1	837
Chiciu-Calarasi	11.0	26.2	75.4	775
Vadu Oii	7.1	24.4	72.4	1042
Braila	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

The results of the second computing programme alowed among other things to determine the multiannual average and annual maximum values of the bedload discharges as well of the coarse sediment in suspension discharges in hydrometrical cross-sections on the Danube downstream the Iron Gate dam, for the period 1840-2012 (Table 8).

The data of the table above show how the multiannual average discharge of coarse sediment varies along the Danube River. The table contains also the annual maximum values of this discharge at different hydrometrical cross-sections (Bondar, C., 1975; Bondar, C., Iordache, G., 2012) :

For the bedload:

- the multiannual average values of the bedload discharge vary between 14.6 kg/s at Gruia and 5.6 kg/s at Ceatal Ismail (the Danube Delta apex);
- the maximum values of the bedload discharge vary between 23.9 kg/s at Zimnicea and 47.9 kg/s at Grindu.

For the coarse sediment in suspension:

- the multiannual average values of the coarse sediment in suspension discharge vary between 54.1 kg/s at Zimnicea and 130.1 kg/s at Ceatal Ismail;
- the maximum values of the coarse sediment in suspension discharge vary between 400 kg/s at Corabia and 2 048 kg/s at Ceatal Ismail.

4. CONCLUSIONS

The sediments transported by the lower Danube can be split in two main categories: the fine grained fraction under 0.063 mm and the coarse grained fraction with sizes larger than 0.063 mm. The paper presents the main hydrological characteristics of the total sediment transport (fine and coarse) as well as of the bedload and of the coarse sediment in suspension for the Lower Danube River (the Romanian section of the river). The fine grained fraction is transported by the water current exclusively in suspension. The empirical functions for the hydromorphological stability of the river bed and for the transportation of the bedload and of the coarse grained sediment in suspension have been established.

The average bedload specific discharge and the average concentrations of the coarse sediment in suspension in the hydrological cross-sections depend linearly of the average specific water discharge.

Using the empirical functions of the coarse-grained alluvial transport the daily coarse sediment discharge, bedload and in suspension, along the Romanian section of the Danube for the period 1840-2012 have been determined. Multiannual average values and the maximum annual values of the coarse sediment (bedload and in suspension) discharges in the considered hydrometrical sections downstream Iron Gate dams have been computed. The results of this analysis can be synthetised as follows:

For the bedload:

- the multiannual average values of the bedload discharge vary between 14.6 kg/s at Gruia and 5.6 kg/s at Ceatal Ismail (the Danube Delta apex);
- the maximum values of the bedload discharge vary between 23.9 kg/s at Zimnicea and 47.9 kg/s at Grindu.

For the coarse sediment in suspension:

- the multiannual average values of the coarse sediment in suspension discharge vary between 54.1 kg/s at Zimnicea and 130.1 kg/s at Ceatal Ismail;
- the maximum values of the coarse sediment in suspension discharge vary between 400 kg/s at Corabia and 2 048 kg/s at Ceatal Ismail.

Part of the data regarding water discharges used in this paper was obtained in annual study campaignes performed by the National Institute of Marine Geology and Geoecology – GeoEcoMar. The authors would like to express their gratitude for the permission of using these data.

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