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ACTUAL REGIME OF WATER-SEDIMENT FLOW IN THE LOWER DANUBE RIVER

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Abstract: The actual regime of water-sediment flow in the Lower Danube River, from 1985 to 2000, has been analized and compared with the natural regime, from 1931 to 1965. The analysis has been carried out by means of a large amount of hydrologic data collected at a number of 21 hydrometric stations along the Lower Danube River, from its entrance into Romania at the Bazias Village to its discharging mouths at Black Sea.

Keywords: Lower Danube River, actual regime, natural regime, water flow, sediment transport, hydrometric station, hydrologic data.

Introduction

The Danube River is the second largest river in Europe – the Great Blue Diagonal of Europe.

The total length of the Danube River is 2857 km, from which 1075 km (37,6%) in Romania, and its the catchment aria is 817.000 Km^2 within 18 countries, from which 232.000 km^2 (28,4%) in Romania (Fig.1).

Flowing through nine countries and crossing four capital cities (Beograd, Budapest, Bratislava, Vienna) and other great cities, the Danube River is a major international water way and resource in Europe.

Fig. 1. The Danube River basin

The Lower Danube River flows in Romania from the Bazias Village (km 1072,5) to the Ceatal Izmail bifurcation (km 80,5) and discharges into the Black Sea by three branches (Chilia, Sulina and St.Gheorghe), via the Danube Delta, the youngest low-wet-land of Europe.

In the recent history of water-sediment flow in the Lower Danube River, one may distinguish the following three different periods of time:

- a first period, up to the year 1965, when a natural (undisturbed) flow regime occurred,
- a second period, from 1965 to 1985, when a transitory flow regime (from natural to actual) occurred; it is influenced by the great hydrotechnical fluvial systems Iron Gate 1 (completed in 1972) and Iron Gate 2 (completed in 1985), as well as by severe changes of the major Romanian tributaries' contributions (the Jiu, Olt, Arges and Siret rivers, controlled by dams and reservoirs), and
- a third period, from the year 1985 up to present, when an actual (disturbed) flow regime has occurred,

each of them with their own particular hydraulic and sedimentologic characteristics.

The actual regime of water flow and sediment transport in the Lower Danube River in Romania has been recently investigated and the main results are reported below.

The study has been carried out by means of a large amount of data collected at a number of 21 hydrometric stations and point gauges along the Lower Danube River (Fig.2).

Several other information and data reported by Diaconu et al. (1963), Stanescu et al. (1967), Stancik et al. (1988), Liptak (1993), Behr et al. (2000), IHP-UNESCO (1986, 1993) and INMH-PHARE (1997) have been used as well.

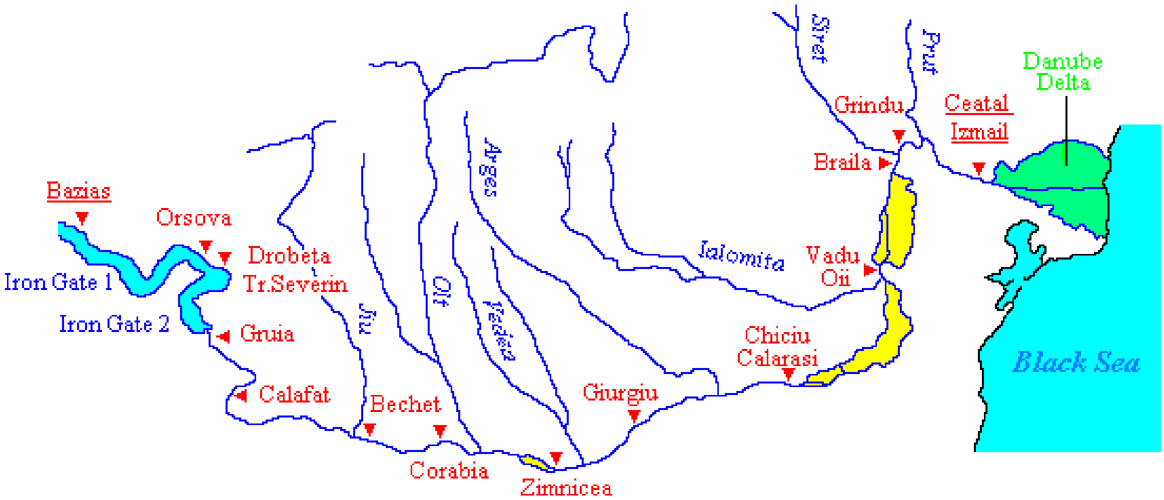

Fig.2. Lower Danube River in Romania

Water flow regime

The long-term water flow regime recorded from 1931 to 2000 at the two extremal hydrometric stations, at Bazias Village and the Ceatal Izmail bifurcation in the Lower Danube River in Romania is shown in figure 3.

Clear distinction between natural, transitory and actual flow regime can be noticed.

The natural water flow regime, from 1931 to 1965, is characterized by an average multi-annual discharge of 5480 m^3/s at Bazias and 6380 m^3/s at Ceatal Izmail, while the actual flow regime, from 1985 to 2000, is characterized by a discharge of 5180 m^3/s at Bazias and 6180 m^3/s at Ceatal Izmail.

The difference in the flow rate of about 900 to 1000 m^3/s at Bazias and Ceatal Izmail is given by the contribution of major tributaries from Romanian territory (about 650 m^3/s) and from Bulgarian territory (about 100 m^3/s in total), as well as of the drainage bazin (up to 250 m^3/s).

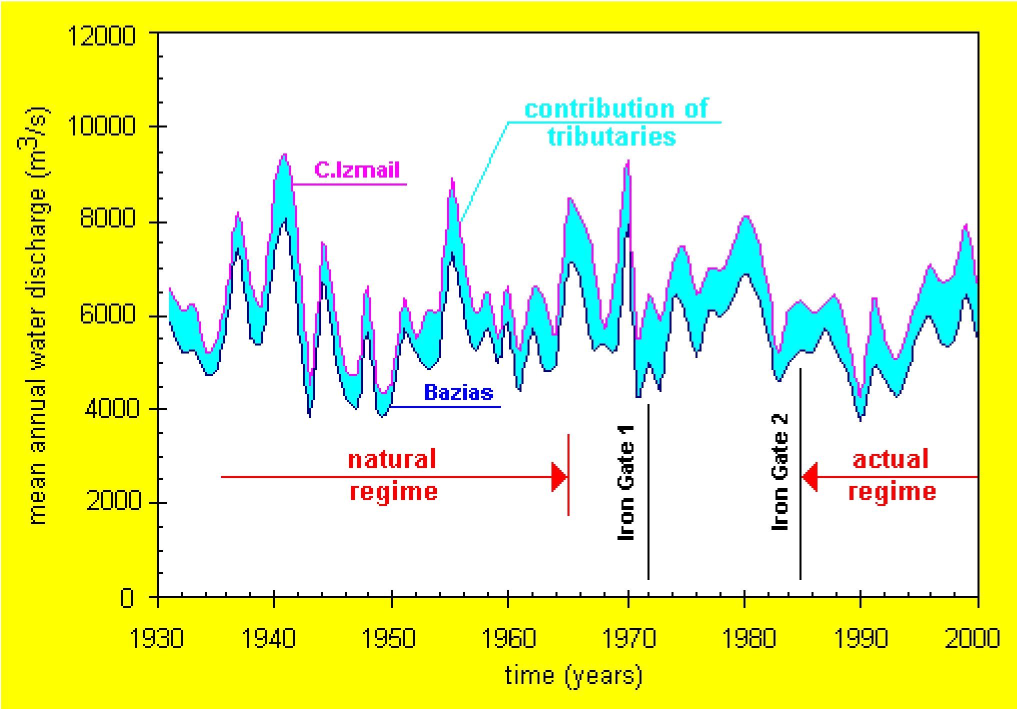

Fig.3. Flow regime in the Lower Danube River from Bazias to Ceatal Izmail

The multi-annual flow regime in the major Romanian tributaries (the Jiu, Olt, Arges, Siret and Prut rivers) from 1950 to 2000 is shown in figure 4.

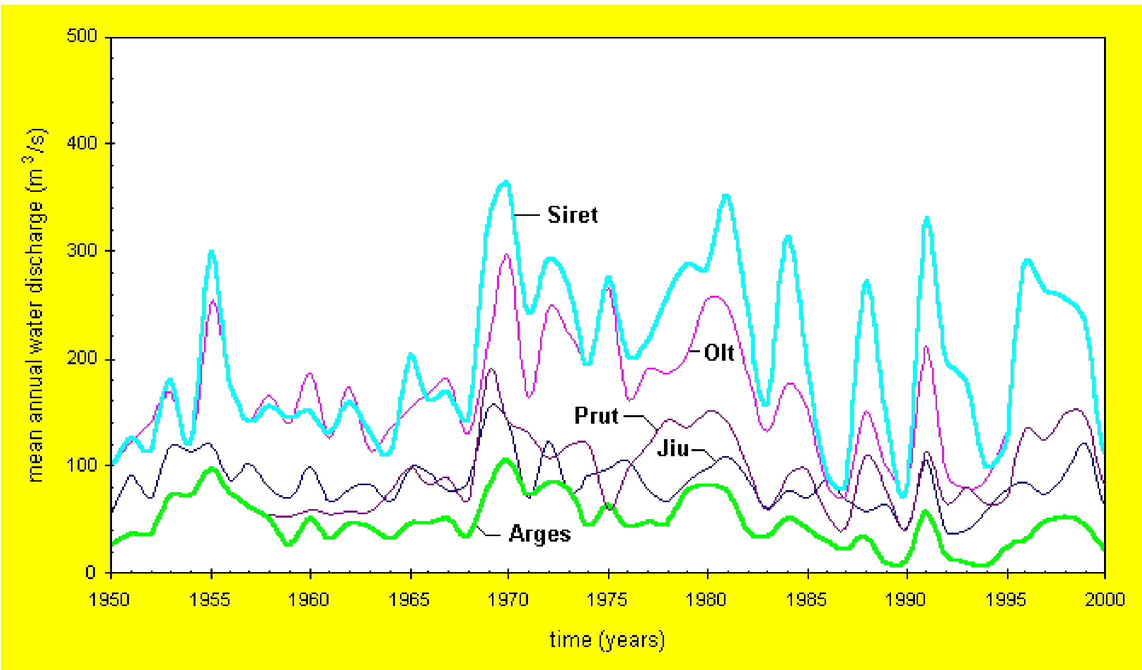

Fig.4. Flow regime in the major Romanian tributaries

The actual hydrulic regime of water flow in the Lower Danube River flow, from 1985 to 2000, is well defined by the depth-discharge curves, established in different locations with direct measurement data in the following dimensionally homogeneous form:

$$h_m = a\,\frac{Q^{2/5}}{g^{1/5}} + b \qquad (1)$$

in which h_m is the mean flow depth (in m), Q = water discharge (in m^3/s), g = gravitational acceleration (= 9.81 m/s^2), and a, b = numerical constants with values given below:

a = 0.45 and b = - 0.89 at Calafat station (upstream end),
a = 0.22 and b = 12.04 at Ceatal Izmail station (downstream end),

as shown in figure 5. It is interesting to note that the line slope is almost constant, a = 0.45 for the flow in the upstream and middle reaches of the river, from Calafat to Vadu Oii, and a = 0.22 for the flow in the downstream reach of the river, from Braila to Ceatal Izmail, while the line interception b is variable in each location (from –2.1 at Corabia, to +5.0 at Grindu and Isaccea and +12.0 at Ceatal Izmail).

Such liniar relationships could be extremely useful in current practice, particularly when extrapolation procedures are needed.

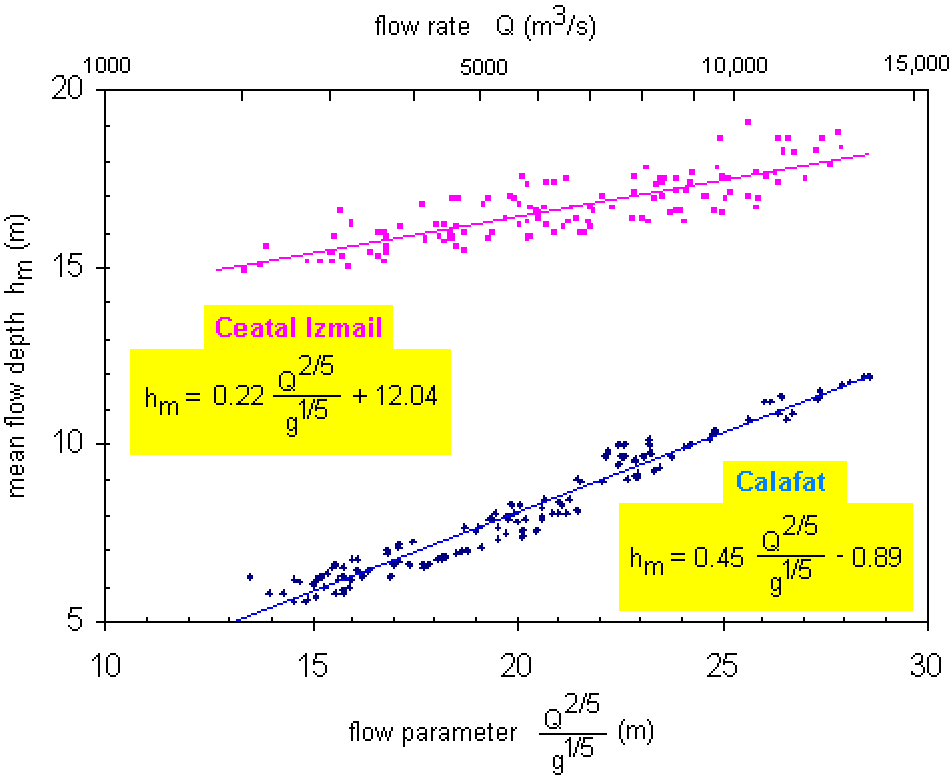

Fig.5. Depth-discharge curves for the actual flow regime in the Lower Danube River at Calafat, Giurgiu and Ceatal Izmail

The steady flow regime in the Lower Danube River has been studied by means of the HEC-RAS software (vrs. 3.0, January 2001) built by the US Army Corps of Engineers, Hydrologic Engineering Center (Werner et al., 2001).

Hydraulic calculations have been carried out for the river reach from Bechet (km 679.0) to Chiciu-Calarasi (km 364.8) hydrometric stations, where a full set of hydrologic and bathymetric data was available.

The computer model has been calibrated for the flow recorded in september, 1983, aiming to evaluate the most probable values of the Manning roughness coefficient along the river channel.

For various engineering and forecast purposes, the HEC-RAS model has been then used for numerical simulations of the flow regimes of different probabilities of occurrence (10%, 5% and 1%) along the river reach. The computed water surface long profile of the 1% flow (with an average multi-annual discharge of 8640 m^3/s at Bechet and of 9060 m^3/s at Chiciu-Calarasi, the contribution of tributaries being considered) is shown in figure 6. Many other calculation results (flow depth and velocity, wetted perimeter and hydraulic radius, Froude number) became available as well.

Due to the good and encouraging results obtained for steady flows along the river reach from Bechet to Chiciu-Calarasi, the HEC-RAS model has been later on utilizead for another but shorter river reach, from Cernavoda City to Harsova Town.

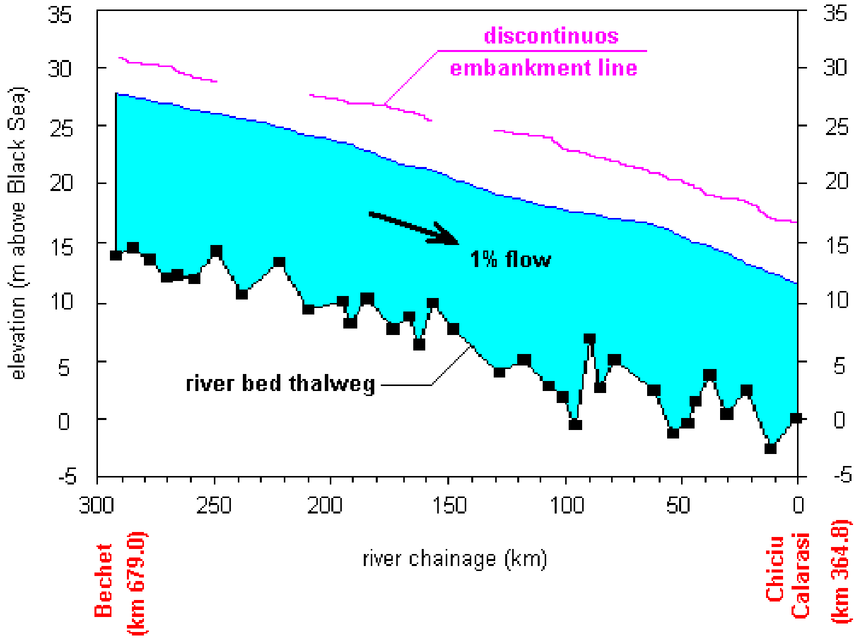

Fig.6. Computed water surface for 1% flow in the Lower Danube River from Bechet to Chiciu-Calarasi

Sediment transport regime

Along the Lower Danube River from the Bazias Villlage to the Ceatal Izmail bifurcation, the sediment transportation is mainly developed in suspension, representing about 90% to 95% from the total.

The sedimentary material transported as suspended-load is dust and very fine sand, with an average size of 0.01 to 0.04 mm, while the material transported as bed-load is a non-homogeneous mixture of fine and medium sand, with an average size of 0.15 to 0.80 mm.

The long-term sediment transport regime recorded between 1931 and 2000 at the Orsova and Ceatal Izmail hydrometric stations is shown in figure 7.

A severe reduction in sediment transport rate (mean annual discharges of suspended-load) is evident during last few decades, due to general climatic changes in the region, as well as to hydrological and anthropical changes that have been produced in the river channel and its tributaries, by damming in particular.

The multi-annual sediment transport regime in the major Romanian tributaries (the Olt, and Arges rivers with several reservoirs in cascade subject to severe silting processes, and the Siret river) is shown in figure 8.

The tendency in sediment transport reduction in the above mentioned period of time has been expressed by the following relationships at various locations along the river:

Orsova station $$R = -19.08T + 38210 \tag{2a}$$
Zimnicea station $$R = -16.11T + 32690 \tag{2b}$$
Giurgiu station $$R = -18.41T + 37300 \tag{2c}$$
Chiciu-Calarasi station $$R = -24.66T + 49670 \tag{2d}$$
Vadu Oii station $$R = -24.77T + 49900 \tag{2e}$$
Ceatal Izmail station $$R = -18.95T + 38550 \tag{2f}$$

where R is the mean annual suspended-load discharge (in kg/s) and T = time (in years from 1931).

Similar relationships have been developed for sediment transport regime in the Chilia, Sulina and St. George branches of the Danube River discharging in the Black Sea, as follows:

Periprava station in the Chilia branch	$R = -11.74T + 23850$	(3a)
Sulina station in the Sulina branch	$R = - \ 3.60T + 7320$	(3b)
St. George station in the St. George branch	$R = -3.79T + 7690$	(3c)

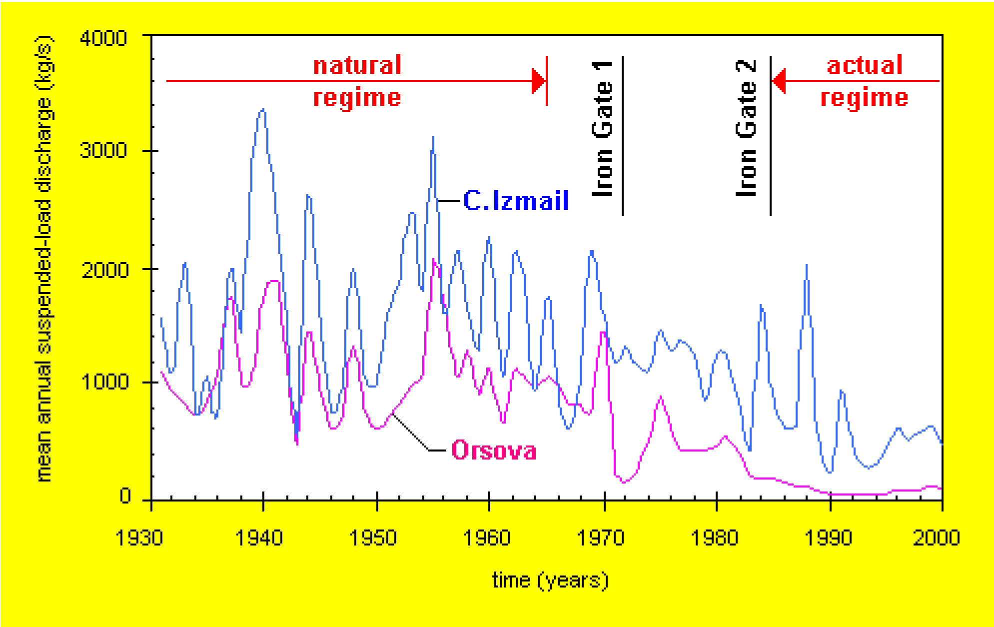

Fig.7. Sediment transport regime in the Lower Danube River from Orsova to Ceatal Izmail

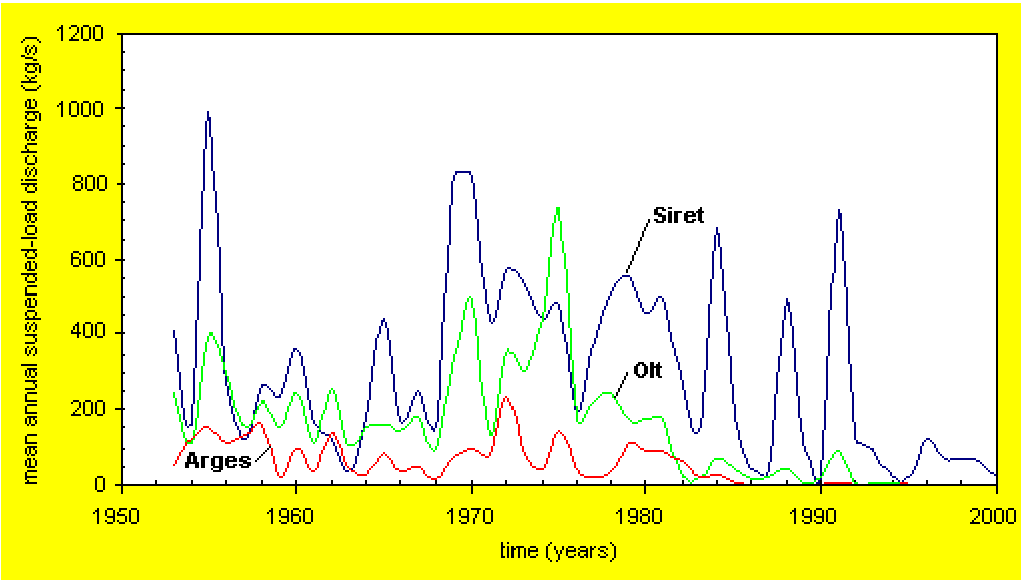

Fig.8. Sediment transport regime in the major Romanian tributaries

The natural and actual regimes of suspended sediment transportation in the Lower Danube River in Romania, from 1931 to 1965 and from 1985 to 2000, are given in table 1 and shown in figure 9 (mean annual quantities of transported materials in suspension).

Drastic reduction in the actual to natural suspended sediment transport, of about 90% to 65%, is recorded along the Danube River channel, from the Gruia Village and Calafat Town (downstream the Iron Gates 1 and 2) to the Ceatal Izmail bifurcation.

Table 1. Suspended sediment transport in the Lower Danube River in Romania (natural and actual regime).

Hydrometric Station	Mean annual quantities of suspended sediment transported in the Danube River (in million of tonnes per annum)	
	Natural regime from 1931 to 1965	Actual regime From 1985 to 2000
Bazias	33.92	3.82
Orsova	33.95	2.93
Gruia	34.02	2.71
Calafat	44.43	3.55
Bechet	51.63	15.08
Corabia	53.08	11.20
Zimnicea	41.59	14.61
Giurgiu	46.14	14.80
Chiciu	53.81	15.37
Vadu Oii	53.08	11.58
Braila	51.72	12.56
Grindu	53.87	12.75
Ceatal Izmail	53.30	18.43

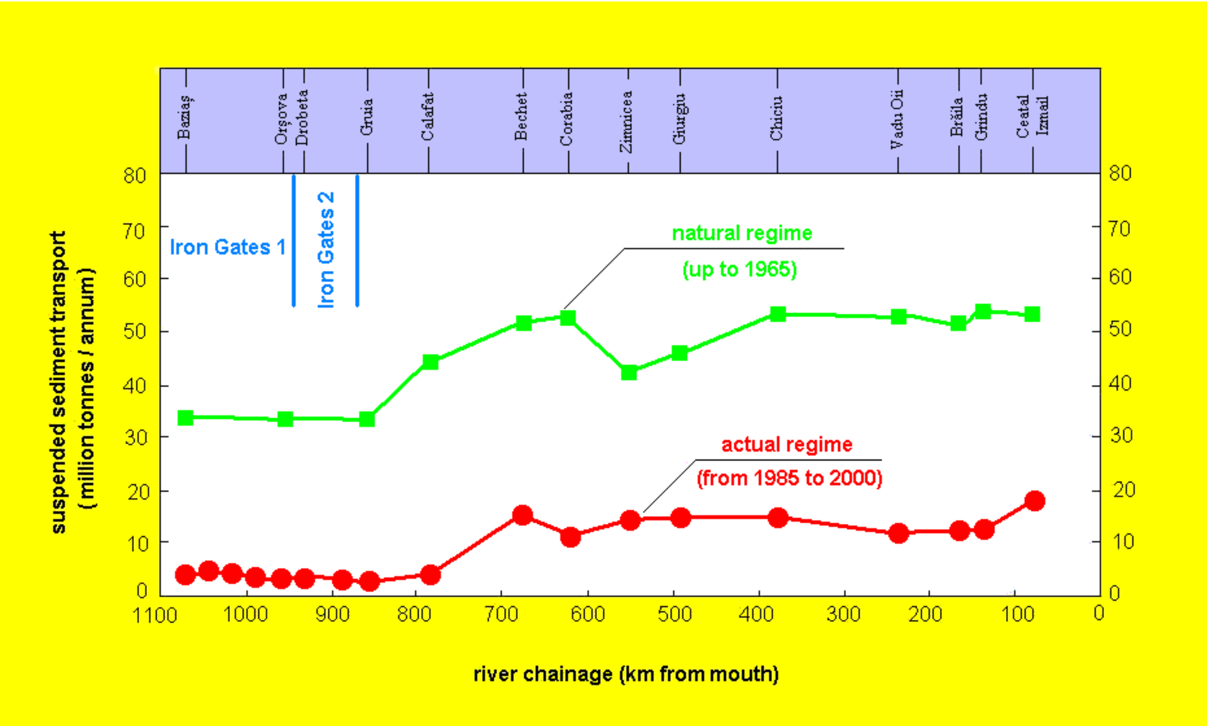

Fig.9. Natural and actual regime of suspended sediment transport in the Lower Danube River

The actual regime of water-sediment flow in the Lower Danube River in Romania, from 1985 to 2000, expressed by the mean annual water and suspended flow rate variation along the river, is shown in figure 10.

Mean annual water discharges increase regularly from 5180 m^3/s at Bazias to 6180 m^3/s at Ceatal Izmail, with a contribution of the major tributaries of about 1000 m^3/s in total, as already mentioned above.

Mean annual sediment discharges vary from 120 kg/s at Bazias to 90 kg/s at Gruia, up to 590 kg/s at Ceatal Izmail, with the following three aspects of sediment transportation which are evident:

– retention of sediment in the Iron Gates 1 and 2 Reservoirs (silting process),
– regeneration of sediment load with solid materials from the river bed and banks, over very long distances downstream of reservoirs (morphological process),
– deposition of sediment in the multi-branch river flow (from Chiciu-Calarasi to Grindu).

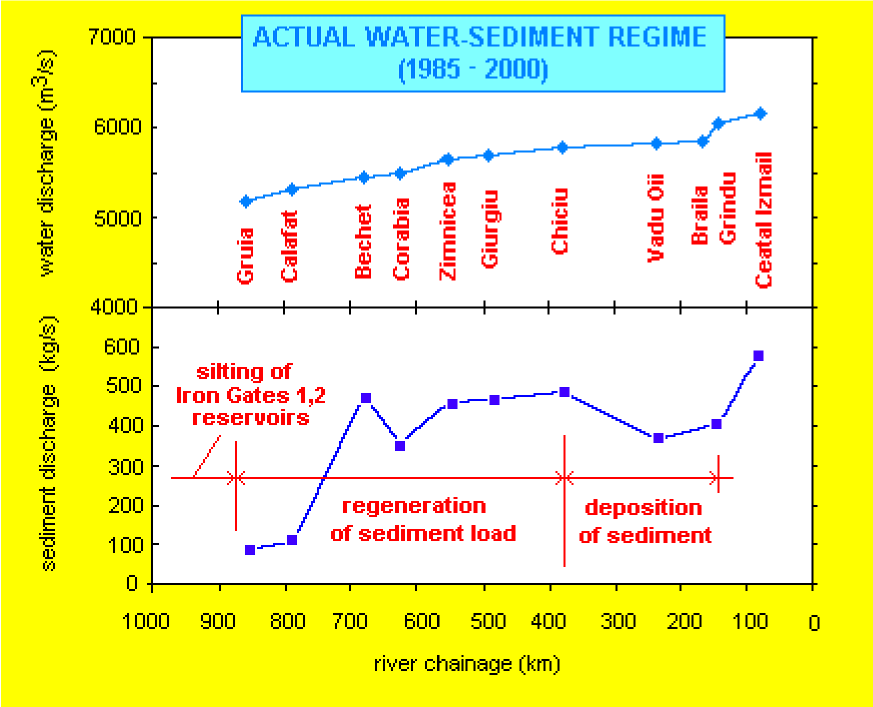

Fig.10. Actual regime of water-sediment flow in the Lower Danube River

Aiming to describe quantitatively the actual sediment transport in the Lower Danube River in Romania, from 1985 to 2000, several empirical and semi-empirical relationships have been developed by means of measurement data at all hydrometric stations along the river.

For various hydrological and environmental purposes in the region, the actual transport of sediment (suspension and bed-load) has been expressed by the following empirical relationships:

$$Q_s = const\ Q^m \qquad \text{and} \qquad Q_b = const\ Q^n \tag{4}$$

where Q_s and Q_b are the sediment discharges (in kg/s), Q = water discharge (in m^3/s), *const*, *m* and *n* = constants and exponents resulting from statistical analysis of data. Such relations for particular sediment transport conditions at the Calafat and Ceatal Izmail stations are given in Table 2

Table 2. Empirical relationships for sediment transportation (actual regime from 1985 to 2000) in the Lower Danube River, at the Calafat and Ceatal Izmail hydrometric stations.

Hydrometric Station	Suspended-load Qs (in kg/s)	Bed-load Qb (in kg/s)
Calafat station	$Q_s = 2.09\times10^{-4}\ Q^{1.511}$	$Q_b = 1.37\times10^{-5}\ Q^{1.381}$
Ceatal Izmail station	$Q_s = 1.65\times10^{-6}\ Q^{2.212}$	$Q_b = 5.12\times10^{-11}\ Q^{2.706}$

For many other different hydraulic and engineering purposes in the region, the suspended sediment transportation has been expressed by several semi-empirical equations derived from the “*stream power theory*” (Rooseboom, 1975, 1992, Yang, 1976, 1997, Yang and Molinas, 1982) or from the “*gravitational theory*” (Velikanov, 1954, Rossinsky, 1967, Rossinsky and Kuzmin, 1972). They have been developed with measurement data at all hydrometric stations along the river.

Equations based on the "stream power theory" indicate that the suspended sediment concentration depends exponentially on the power of flow, as follows:

$$C_s = const\,\left(V_m\,S_f\right)^{exp} \tag{5}$$

where C_s is the concentration of suspended sediment (turbidity - in kg/m^3), V_m = mean flow velocity (in m/s), S_f = energy flow slope (in m/km), and $V_m S_f$ = stream power. The numerical values of the *const* are from 0.24 (at Calafat) to 0.34 (at Ceatal Izmail) and of the *exp* are from 0.83 (at Calafat) to 0.40 (at Ceatal Izmail), as shown in figure 11. Similar equations have been derived for all locations of hydrometric stations along the river.

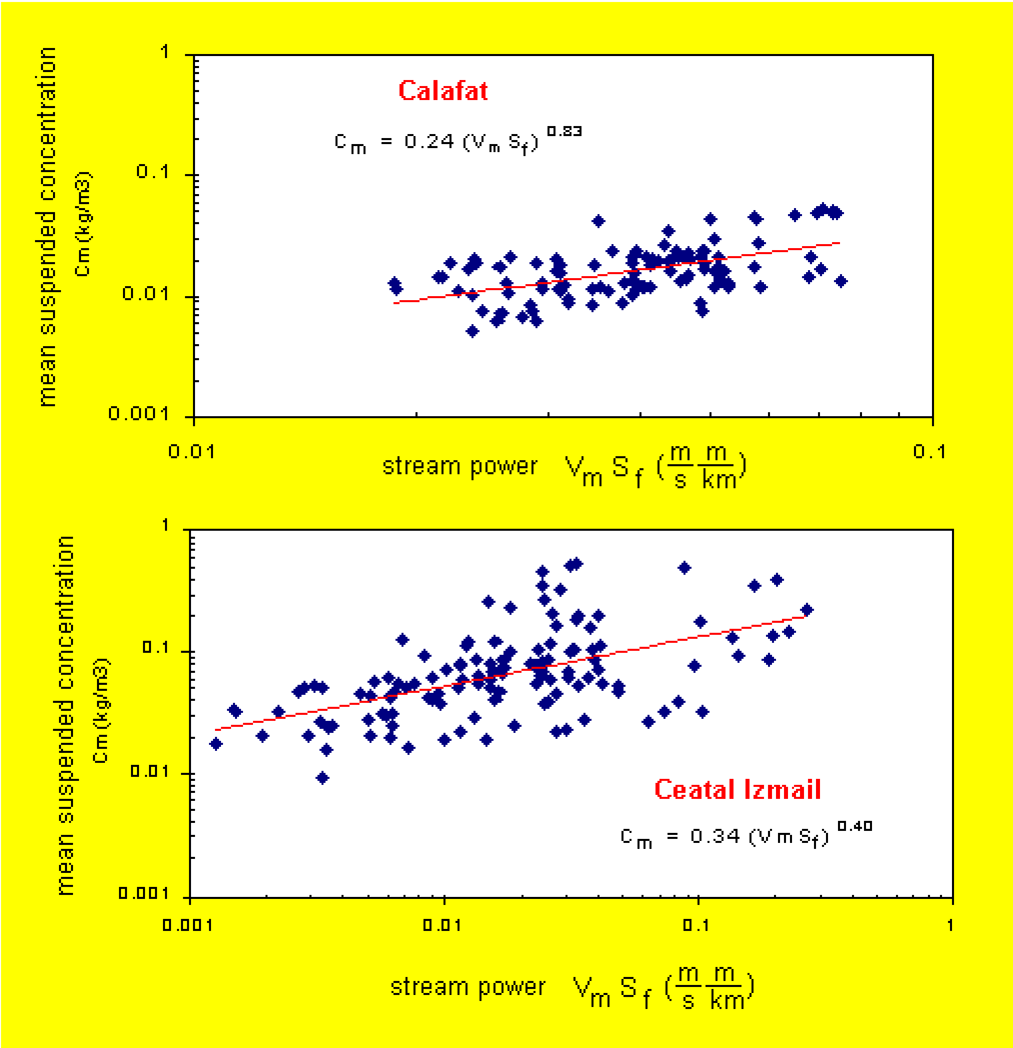

Fig.11. Stream-power sediment transport equation at the Calafat and Ceatal Izmail stations

Equations based on the "*gravitational theory*" indicate that the suspended sediment concentration depends exponentially on a hydraulic parameter defined as a function of the flow velocity, flow depth and sediment fall velocity, as follows for the Ceatal Izmail station:

$$C_s = 22.13\times10^{-3}\left(\frac{V_m^3}{g\,h_m\,w}\right)^{0.421} \tag{6}$$

where C_s is the concentration of suspended sediment (turbidity - in kg/m^3), V_m = mean flow velocity (in m/s), h_m = mean flow depth (in m), w = fall velocity of suspended sediment (in m/s), and g = gravitational acceleration (= 9.81 m/s^2). Similar equations are going to be derived for flow conditions at all locations of hydrometric stations along the river.

Conclusion

The main characterisics of the actual regimes of water flow and sediment transport in the Lower Danube River in Romania, from 1985 to 2000, have been studied by means of a large amount of hydrological data collected at a number of 21 hydrometric stations along the river. A comparative analysis with the natural water-sediment flow regime, from 1931 to 1965, has been carried out as well.

The natural and actual flow regimes along the river channel have been defined by the longitudinal variation of the mean annual water discharges, showing contribution of the major tributaries from Romanian territory.

The main hydraulic features of the water flow in the river channel (depth-discharge curves and flow porfiles) have been successfully investigated by means of measurement data recorded at various hydrometric stations and by making use of the advanced HEC-RAS computer software.

The natural and actual sediment transport regimes along the river channel have been defined by the longitudinal variation of the mean annual suspended sediment discharges. The significant reduction in sediment transportation during last few decades due to various natural and anthropic causes (general climatic changes in the region, silting of the upstream reservoirs, sediment trapping of reservoirs-in-cascade from the tributaries) is revealed.

For various engineering and environmental purposes in the region, several empirical relationships and semi-empirical equations have been derived for different locations along the river channel.

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