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RESERVOIR SEDIMENTATION

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BUCHAREST

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1. INTRODUCTION

Reservoirs produce large discontinuities in terms of flow regime, leading to the cessation of alluvial transport, initially in the area of change of the flow regime (tail of reservoir), as well as changes in riverbed profiles and adjacent slopes. These processes lead to the sedimentation of the reservoirs, and in the case of shallow lakes, even to the creation of deltaic areas.

The loss of storage represents the main effect of the sedimentation phenomenon with direct consequences on the attenuation volume, as well as on its other functions water supply, hydroelectricity, navigation, irrigation etc.

Dams have probably the longest expected life of all large-scale hydraulic structures. The main threats that can endanger the longevity of a dam are the sedimentation of the reservoir and the aging of the structure. The high sedimentation rate of the reservoir, in addition to the decrease in storage volume and consequently increasing the risk of flooding, significantly reduces the solid flow in the river and the degradation of downstream areas. Sediments obstruct the intakes and amplify the abrasion process of hydraulic machines, reducing efficiency and increasing maintenance costs. Furthermore, the costs of drinking water treatment are influenced by the amount of the total suspended solids that are transported by the water currents.

Small reservoirs are prone to sedimentation as a result of bank erosion, a phenomenon induced by waves in areas with erodible catchments or with a greater slope than the natural one. After the commissioning of the reservoir, a fast sedimentation process is carried out, especially on the areas located on the lower course of the rivers. The rapid sedimentation process is explained throughout the erosion of the riverbed which is favored by factors such as geological nature of the formation in the river basin or the torrential nature of the flow.

Erosion and sedimentation processes, land cover, land use, river basin hydrology are closely related to climate change and are amplified by a wide range of human activities that are necessary but also harmful to the environment: intensive deforestation, land use change, urbanization and infrastructure development etc.

Anthropogenic intervention is significant and requires a sustainable management of water resources by monitoring and controlling sediment dynamics. The application of solutions in order to reduce the sedimentation rate must be standardized for each reservoir due to the different conditions of location, construction, operation etc.

2. THE PROBLEM OF MORPHOLOGICAL CHANGES

Globally, the sedimentation phenomenon has a significant social, economic and ecologic impact and is a key issue in the sustainability of reservoirs. Currently, the gross storage volume of dams worldwide is 6 100 km³, of which 2 000 km³ of it has been lost due to the sedimentation process. According of the forecasts, without taking into account the execution of new dam constructions, it is estimated that by 2050 the total capacity of the reservoirs will be reduced by more than half (Figure 1). The average values of the sedimentation rate differ depending on the region and vary between 0,3% and 2% per year, resulting in an overall average of 0,8% per year (The International Commission on Large Dams – ICOLD 2009).

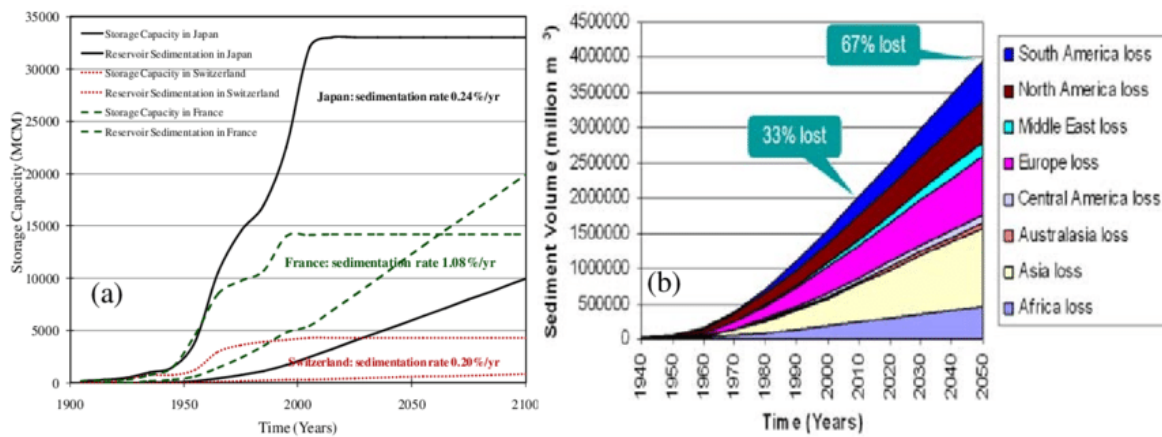


Figure 1 – Forecasts regarding the reservoir sedimentation (ICOLD 2009)

Studies conducted worldwide have reported significant problems of sedimentation and loss of volume in reservoirs in recent years, therefore the sedimentation problem represents a very important issue due to its size and geographical spread.

- in the USA, the estimates made between the years 1960 – 1970 showed that 64% of reservoirs have a lifespan of less than 100 years, some of them being affected by a intensive sedimentation process. Consequently the St. Augustine reservoir was 95% sedimented in 13 years, and Spring reservoir in 20 years;
- in China based on the date collected from 236 reservoirs, by the end of 1981 the total amount of sediment deposited was 11,5 billion m³ representing 14,2% of their total volume, which means 0,8 billion m³ loss of annual storage. Nationwide, the loss of volume is about 2,3% per year;

- in Japan, out of the total storage of 729 reservoirs with volumes larger than 1 million m³ (17,3 billion m³), 1,2 billion m³ are sedimented, which corresponds to 6,9% of the total storage;
- in Spain the initial storage of 101 reservoirs with a total volume of 18 billion m³ operated since the end of the 19th century decreased by 733 million m³ which is about 4%. Approximately 5% of reservoirs are affected by a volume reduction of 50% or more, and 79% register a loss in volume by sedimentation less than 20%;
- in Pakistan, at the Tarbela reservoir, the storage of 14,3 billion m³ was reduced in 22 years of operation by about 20% or 2,9 billion m³.

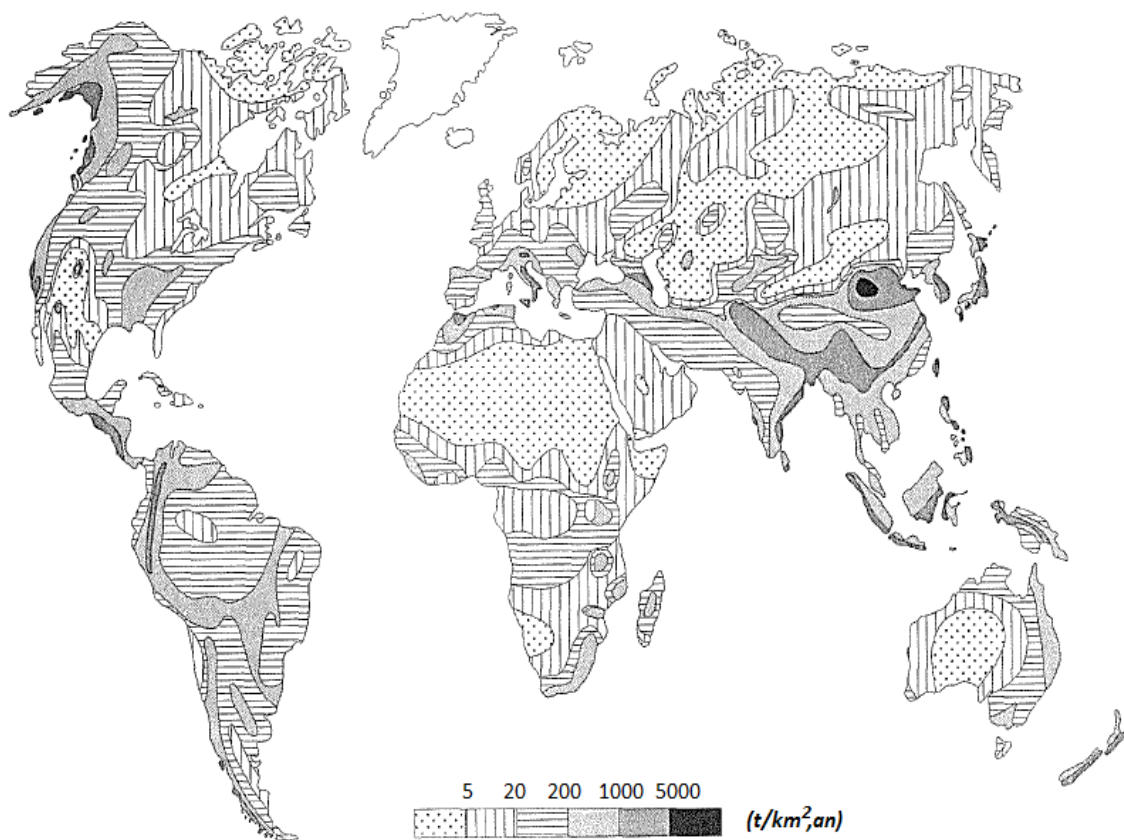


Figure 2 – Global annual average solid flow distribution
(Lvovich, 1991)

2.1. Solid flow in Romanian rivers

It is known from older studies (before 1992) that in Romania the rivers carry significant quantities of sediments, an average of 48 tones per year and km of watercourse, which is about 207 tones / ha per year.

In Romania, reservoirs sum a total volume of sediments of approximately 13 billion m³ representing a third of the total volume of water transported in a year by local rivers (Jelev, 1992). The average value of solid runoff is 1,75 t / ha / year, the rivers transporting an annual amount of sediments of 45 million tones / year (Ujvari, 1972).

An important aspect of solid runoff is variability, because the transport of sediments does not increase in the same percentage with liquid flows, they are characterized by an exponential ratio. The reduction of liquid flows decreases the energy of water erosion resulting in the transport of a smaller amount of alluvium, while the increase of flows intensifies the sediment transport.

“The distribution of solid runoff during the years follows almost faithfully the regime of liquid runoff” (Ujvari, 1922). Sediment runoff has great variations both in space and in time. The annual differences that occur are due to the torrential regime of watercourses that is induced by heavy rain events during which the critical drive velocities of suspended sediments occur earlier than in the case of moderate floods. About 50% of the annual volumes of sediments are produced in less than a month, when floods are recorded.

The rapid sedimentation process is explained by the energetic action of riverbed erosion, favored by the following factors:

- ✓ the geological nature of the formations in the river basin;
- ✓ the torrential nature of the flows;
- ✓ the pulsating nature of the flows discharged in the river by the operation of the upstream power plants with higher values than the natural regime.

In our country there are dams that have been functional for centuries (such as those in the Banat mountains or the Metaliferi mountains), but also reservoirs that have clogged over a period of several years. From the data we have at our disposal we can retain some general observations such as:

- in the whole country, in an average of 15 years, about 200 million m³ of sediments were deposited in reservoirs on the inland rivers (of which almost half only in the reservoirs located on Arges and Olt rivers), with an annual rate of 13,4 million m³, which represents 27% of the total multi-annual average sediment transport;
- the most important sedimentation rates were recorded on the reservoirs located on Arges river: Pitesti 15,7%, Bascov, 11,7%, Oiesti 9,5%, Cerbureni 7,3% and Curtea de Arges 5,3%; also, Galbeni reservoir located on Siret, 10,6%;

- average annual rates of sedimentation were registered at the first built reservoirs located on the Olt river: Govora 8,27%, Rm. Valcea 5,63% and Daesti 4,90%; in the same category are the Pangarati reservoir on Bistrita, 3,45% or Pucioasa on Ialomita, 2,58%;
- low sedimentation rates are registered at the large reservoirs, Izvorul Muntelui 0,03% and Vidraru 0,04%, which ensures a millennial operation, if some unpredictable situations do not occur.

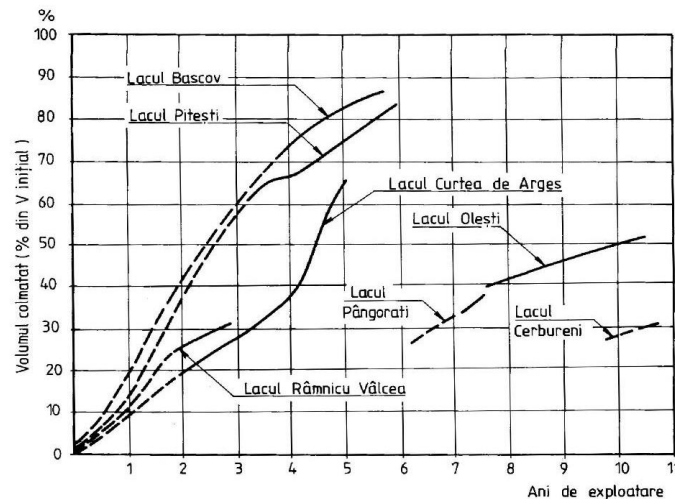


Figure 3 – Sedimentation rates of Romanian Reservoirs

As can be seen from the graphs below, the reservoirs in Romania are characterized by relatively low capacities. Almost 90% of the existing reservoirs have storages below 200 million m³, and half of them below 20 million m³. The configuration and flow conditions of the Romanian rivers did not offer great possibilities for the construction of large dams and, implicitly, of large reservoirs. The few exceptions are known; Izvorul Muntelui reservoir, the largest on the inland rivers, Vidraru on Arges, Vidra on Lotru, Siriu on Buzau, Gura apelor on Rau Mare etc.

Many of the existing reservoirs are constructed in cascade on the largest rivers (Bistrita, Siret, Buzau, Arges, Olt), with a particular operation regime, which directly imposes a certain sedimentation rate. This explains the large number of reservoirs on the rivers Olt, Arges and Siret, illustrated in the figure below. The reservoirs storage and operational regime are important factors that control the degree of sediment retention in the source area.

The storage of reservoirs is decisive for evaluating the rate and duration of the sedimentation process due to a very simple reason: the larger the reservoir, the more it can store sufficiently large quantity of sediments without affecting its functionality. On the contrary, a low storage

reservoir can be clogged in a relatively short time, several years or several decades, even at relatively modest sediment inflows.

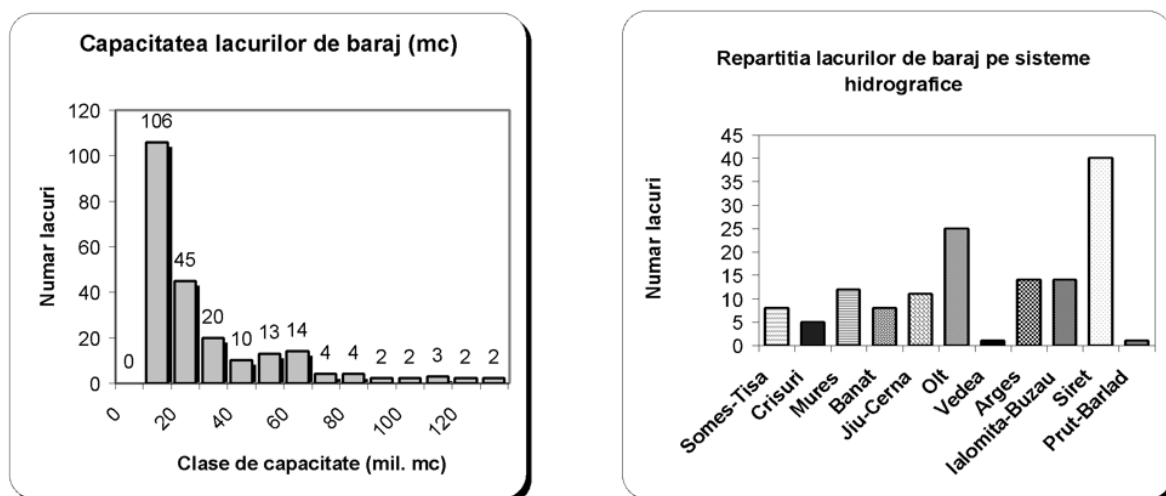


Figure 4 – Distribution of reservoirs in Romania

(on the left, the histogram of the reservoirs with storage under 140 million m³; on the right, the distribution of the reservoirs on hydrographic systems)

The processes from reservoirs determine a permanent transformation of the morphology with the tendency towards extinction. Also, the clogging of reservoirs is with sediments of fluvial origin (alluvium), of local origin (abrasion, dust falling on the water surface, organic materials) contributes to morphological transformation.

Among the factors that contribute with a particular intensity to the sedimentation of smaller reservoirs, located on the hill and plain regions, are the river alluvium. Their penetration into reservoir is closely related to the solid flow, the specific erosion in the reservoirs area. The reservoirs can be classified (J. Ujvari) according to sedimentation environment in which they are located in:

- ≤ 1 tones / ha / year - slow sedimentation;
- $e = 1-5$ tones / ha / year - possible rapid sedimentation of the reservoirs;
- $E \geq$ tones / ha / year - rapid sedimentation of reservoirs.

The slowest rate of sedimentation occurs in the mountain regions, where erosion-resistant rocks predominate. This can be observed at the alpine lakes, which are over 10,000 years old and where the thickness of the sediments is not yet very significant. At the opposite end are the lakes located in the sub-Carpathian regions and the Moldavian Plateau, where many small lakes have sometimes been sedimented after a single flood.

Nr. crt.	Bazinul hidro-grafic	Lacul de acumulare	Volum inițial 10 ⁶ m ³	Volum colmatat		Anul începerii exploataării	Sursa
				%	10 ⁶ m ³		
1	Argeș	Vidraru	420,000	-	-	1967	Fl. Ionescu (1980)
2		Oiești	1,800	74	1,330	1967	I. Ichim <i>et al</i> (1994)
3		Cerbureni	1,620	68	1,100	1966	“
4		Curtea de Argeș	0,890	88	0,700	1972	“
5		Zigoneni	13,300	15	2,000	1973	“
6		Vilcele	40,000	62	2,500	1977	“
7		Bascov	5,400	93	5,000	1971	“
8		Pitești	4,800	85	4,000	1970	“
9		Ogrezeni	0,500	100	0,500	1967	“
10		Baciu	0,600	38	0,230	1967	“
11		Vilsan	0,200	50	0,100	1967	“
12		Cumpăna	0,260	38	0,100	1967	“
13		Budeasa	26,44	10,3		1980	D. Roșca (1987)
14	Ialomița	Paltinu	56,000	4	2,000	1972	Fl. Ionescu (1980)
15		Pucioasa	10,600	22	2,300	1974	“
16		Voila	0,500	70	0,350	1972	“
17	Olt	Săcele	18,300	1,6	0,300	1976	“
18		Vidra	340,000			1974	“
19		R. Vâlcea	19,000	33	6,300	1974	“
20		Dăești	10,800	32	3,500	1976	“
21		Riureni	7,300	14	1,000	1977	“
22		Govora	18,500	27	5,000	1975	“
23		Băbeni	59,650	8,3		1977	“
24		Străjești	202,70	3,2		1978	D. Roșca (1987)
25		Ionești		2,5		1980	“
26		Luduș	0,300	100	0,300	1964	Fl. Ionescu (1980)
27	Mureș	Mintia	5,000	74	5,700	1965	“
28		Cinciș	43,000	3,5	1,500	1969	“
29	Siret	Bucecea	14,400	12,8	1,85	1978 (evaluare pentru 1978-1986)	P. Olaru (1992)
30		Galbeni	40,000	18,9	7,500	1983 (evaluare 1984-1986)	“
31		Poiana Uzului	170,000	1,40	2,500	1975 (evaluare 1975-1986)	“
32		Iz. Muntelui	1230,000	1,3	16,000	1962	Rădoane (1983)
33		Pingărați	6,700	40	2,700	1964	Ciaglic <i>et al</i> (1973; Rădoane, 1986; 1999)
34		Vaduri	5,600	34,6		1966	Rădoane (1999)
35		Bitca Doamnei	10,000	27,2		1966	“
36		Piatra N.	12,000	3,4	0,400	1966	“
37		Racova	8,600	36	3,100	1964	P. Olaru (1992)
38		Gîrleni	5,100	37,4		1965	“
39		Lilieci	7,400	12,6		1966	“
40		Bacău	7,400	15,8	0,300	1966	“
41		Belci	12,000	50	6,000	1964 (distruș 1991)	“
42		Pușcași (r. Racova)	17,200	62,3	10,900	1973 (evaluare 1973-1998)	Gh. Purnavel (1999)
43		Antohești (r. Berheci)	0,220	40,91	0,090	1984 (evaluare 1984-1995)	“
44		Găiceana (r. Ghilăvești)	0,410	41,46	0,170	1984 (evaluare 1984-1995)	“
45		Cuibul Vulturilor (r. Tutova)	9,500	32,63	3,100	1978 (evaluare 1978-1992)	“
46		Rîpa Albastră (r. Simila)	10,600	21,13	2,240	1979 (evaluare 1979-1993)	“
47		Fitichești (r. Pereschiv)	5,500	52,60	2,890	1977 (evaluare 1977-1993)	“
48	Bahlui	Tansa	33,000	1	0,300		Pricop <i>et al</i> (1990)
49		Plopi	24,000	1	0,250		“
50		Pod Iloaiei	37,000	32,3	11,948	1964 (evaluare 1964-1975)	Zavati, Giurma (1982)
51		Cucuteni	14,000	5,43	0,761	1964 (evaluare 1965-1975)	“
52		Ezăreni	3,500	13,6	0,476	1963 (evaluare 1963-1975)	“
53		Ciubești	12,300	5,2	0,637	1963 (evaluare 1963-1975)	“
54		Chirița	7,500	13	0,100		Fl. Ionescu (1980)
		Aroneanu		19,98	0,296	1964 (evaluare 1964 – 1985)	Pricop <i>et al</i> (1990)
55	Jijia	Hălțeni	3,500		0,030	1981 (evaluare 1981-1989)	Amăriucăi, Hlihor (1990)
56	Jiu	Ișalnița	5,000	92	4,600	1960	Fl. Ionescu (1980)

Figure 5 – Sedimentation report for Romanian reservoirs (data based on direct measurements)

2.2. Sediment sources

Romania is located in a temperate-continental climate and the presence of the Carpathians are defining in the distribution and regime of geomorphological processes and which ultimately express the morphodynamical specificity of the territory, which gave a special importance to the alluvium runoff on internal river basins. The work of Diaconu (1971) exposed for the first time a global image of the erosion process that occur inside the country's territory, of great importance regarding the forecasts on the sedimentation of reservoirs. Subsequently, two syntheses were elaborated regarding a general picture of the Romanian relief dynamics. The first, having as author Motoc (1984), proposes an image on the entire territory of Romania, regarding the effluence of alluvium in relation to the main types of morphogenetic processes and the largest relief steps of the country. The second synthesis, elaborated by Mociornita and Brates (1987), is based on the entire data obtained from the national network of measurements, over a period of 35 years. After this date, no other updated syntheses are known to be conducted, except only resumes and interpretations of those mentioned, such as, for example, the one in the Unesco volum, redacted by Zavoianu, Walling, Serban (1999), entitled "Vegetation, land use and erosion processes".

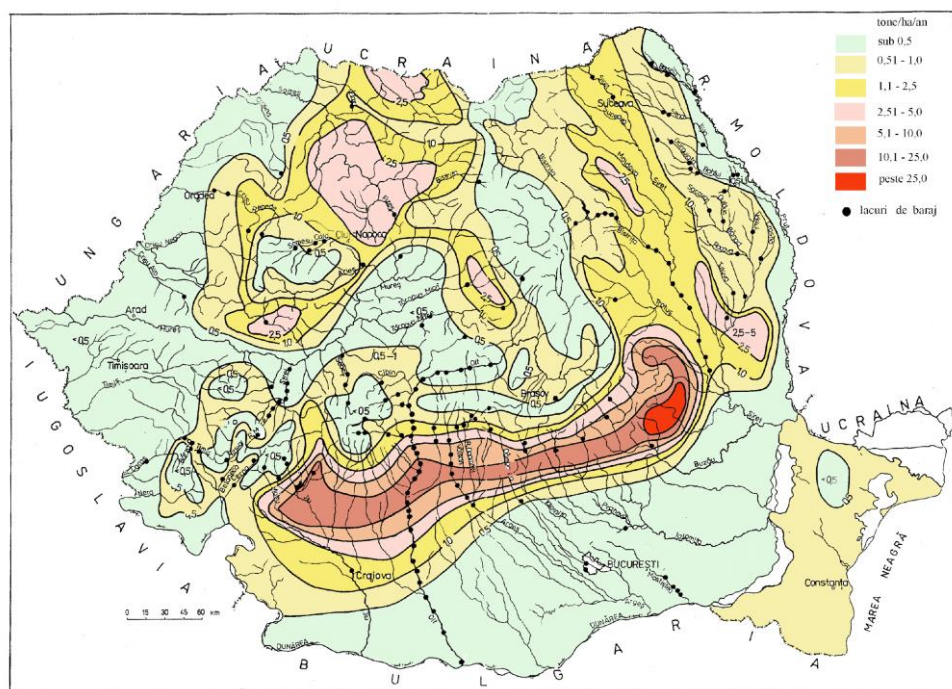


Figure 6 – Specific production of sediments in the Romanian territory

Two of the control factors, based on which the sediment sources for a large territory are analyzed, such as that of Romania, are the following: the lithological composition of the alluvial generating substrate and the size of the river basins that ensure a selection of alluvial

volumes transported from the source area to the effluent one. These factors are argued in literature (by authors who have proposed models in order to predict alluvial production, such as Gregory and Walling, 1976; Burns, 1978; Janson, 1982; Zachar, 1982; De Villiers, 1985; Yiu Guo Kang, 1985 etc., the model of progressive multiple regression for the evaluation of the alluvium production in river basins with an area under 400 km² (Ichim and Radoane, 1987).

2.3. Sedimentation stages

The steps of the sedimentation process in a reservoir, illustrated in the figure below, can be described as follows:

1. In natural regime the water course is characterized by a morphological stability;
2. The initial stage of the sedimentation process begins at the tail of the reservoir, where heavier bottom alluvium is deposited, forming the so-called reinforced bank;
3. The prism of the bottom alluvium advances over the prism created by the suspended alluvium, extending at the same time in the backwater zone, where an increase of the free surface level appears;
4. The sedimentation process continues, until after a certain number of hydrological cycles, the prism of suspended alluvium reaches the dam;
5. The initial volume of the reservoirs up to the Normal Retention Level is practically sedimented, the alluvium being partially deposited in the backwater area, and another being discharged downstream;
6. In the final theoretical stage of the process, the deposits evolved until the cancellation of the reservoir functions and the reappearance of the initial slope (i_0).

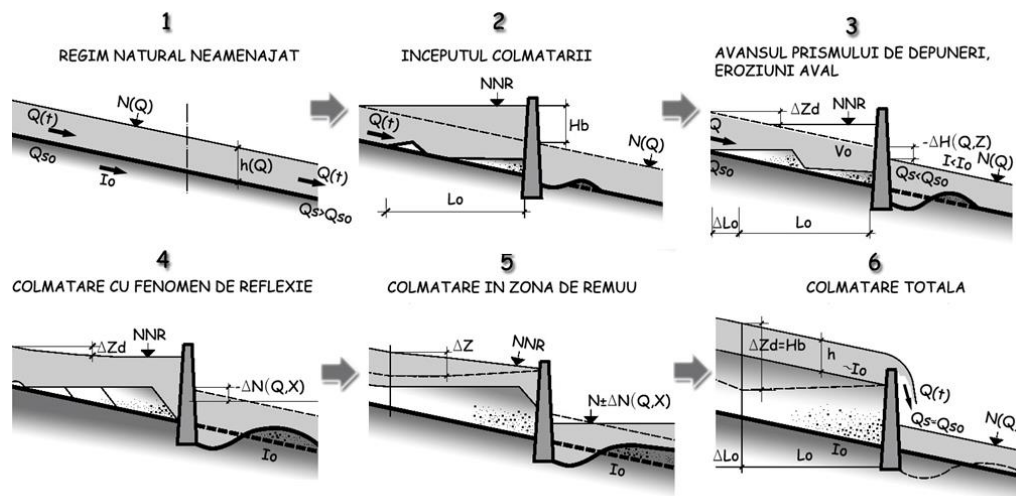


Figure 7 – Sedimentation stages

2.4. Sediment pressure on hydrotechnical structures

In reservoirs the velocity is reduced and as a consequence the sediments are deposited. The large grained sediments (sands and gravels) are deposited in the upstream part, and the finest sediments (clay and mud) reach the front of the dam. Fine sedimented particles are a mass of material whose mechanical proprieties are similar to those of a liquid, with an internal friction angle almost equal to zero. The pressure produced by these deposits on the dam is determined approximately, depending on a series of factors such as: interior friction angle, friction angle between alluvium and dam, volumetric weight, water saturation, slope, riverbed slope, etc.

Assuming a vertical linear variation of the alluvium pressure, the unit pressure at the base of a depth layer h_{al} , will be:

$$p_{al} = \gamma'_{al} \cdot h_{al}$$

where: $\gamma'_{al} = \gamma_{al} - \gamma \cdot (1 - n)$ – volumetric weight of alluvium in water;

γ_{al} –volumetric weight of dry alluvium;

γ – volumetric weight of water;

n – alluvium porosity.

Usually γ_{al} varies between 1.3 and 1.8 tones/m³, and porosity between 10% and 30%. At small thicknesses of the sediment layer in relation to the height of the dam, the pressures exerted on the face of the dam are reduced and consequently neglected. If the thickness of the sediment layer is large, the effect of the sediment pressure must be reduced in comparison to that resulting from the formula, taking into account zero friction angles, due to the effect of the pressure above.

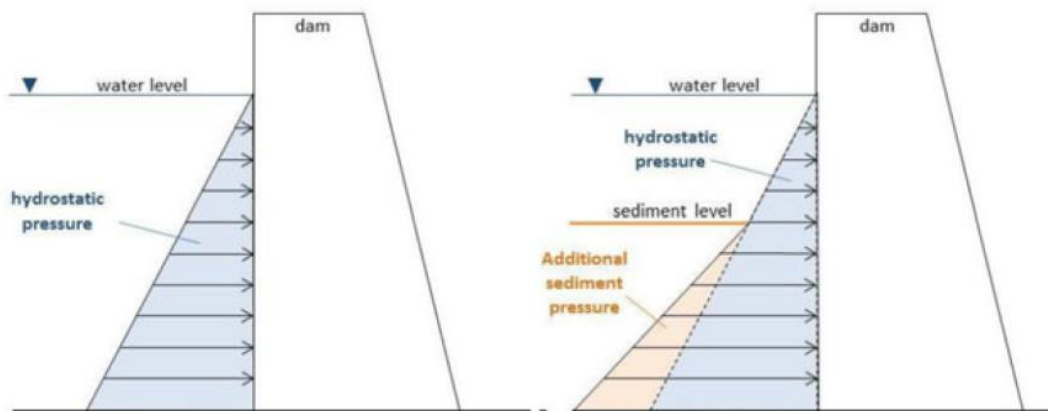


Figure 8 – Additional pressure from sediments

3. STABILITY OF THE MOBILE BED IN THE STORAGE AREA

3.1. Sediment movement

3.1.1. The general mechanism of sediment movement

Alluvium / sediments are solids in form of particles (granules) which, after their detachment from the earth's crust (riverbed) or from the earth's crust by the action of forces of any kind, under the force of water currents that form on the earth's surface.

Three phases can be distinguished in the movement of sediments:

- The **erosion** phenomenon which consists in the disintegration of the soil into granular particles under the action of water or other agents;
- The **transport** phenomenon, water serving as a fluid medium that drive the alluvium;
- The **sedimentation** of transported alluvium.

In general, in the mountainous and hill areas, erosion is strong and predominant, while the phenomenon of sedimentation occurs in the plain area. The transport phenomenon is followed by the particle wear, which results in a decrease in the diameter of the granules from the mountain to the plain. The finest particles are driven by the river water that flows into the seas and form deltas and contributes to the construction of coastal areas. The phenomenon of erosion and sedimentation also occurs in the area of hydrotechnical constructions in the operation period with significant effects.

For the study of the movement of alluvium in water flows, non-cohesive materials are considered, whose particles have an isolated movement, practically independent of each other, between them occurring phenomena that lead to an adhesion of the particles. It is also taken into account that the movement in the riverbed is turbulent.

The movement of alluvium in a stream of water takes place in jumps. In a turbulent current on an alluvium particle / granule located on the riverbed, act both longitudinal and ascending forces, whose sizes have a pulsating nature. Longitudinal forces are dependent on the opposition of the particles (shape and friction) and the vertical distribution of water velocities. Ascending forces are the result of pressure forces acting on the lower and upper sides of the particles.

The forces that oppose to the movement occur from their own weight under water and from the reactions of neighboring particles.

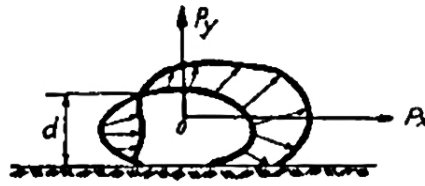


Figure 9 – Pressure distribution on a solid particle

The following forms of movement of isolated particles (Gilbert) can be distinguished:

- **sliding movement (a)** in which the particles are translated on the bottom of the bed without rotating;
- **rolling movement (b)** in which the particles roll around their axis;
- **saltation movement (c)** during which the particles initially located on the bottom on the riverbed are dislocated and follow a curvilinear trajectory and return to the bottom periodically;
- **suspended movement (d)** during which the particles are moving in a stream of water without coming in contact with the riverbed.

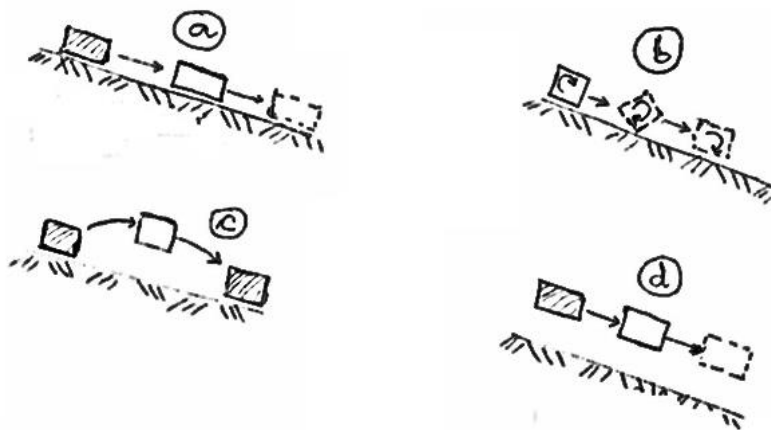


Figure 10 – Alluvium movement

3.1.2. Erosion and sedimentation

Erosion represents the dislocation and transport of soil elements throughout water, glaciers, wind and waves.

A particle is detached and tends to move due to the action of an active force (in the case of water the hydrodynamic force) and is held by its own weight and friction forces (in the case of water the friction force corresponding to the submerged weight).

At limit, by equalizing the forces that act on a particle and transposing them in the form of tangential efforts on the riverbed, the critical drive effort is obtained (τ_c), which corresponds

to a critical drive velocity (v_c). For real flows (turbulent - $Re > 2$), the critical drive velocity can be determined with the Shields function as follows:

$$v_c = 0,224 \sqrt{\left(\frac{\rho_s}{\rho} - 1\right) \cdot g \cdot d}$$

where: ρ_s – particle density (solid);

ρ – water density;

g – gravitational acceleration;

d – particle diameter.

Sedimentation represents the process by which suspended particles carried by water streams are deposited due to gravity. The rate of sedimentation (the rate at which particles are deposited) of particles under static conditions is given by Stokes' law:

$$V_s = \frac{g \cdot (s - 1) \cdot d^2}{18 \cdot \nu}$$

where: V_s – velocity limit for which the particle deposition occurs;

g – gravitational acceleration;

s – specific weight of the particle;

d – particle diameter;

ν – kinematic viscosity of the fluid.

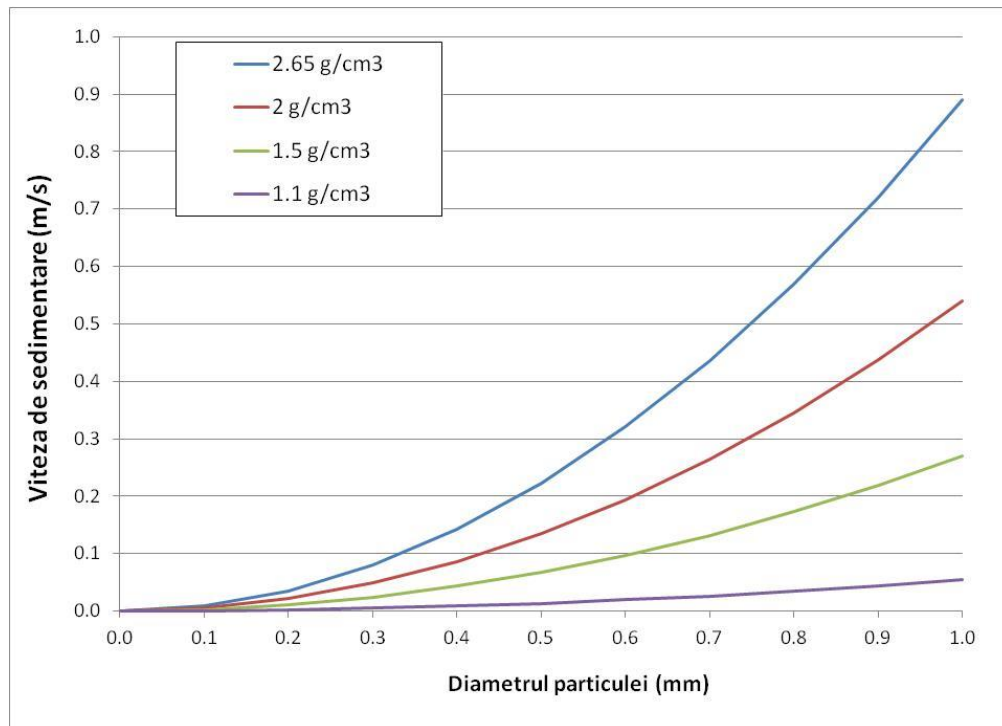


Figure 11 – Sedimentation rate according to Stokes' law
(for different particle types, having densities of 2,65; 2,0; 1,5; 1,1 g/cm³)

3.1.3. Sediment properties

The sediments that form the riverbed and those that form the solid flow are not composed of homogeneous particles but consist on a mixture of particles with different physical and geometric characteristics. The characteristics of sediment particles are:

- Granule size (d);
- Granule shape (k_v, k_s);
- Specific weight (γ_s, γ'_s);
- Settling velocity (w).

Depending on the size of the granules, sediment materials are divided into:

- clays $d > 0,005$ mm;
- dusts $0,005 < d < 0,05$ mm;
- sands $0,05 < d < 2$ mm;
- gravel $2 < d < 20$ mm;
- boulders $d > 20$ mm.

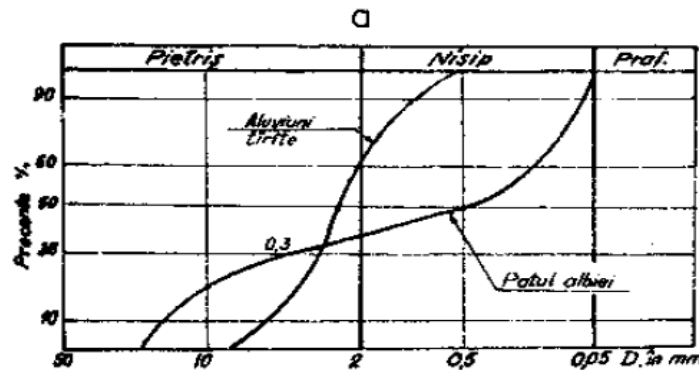


Figure 12 – Grading curve of sediments

Particle dimensions

The size of an alluvial particle is expressed by the minimum diameter of the sieve mesh through which the particle can pass. Because the alluvial layers are very heterogeneous in terms of the size of the composing particles, their characterization from this point of view is done by grading curves. The grading curves are obtained by analyzing the particle size and are graphical represented with the function $d = f(p)$.

The degree of non-uniformity of an alluvial layer, in terms of the size of particle composition, is expressed by a coefficient on non-uniformity defined as the ratio:

$$\mu = \frac{d_{60}}{d_{10}}$$

- For values $\mu < (3...4)$ the sediment layers are considered uniform;
- For values $\mu > (3...4)$ the sediment layers are considered uneven.

Particle shapes

The shape of alluvial particles is irregular and various. The shape influences their processes and type of movement. Thus, for example, a lenticular particle will move in a different way compared to an angular or ellipsoidal particle. For this reason, form parameters have been introduced that allow the evaluation of the form. Volume parameter (k_v) and surface parameter (k_s).

Volume parameter (k_v) represents the ration:

$$k_v = \frac{v}{d^3}$$

where: v is the volume of the particle;

d is the diameter of the circumscribed circle to the plane projection of the particle placed in the most stable position.

It can be observed that the maximum value of the volume parameter is obtained for a spherical particle:

$$k_v = \frac{\pi \cdot d^3}{6 \cdot d^3} = \frac{\pi}{6} = 0,524$$

The values of the volume parameter for natural alluvial particles are close to 0,4.

Surface parameter (k_s) is defined as the ration:

$$k_s = \frac{s}{d^2}$$

where: s is the surface of the plane projection of the alluvial particle;

d is the circumscribed circle to the plane projection of the particle.

The maximum value of the surface parameter, obtained for a spherical particle, is:

$$k_s = \frac{\pi \cdot d^2}{4 \cdot d^2} = \frac{\pi}{4} = 0,785$$

Specific weight

The specific weight of alluvial particles (γ_s) varies within the limits (21...28) kN/m³. The average specific weight is 26 kN/m³. The specific gravity in submerged state, (γ'_s) represents the specific weight measured under water and can be determined with the relation:

$$\gamma'_s = \gamma_s - \gamma$$

where: γ is the specific weight of the water ($\gamma = 9,81 \text{ kN/m}^3$).

Settling velocity

The settling velocity (w) represents the velocity of an alluvial particle that falls freely into water in the rest state. Is depended on the size of the alluvial particle (d) and its specific weight (γ_s). For **REYNOLDS** numbers:

$$R_e > 1; R_e = \frac{w \cdot d}{\gamma}$$

The settling velocity is given by the equation: $w = \frac{1}{18} \cdot \frac{\gamma_s - \gamma}{\mu} \cdot d^2$;

where: d is the diameter of the alluvial particle;

γ is the kinematic viscosity coefficient;

μ is the dynamic viscosity coefficient.

The settling velocity is used in particle size analysis performed by the sedimentation method.

Criteria for assessing the stability of bottom alluvium

The beginning of the movement of the riverbed alluvium can be assessed using one of the following criteria:

- flow rate criterion;
- tangential drive effort criterion;
- specific liquid flow criterion.

Mainly, in order to establish the beginning of the movement of the riverbed alluviums, the following values are compared:

- effective flow rate (u_{ef});
- tangential effort of effective drive (τ_{ef});
- the actual specific liquid flow (q_{ef}) with the following values:
 - ✓ critical flow rate (u_{cr});
 - ✓ critical tangential drive effort (τ_{cr});
 - ✓ critical specific liquid flow (q_{cr}).

The effective values of the parameters (u , τ , q) depend on the flow proprieties:

- hydraulic gradient (I);
- the size of the liquid flow (Q);
- the water depth in the riverbed (h);

The critical values of the parameters (u , τ , q) depend on the alluvium proprieties:

- size of alluvium particles (d);
- specific weight (γ_s sau γ'_s);
- shape of alluvium particles (k_v , k_s).

3.1.4. Tangential values of the drive force, flow rate in the riverbed and specific liquid flow

Effective tangential drive effort

Considering a sector in the river of length L , the force of the water through which the current in the river induce stress on the walls is equal to the tangential component of the weight of the volume of water:

$$F = G_T$$

where: F is the force induced by the water on the walls;

G_T is the tangential component of the weight of the volume of water.

The force F can be written as the result of the tangential driving effort induced on the lateral surface of the river sector:

$$F = \tau_{ef} \cdot P \cdot L$$

where: τ_{ef} is the tangential effective drive effort;

P is the wet perimeter on the river cross section;

L is the length of the considered river sector.

$$G_T = G \cdot \sin \alpha = \Omega \cdot L \cdot \gamma \cdot \sin \alpha$$

where: G is the weight of the volume of water in the river sector;

α is the angle made by riverbed with the horizontal line;

Ω is the cross-section area of the river.

By equalizing the two forces F and G_T is obtained:

$$\tau_{ef} \cdot P \cdot L = \Omega \cdot L \cdot \gamma \cdot \sin \alpha$$

$$\tau_{ef} = \frac{\Omega}{2} \cdot \gamma \cdot \sin \alpha = R \cdot \gamma \cdot \sin \alpha = R \cdot \gamma \cdot I$$

Effective flow velocity

The effective flow rate can be determined with the Chezy formula:

$$u_{ef} = c \cdot \sqrt{R \cdot I} = C \sqrt{h \cdot I}$$

$$c = \frac{1}{n} \cdot R^{1/6} = \frac{1}{n} \cdot h^{1/6}$$

$$u_{ef} = \frac{1}{n} \cdot h^{2/3} \cdot I^{1/2}$$

where: n rugosity coefficient:

h and I are explicated above.

The roughness coefficient (n) can be determined with direct measurements or by means of empirical equations:

- The deduction of the roughness coefficient (n) with direct measurements:

The geometric dimensions of the river sector and the hydraulic slope are established by topographic measurements; the liquid flow is determined by hydrometric measurements then the roughness coefficient is calculated from the Chezy formula:

$$n = \frac{1}{u_{ef}} \cdot h^{2/3} \cdot I^{1/2}$$

- The deduction of the roughness coefficient (n) with empirical equations:

CHANG equation:

$$n = 0,016 \cdot d_m^{1/6}$$

where: d_m is the average diameter of the alluvial particles in the riverbed expressed in (mm).

ALTUNIN-BUZUNOV equation:

$$n = \frac{1}{21} \cdot d_r^{1/6} = \frac{1}{21} (0,75 \cdot d_{90})^{1/6}$$

where: d_r is the representative diameter of the alluvium (mm);

d_{90} is the diameter 90 from the grading curve of alluvium in the riverbed.

Effective specific liquid flow

The actual specific liquid flow rate is determined starting from formula:

$$q_{ef} = \frac{Q}{B} = \frac{u_{ef} \cdot \Omega}{B} = \frac{1}{n} \cdot h^{2/3} \cdot I^{1/2} \cdot h$$

$$q_{ef} = \frac{1}{n} \cdot h^{5/3} \cdot I^{1/2}$$

Equilibrium limit of an isolated alluvial particle

In order to determine the calculation relation for the critical values of the parameters u_{cr} , τ_{cr} , q_{cr} , the equilibrium limit needs to be analyzed.

The alluvial particle is under the influence of the following forces

- G alluvial particle weight;
- H_1 frontal force of the water current;
- H_2 suction force of the water current;
- V the ascending force due to the pressure gradient produced by the large difference between the velocity of the water flow in the lower part of the particle and that in the upper part.

These forces can be expressed as follows:

$$H = H_1 + H_2 = k_1 \cdot \gamma \cdot \frac{u_f^2}{2 \cdot g} \cdot d^2$$

$$V = k_2 \cdot \gamma \cdot \frac{u_f^2}{2 \cdot g} \cdot d^2$$

$$G = k_3 \cdot (\gamma_s - \gamma) \cdot d^3$$

where: k_1, k_2, k_3 are the surface and volume parameters;

$(\gamma_s - \gamma)$ is the specific submersed weight;

u_f is the velocity in the riverbed area;

g is the gravitational acceleration;

d is the diameter of the alluvium particle.

The suspended movement hypotheses

The equilibrium equation in case of suspended movement is:

$$G = V$$

or by replacement:

$$k_3 \cdot (\gamma_s - \gamma) \cdot d^3 = k_2 \cdot \gamma \cdot \frac{u_f^2}{2 \cdot g} \cdot d^2$$

The velocity at the riverbed (u_f) must be replaced by the average velocity (u) so a value of the critical velocity can result, comparable to the value of the actual velocity determined as the average speed in Chezy's equation. For this purpose, the following replacement needs to be made:

$$u_f = \alpha \cdot u$$

where: u is the average flow rate;

α is a mediation coefficient whose values vary within the limits (0,5...0,8).

$$k_3 \cdot (\gamma_s - \gamma) \cdot d = k_2 \cdot \gamma \cdot \frac{\alpha^2 \cdot u^2}{2 \cdot g}$$

The dragging movement on the riverbed hypotheses

The equilibrium equation in case of the dragging movement is:

$$(G - V) \cdot f = H$$

where: f is the friction coefficient.

$$\left[k_3 \cdot (\gamma_s - \gamma) \cdot d^3 - k_2 \cdot \gamma \cdot \frac{u_f^2}{2 \cdot g} \cdot d^2 \right] \cdot f = k_1 \cdot \gamma \cdot \frac{u_f^2}{2 \cdot g} \cdot d^2$$

$$k_3 \cdot (\gamma_s - \gamma) \cdot d \cdot f = (k_1 + k_2 \cdot f) \cdot \gamma \cdot \frac{u_f^2}{2 \cdot g}$$

The following result can be obtained by a procedure similar to the one used previously

$$u_{cr} = a_2 \sqrt{g \cdot d}$$

$$a_2 = \frac{1}{\alpha} \sqrt{\frac{2 \cdot k_3 \cdot f}{k_1 + k_2 \cdot f} \frac{(\gamma_s - \gamma)}{\gamma}}$$

Rolling movement hypothesis

The equilibrium equation in the case of the rolling motion hypothesis is a momentum equation. In order to write the momentum equation, the following are necessary to be known:

- ✓ The position of the point around which the rolling movement occurs;
- ✓ The distance between the respective point and the point of application of the forces that stresses the alluvial particle.

In order to know the elements mentioned above, it is sufficient to consider two additional hypotheses regarding the shape of the alluvial particles and the position of the point around which the rotation occurs.

In consequence it is assumed that the alluvial particle has a circular shape in a vertical section and that the rolling movement occurs around a point A. The equilibrium equation for the rolling movement hypothesis is:

$$(G - V) \cdot \frac{d}{2} \cdot \sin\beta = H \cdot \frac{d}{2} \cdot \cos\beta$$

$$(G - V) \cdot \operatorname{tg}\beta = H$$

This equation has the same form as the equilibrium equation in the dragging movement hypothesis where:

$$\operatorname{tg}\beta = f$$

Even the physical significance of the parameter ($\operatorname{tg}\beta$) is very close to the friction coefficient (f) since (β) can be interpreted as the friction angle of the alluvium. The expression of the critical velocity in the rolling movement hypothesis is:

$$u_{cr} = a_3 \sqrt{g \cdot d}$$

where:

$$a_3 = \frac{1}{\alpha} \sqrt{\frac{2 \cdot k_3 \cdot \operatorname{tg}\beta}{(k_1 + k_2 \cdot \operatorname{tg}\beta)} \frac{(\gamma_s - \gamma)}{\gamma}}$$

Conclusion

It can be easily observed that the general form of the expression for deducing the critical velocity is independent of the alluvial particle movement hypothesis. In general, it is:

$$u_{cr} = a\sqrt{g \cdot d}$$

The coefficient (a) has different forms (a_1, a_2, a_3) depending on the considered movement hypothesis. The value of this coefficient determined experimentally varies within the limits:

$$A = (5 \dots 5,8)$$

Airy's law

Starting from the general form of the critical velocity, the diameter of the alluvial particle that the water flow can dislocate is:

$$d = \frac{1}{g \cdot a^2} \cdot u^2$$

The weight of the alluvial particle is:

$$G = k_v \cdot (\gamma_s - \gamma) \cdot d^3 = \frac{k_v \cdot (\gamma_s - \gamma)}{g^3 \cdot a^6} u^6$$

$$G = A \cdot u^6$$

where A is a coefficient with the following value:

$$A = \frac{k_v \cdot (\gamma_s - \gamma)}{g^3 \cdot a^6}$$

Airy's law shows that the weight of alluvial particles upon who the water can induce movement increases direct proportional with the flow rate at the sixth power. This means that a small increase in the flow rate leads to a significant increase in the weight of alluvial particles displaced by the current.

Example:

- For a flow rate of 1 m/s the weight of the alluvial particle displaced by water is G;
- For a flow rate of 2 m/s the weight of the displaced particles is 64 G.

Airy's law is valid for large alluvial particles that satisfy the following condition:

$$\frac{h}{d} \leq 10$$

Critical values of velocity, tangential drive effort and specific liquid flow

M.A. Velicanov established the value of the critical drive velocity considering an isolated particle and the rolling movement hypothesis:

$$u_{cr} = 3,14 \cdot \sqrt{15 \cdot d_m + 0,006}$$

where: d_m is the average diameter of the alluvial particles (m).

I.I. Levi analyzed the stability of the homogeneous alluvial layer considering the dragging movement hypothesis. The horizontal force that causes the movement is the tangential drive effort:

$$\tau = \gamma \cdot I \cdot h = \gamma \cdot \frac{I \cdot h \cdot c^2}{c^2} = \gamma \cdot \frac{u^2}{c^2}$$

because: $I \cdot h \cdot c^2 = u^2$

considering:

$$\lambda = \frac{8 \cdot g}{c^2}$$

or

$$c^2 = \frac{8 \cdot g}{\lambda}$$

results:

$$\tau = \gamma \cdot \frac{u^2}{8 \cdot g}$$

Adding the flow rate in the river $u_f = \alpha \cdot u$ results:

$$T = \gamma \cdot \lambda \cdot \frac{u_f^2}{8 \cdot \alpha^2 \cdot g}$$

where: c is the ratio between the surface on which the ascending force and the total surface act, the weight of the alluvial layer is:

$$G = m \cdot d_m \cdot (\gamma_s - \gamma)$$

the ascending force is:

$$v = k \cdot \gamma \cdot m \cdot c \cdot \frac{u_f^2}{2 \cdot g}$$

the limit slip equilibrium relation is:

$$(G - V) \cdot f = \tau$$

$$\left[m \cdot d_m \cdot (\gamma_s - \gamma) - k \cdot \gamma \cdot m \cdot c \cdot \frac{u_f^2}{2 \cdot g} \right] \cdot f = \gamma \cdot \lambda \cdot \frac{u_f^2}{8 \cdot \alpha^2 \cdot g}$$

critical riverbed velocity is:

$$u_f \cdot cr = \sqrt{g \cdot d_m \cdot \frac{2 \cdot (\gamma_s - \gamma) \cdot f \cdot m}{\left(\frac{\lambda}{4 \cdot \alpha^2} + k \cdot c \cdot f \cdot m\right)}}$$

considering a , the bottom of velocity:

$$u_f \cdot cr = a \cdot \sqrt{g \cdot d_m} = \frac{1}{\sqrt{\lambda + k \cdot cvf \cdot m \cdot \alpha^2}}$$

It has been demonstrated experimentally that λ , k , α are functions of the relative roughness of the riverbed ($\frac{h}{d_m}$), and the previous relations can be written as:

$$u_{cr} = a \cdot \sqrt{g \cdot d_m} \cdot f \cdot \left(\frac{h}{d_m} \right)$$

Levi established experimentally the function $f \left(\frac{h}{d_m} \right)$ as:

- ✓ for $\frac{h}{d_m} > 60$; $u_{cr} = 3,2 \cdot \sqrt{g \cdot d_m} \cdot \log \left(\frac{h}{d_m} \right) \left(\frac{d_{max}}{d_m} \right)$
- ✓ for $10 < \frac{h}{d_m} < 60$; $u_{cr} = 1,4 \cdot \sqrt{g \cdot d_m} \left(1 + \ln \sqrt{\frac{h}{7 \cdot d_m}} \right) \cdot \left(\frac{d_{max}}{d_m} \right)$

where: d and h are expressed in meters.

Goncharov, using a similar procedure stability procedure for uniform alluvial layers:

- ✓ for $d_m > 1,5 \text{ mm}$ and $\frac{d_m}{h} \leq \frac{1}{5000}$
- $$u_{cr} = 1,4 \cdot \sqrt{g \cdot d_m} \left(\frac{d_m}{d_{max}} \right)^{\frac{1}{n}} \cdot \log \frac{12 \cdot h}{d_{90}} \text{ (m/s)}$$

where: $n = (8 \dots 10)$, h , d are expressed in (m).

- ✓ for $0,25 \text{ mm} < d < 1,5 \text{ mm}$

$$u_{cr} = 35 \cdot d_m^{0,25} \cdot \left[\log \left(7,5 \cdot \frac{h}{d_m} \right) - 6d_m \right] \text{ (m/s)}$$

where: h , d are expressed in (mm).

Starting from the limit equilibrium of rolling movement and admitting a logarithmic distribution of velocities near the riverbed, Goncharov obtained:

$$u_{cr} \cdot a = \log \frac{8,8 \cdot h}{d_{90}} \sqrt{\frac{2 \cdot g \cdot d_m}{3,5} \cdot \frac{(\gamma_s - \gamma)}{\gamma}}$$

where: $u_{cr}a$ is the limit value of the velocity that ensures the absolute stability of the alluvial particles. The start of the alluvial particle movement occurs for riverbed values higher than 40%. This means that the initial critical velocity is:

$$u_{cr} \cdot i = 1,4 \cdot u_{cr} \cdot a$$

Critical tangential drive effort

Starting from the limit equilibrium equation of an isolated particle:

$$(G - V) = H$$

By introducing the expressions of the forces G , V , H , replacing the riverbed velocity with the average velocity ($u_f = \alpha \cdot u$) and rearranging the terms of the equation results:

$$f \cdot k_3 \cdot d^3 \cdot (\gamma_s - \gamma) = (k_1 + f \cdot k_2) \frac{u^2}{2 \cdot g} \gamma \cdot d^2 \cdot \alpha^2$$

Multiplying and dividing the right member by 4λ results in:

$$f \cdot k_3 \cdot (\gamma_s - \gamma) \cdot d = \frac{4 \cdot (k_1 + f k_2)}{\lambda} \cdot \lambda \cdot \gamma \cdot \frac{u^2}{8 \cdot g} \cdot \alpha^2$$

$$\gamma \cdot \lambda \cdot \frac{u^2}{8 \cdot g} = \tau$$

$$\tau_{cr} = A \cdot (\gamma_s - \gamma) \cdot d$$

Critical specific liquid flow

Starting from the general expression of the specific liquid flow:

$$q = \frac{1}{n} \cdot I^{1/2} \cdot h^{5/3}$$

Considering Chang's formula for the roughness coefficient and expressing the depth of the water in the river from the relation of the critical tangential drive effort:

$$h = \frac{\tau_{cr}}{\gamma \cdot I} = \frac{A \cdot (\gamma_s - \gamma)}{\gamma \cdot I}$$

we can obtain the general expression for the critical specific liquid flow:

$$q_{cr} = k \cdot \frac{d_m^{m_1}}{I^{m_2}}$$

where: coefficient (k) and exponents (m_1), (m_2) have different values.

3.2. Sediment transport

3.2.1. General description

If the value of the shear force acting on the ground exceeds the critical value then the sediment transport occurs (when $\tau_0 > \tau_{0,cr}$, results q_s).

According to the origin of the transported material, the difference is made by the following:

- 1) Alluvial deposits – their origin is located in the alluvial layer, and the mode of transport is in the form of an alluvial bed depending on the size of the particles in the layer and the flow conditions.
- 2) Flow of transported alluvium - the size of the particles is smaller than that of the particles in the alluvium layer, and their source of origin is external (erosion). They are transported only as a suspended load, their size being, in general, less than 50 m. They are defined by the upstream incoming quantity and not by the composition and proprieties of the material from the alluvial bed. The flow of alluvium is mostly

determined by the erosion of the land surface. Depending on the particle size of the material and the flow conditions, the sediment particles move as follows:

- alluvial bed: the movement of particles is in permanent contact with the bed, by rolling, dragging or disordered movement;
- suspended load: the movement of particles in the current. The suspended load contains part of the alluvium deposits (particles < 50 µm).

The materials from the alluvial bed, which make up the coarse part, are transported near the riverbed. The bed layer is considered to be a layer in which the mixture caused by the turbulence is so low that it cannot influence the sedimented particles and therefore the suspension of the particles is impossible in the alluvial layer. The average distance traveled by any particle in the alluvial layer (as a series of successive movements) is a constant distance summing the diameters of 100 particles independent of the flow state, the transport rate and the composition of the layer in the alluvial bed.

The load of the material from the alluvial bed is stored mainly at the base of the reservoirs, this being the main cause of the morphological changes' characteristic to alluvial rivers. There are a number of numerical formulas to predict the transport of alluvium, some of which are presented below:

1) Van Rijn (1984)

Van Rijn assumes that the motion of alluvial particles is dominated by their jump, under the influence of hydrodynamic forces and gravity. After 130 experimental studies with water depth < 0,1 m, Freud's number < 0,9 and particles with a diameter between 200 – 2000, he defined the rate of alluvium transported as follows:

$$q_b = 0,053 \cdot [(s - 1) \cdot g]^{0,5} \cdot D_{50}^{1,5} \cdot D_*^{-0,3} \cdot T^{2,1}, \text{ for } T < 3$$

$$q_b = 0,1 \cdot [(s - 1) \cdot g]^{0,5} \cdot D_{50}^{1,5} \cdot D_*^{-0,3} \cdot T^{2,1}, \text{ for } T \geq 3$$

Where T is a parameter of the shear stress given by the relation:

$$T = \frac{\tau'_0 - \tau_{0,cr}}{\tau_{0,cr}}$$

where: s – relative density;

D₅₀ – particles with diameter 50;

D* - dimensionless particles;

$\tau_{0,cr}$ - critical shear stress moment, [N/m²];

G – gravitational acceleration [m/s²].

2) Meyer-Peter-Mueller (1948)

After experimental studies on cross sections with dimensions 2x2 m, length of 50 m, particle diameter 0,4-29 mm, slope between 0,0004-0,02, and water depth 0,1-1,2 m, it was developed a formula for the rate of alluvium transport as:

$$q_b = 8 \cdot \sqrt{(s-1) \cdot D_m^3} \left(\mu \cdot \frac{h \cdot I}{(s-1) \cdot D_m} - 0,047 \right)^{1,5}$$

$$\mu = \left(\frac{c}{c'_{90}} \right)$$

$$c = 18 \cdot \log \left(\frac{12 \cdot h}{k_s} \right)$$

$$c'_{90} = 18 \cdot \log \left(\frac{12 \cdot h}{D_{90}} \right)$$

where: D_m – diameter of the most important particle [m];

μ – form or efficiency factor;

h – water depth [m];

I – energy gradient;

k – actual bed roughness;

s – relative density;

c – Chezy's coefficient.

If the value of the shear velocity exceeds the settling velocity of the particles, it means that they can be lifted to a level where the turbulent forces are equal or even greater than the weight of the immersed particles. The concentration of the suspended load decreases as it approaches the surface, and the decrease rate depends on the ratio between the settling velocity and the value of the shear velocity (w_s/u_*) (Van Rijn, 1993). The particle settling velocity is an important parameter in the study of suspension and sedimentation. The velocity of the settling particles is given by the equation:

$$w_s = \left[\frac{4 \cdot (s-1) \cdot g \cdot D}{3 \cdot C_D} \right]^{0,5}$$

the C_D depends on the Reynolds number and the particle shape coefficient. When $Re < 1$ the $C_D = 24 / Re$ and then the equation of the settling velocity of the particles is given by:

$$w_s = \frac{(s - 1) \cdot g \cdot D^2}{18 \cdot \nu}$$

where: ν - kinematic viscosity coefficient [m²/s].

The most suitable way to simulate sediment suspension is by using the Advection – Diffusion equation. Despite this, several formulas have been developed to be able to express the load of suspended sediments. This was due to the difficulty of calculating the suspended sediments using the complex Advection – Diffusion equation.

The integrated depth of suspension transport is defined by Van Rijn (1993) as the product of the velocity (u) and the concentration (c) at the loading edge of the bed layer (z = a) at the water surface (z = h) by the formula:

$$q_s = \int_a^h uc^* dz$$

This equation requires information on the velocity profile, concentration as well as a known reference concentration (c_a) at z = a.

The basic equation that describes the distribution of the concentration in uniform constant flow and low concentration because the settling velocity of the particles is supposed to be constant. The equation is expressed by the means of the following:

$$C^* w_s + \epsilon_s \frac{dc}{dz} = 0$$

Chien (1954) applies the above formula in order to determine the z parameter from measured concentration profiles. The measured values of z (z = w_s/βku_{*}) were compared with the measured values of z, and the results revealed that the measured values of z were lower, which can be interpreted as a factor greater than 1.

$z = \frac{w_s}{\beta \kappa u_*}$	$\frac{u_*}{w_s} (\kappa = 0.4, \beta = 1)$	Distributia particulelor suspendate in functie de adncime
5	0.5	Particule suspendate in apropierea stratului de pat ($z < 0.1h$)
2	1.25	Particule suspendate la mijlocul adancimii ($z < 0.5h$)
1	2.5	Particule suspendate la adancimea apei
0.1	25	Particule suspendate aproape uniform in adancime

Figure 13 – Distribution of suspended particles depending on the depth

In mixtures with high concentrations, the settling velocity of particles is not constant, but depends on the concentration because the particles that obstruct each other during settling. Van Rijn (1993) represents the liquid mixture coefficient (ϵ_f) as:

$$\epsilon_f = \kappa u_* h \frac{z}{h} \left(1 - \frac{z}{h}\right)$$

In lower regime, the diffusion of sedimented particles is closely related to the liquid mixture coefficient (ϵ_s) as follows:

$$\epsilon_s = \beta \epsilon_f$$

β is the factor that describes the difference in diffusion of liquid particles and a discrete phase particle in the sediment that is supposed to be constant in depth:

Van Rijn (1984) describes the factor as:

$$\beta = 1 + 2^* \left(\frac{w_s}{u_*}\right), \text{ for } 0.1 < \frac{w_s}{u_*} < 1$$

A value of $\beta > 1$ reveals a dominant influence of the centrifugal force due to which the particles are whirled at the same time as the same with the increase of the effective mixing length, therefore is not advised to use a value greater than 2.

Full load transport. It is difficult to tell the difference between a bed load and the transport of the suspended load. Some material from the bed load is transported as a suspended load, and because of this there are certain formulas that determine the sediment load as a total load. This represents the total amount of the bed load. There are also some direct empirical formulas that determine the load. Some of them are explained below:

Engelund-Hansen (1967): The method is based on the concept of energy balance:

$$q_t = 0,05 \cdot \sqrt{g \cdot (s - 1) \cdot D_{50}^3} \left(\frac{h \cdot I}{(s - 1) \cdot D_{50}} \right)^{5/2} \cdot \frac{C^2}{g}$$

Einstein (1950), Bagnold (1966), Bijker (1971), VanRijn (1984): The total load of the particles can be obtained by summing q_b with the suspended transport load:

$$q_t = q_b + q_s$$

3.2.2. Sediment transport due to the density currents

If water on a preset density moves to water with a slightly different density, the flow can be sunken. The difference in density depends on the temperature, salt concentration or even both (Vanoni, 1977).

In general, the specific weight of the “influent flow” is higher that of the reservoir because it carries sediment and it is transferred on the stratification. The point at which the inflow of the river disappears below the surface of the reservoir is called the immersion point.

The water flow carries mostly particles of fine materials such as clay and mud and moves near the bed, at the base of the dam forming soft deposits as shown in the image below. According to Vanoni (1977), the relationship between sediment concentration and weight difference in specific gravity is:

$$\frac{\Delta\gamma}{\gamma} = \frac{C}{100} \cdot \left(1 - \frac{S_f}{S_s} \right)$$

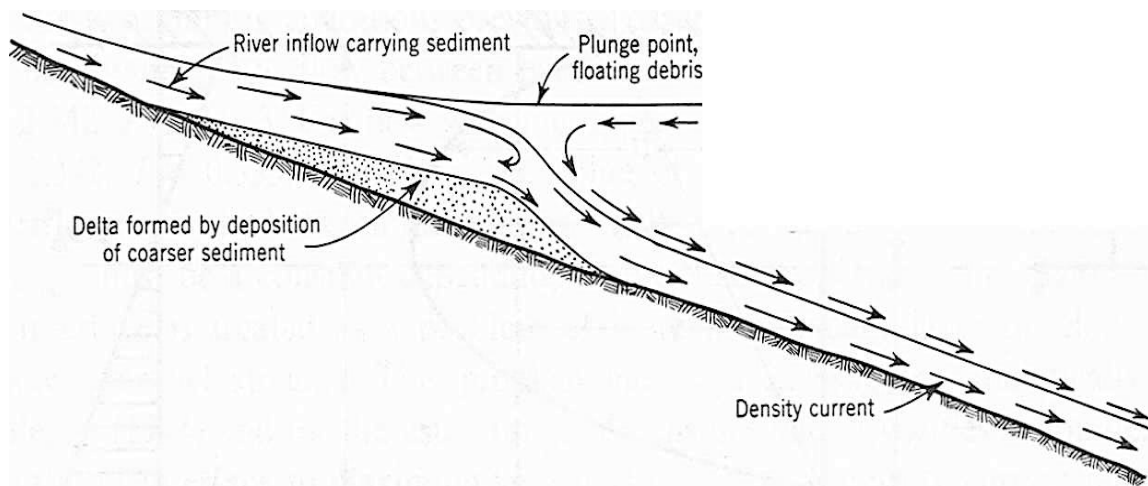


Figure 14 – Deltaic deposits formation

3.2.3. Sediment deposit

Reservoir sedimentation is the process of sediment depositing after dam construction. The construction of a dam determines a reduction of the flow that produces the settlement transported by the influent flows (Yonas, 2005).

Sediment depositing in a reservoir causes a decrease in terms of water storage capacity, inadequate navigation, loss of benefits due to downstream floods, sediment in hydropower equipment, blockage of intakes and gates etc. (Yonas, 2005).

The sedimentation of the reservoir is closely related to the settling rate which depends on the shape and size of the sediment particles, water density, settling rate W_s , steady time, (ratio between the storage capacity of the reservoir m^3 and the discharge flow m^3/s). Depending on the method of transport, we encounter two types of deposits: alluvial deposits and the settling of the suspended load. The consequences and types of reservoir sedimentation are showed below:

Alluvial deposits. Particles in alluvial deposits tend to deposit when the velocity of the water near the bed decreases due to changes in hydraulic conditions, the velocity becoming less than the critical velocity (V_{cr}). According to Van Rijn, the critical speed is given by the formula:

$$V_{cr} = 8,5 \cdot D_{50}^{0,6} \cdot \log \left(\frac{12 \cdot h}{3 \cdot D_{90}} \right) \text{ for coarse sediments } 0.5 < D < 2.0 \text{ mm}$$

$$V_{cr} = 0,19 \cdot D_{50}^{0,1} \cdot \log \left(\frac{12 \cdot h}{3 \cdot D_{90}} \right) \text{ for fine sediments } 0.1 < D < 0.5 \text{ mm}$$

Suspension load deposits. Suspended sediments remain in this state until their terminal velocity is lower than the vertical velocity. Some of the very small particles such as clay and mud cannot be deposited due to their very small weight, but due to the cohesion of two or more sedimented particles flakes are formed which have a bigger weight and the higher terminal velocity being thus able to deposit as coarse particles (Vanoni, 1975). Engelund (1965) provides the following criteria to indicate the suspension and deposition of suspended particle. Deposition occurs when the critical velocity is 0,25 time lower than the deposition rate.

$$\frac{V_{cr}}{w_s} = 0,25$$

4. EVOLUTION OF THE SEDIMENTATION PROCESS IN EXISTING RESERVOIRS

4.1. Reservoir Prundu

Among the reservoirs in Romania that are significantly affected by the clogging phenomenon is Prundu dam located on Arges river. The hydrotechnical structure, with a designed volume of 2,288 million m³, was put into operation in 1971 with multiple functions: water supply for industry, irrigation, hydroelectricity and flood mitigation.

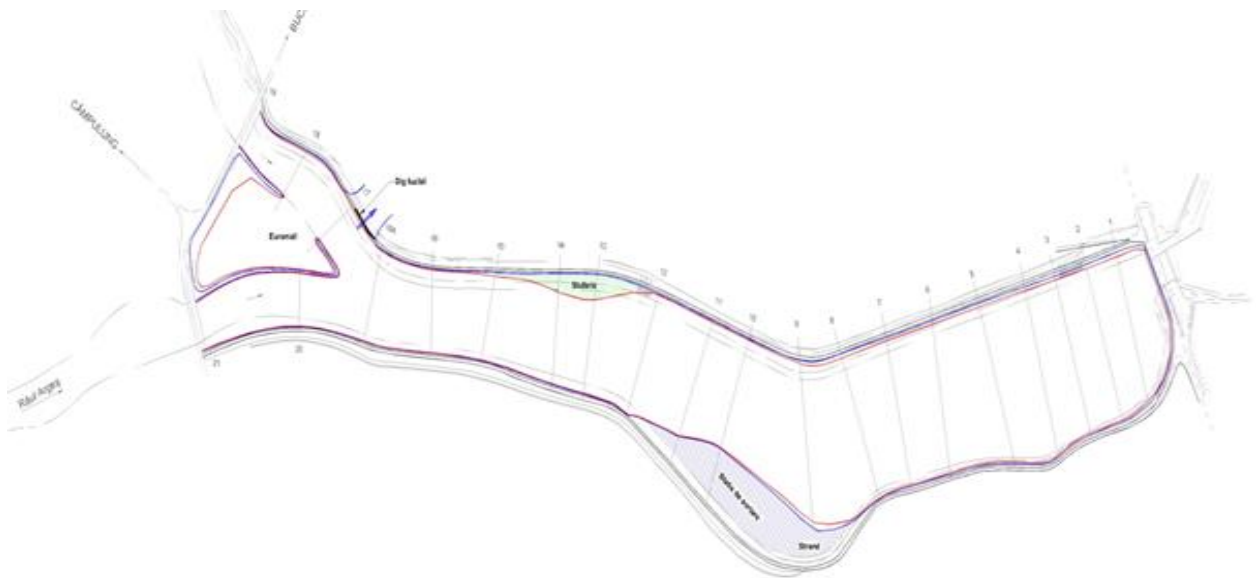


Figure 15 – General layout of Prundu reservoir

Located on the middle course of the Arges river, in an area subjected to erosion, the reservoir has suffered since the commissioning, during the operation period 1971 - 1976, of a strong sedimentation process that led to the raising of the reservoir bed by 3 - 4 m.

According to the topo-bathymetric measurements performed by ISPH (Institute of Hydropower Studies and Designs) in 1976, it was revealed that the reservoir was clogged in a percentage of approximately 87%, between 1971 and 1976. Given the high rate of sedimentation of the reservoir, in order to ensure the normal operation of the functions (flood protection water supply), works were carried between 1978 and 1986 in order to raise the embankments and the same time sediment removal measures were taken (dredging of the reservoir). Following visual observation made in the period on which the reservoir was emptied, revealed that currently the degree of sedimentation is 85%.

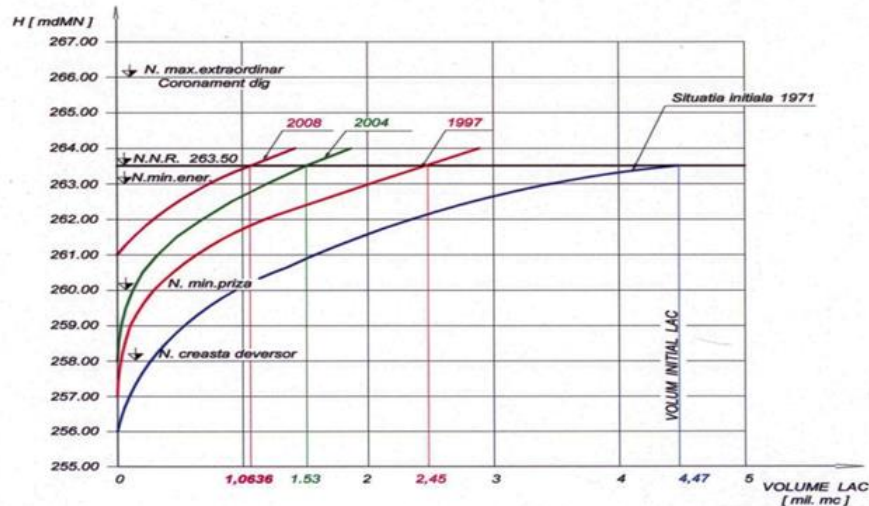


Figure 16 – Storage curve evolution since commissioning (1971)

4.2. Reservoir Pucioasa

Pucioasa reservoir is located on the middle course of Ialomita river, downstream of its confluence with Ialomicioara 2 river (west), but upstream the confluence with the Bizdidel river, with a catchment area of 436 km². The reservoir is located in the sub-Carpathian area, which explains the high sedimentation rate.



Figure 17 – General layout of the Pucioasa reservoir

Bathymetry measurements of Pucioasa reservoirs were performed ever several years: 1993, 1999, 2002, 2006, 2009, 2010, 2016, measurements that indicated a reduction by one third (33%) of the storage at Normal Retention Level, between the years 2010 – 2016, from 3,31 to 2,22 million m³. The degree of sedimentation indicates a significant increase from 65,2%, in 2010, to 76,6%, in 2016, higher than the average of the entire 43-year period (1,78%). Despite that in 2011 the reservoir was completely emptied of water, it was not possible to carry out efficient flushing procedures, as happened during the floods in 2005 – 2007. This represented the main reason why the sedimentation rate has been risen.

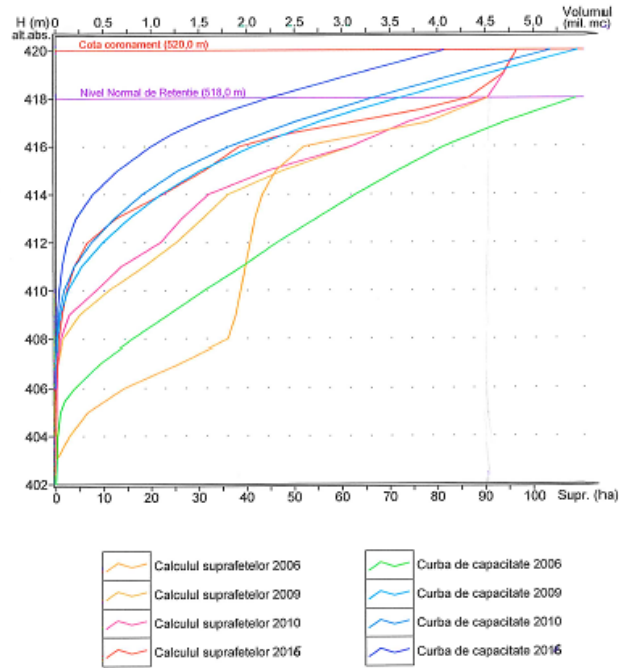


Figure 18 – Storage and surface curve of Pucioasa reservoir (2006 – 2016)

4.3. Three Gorges Dam

The Three Gorges Dam is located on the Yangtze River with the main use for flood mitigation and hydropower. The Yangtze River is the longest river in China and is ranked 3rd in the world, with a length of 6 390 km. The multiannual average flow of the Yangtze River is 32 000 m³/s (Danube 6 500 m³/s) and led to the development of a hydroelectrical power plant with an installed capacity of 22 500 MW (2 100 MW – Iron Gates 1).



Figure 19 – Three Gorges Dam

According to conducted studies, the annual amount of sediments stored in the reservoir is approximately 1,64 billion tons and represents only 40% of the predicted value during the design period. Studies show that the sedimentation process occurs predominantly during flood periods. In July 2013, 103 million tons of sediments were registered, representing 81% of the total annual quantity, being mainly concentrated between 11 and 16 July during a major flood. During the before mentioned flood, the total amount of sediment was 60,5 million tons, representing 50% of the total annual quantity. The results of the studies according to which the sedimentation process occurs in a single flood offer advantages regarding the optimization measures to control floods in order to increase the amount of sediments discharged from the reservoir, respectively the amount of sediment deposited.

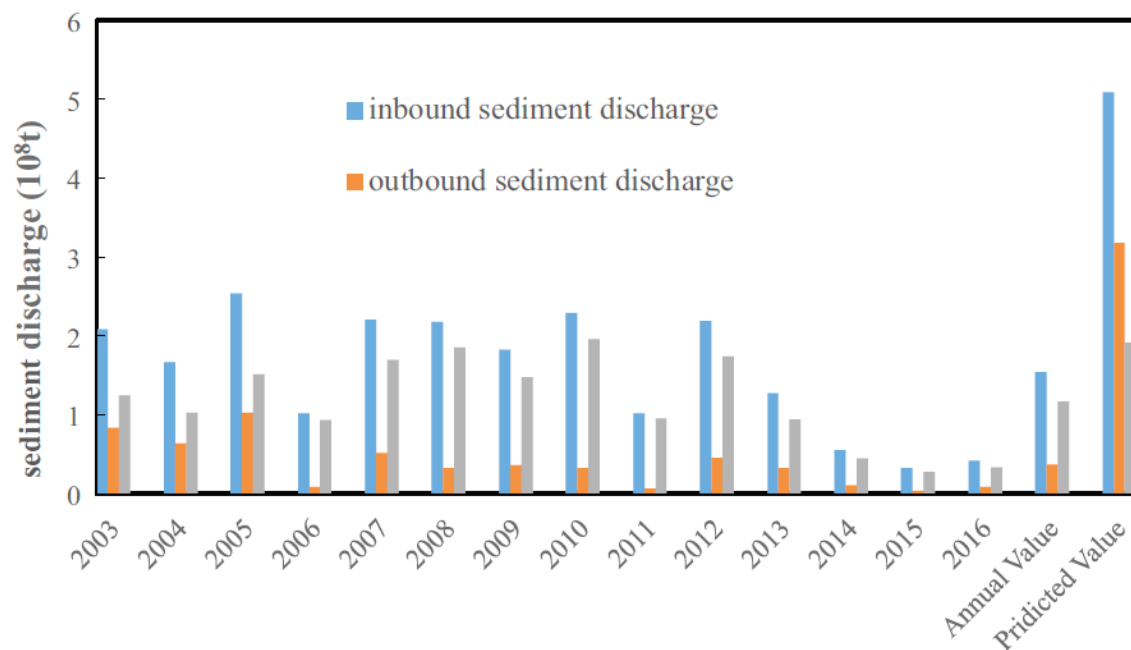


Figure 20 – Sediment balance in Three Gorges Reservoir

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