The future of reservoirs in the Siret River Basin considering the sediment transport of rivers (Romania)

Petru OLARIU[1], Gianina Maria COJOC[1]*, Alina TIRNOVAN[1] and Florin OBREJA[1]
[1] Siret Water Administration

* Correspondence to: Gianina Maria Cojoc, Siret Water Administration, Romania. E-mail: nigiana_c@yahoo.com.

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ABSTRACT: The Siret River Basin is characterized by an important use of hydro potential, resulted in the number of reservoirs constructed and operational. The cascade power stage of the reservoirs on Bistrita and Siret rivers indicate the anthropic interventions with different purposes (hydro energy, water supply, irrigation etc.) in the Siret River Basin. In terms of the capacity in the Siret River Basin there is a dominance of the small capacity reservoirs, which is given by the less than 20 mil m³ volumes. Only two lakes have capacities over 200 mil m³: Izvoru Muntelui on Bistrita River and Siriu on Buzau River. Based on the monitoring of the alluvial flow at the hydrometric stations, from the Siret River Basin, there have been analysed the sediment yield formation and the solid transit dimensions in order to obtain typical values for the geographical areas of this territory. The silting of these reservoirs was monitored by successive topobatimetric measurements performed by the Bureau of Prognosis, Hydrology and Hydrogeology and a compartment within Hidroelectrica S.A. Piatra Neamt Subsidiary. The quantities of the deposited sediments are very impressive. The annual rates range betwee3 000 – 2 000 000 t/year, depending on the size of the hydrographical basin, the capacity of the reservoirs, the liquid flow and many other factors which may influence the upstream transport of sediments. These rates of sedimentation lead to a high degree of silting in the reservoirs. Many of them are silted over 50% of the initial capacity and the others even more. The effects of the silting have an important impact when analysing the effective exploitation of the reservoirs.

KEY WORDS: Reservoir, silting, alluvial deposits, Siret River Basin

1. Introduction

The complex influences of the human society on the environment have gained lately a momentum with unpredictable consequences, as a result of the fast development of the economic activities.

It is interesting that although most of the hydro-technical works had beneficial purposes for human society, they generated negative, sometimes disastrous side effects.

As consequence of some of his activities, man has been changing the landscape both indirectly, influencing the dynamics of the geomorphologic modelling processes, and directly, through the construction of certain developments, becoming an active morphogenetic factor, which for a short period of time was particularly important and sometimes it was dominant. Also the economy has both destructive and constructive implications on the environment taking into consideration the different modifications which it implies (Olariu, 1988, 1990, 1992).

In order to harness more effectively the whole natural potential of the territories and to achieve an optimum landscape, the human activity induces both positive influences, but also many negative consequences. The impact of the human activity and the geographic environment is an issue that arouses much interest for the researchers. Aspects of the perspective are still less known.

Most effects of the human activity on the geographical environment (in this case the Siret River Basin) are of course those resulting from the development of the Siret and Bistrita rivers for the primordial economic interests such as: hydropower, drinking water supply, irrigation, industrial water supply, prevention and flood control, exploitation of gravel, soil erosion control works (C.E.S.).

The Siret River basin is characterized by a wise use of the hydrologic potential, expressed in the number of the constructed and put into operation reservoir dams. The cascade development of the reservoirs on the Siret and Bistrita rivers indicates the degree of development of this hydrographical basin (Olariu, 1997).

Reservoirs have a significant impact on the transit of the silt, because their construction leads to discontinuities. At the time of execution it can be noticed an increase in turbidity and in the solid flow and after entering the service the processes of silting developed (Olariu and Gheorghe, 1999). Unlike the liquid flow the solid flow depends on the resistance to erosion of the rocks, on the slopes, on the vegetation cover and on plant phenological state.

2. Methods

The researches were carried out on the basis of the existing data sources, the water cadastre, or data from the monitored hydrometrical stations. The database comprises liquid flow measurements and solid flow measurements from the Siret River basin. The database from the Siret River basin comprises measurements of levels, solid and liquid flow rates etc.

In terms of flow the hydrometric network monitors only the flow of sediment in suspension because it no longer performs measurements of bed load at the hydrometric stations. Other data used in the silting analysis and the alluvial transit are represented by topobatimetric studies on the reservoirs (volumetric curves), data stored at the Siret Water Basin Administration.

In order to achieve the objectives of this work it was required the processing of the database, both graphically and statistically. Graphic processing of data was done using Microsoft Excel application, and for the construction of the maps it has been used the ArcGIS software.

In this article are analysed the degree of silting of the reservoirs and the impact on the alluvial transit on the reservoirs from the Siret River basin.

The suspended silt in the hydrometric network is monitored for 60 years. It should be noted that during this period, one can distinguish two stages: the first when the works have been performed in the hydrometrical area, stored in the National Development Program which ended in the years

1992-1994, 1995, and the second when there were valued only the gravel resources decreasing in time.

3. Study area

The Siret River is the biggest river in Romania. It springs from the Ukrainian Carpathians at an altitude of approximately 1238 m (Ujvari, 1972) and drains, within its catchment the central-eastern part of the Eastern Carpathians and a part of the South-Eastern Carpathians, the Moldavian Sub-Carpathians and the northern part of South-Eastern Sub-Carpathians, the Moldavian Plateau and the Lower Siret Plain.

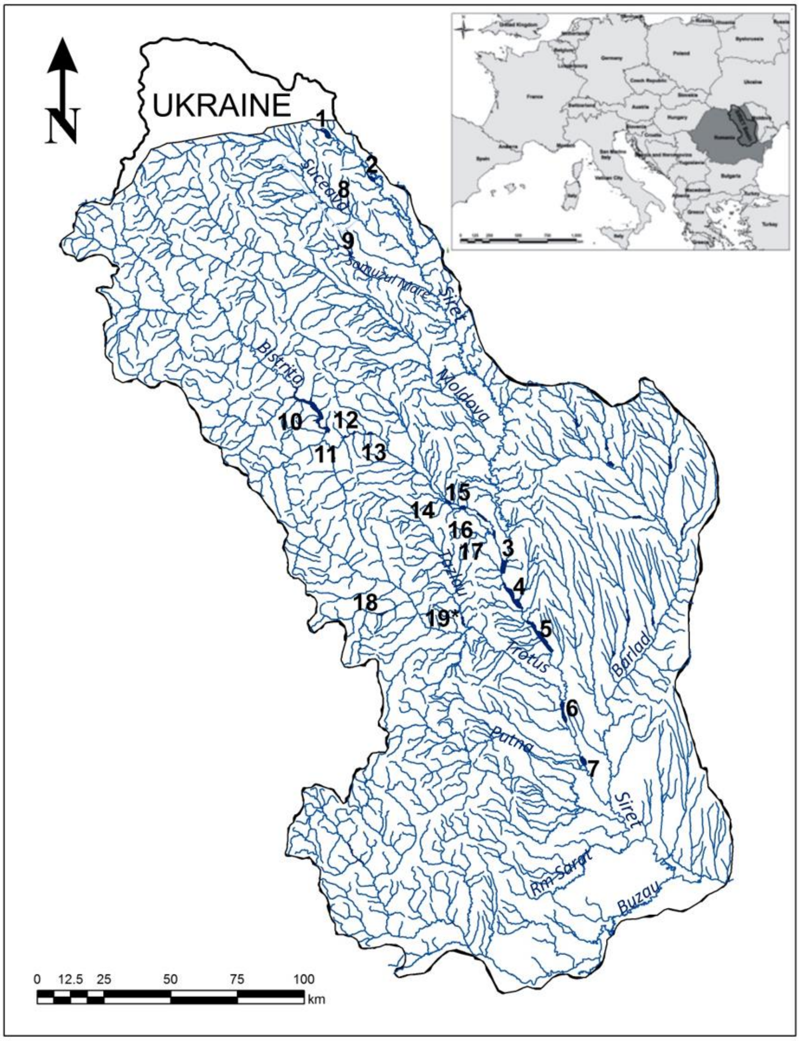

Figure 1. Reservoirs in the Siret River Basin.

The catchment of the Siret River covers an area of 44 871 km^2 from which 42 890 km^2 in Romania (18% of Romania's surface). The Siret River Basin Sector which is under the Siret Water Basin administration occupies 28 000 km^2 (11.8% of Romania's surface). In the Siret River basin there are 1013 streams encoded with a length of 15 157 km (19.2% of the water cadastre network in Romania), of which 734 rivers with a total length of 280 km are under the administration of Siret Water Basin.

The main tributaries on the right side of the Siret River are: Siretul Mic, Suceava, Moldova, Bistrita, Trotus, Putna and Buzau; and on the left side: Polocin and Barlad. The liquid and solid flows of the Siret River basin are formed predominantly from the flows of Suceava, Moldova, Bistrita and Trotus rivers.

The cascade power stage from the Siret River Basin is made up of the following dams and reservoirs: Bucecea, Galbeni, Rogojesti, Racaciuni, Beresti, Calimanesti, Movileni – on *Siret River*: Somuz II Moara – on *Somuzul Mare River*; Izvoru Muntelui, Pangarati, Vaduri, Batca Doamnei, Racova, Garleni, Lilieci, Bacau II – on *Bistrita River*; Poiana Uzului – on *Uz River* and Belci – on *Tazlau River*.

In 1976 a complex power stage of the water courses and of the hydrographical basins from the Siret River basin was founded through a specific program. According to this program in the Siret River basin it was proposed to:

- Use the water resources in the basin, and the excess in the limitrophe areas: Jijia, Sitna, Barlad, Ialomita, Mostistea through their interconnection;
- Construct a complex cascade of reservoirs both on the Siret River and its main tributaries, respecting the principle of maximum recovery of the agricultural land;
- Develop works to combat soil erosion and the humidity excess, works for the torrents development and for irrigating extended areas;
- Develop works for protection against floods, bed regularization and consolidation of banks.

The total number of reservoirs in the program was 115 (Olariu, 1988, 1990, 1997).

4. Results

The silting of the reservoirs was monitored by successive topobathymetric measurements performed by the Bureau of Prognosis, Hydrology and Hydrogeology and a compartment within Hidroelectrica S.A. Piatra Neamt Subsidiary.

The highest alluvial flows registered in spring: 14020 kg/s on May 3rd, 2008 at Itcani hydrometrical station, respectively 15633 kg/s on April 11, 1979 at Dragesti hydrometrical station on Siret River (Olariu, 1997; Siret Water Administration, 2012).

In the Siret River basin are characteristic some areas, as it follows:

a. **The mountain area** with large slopes, hard rocks, extensive forests, but with low erosion potential: ρ (alluvial production)=0.5-2.0 t/ha/year;
b. **The sub-Carpathian area**. Here the slopes remain quite high, the rocks are less harsh, sometimes even friable; there are rather extensive deforested areas with a high degree of arable lands. Here we have ρ (alluvial production) = 5-15 t/ha/year.

Regarding the sub-Carpathian area it should be noted that the production of sediment increases from North to South, from 4 - t/ha/year in Culmea Plesu area, to 15 -25 t/ha/year in the Carpathian arch area.

c. **The plateau area** with medium slopes, low intensity erosion, extensive arable lands: ρ =1-5 t/ha/year.

The basic elements of the solid and liquid runoff from the main hydrometrical stations of the Siret River Basin are presented in the table below (Table 1).

Table 1. Basic elements of the liquid and solid runoff (F – the area of the hydrographic basin, Hmed – medium altitude of the basin, Qmed – medium liquid flow; Qmax – maximum liquid flow; Qmin – minimum liquid flow; S – alluvial flow; R – suspended alluvial flow; G – bed load flow; q – specific liquid flow. The bed load describes particles in water which are transported along the bed. Usually the bed load is larger than the suspended load and moves by rolling, sliding and hopping. Downstream the bed load is smaller and more rounded than upstream.

No	River	Hydrometrical station	F (km²)	Hmed (m)	Qmed (m³/s)	Qmax (m³/s)	Qmin (m³/s)	Torrential coef.	S (kg/s)			Annual volume 10^6t	Alluvial production ρ (t/ha/yr)	q (l/s/km²)
									R	G	Total			
1	Siret	Siret	1637	572	13.0	1193	0.900	1326	8.77	1.67	10.4	0.331	2.02	7.94
2		Hutani	2115	515	15.4	875	0.830	1054	11.9	2.38	14.3	0.451	2.13	7.28
3		Lespezi	5888	513	37.2	2414	3.35	721	50.8	10.2	61.0	1.93	3.28	6.32
4		Dragesti	11846	525	78.1	2930	7.70	381	112	11.2	123	3.88	3.28	6.59
5		Racatau (Adjudu Vechi)	20348	647	155	2775	16.5	168	10.9	1.10	12.0	0.379	0.190	7.62
6		Lungoci	36098	539	213	4650	34.4	135	242	24.2	266	8.39	2.32	5.90
7	Suceava	Brodina	366	990	4.27	426	0.400	1065	2.83	2.26	5.09	0.161	4.40	11.7
8		Itcani	2334	629	16.6	1710	1.88	910	15.0	3.00	18.0	0.568	2.43	7.11
9	Solonet	Parhauti	204	467	1.22	382	0.100	3820	3.63	0.750	4.38	0.138	6.76	5.98
10	Moldova	Prisaca Dornei	664	1087	9.05	304	1.04	292	2.52	2.00	4.52	0.143	2.15	13.6
11		Tupilati	3928	703	32.8	1402	2.67	525	34.4	6.88	41.3	1.20	3.16	8.35
12	Moldovita	Dragosa	463	934	5.07	498	0.460	1083	2.10	1.68	3.78	0.119	2.57	11.0
13	Bistrita	Dorna Giumalau	758	1255	12.1	310	1.89	164	1.89	1.89	3.78	0.119	1.57	16.0
14		Dorna Arini	1690	1206	25.0	580	3.88	149	3.99	3.99	7.98	0.252	1.49	14.8
15		Frumosu	2858	1172	38.1	772	6.38	121	7.86	6.26	14.1	0.448	1.57	13.3
16	Dorna	Dorna Candreni	565	1138	7.51	221	0.640	345	0.970	0.970	1.94	0.061	1.07	13.3
17	Trotus	Goioasa	781	1052	6.50	353	0.800	441	3.68	2.94	6.62	0.209	2.68	8.32
18		Targu Ocna	2091	924	17.5	1490	2.05	727	16.1	3.22	19.3	0.609	2.91	8.37
19		Vranceni	4092	734	35.0	2948	3.43	859	34.6	3.46	38.1	1.20	2.93	8.55
20	Tazlau	Helegiu	998	520	6.85	1556	0.150	10373	11.0	2.20	13.2	0.417	4.18	6.86
21	Putna	Tulnici	313	990	4.44	342	0.490	698	3.39	2.71	6.10	0.193	6.17	14.2
22		Colacu	1087	921	12.0	1567	1.00	1567	35.7	7.14	42.8	1.35	12.4	11.0
23		Botarlau	2450	554	15.3	1598	3.09	517	89.0	8.90	97.9	3.09	12.6	6.24
24	Milcov	Reghiu	116	595	1.12	394	0.020	19700	6.25	1.25	7.50	0.237	20.4	9.66
25		Golesti	406	410	1.47	696	0.010	69600	18.9	1.89	20.8	0.656	16.2	3.62
26	Ramna	Groapa Tufei	180	421	0.673	514	0.010	51400	21.4	2.14	23.5	0.742	41.2	3.74
27		Jiliste	398	315	0.850	600	0.010	60000	34.1	3.41	37.5	1.18	29.6	2.14
28	Ramnicu Sarat	Tulburea	187	819	1.58	335	0.050	6700	10.0	5.00	15.0	0.473	25.3	8.45
29		Tataru	1048	295	2.53	282	0.030	9400	35.2	3.52	38.7	1.22	11.6	2.41

Comparing the average rate of sediment in suspension, calculated by the year 1995 with those calculated in the year 2010, we may find that at the main hydrometrical stations in the Siret River basin there are significant differences, although the values corresponding to the year 2010 are generally lower (Table 2).

Significant exceptions can be seen at the hydrometrical station Frumosu on the Bistrita River, where we find a significant increase (probably because of the deforestation), at the hydrometrical station Golesti on the Milcov River and at the hydrometrical station Tulburea on the upper course of the Ramnicu Sarat River, where probably the cause is the deforestation in recent years (Table 2).

Table 2. Comparative analysis of the sediment production in 2010 compared to 1995 (ρ – alluvial production)

No	River	Hydrometrical station	ρ 1995 (t/ha/year)	ρ 2010 (t/ha/year)
1	Siret	Siret	2.16	2.02
2		Huțani	2.65	2.13
3		Lespezi	3.11	3.28
4		Drăgesti	3.61	3.28
5		Adjudu Vechi	1.96	0.19
6	Suceava	Ițcani	2.27	2.43
7	Moldova	Tupilați	3.46	3.16
8	Bistrița	Frumosu	0.89	1.57
9	Trotus	Vrânceni	3.51	2.93
10	Putna	Colacu	10.6	12.4
11		Botârlau	15.4	12.6
12	Milcov	Golești	14.5	16.2
13	Ramnicu Sarat	Tulburea	18.6	25.3
14		Tataru	14.1	11.6

The complex power stage of the water courses and of the hydrographical basins from the Siret River basin was founded by a program developed in 1976 (Olariu, 1988, 1990, 1997).

This very ambitious development program involved special economic efforts, relocation of human settlements, things that were not quite feasible. Plus, it was very little taking into account the many negative side effects, for these works. However, a great part of these objectives would have been particularly needed.

Currently operates a number of 18 important reservoirs, mainly on Bistrita and Siret rivers (Tabel 3). Figure 2 shows the comparison between the liquid and solid flow rates from hydrometrical stations on the Siret River, located upstream and downstream the reservoir, characteristic for the periods before the construction of the reservoirs and for the period after the construction of the reservoirs. There can be noticed significant decrease in the alluvial transit. If the hydrometrical station is closer to the dam then the registered values are higher than the ones registered more downstream. Examples: in the case of the existing reservoir, at Hutani hydrometrical station, the reduction is 43%, meanwhile at Adjudu Vechi hydrometrical station, located at about 6 km downstream Beresti dam, the reduction is 84%. From the chart it can also be noticed the capacity to recover the sediment (full recovery at Dragesti hydrometrical station and partial recovery at Lungoci hydrometrical station).

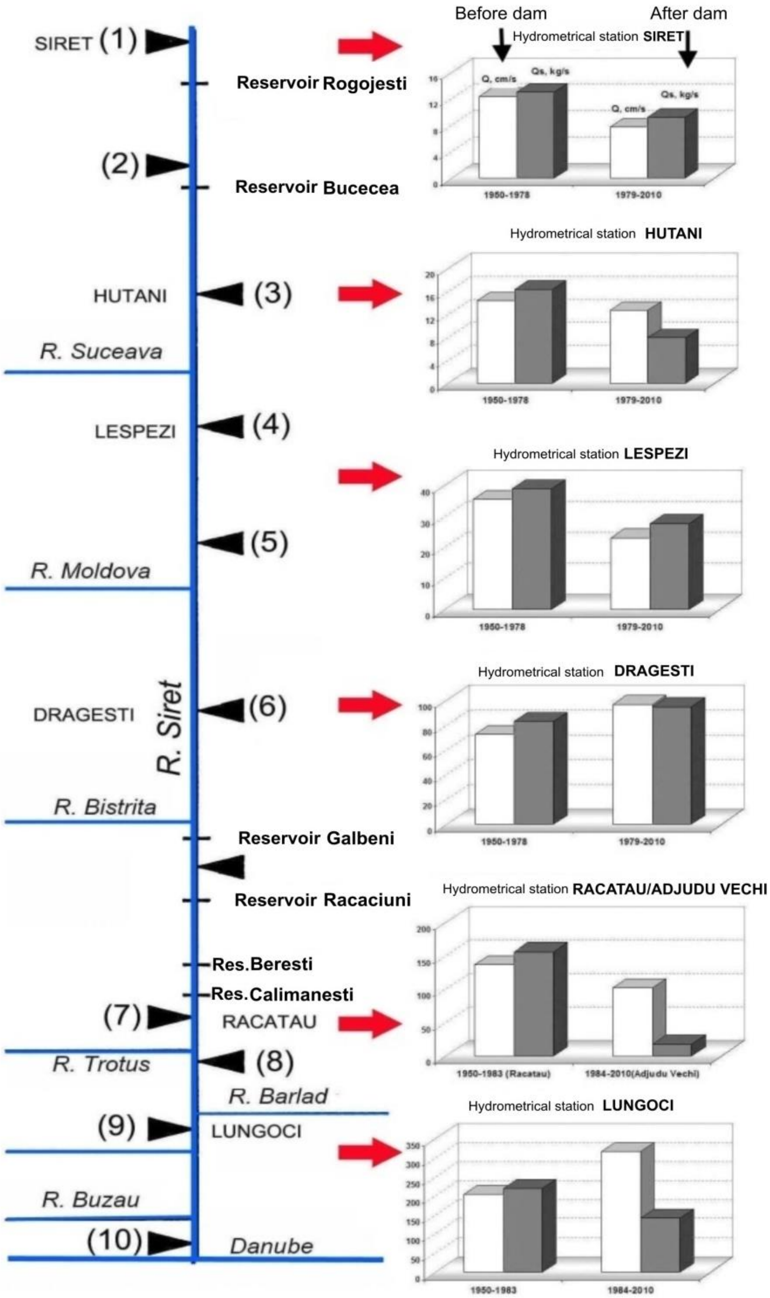

Figure 2. The regional impact of dams on sediment transport in the Siret River (Olariu and Gheorghe, 1999, with additions Radoane M et al, 2013): (a) schematic illustration of the hydrometrical stations, dam localization and confluences along the Siret River; (b) the average values of liquid and suspension solid flows before (left column) and after (right column) the constructions of dams.

The solid flows diverted from the flow regime are stored in reservoirs, contributing to their gradual silting. In the case of Bucecea reservoir the current volume represents half of the initial volume (Siret Water Basin Administration, 2012). The data about the reservoir silting in the Siret River Basin are presented below, in table 3:

Table 3. The silting of the reservoirs (CY – the year of commissioning; V – the volume of the reservoir)

No	River	Reservoir	CY	Initial volume (mil m³)	Topobathymetric measurements								Silted volume (mil m³)	Years	Silting rate (% per year)	Degree of silting (% per year)	Source*
					V (mil m³	Year	V (mil m³)	Year	V (mil m³)	Year	V (mil m³)	Year					
1	Siret	Bucecea	1977	10.0	6.77	1996	4.97	2009	14	1995	10	2010	5.03	32	1.6	53	1, 2
2		Galbeni	1983	39.6	32.1	1986	16	1988					29.6	27	2.8	75	1, 2
3		Rogojesti	1986	38.4	27.7	2010							9.70	24	1.05	25	1
4		Racaciuni	1986	103.6	92.0	1998	88.94	2010					16.66	24	0.6	14	1, 2
5		Beresti	1986	160	158	1998	120.4	2010					39.6	24	1	25	1, 2
6		Calimanesti	1993	52.0	44.3	2010							7.70	17	0.9	15	1
7		Movileni	2009	46.53													1
8	Dragomirna	Dragomirna	1986	19.22	17.4	2011							1.82	26	0.4	10	1
9	Somuzul Mare	Somuz II Moara	1976	11.3	6.00	2011							5.30	36	1.3	47	1
10	Bistrita	Izvoru Muntelui	1960	1230	1121	1988	1102	1997					126	17	0.6	10	2
11		Pangarati	1964	6.7	3.44	1987	2.38	1995					4.32	31	2.1	64	2
12		Batca Doamnei	1964	10.0	7.20	1987	6.79	1995					3.21	31	1.4	32	2
13		Racova	1965	8.65	4.28	1983	3.19	1995	Disaffected in 2011				5.46	30	2.1	63	2
14		Garleni	1965	5.10	3.80	1982/1983	1.97	1995					3.13	30	2	61	2
15		Lilieci	1965	7.40	6.6/5.4	1983	5.53	1995					1.87	30	0.8	25	2
16		Bacau	1966	5.40	4.40	1986	4.23	1995					1.17	29	0.7	22	2
17		Vaduri	1966	5.0	4.43/2.39	1981/1982	2.13	1995					2.87	29	2	58	2
18	Uz	Poiana Uzului	1970	90.0	85.6	2009							4.40	39	0.1	5	1, 2
19	Tazlau	Belci	1962	12.5	7.70	1975	5.97	1986	2.56	1991	Destroyed in 1991		9.94	29	2.7	80	1, 2

*1 Siret Water Administration, Bacau (2012); 2 P Olariu (1992).

Obreja (2012) has shown that the annual sedimentation rates range between 3 000-2 000 000 t/year, depending on the size of the basin, the capacity of the reservoirs, the runoff and many other factors that may influence the upstream transport of the sediment. As can be seen the quantities of the sediment deposited are impressive. This results in a high degree of silting in the reservoirs. The majority of the reservoirs are silted over 50% from the initial capacity, and the rest even more.

Thus we give the example of some reservoirs from the Siret River Basin which has a high degree of silting:

- Siret River: Bucecea and Galbeni reservoirs (Olariu, 1992; Siret Water Administration, 2012**)**. The recent data indicate the fact that both reservoirs are silted over 50-60% from the initial capacity;
- Bistrita River: Pangarati, Vaduri, Batca Doamnei, Racova, Garleni reservoirs (Ciaglic et al., 1973; Radoane M, Radoane N, 2005) are silted over 60-70% from the initial capacity;

- Tazlau River: when the dam Belci was destroyed in 1991, the degree of silting of the reservoir was up to 60% (Olariu, 1992);
- Horodnic River: the impermanent reservoir Horodnic I (Siret Water Basin Administration, 2012) was silted 80%.

Table 4. The silting time of the reservoirs in the Siret River Basin (T50% - the number of years the reservoirs will be silted 50%; the year 50%/100% - the year the reservoir will be silted 50%/100%)

Reservoir	CY year	T50%	50% year	100% year
BUCECEA	1978	21	1999	2020
VADURI	1966	70	2036	2106
GARLENI	1965	34	1999	2032
LILIECI	1966	80	2046	2125
BACAU	1966	54	2020	2075
ROGOJESTI	1986	87	2073	2161
HORODNIC	1980	33	2013	2047
MIHOVENI	1989	17	2006	2024
SOMUZ MOARA	1976	90	2066	2156
IZVORU MUNTELUI	1960	984	2944	3928
POIANA UZULUI	1986	235	2221	2456
BELCI*	1963	18	1981	1999

*destroyed in 1991

Starting from the annual rates of sedimentation of the reservoirs from the Siret River basin we have managed to calculate the times of silting for these hydro-technical developments. In table 4, these parameters are very well illustrated. We can thus see that the majority of these reservoirs, in roughly a century, will be silted in full. The only exceptions are the reservoirs from the mountainous area which have very high capacities (Izvoru Muntelui, Poiana Uzului). Also the majority of these reservoirs are silted over 50%.

In this context one might formulate the idea that in the areas of plains and hills should not be constructed reservoirs. But, the land that would remain after the full silting of the reservoirs could be properly harnessed. For example, in the former Belci reservoir, the land can be used for agriculture without any problems. At the same time, the beds the water courses provide impressive amounts of gravel pits which can be used in construction. Between the years 1984-1988 the amount of ballast overcame 10 million m^3.

5. Conclusions

The liquid and solid flow rates in a given basin reflect the complex geographical conditions of the concerned territory, and the impact of the human factor becomes more prominent with the economic development.

In the last 60 years in the Siret River basin, the need of economic development has imposed major upgrading of the water courses and the hydrographical basins. The targets of these works are producing electric hydro-energy, the supply of drinking and industrial water for the settlements, the maximum flow flood control, irrigation, etc.

All this has produced significant changes in the transit of silt. The monitoring of the suspended silt is carried out at several stations hydrometric station for 50-60 years, so there is a database in order to analyse the sediment transit under influence of the human factor.

After putting into operation of the reservoirs (especially those on the Siret River) there has been monitored their influence on the solid flow by measurements taken at the hydrological stations located upstream and downstream the reservoirs. These influences are more significant immediately downstream the dams, and then the influences are less affective due to the recovery of the sediment load. For example, in the case of the hydrometrical station Adjudu Vechi, located 6 km downstream Beresti dam, the influence is 84%, at the hydrometrical station Hutani (15 Km downstream Bucecea dam) the influence is 43%, and at the hydrometrical station Lungoci (80 Km downstream Beresti dam), the influence is 45%. For larger distances from the dams, the silt loads regenerates.

The lacustrine basins withhold a certain amount of sediments (especially the most coarse) leading to the gradual silting of the reservoirs. Some reservoirs have higher silting rate (Galbeni – on Siret river 2.8%, Belci – on Tazlau river 2.7%), and others (particularly those in the mountain area) have lower silting rate (Izvoru Muntelui – on Siret river 0,6%, Poiana Uzului – on Uz river 0,1%).

It should be noted that, through silting the reservoirs gradually lose the net volume and in time, they become non-functional. The situation was critical in the case of Belci Reservoir, but the dam was destroyed during the 1991 flooding, before being completely silted. In the case of the Bucecea Reservoir the silting process is imminent, even though in the last 25 years the rate of silting was reduced when constructed the Rogojesti Reservoir upstream.

However, considering the important role of the reservoirs and taking into account the necessity of the efficiency analyses followed by an expert judgment, even for a shorter period of time, we believe that such work should be continued. The benefits offered by these reservoirs are very important after decommissioning due to the fact that the lands can be used properly in agriculture or for any other utility.

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