USING SINGLE-BEAM ECHO-SOUNDER FOR ASSESSING THE SILTING RATE FROM THE LARGEST CROSS-BORDER RESERVOIR OF THE EASTERN EUROPE: STANCA-COSTESTI LAKE, ROMANIA AND REPUBLIC OF MOLDOVA

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Abstract: Stanca-Costesti Reservoir holds the largest amount of water among reservoirs located in Romania and has multiple purposes, such as flood mitigation, hydropower production, irrigation etc. Our bathymetric survey was conducted along longitudinal, as well as transverse alignments, so as to cover the entire lacustrine surface by using an echo-sounder. Data from three different surveys were employed, i.e. topographical (dating back to 1977, before the onset of flooding) and bathymetrical (1986 and 2000) surveys. The drainage basin of this reservoir extends across three countries, Romania, Ukraine and Republic of Moldova, and whereas the mountain sector of the basin is mostly covered by forest, the lowland (the Moldavian Plateau) is used for agriculture, i.e., cereal crops. Thus, deforestation and inappropriate tillage techniques employed within this basin result in increased soil erosion. Most of the sediment load is carried during flood events, which have grown increasingly common, particularly in summer. The terraces formed along the downstream sector of the reservoir are not covered by alluvium, whereas the corresponding terraces from its upper sector have been covered by submerged glacises. Moreover, in the area of Ciugur river mouth we observed a submerged valley, as well as several submerged natural levees. The deepest area of the reservoir (29.2 m) is located adjacent to the dam and is thought to be the outcome of a circular current generated by the lake bottom morphology. The silting degree is rather high, ranging up to an index value of 7.3% over 33 years.

Keywords: echo-sounder survey, GIS modeling, underwater topography, sedimentation rate, soil erosion, cross-border reservoir.

1. INTRODUCTION

Prut river basin is located in the northeastern part of Danube basin and is bordered by three major basins, i.e., Tisa to the northwest (spreading over the territories of Ukraine, Romania and Hungary), Siret to the west (partially overlaying Ukrainian territory) and the Dnestr to the northeast (in the Republic of Moldova), thus occupying the eastern part of Romania. Prut River has its origin in the Ukrainian Carpathians and the confluence with the Danube occurs in the vicinity of Galati urban area. The area of the drainage basin amounts to 27,500 km², of which 10,967 km² on the Romanian territory (accounting for approx. 4.6% of the latter) (Romanescu et al., 2011, 2014, 2015a, 2016, 2017a).

The headwaters of Prut river are located on the northeastern slope of Cernahora Massif (in the Ukrainian Carpathians) at 1,580 m a.s.l., whereas the confluence to the Danube occurs at just 2 m asl. Prut river basin overlies portions of the territories of three countries: Ukraine, Romania and the Republic of Moldova. The length of the river from its springs to Oroftiana (where it enters Romanian territory) is 211 km, whereas the area of this sector amounts to 8,241 km². The slope gradient of the long profile is 6.4% and the sinuosity coefficient ranges to 1.18. The total length of Prut River, the second longest tributary of Danube, is 952.9 km. Its valley forms the border between Romania and Ukraine (over 31 km), and Romania and the Republic of Moldova (over 711 km), respectively. Prut River is the last major tributary of the

Danube before it reaches the Black Sea (Romanescu & Stoleriu 2017).

The average elevation of the basin ranges from 130 m in the central area to 2 m a.s.l. in the confluence area, such that the mean slope gradient of the basin is approx. 0.2%. Prut river basin includes no less than 248 tributaries and has an elongated shape, approx. 30 km-wide (average width). The total length of the drainage network amounts to 11,000 km of which 3,000 km are permanent streams (33%) and the remaining 8,000 km are intermittent streams with temporary discharge (67%). The density of the drainage network is 0.41 km/km^2, and thus above the average calculated for the Romanian territory (0.33 km/km^2). As regards the land use, 57% of Prut basin is covered by arable land, whereas forests account for 21.4% of the basin area. Perennial crops cover 13.3% of the basin area, while the water surface accounts for just 1.19% of the area (Romanescu et al., 2017a, 2017b, 2018).

The friable rocks typical for the geology of the Moldavian Plateau commonly provide a significant sediment yield in local rivers. This has resulted in long-standing studies regarding slope erosion in Eastern Romania (Radoane & Radoane 2005; Romanescu 2013; Romanescu & Stoleriu 2013; Romanescu et al., 2012a, 2012b, 2015b). Similar erosion problems are tackled in the foreign literature (Joeckel & Diffendal 2004; Thiemeyer et al., 2005; Lóczy et al., 2009; Diemer et al., 2011; Lóczy & Gyenizse 2011; Neavy et al., 2012; Zhang et al., 2015).

The intensity of soil erosion is reflected with some degree of accuracy by sediment accumulation in large-scale reservoirs. Various studies on sedimentation rates in reservoirs have been published abroad; however, they remain scarce in the Romanian literature (Morris & Fan 1997; Batuca & Jordaan 2000; White 2001; Radoane & Radoane 2005; Tamene et al., 2006; Wheater & Evans 2009; Grindlay et al., 2011; Mavina et al., 2011; Maren et al., 2013; Murakami et al., 2013; Revuelto et al., 2014; Mihu-Pintilie et al., 2016).

The vast majority of Romanian reservoirs have multiple purposes, i.e., flood mitigation, hydropower production, irrigation, water supply, fish farming, etc. (Romanescu et al., 2010; Mihu-Pintilie et al., 2014a,b; Cozma et al., 2015). After the construction of Stanca-Costesti dam a significant decrease in flood severity along the lower Prut, downstream of the reservoir, was documented (Romanescu et al., 2011; Romanescu 2013; Romanescu & Stoleriu 2013). To date over 1,200 reservoirs were built up in Romania, of which 246 were included in the World Register of Large Dams.

This study aims to document the evolution of the silting rate in Stanca-Costesti reservoir, considering the increase in the soil erosion rate in Prut river basin. This increase is likely an effect of boosting deforestation in the mountain areas (Romania and Ukraine) and inadequate agricultural techniques on arable lands in the tableland area (Moldavian Plateau), such as downhill tillage, as opposed to contour line tillage. Our study introduces the first accurate measurement of sedimentation rate in the largest reservoir in Romania and the Republic of Moldova.

1.1. Study area

Stanca-Costesti reservoir is located on the middle course of Prut River which collects tributaries from Romania, Ukraine and the Republic of Moldova (Fig. 1). The hydroelectric power plant was called into operation in 1978. The entire hydropower complex was built by Romania and the former USSR in the vicinity of Stefanesti urban area in Botoşani County, 576 km upstream of the confluence to the Danube. The main purposes of the hydro-technical node included river flow regulation, water supply, irrigation, and flood control and electricity generation. Stanca-Costesti hydro-technical node (HN) is rated as a class I (major importance) structure. The area of the reservoir is 5,900 ha at normal retention level (NRL), whereas its maximum volume ranges up to 1,400 million m^3.
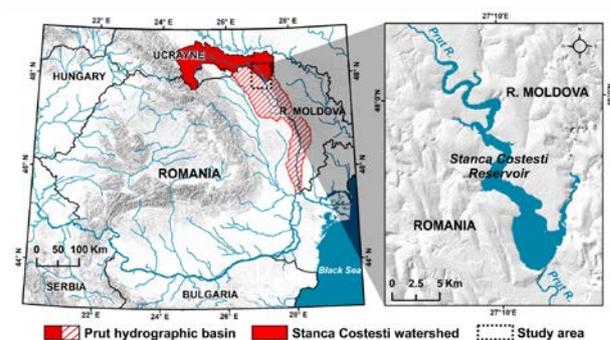

Figure 1. Geographical location of Prut river basin and Stanca-Costesti reservoir within the regional context

The hydropower complex is shared into equal parts by Romania and the Republic of Moldova. The power plant has an installed capacity of 30 MW. The border between the two countries divides Stanca-Costesti reservoir in half. This is the largest reservoir, in terms of both area and water volume, built on the rivers pertaining to either of the two countries. According to the Romanian Register of Large Reservoirs (currently comprising of 247 items), Stanca-Costesti dam ranks 49th in terms of the dam height, and 2nd in terms of the volume of water stored in the reservoir (1,290 hm^3, below Porţile de Fier I

reservoir - 2,100 hm³), respectively. The length of the reservoir at a normal retention level (NRL 90.80 m) is 70 km, whereas the maximul level (Nmax 99.50 m) length is 90 km. The area of the reservoir is 5,900 ha at NRL, and 9,200 ha at Nmax, respectively.

Stanca-Costesti is a gravity dam composed of concrete, built by using 15 m-long plots. The crest elevation is 102.50 m, the length is 650 m, whereas the height ranges from 10 to 12 m. The discharge rate calculated for the 0.1% expected frequency is 1,560 m³/s (elevation – 99.50 m). The body of the dam contains a backup spillway which evacuates from the reservoir various amounts of water during periods when the pressure node is not functional. The capacity of this spillway is 35 m³/s. The main spillway is a 46 m high tower type spillway built from monolith reinforced concrete. It is embedded in limestone and has 6 waterways closed by flat sluices, of which 2 supply water for the hydropower plant (73 m threshold elevation), and the remaining 4 are used for evacuating the flood discharge (71 m threshold elevation). Their cross section is 4 x 6 m. The 2 middle galleries serve as water feeders for the turbine, whereas the other 4 (located in pairs on either side of the two power galleries) are employed for evacuating flood waters from the reservoir. The width of each gallery is 4 m, the height is 5.6 m, and the walls are 1.3 m thick. The volume of the compensation reservoir is 630,000 m³, corresponding to an elevation of 62.50 m. The discharge capacity of the spillway is 1,300 m³/s.

2. MATERIALS AND METHODS

The hydrological data employed in this study were provided by the 9 gauging stations located on Prut river: Oroftiana, Radăuţi Prut, Stanca-aval, Ungheni, Prisacani, Dranceni, Falciu, Oancea and Sivita (at the confluence with the Danube) (Fig. 2). The first gauging station was installed in Ungheni in 1915 (Table 1), whereas the newest one was brought into service in Sivita in 1978. However, the hydrological data regarding the water level and discharge go farther back and were provided by gauging stations which had different locations. A detailed hydrological analysis required the study of monthly and annual mean data, as well as the multiannual average data from all the gauging stations. In order to highlight the function of Stanca-Costesti reservoir we targeted primarily the hydrological data provided by Radauti Prut and Stanca-aval (downstream of the reservoir) stations. The methods employed for computing the sedimentation rate in Stanca-Costesti reservoir are in accordance with the latest developments in this field (Mitasova et al., 2004; Duarte et al., 2011; Guerrero & Lamberti 2011;

Shah-Fairbank et al., 2011; Estigoni et al., 2014; Anderson & Martinez 2015). The topographical surveys carried out in Stanca-Costesti area were performed by using a LEICA TCR 1201total station, which is, alongside the LEICA GPS 1200, a part of the SYSTEM 1200 LEICA. The coordinates of the survey markers were provided by Botosani Ordnance Survey. It has recorded 20 landmarks, evidenced in the field by wooden pegs in order to ensure an optimal coverage of the entire reservoir area. The acquired data were processed by using the AutoCAD software.
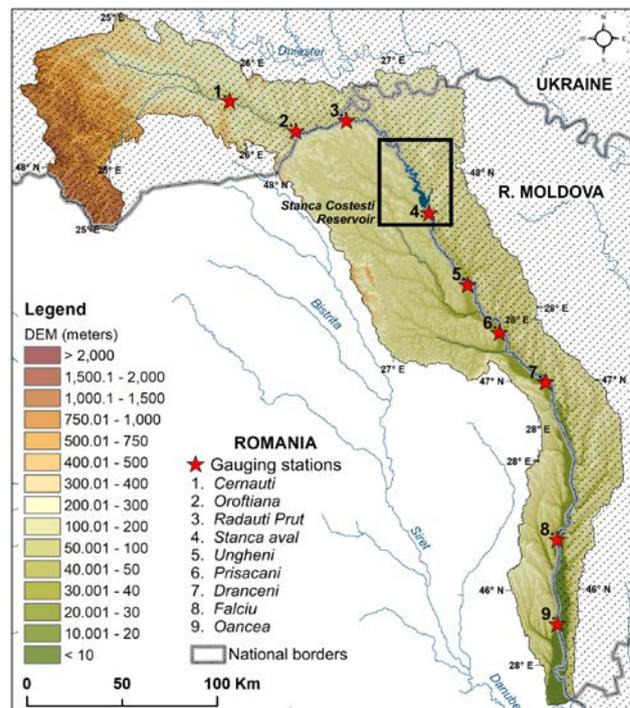

Figure 2. Prut river basin and its main gauging stations (red stars), where lacustrine basin is highlighted in the black frame

A GPS was employed for the accurate delineation of the reservoir perimeter. The data from the topographic survey was converted to the Stereo 70 Projection. The bathymetric measurements were carried out using a echo-sounder (Bathy-500DF Dual Frequency). The resolution of this device is 1/1 cm and it has GPS navigation incorporated.

The processing of the bathymetric data and thematic maps completion were performed by using the TNTMips v.7.2 and ArcGis v.10.2 software's. A digital terrain model was obtained, and the resulting graphs were used to infer and interpret geomorphological processes. Over 750,000 were indexed, whereas 650,000 were interpolated in the graphs. Three longitudinal (a middle path and two side ones), as well as 17 transverse paths were scanned. Special attention was granted to areas where tributary streams join the reservoir.

Table 1. Morphometric data for the gauging stations located in Prut river basin (Romania)

River	Gauging station	Gauge station	County	Year of establishment	Geographical coordinates		River length from the confluence (km)	Data regarding the drainage basin		Stage datum - meters above Black Sea
					Lat. N	Long. E		Area (km²)	Elevation (m)	
Prut	Oroftiana	Botosani	BT	1976	48°11'12"	26°21'04"	714	8,020	579	123.47
	Radauti P.			1976	48°14'55"	26°48'14"	652	9,074	529	101.87
	Stanca av.			1978	47°47'00"	27°16'00"	554	12,000	480	62.00
	Ungheni	Iasi	IS	1914	47°11'04"	27°48'28"	387	15,620	361	31.41
	Prisacani			1976	47°05'19"	27°53'38"	357	21,300	374	28.08
	Dranceni	Vaslui	VS	1915	46°48'45"	28°08'04"	284	22,367	310	18.65
	Falciu			1927	46°18'52"	28°09'13"	212	25,095	290	10.04
	Oancea	Galati	GL	1928	45°53'37"	28°03'04"	88	26,874	279	6.30
	Sivita			1978	45°37'10"	28°05'23"	30	27,268	275	1.66

In order to assess the sedimentation rate in Stanca-Costesti reservoir three datasets were employed: land survey data acquired prior to reservoir flooding (1977); bathymetric measurements from 1986, performed on ice bridge, using improper instruments (plumb line); and the measurements made in 2010 using state of the art instruments. Thus, two accurate datasets were available: 1977 and 2010. The data was related to the NRL (Normal Retention Level). The assessment of the volume of alluvium required 3 steps:

a. obtaining 40 topographic cross sections for 1977, 1986 and 2010 in order to extract the active surfaces;
b. computing the active surfaces of each cross section by using the trapezoidal rule;
c. calculating the partial volumes of the segments delineated by two consecutive cross sections (Diaz et al., 2014)

In order to draft the general land use/land cover map of the area supervised classification using the maximum likelihood classification option in ArcGIS was employed. The Landsat ETM+ spectral bands used to establish the land use/land cover classes were downloaded from the Global Land Cover Facility server. The cartographic materials belong to the ample collection pertaining to Alexandru Ioan Cuza University of Iasi (Geoarcheology Lab.): land survey maps (scale 1:5,000), ortophotos and satellite imagery. Some data were also provided by the Stanca-Costesti Hydropower Node and the local Mayor's offices from Stefanesti, Ripiceni (RO) and Costesti (MD).

3. RESULTS

The average multiannual discharge recorded on Prut River at Oroftiana gauging station is 70.00 m³/s (1950-1990). The lowest average multiannual monthly discharge was recorded in January (28.7 m³/s), whereas the highest value (125.2 m³/s) was documented in April. The lowest average annual discharge was 26.2 m³/s, in 1990, while the largest value recorded was 129 m³/s, in 1955.

The average multiannual discharge recorded on Prut River at Radauti Prut gauging station is 82 m³/s (1950-2011). Similar to the previous station, the lowest average multiannual monthly discharge was also recorded in January (36.8 m³/s) and the highest value (142.9 m³/s) in April. Furthermore, the lowest average annual discharge was 34.2 m³/s (1990), whereas the highest documented value was 156 m³/s (2010).

The average multinnual discharge recorded at Stanca-Costesti gauging station is 84 m³/s (1950-2011). The month where the average multiannual monthly discharge was the lowest was January (41.4 m³/s), whereas the highest value (127.9 m³/s) was documented in May. The lowest average annual discharge was 37.9 m³/s, in 1987, while the largest value recorded in this station was 150 m³/s, in 1955.

Prut river basin spreads over the territory of three countries: Romania, Ukraine and the Republic of Moldova. However, the largest extent of the drainage basin of Stanca-Costesti reservoir pertains to Ukraine. The dam is located in the middle section of the basin (Fig. 3). The area of the basin upstream of the reservoir amounts to 11,650 km², of which 8,764 km² in Ukraine, 2,210 km² in the Republic of Moldova and just 675 km² in Romania.
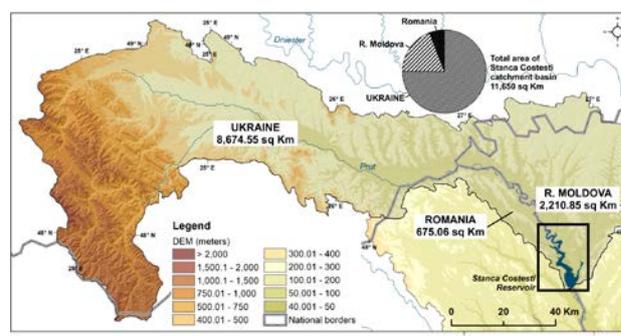

Figure 3. Prut river basin upstream of Stanca-Costesti reservoir, where lacustrine basin is highlighted in the black frame

The bathymetric survey revealed the depth of the reservoir increases in the downstream sector. The maximum depth of 29.2 m is reached in the vicinity of the dam (Fig. 4). The greatest depths occur near the steep rocky banks, whereas the least deep areas are located in the upstream sector and by the junctions with the main tributaries.
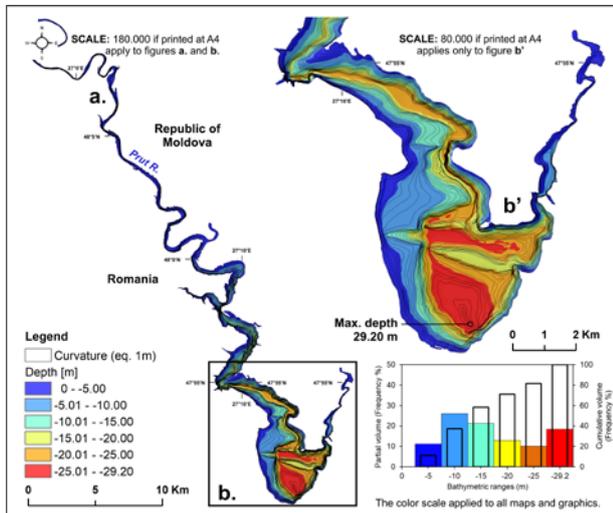

Figure 4. Bathymetric map and distribution of depth ranges of Stanca-Costesti reservoir for a. entire lacustrine basin, and b.-b' lower sector with maximum depth area

Within the reservoir the depth ranges from 10 to 15 m. The Moldovan-side bank is rather steep and the mid-channel- is located nearby it, whereas the Romanian-side bank is gentler, extending gradually towards the center of the reservoir. The smaller depth of the reservoir in the upstream sector is an effect of silting, as the river creates its own alluvial fan within the reservoir. Thus, the grain size indicates that sediments are coarser upstream and finer downstream. Moreover, the vertical sequence in terms of the particle size is very similar, from the bottom to the surface.

The largest amount of alluvium originates in the agricultural lands, particularly from Romania and the Republic of Moldova. The upper basin is located in the mountainous area in Ukraine and is well forested, thus resulting in low erosion rates (Fig. 4).

In terms of the share of depth ranges, the 5-10 m (26.10%) and 10-15 m (21.24%) classes are prevalent, whereas the 20-25 depth range has the smallest share (10.18%) (Fig. 4). Overall, we observed that the ratios of depth ranges are strikingly uniform. However, the share of the depth range over 25 m (18.48%) is rather surprising.

The map depicting the distribution of slope gradients within the reservoir closely follows the bathymetric map, i.e. the highest slope gradients commonly occur in the deepest areas, adjacent to the rocky banks from the Moldovan side and in several spots on the Romanian side. The areas with slope gradients under 1° are prevalent (44.8% of the reservoir area), followed by the 1-3° class (40.6%). The areas with gradients ranging from 7 to 10° account for less than 1.1% of the reservoir area, whereas the class of slope gradients over 20° account for 0.005% (Fig. 5 and 6).
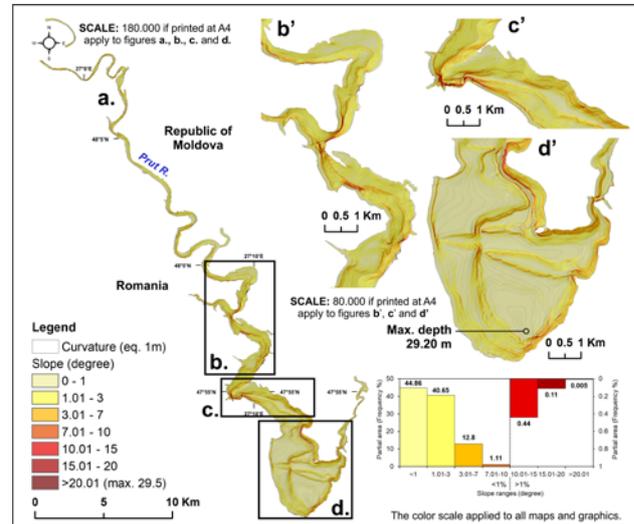

Figure 5. Slope gradient map and distribution of gradient classes in Stanca-Costesti reservoir for: a. entire lacustrine basin, b.-b' upper sector, c.-c' middle sector, and d.-d' lower sector with maximum depth area
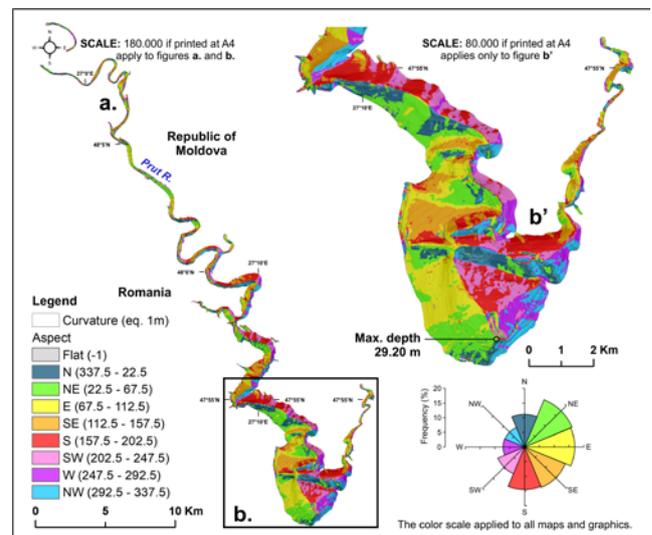

Figure 6. Slope aspect map and distribution of aspect classes in Stanca-Costesti reservoir for a. entire lacustrine basin, and b.-b' lower sector with maximum depth area

The large area of the reservoir and the diverse land morphology it inherited have resulted in a diverse slope aspect of the study area. The NE (17.5%) and E (17.0%) aspects are prevalent in terms of the slope aspect distribution, whereas the W (7.3%) and NW (7.1%) aspects hold the smallest shares (Fig. 6).

In order to document the degree of reservoir silting, both longitudinally and transversally, 17 cross sections between the Romanian and Moldovan banks were analyzed (Fig. 7). These sections were selected so as to highlight the pattern of sediment deposition or erosion. We were particularly interested in confluence sectors where alluvia are commonly deposited in significant amounts. The measurements were carried out on 19 July 2010, when the water level was 89.28 m. The level measured on that particular day was employed instead of using the normal level of retention (NRL),

i.e. 90.80 m. When the NRL is employed, the maximum depth is 30.7 m. The measured cross sections show a low degree of silting in the vicinity of the dam, whereas the silting is rather high in the upstream sector (Fig. 8, 9 and 10).

4. DISCUSSIONS

The water discharge increases on Prut River from upstream to downstream, from 70 m³/s (Oroftiana) to 82 m³/s (Radauti-Prut) and 84 m³/s
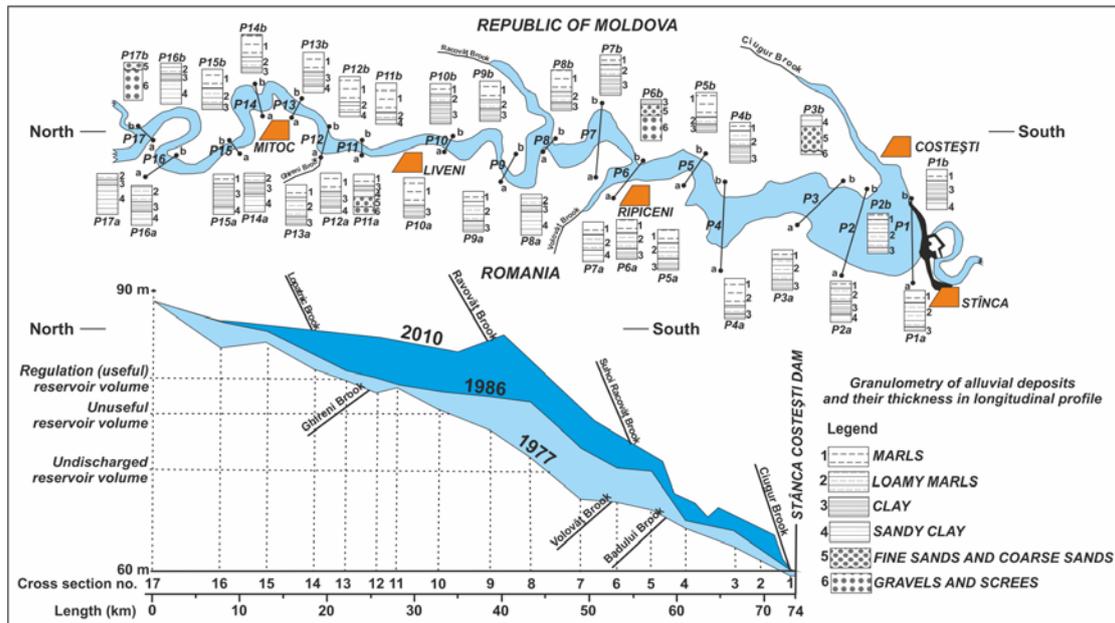

Figure 7. Distribution of sedimentation monitoring cross sections in Stanca-Costesti reservoir
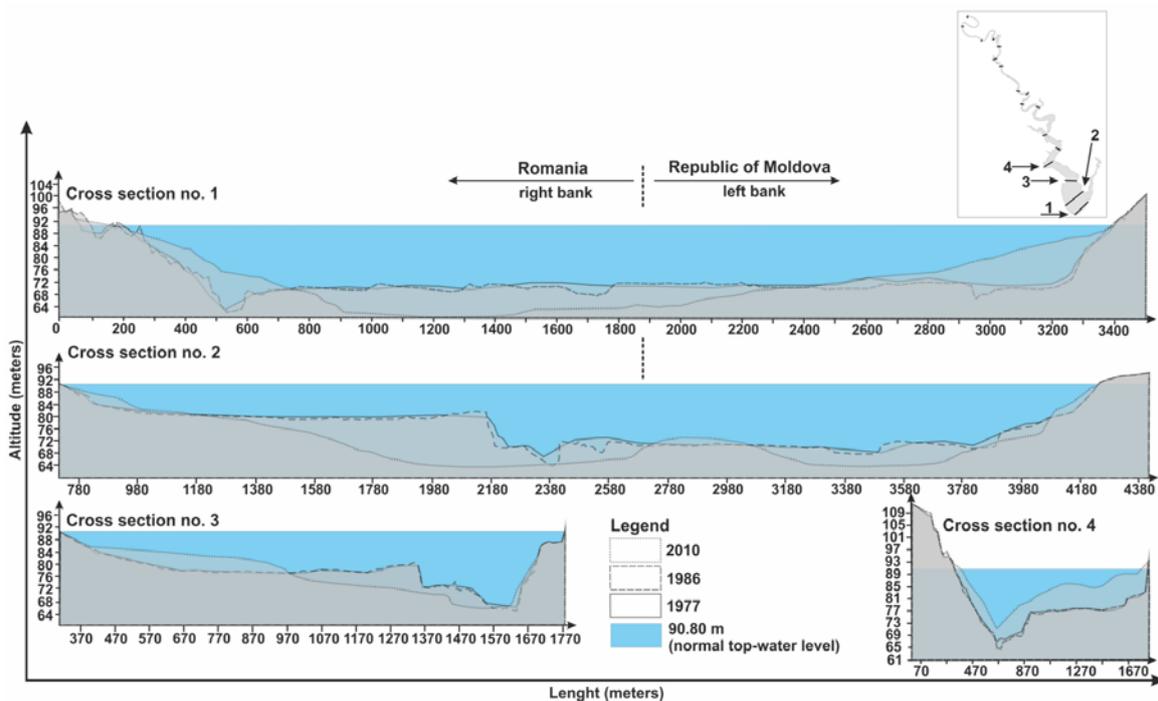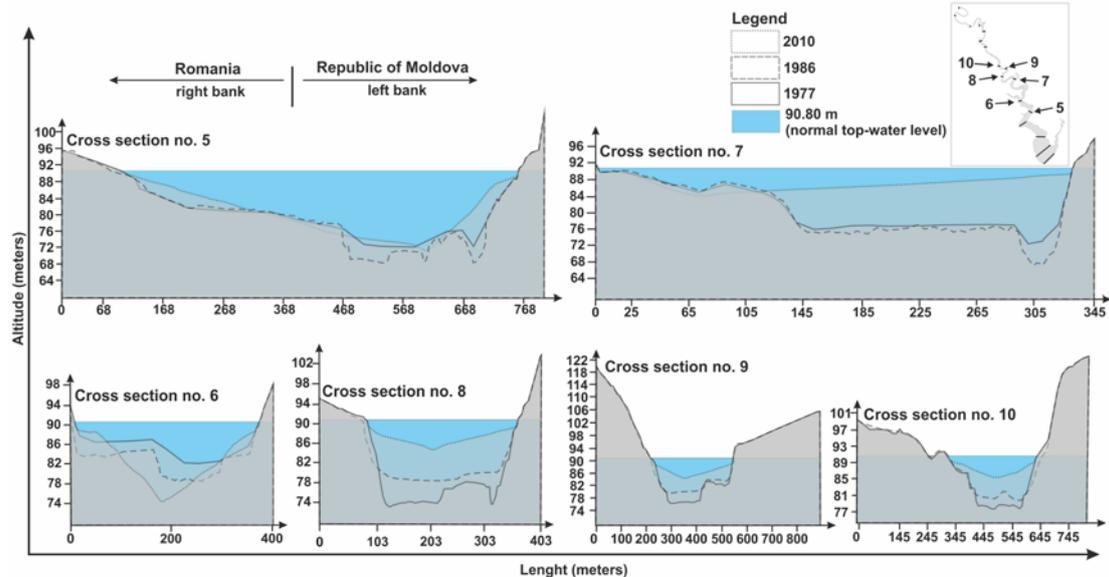

Figure 8. Cross sections no. 1 – 4
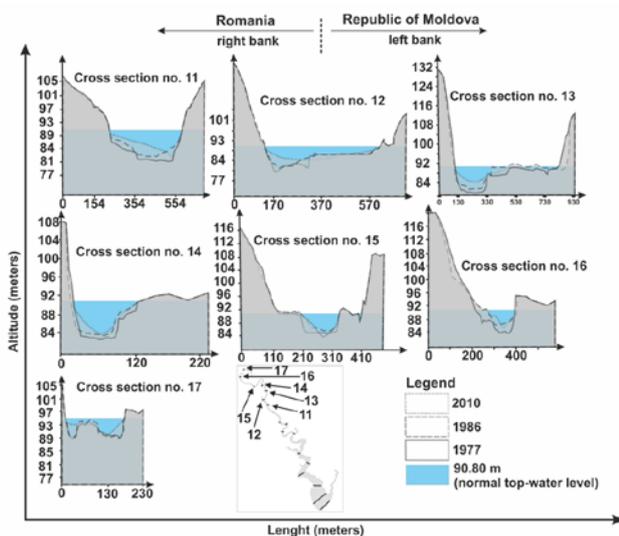
Figure 9. Cross sections no. 5 – 10

Figure 10. Cross sections no. 11 – 17

(Stanca-Costesti), respectively. Stanca-Costesti gauging station is located downstream of the reservoir dam. The monthly minimum values occur during the winter season (January) when the water is mostly retained in the shape of snow and ice. In turn, the maximum values occur in early spring (April-May) as a result of thawing in the upper basin. The maximum value measured at Stanca-Costesti gaunging station, which is lower than expected (as compared to upstream stations) is due to a large amount of water being retained within the reservoir (which has a low level during winter). The main purpose of Stanca-Costesti reservoir is flood control (Romanescu et al. 2011). Downstream of the dam a minimum sanitary discharge of 35 m^3/s is granted.

The drainage basin supplying Stanca-Costesti reservoir pertains to Romania, Ukraine and the Republic of Moldova, all of which have mainly agricultural economies. The vast majority of the land included in this basin (from both Romania and the Republic of Moldova) is covered by grain crops. Thus, erosion rates are high, particularly during spring when thawing occurs and the land is fallow. The high erosion rates are further increased by the usage of improper plowing techniques (i.e. parallel to slopes), as opposed to contour plowing. However, the erosion rate in Ukraine (in the upper sector of the basin) is low as a result of the high forest coverage (over 50%) (Fig. 11, Table 2).
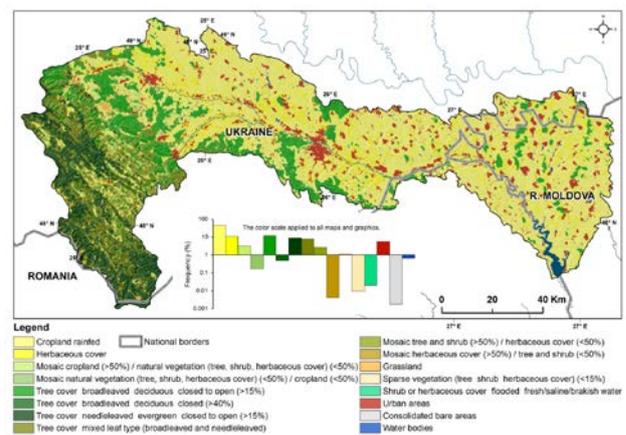

Figure 11. Land use map for Stanca-Costesti reservoir watershed. The histogram refere to distribution of main land use categories and the colour scale used is simillar with map legend.

The multiannual average suspended solid load is high upstream of the reservoir (55.06 kg/s at Radauti Prut) and rather low downstream of the dam (2.28 kg/s). Therefore, the bulk of the sediments carried by the river between the headwaters and Stanca-Costesti are stored within the reservoir. The dragged coarser solid alluvium is composed of

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gravel originating in both the crystalline and flysch Ukrainian Carpathians (Cruceanu et al., 2015).

Table 2. Area and percentage share of land use/land cover classes in the drainage basin of Stanca-Costesti reservoir

Land use category	Surface (ha)	Surface (%)
Anthropic areas	148,892.85	12.78
Agricultural land	320,387.58	27.50
Pastures	37,281.46	3.20
Forests and shrubs	601,979.14	51.67
Meadows	24,465.96	2.10
Wetlands	14,446.57	1.24
Water bodies	17,592.19	1.51
Total	**1,165,045.76**	**100.00**

Along Prut river, from the headwaters to Stanca-Costesti reservoir, gravel (ranging from 50-40 mm upstream to 15-7 cm downstream, entering the reservoir) and coarse sands are prevalent. The finer material stems from the Moldavian Plateau facies and is composed mainly from friable rocks (i.e. limestone, sandstone, loess deposits etc.) (Fig. 7). Part of the gravel is eventually carried downstream of the dam; however, this is supplied mainly by the old deposits, washed by the spillway water which commonly carries small sediment loads. These gravels occur as far as 37 km downstream of the dam, forming a *hydraulic pavement*. Thus, it appears that Stanca-Costesti reservoir is the area where the „particle size leap" from gravel (8-7 mm) to sands (1 mm) occurs.

The fast silting of the reservoir is caused by the torrential regime of Prut river upstream of Stanca-Costesti. The largest share of the alluvium is accumulated during flood events. Prut river, alongside Siret (the longest rivers in eastern Romania), recorded the highest historical water discharge values among Romanian rivers thoughout the entire period of measurements: 7,146 m³/s (2008) and 4,650 m³/s (2005). 2008 was a very particular year in terms of the hydrological regime for all eastern Romanian rivers: the strongest flood events in the history of systematic measurements were recorded that year. Moreover, in 2008 the largest amount of water was carried through the Stanca-Costesti reservoir. This resulted in the most massive flood event ever to occur in Romania, when the historical discharge value (7,146 m³/s) was documented at Radauti-Prut (upstream of the reservoir) (Romanescu et al. 2012 a,b). The peak discharge values were recorded on 28.VII.2008, between 9-12 P.M. After two years of analyses, this historical value was replaced with 4,240 m³/s. The reasons invoked for this replacement are questionable, as the maximum level and the tidal bore could not indicate the latter value, which is

considerably lower. The former value (7,140 m³/s) was the maximum historical value measured throughout Romania, whereas the latter (4,240 m³/s) is only the second highest value, after the one measured on Siret river in 2005 (4,650 m³/s) (Romanescu & Nistor 2011). During the past two decades we have documented an increase in high waters during the summer, particularly in August. The largest flood events occurred in 1988, 1998, 2005, 2006, 2007, 2008, 2009, 2010, 2011 (Table 3).

Table 3. Historical water discharge values at Radauti Prut and Stanca-Costesti gauging stations

Gauging station /year	Radauti Prut (m³/s)	Stanca Costesti (m³/s)
1988	1,780	651
1998	1,960	-
2005	2,640	570
2006	1,168	496
2007	803	-
2008	7,146 (4,240 reevaluated discharge)	1,050
2009	419	-
2010	2,310	885
2011	428	-

The deepest points of the reservoir occur in the vicinity of the dam and result from linear and circular submerged currents. The latter type of currents is also generated by the presence of natural levees on Ciuhur stream, such that the deepest sector has a circular shape (Fig. 12).

The map depicting the aspect of submerged slopes indicates relatively uniform shares for each aspect class, which is consistent with the symmetry of the valley (i.e. relatively equally developed hillslopes on both banks) (Fig. 6). During the first analyzed time frame (1977-1986) a high silting rate was documented in the vicinity of the dam, as opposed to lower rates upstream. During the second stage (1986-2010) the silting rate increased upstream, whereas the trend was inverse downstream. The changes in the silting rates likely result from the decrease in the slope gradient of the long profile, which allows for a fast deposition of coarse sediments upstream (forming a vast fan delta), thus leaving only the finer particles to be carried downstream. Moreover, the intensive silting occurring upstream is also an effect of the reduced depth of the reservoir in this sector.

In the downstream sector of the reservoir erosion phenomena arise due to circular currents generated by the tributaries' flow and the presence of local barriers. Circular currents form nearby the dam which leads to scouring (piping) of the alluvia. Furthermore, bottom stream flow ensures that sediments are promptly removed, thus resulting in low silting rates.
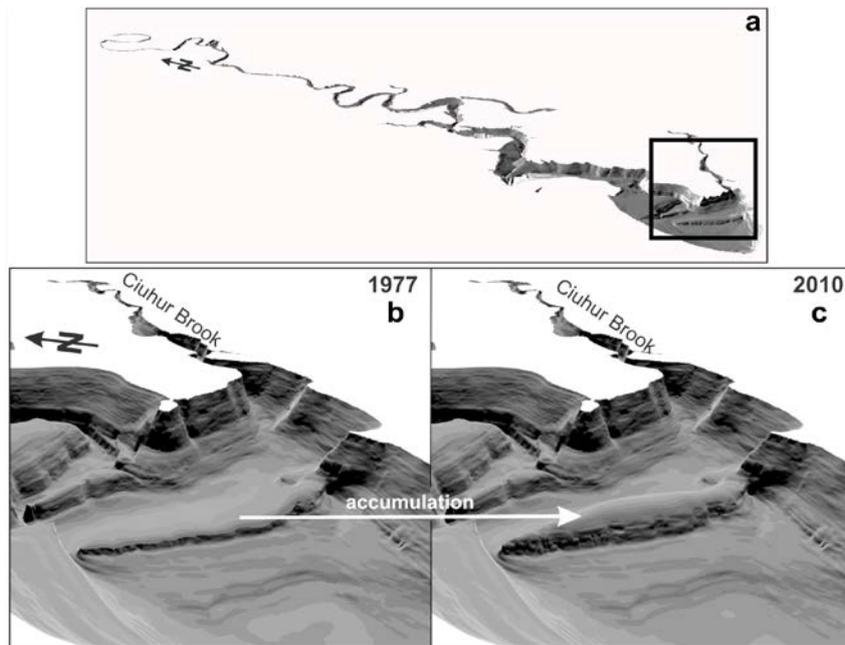
Figure 12. Alluvial build-up at the submerged junction with Ciuhur stream: a. hillshade relief of Stanca-Costesti lacustrine basin, b. lower sector in 1977, and c. lower sector in 2010

The old terraces of Prut River are still well defined in the downstream sector and lack recent alluvial depositions for the most part (c.s. no. 1, Fig. 8). Conversely, the terraces in the upstream sector are covered entirely by sediments (c.s. no. 6, Fig. 9). Moreover, several broad submerged glacises have cropped up, particularly by the steep banks (c.s. no. 2, 4, Fig. 7 and 8).

The low water speed in Stanca-Costesti reservoir results in the shaping of transverse submerged valleys, elongated between opposing banks. The most telling example is Ciuhur stream (on the Moldovan side), which, despite its low average multiannual discharge (0.7 m^3/s), succeeds in creating a large valley with lateral natural levees, which inherit the old shapes from the common riverbed with Prut river (Fig. 4 and 12).

In the lower sector of the reservoir the alluvial deposition is uniform on both sides (Romanian and Moldovan), since the slopes are very similar in terms of gradients and aspect (Fig. 5). However, in the middle and upper sectors sediment deposition occurs alternately from one slope to the opposite, depending on the slope gradient. Submerged glacises are lacking in the vicinity of rocky banks. The valley is narrow in the upstream sector, as it occupies an old gorge carved in limestone. The steep walls of the ancient gorge are noticeable in the cross sections.

The total amount of alluvium accumulated in Stanca-Costesti reservoir is 34,779,189.03 m^3. From 1977 to 1986 the stored amount was 4,945,892.15 m^3, whereas the following stage saw 4,945,892.15 m^3 of sediments deposited in the reservoir. The average annual silting rate is 65,869.68 m^3. The silting degree is relatively high, i.e. 7.3% over a period of 33 years (Table 4).

The silting degrees of large Romanian reservoirs are relatively low; most of these water bodies are located in mountainous areas, whereby the geology comprises typically of hard rocks, and thus erosion rates are low: Vidra on Lotru river 0.30% (1973), Vidraru on Arges river 0.71% (1966), Izvorul Muntelui on Bistrita 0.45% (1960), Fantanele on Somesul Cald 0.41% (1978), Portile de Fier I on the Danube 24.58% (1971) etc. There are, however, instances where smaller sized reservoirs have higher silting rates, such as Oesti on Arges river 89.83% (1967), Vadeni on Jiu 82.34% (1989), Curtea de Arges on Arges 73.33% (1971), Racova on Bistrita 63.05% (1965), Daesti on Olt 56.15% (1976), Candesti on Buzau 54.05% (1989) etc. Some of the most significant reservoirs located in the Moldavian Plateau (on Siret river, the largest river in Romania), most of which have the same purposes as Stanca-Costesti, are silted to various degrees: Galbeni 60.83%, Racaciuni 11.28%, Beresti 6.44%, Calimanesti 8.58%. Stanca-Costesti reservoir is not mentioned in these datasets because no measurements have been performed on its silting degree since 1986.

5. CONCLUSIONS

Stanca-Costesti reservoir is located on the middle course of Prut River and is the largest reservoir in Romania and the Republic of Moldova. Its main purpose is flood control. The power plant has an installed capacity of 30 MW, which is equally divided between Romania and the Republic of Moldova.

Table 4. The volumes of sediments ($10^4 m^3$) stored in Stanca Costesti reservoir between 1977-2010

Cross section segment	Distance between cross section (km)	1977-1986 Vol. ($10^4 m^3$)	1986-2010 Vol. ($10^4 m^3$)	1977-2010 Vol. ($10^4 m^3$)	Average yearly volume ($10^4 m^3$)
1-2	2.234	-126.87	-2,638.52	-2,765.39	-83.79
2-3	3.602	-327.40	-2,311.10	-2.638.51	-79.95
3-4	5.408	179.92	2,463.98	2,643.90	80.11
4-5	3.253	183.09	1,552.03	1,735.12	52.57
5-6	3.938	-192.35	202.18	9.82	0.29
6-7	9.047	-543.61	1,151.83	608.22	18.43
7-8	4.367	152.96	922.34	1,075.30	32.58
8-9	2.840	214.10	444.94	659.04	19.97
9-10	1.877	95.38	268.17	363.55	11.01
10-11	5.986	291.15	552.89	844.05	25.57
11-12	1.779	60.63	64.85	125.48	3.80
12-13	2.656	94.24	111.13	205.38	6.22
13-14	3.873	111.09	113.19	224.28	6.79
14-15	5.067	66.40	12.52	78.92	2.39
15-16	4.620	113.81	5.50	119.32	3.61
16-17	6.808	122.01	6735	189.37	5.73
Total	**67.362**	**494.58**	**2.983.32**	**3,477.91**	**-**

The bathymetrical measurements were performed with a precision echo sounder (Valeport Midas Surveyor) with a 1/1 cm resolution, on both longitudinal and transversal paths spanning the entire surface of the reservoir. In order to assess the sedimentation rate in Stanca-Costesti reservoir three datasets were used: land survey data (1977, prior to reservoir flooding) and bathymetric data from 1986 and 2010.

Prut River has its origin in the Ukrainian Carpathians and the confluence with the Danube occurs in the vicinity of Galati urban area. The drainage basin of this reservoir extends accross three countries, Romania, Ukraine and Republic of Moldova. The geology of the mountain sector of Prut basin consists of crystalline schist and flysch rocks, while the Moldavian Plateau is mostly composed of friable rocks, such as limestone, sandstone and loess deposits. Moreover, whereas the mountain sector is mostly covered by forest, the lowland (the Moldavian Plateau) is used for agriculture, i.e., cereal crops. The accelerated soil erosion is a result of massive deforestation, particularly post-1989, when private ownership over the land was restored for most of these lands.

The alluvial deposits stored in the reservoir consist mainly of gravel originating in the mountain sector of the basin and sands from the lowlands. Two stages of alluvial deposition were determined: 1977-1986, when the majority of the sediments were stored up in the lower sector of the reservoir; 1986-2010, when sediments accumulated in thicker layers in the upstream sector. The main cause for this is the decrease in the slope gradient. In the upstream sector a huge alluvial fan was built-up, covering the ancient river terraces. Broad submerged glacises formed at the foot of the slopes. The river terraces are still intact in the lower sector of the reservoir, lacking any recent alluvial cover. The valley and the longitudinal levees of Ciuhur stream extend heavily into the reservoir basin behind the dam. The maximum depth is 29.2 m and occurs in the vicinity of the dam, partly as a result of a circular current.

The total volume of sediments stored in the reservoir amounts to 34,779,189.03 m^3, with an annual average deposition rate of 65,869.68 m^3. The silting degree is relatively high, i.e. an index of 7.3% over a period of 33 years. Large reservoirs throughout the Carpathian area commonly have relatively low silting rates: Vidra on Lotru river 0.30% (1973), Vidraru on Arges 0.71% (1966), Izvorul Muntelui on Bistrita 0.45% (1960) etc. The most advanced silting in Romanian reservoirs occurs in: Oesti on Arges river 89.83% (1967), Vadeni on Jiu 82.34% (1989) etc. The reservoirs located in the Moldavian Plateau (on Siret river) are silted to various extents: Galbeni 60.83%, Beresti 6.44% etc.

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