Review Article

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Changes in retention characteristics of 9 historical artificial water reservoirs near Banská Štiavnica, Slovakia

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Abstract: The article is focused on the evaluation of accumulation volume changes in 9 water reservoirs near Banská Štiavnica (Slovakia) by comparing historical maps and using modern bathymetric surveying technologies. The mining region of Banská Štiavnica has been inscribed into the UNESCO List of the World and Cultural Heritage in 1993. Accumulation and transfer of sediments depend mainly on changes of land cover in the watersheds that lead to the loss of retention capacity and reduction of life span of reservoirs. The results of a comparison of two 3D models, one created from historic documentation and the other created from data of field surveying have shown overall reduction in the volume of water totalling 446484 m^3 , i.e. 16.70% from past to current time. Causes of sedimentation were searched in watersheds changes over time. These were identified by comparison of historical aerial imagery (1949) with existing aerial photographs.

Keywords: Aerial images; Banská Štiavnica; bathymetry; echosounding; reservoir

1 Introduction

The examined water reservoirs Halčianska, Bakomi, Belianska, Brennerštôľňanska, Evička, Large Kolpašská, Large, Small Richňavská and Vindšachta are part of the historical water resources system which is along with the town Banská Štiavnica (Slovakia) included in UNESCO

World Heritage list with reference number 400: Historic Town of Banská Štiavnica and the Technical Monuments in its Vicinity (Fig. 1). These are significant technical monuments showing highly-developed hydraulic structures of the past.

During the mining era at the turn of the 17th and 18th century the groundwater had become an existential problem for the resumption of mining operations. The problem became even more serious as the depth of the mineshafts was increasing and the contemporary facilities were not able to drain water from them [1]. Matej Kornel Hell (1653 – 1742) was the first who solved the problem by constructing the water reservoir Vindšachta and extending other ponds (Evička, Upper Hodrušský) to use the energy of accumulated water to propel the pumps for mineshaft draining. As the time went by and mining was advancing even these sources were insufficient. It was Samuel Mikovíni (1700 – 1750) who is credited for constructing and repeatedly extending of the most important reservoirs (Evička, Bakomi, Richňavské, Kolpašské, Beliansky) with ditch and underground mining tunnel planning. The ditch dimensions were 0.63–0.94 metres with the depth of 0.63 metres [1]. The overall network length was more than 110 km.

The nearest comparable hydraulic structures system is located in Harz and Freiberg in Germany. The regression of mining caused that the system's purpose of providing water for mining and metallurgical industry or to drain water from the mining underground was no longer required [2]. They are an important landscape-ecological, landscape and eco-stabilizing element. They represent one of the dominant phenomenon that is characteristic for region's scenery.

The regression of mining is also associated with regression of hydraulic structures system. The number of reservoirs and their total storage volume decreased significantly. Nowadays these reservoirs are utilized for fish breeding, recreation and tourism. 23 out of 60 artificial reservoirs have been preserved up to this day [3].

Changes in the water reservoirs are affected by various factors. The most significant factor is erosion-

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Figure 1: Localization of the Banská Štiavnica and surveyed water reservoirs; 1 – Halčianska, 2 – Belianska, 3 – Evička, 4 – Bakomi, 5 – Large Kolpašská, 6 – Brennerštôľňanska, 7 – Large Richňavská, 8 – Small Richňavská, 9 – Vindšachta.

sedimentation activity, particularly in the watersheds of the reservoirs. Changes caused by anthropogenic activity in the watershed occur often very dynamically. The reasons for relatively intense erosion in their micro watershed is the composition of easily erodible, incompact or tectonically deteriorated products of neogene volcanism, breccia and metamorphosis products along with deforested and bare soil horizons.

In contrast to Urban *et al.* and their conclusions wind erosion only slightly participates to general value of the analyzed area. On the other hand shore erosion caused by dynamic effect of waves and frost erosion significantly wash up fine-grained fractions out of stone lining of the dam.

Determination of amount of accumulated sediment load and periodical data updating of water reservoir storage volume enable the performing of prognosis for further siltation. Results of monitoring enables creation of relevant assumptions for effective safety measures proposal in the watershed leading to minimize the negative outcomes. Therefore bathymetric maps and elevation models of the bottom should be updated regularly [4]. The following application of measures will reduce negative outcomes and operation and maintenance costs of the reservoirs. Numerous authors have devoted their work and research to analysis of the most common and the most serious negative outcomes caused by the increase in accumulated sediment load and successive degradation of water ecosystem [5–8]. Other authors have devoted to landslide dynam-

ics of incompact rocks in connection with dam lakes formation [9]. Bottom sediment transport and bottom morphology changes in terms of high gradient rivers in Morava are analyzed [10–12]. Acoustic devices determining volume changes in the reservoirs were used by many authors in Slovakia and abroad [13–31]. Identical methodology has been utilized in mapping of lakes in Czech, except for certain software processing procedures [32]. In Slovakia, Water Research Institute (hereinafter WRI) has been engaged in this issue for a long time period [33].

2 Data and methods

2.1 Historical bathymetric data

Historical data on water reservoirs conditions were derived from the old projects and volume maps (calculating water volume content) in various scales. Bottom conditions of Halčianska water reservoir were derived from a historical map named “Halčiansky pond – Banská Belá – Banský Studenec” in the scale of 1:10000 from year 1908 [34]; Belianska water reservoir from a historical map “Water volume content of Beliansky pond in B. Belá, scale 1:10000 from year 1855 [35]; water reservoir Evička from a map “Evička pond – Štiavnické Bane”, scale 1:1000 from June 1971 [36]; water reservoir Bakomi from a map “Bakomi pond – Štiavnické Bane”, scale 1:500 from June 1971 [37];

water reservoir Brennerštôľňanska from a historical map “Brenner tó köbözése”, scale 1:250 from year 1897 [38]; water reservoir Veľká Kolpašská from a historical map “Kolpašké lake – Banský Studenec”, scale 1:1000 from year 1889 [39]; Veľká and Malá Richňavská water reservoir from a historical map “Cubic content map of Veľká and Malá Richňavská water reservoir in Štiavnické Bane – ground plan” [40]; Vindšachty from a historical map “A szélaknai nagy tó köbtartalmának meghatározása. 1887-ik évi szeptember havában”, scale 1:1000 [41]. Maps have been scanned at 300 to 600 DPI resolution, converted to TIFF format and consequently georeferenced into coordinate system SJTSK Křovak through plotting points. Cartographic base with a well-known coordinate system consisted of aerial photograms, maps ZM 1:10000. Georeference was done upon minimum of 10 plotting points with outcome residual values approaching zero. Consequently the data from georeferenced historical maps were vectorized into Esri Shapefile format and absolute altitude Z were assigned, data was read from historical maps. Contour elevations were adjusted for the difference caused by the change of applied altitude system H_{Bpv} from H_{Jadran} – 0.46 m. Valid values for the Slovak Republic are –0.40 to –0.42 metres – greater differences occur among historical and published geodetic surveying [42].

2.2 Present bathymetric and topographic data

Field study of individual water reservoirs took place as follows with absolute water-level altitude or dam body of empty Brennerštôľňanska water reservoir: Halčianska – 17.12.2010 (470.90 m.a.s.l.), Belianska – 14.10.2011 (556.6 m.a.s.l.), Evička – 15.10.2011 (664.91 m.a.s.l.), Bakomi – 19.10.2011 (709.5 m.a.s.l.), Brennerštôľňanska – 16.5.2012 (554.13 m.a.s.l.), Large Kolpašský – 23 and 24.5.2012 (598.10 m.a.s.l.), Large Richňavská – 10.7.2013 (725.710 m.a.s.l.), Small Richňavská 14.8.2013 (716.274 m.a.s.l.), Vindšachta – 3.9.2014 (688.4 m.a.s.l.). We decide to use the non-contact surveying method based on the use of ultrasonic depth surveying and position system GNSS for gathering data on the present bottom conditions (16, 21, 24, 25, 43). The device was fixed to a boat and the sets of points with depth and position information were recorded during the cruise along a previously designated track (data X , Y , Z). Complementary data were localised right on the banks and around the water reservoir by technology GNSS rover, Altus APS-3 or Zeiss Theo and Nikon Nivo 3.C theodolite levelling. The same exact procedure was used in other areas, but accumulation processes

caused shift of the reservoir border line, reduction of water surface and parts of the reservoir turned into terrestrial environment. We have observed the most significant reduction of water surface detriment of grounded part in water reservoir Halčianska; damage of the dam and emergency conditions occurred near water reservoir Brennerštôľňanska. Therefore we used technical levelling from the middle along with manual GPS device localisation by Mobile Mapper 6. We carried out a closed polygonal traverse in the terrain. Original reservoir storage volume in the past (Table 1) represents the total water volume at maximum water level. The data were taken from a historical cartographic documentation and consequently verified by calculation in Surfer 11 programme upon vectorized isobaths of those historical maps. Contemporary volume represents reservoir storage volume on the water level that is identical with altitude of water level during the field measurement. Changes in volume were compared on the same absolute water-level altitude.

2.3 Data visualization, calculation of volume change

Calculation of volume change or sediment load under given time was carried out in Surfer 11 environment (Fig. 2). This software often appears in the works of other authors in connection with reservoir bottom modelling [29, 44–46].

Through interpolation method Kriging [47] we generated the grids with cells of 2×2 m dimensions representing two different models. We chose circle as the shape of assessment with radius set in a way that the effective area of interpolation included sufficiency of spatial autocorrelation points. This is a very subjective assessment; optimum for further calculation would be 12 data entries at least [48]. Quality of our predictions has been verified by Cross-Validation procedure [49]. Residual frequency distribution was common, with mean values approaching 0.

After mutual comparison and subtraction of models we acquired the difference that amounts to the sediment load volume in the reservoir. 2D and 3D visualization has been processed in Surfer 11 software.

2.4 Landscape structure analysis and morphometric analysis of watershed

Analysis of angle and orientation of slopes in micro watershed has been processed in ArcGIS environment (Spatial Analyst/Surface analysis/Slope/Aspect) upon 3D ele-

Table 1: Characteristics of reservoirs.

Reservoir	Origin	Volume [m ³]		Perimeter [km]	Area [ha]	Max. depth [m]		Length: water trenches and gallery [km]
		*	**	**	**	* * *	**	
1	1770	256 900	221 026	1.11	3.8	13	13	1.6
2	1747	146 000	138 379	0.55	1.73	18	11.4	1.7
3	1638	110 712	99 795	0.61	1.99	10.4	7.91	2.5 (gallery 1.3)
4	1736	55 750	55 083	0.36	0.11	14.4	8.5	20 (gallery 1.3)
5	1730	719 788	661 987	1.74	8.7	13.5	13.5	0.7
6	1584	68 716	64 715	0.23	0.36	8	0	-
7	1738	861 442	666 163	1.14	7.37	21.1	19.5	24
8	1746	81 326	35 174	0.39	1.16	14.2	6.7	24 (gallery 3.4)
9	1710	372 630	284 458	0.92	4.48	14.2	12.73	12.9 (gallery 1.2)
Σ		2673264	2226780	7.05	29.7			

Explanation: 1: Halčianska, 2: Belianska, 3: Evička, 4: Bakomi, 5: Large Kolpašská, 6: Brennerštôľňanska, 7: Large Richňavská, 8: Small Richňavská, 9: Vindšachta, * situation in the past, ** current situation, * * * reported in the literature [3, 47]

vation model of micro watershed generated out of contour vector model acquired through vectorization of existing maps (scale 1:10000). SLS (Secondary Landscape Structure) of the reservoir watershed has also been processed in ArcGIS environment. We have derived and created the map of landscape cover for both time horizons upon interpretation of orthophotographs from year 2006 with subsequent completion and modification of field study data and upon reinterpretation of black and white photographs from year 1949. We used at least 7 plotting points for georeferencing of historical aerial photographs and since the place of interest was situated in the middle thus covering only a minor part of the aerial photograph we did not carry out orthorectification. Considering that there are almost no distortion effects in the middle of the photograph and residual values were approaching zero, we regarded georeference as sufficiently accurate.

3 Results and Discussion

The study was focused on the analysis of water reservoir volume changes (Table 1, 2), characteristics of reservoir watersheds (Table 3) and landscape structure changes (Table 4). We excluded reservoirs Large and Small Richňavská from our survey as they are situated in watershed drainage divide and the water inflow comes only from collecting trenches without any natural tributary stream of river.

After comparison of historical data and research outcomes we can state that all the reservoirs experience gradual accumulation of sediment load either in a larger or in a smaller extent. The dynamics of erosion-accumulative processes in case of water reservoirs Halčianska, Large Kolpašská, Vindšachta shows the trend of increasing siltation affected by the intensity of anthropogenic activity in the watershed. Calculation of sediment load per one year (arithmetic mean does not consider variations in long term precipitation and only shows informative comparison) indicates the greatest amount of sediment load in water reservoirs Large Richňavská, Kolpašská, Halčianska, Vindšachta a Evička. Data on maximum reservoir depth introduced in available literature [50] differ from actual measured depths (Table 1). The difference is assigned to inaccuracies in methodology of informative measurements in the 90's of the 20th century as well as adoption of inaccurate data by other authors.

Reservoir Large Richňavská is probably the most significant source of sediment load because of multiple stabilizations of dam body immediately after initial percolation. Episodic storm rainfall and a portion of clay loamy sediments or slope abrasion products contribute to this condition as well. Large Richňavská reservoir itself does not have its own watershed and the water source comes from collecting trenches [51]. In contrary, reservoirs like Large Kolpašská, Halčianska, Evička and Vindšachta show significant anthropogenic activity in their watersheds upon erosion intensity and a subsequent sedimentation. Watershed area of reservoirs Evička and Kolpašská is almost

Table 2: Changes of water reservoirs.

Reservoir	Time period [years]	Total volume of sediments [m ³]	Change of area [m ²]	Average volume of sediment per year [m ³ /year]	Sediment thickness [m]	
					Average	Maximum
1	1908 – 2010 [102]	35874	–9373.6	352	2.6	4.45
2	1855 – 2011 [156]	7621	–926.1	49	1.17	4.51
3	1971 – 2011 [40]	10917	–912.6	273	0.86	1.42
4	1971 – 2011 [40]	667	0	17	0.08	0.14
5	1889 – 2012 [123]	57801	0	470	1.02	3.52
6	1897 – 2012 [115]	4001	0	35	0.78	1.12
7	1888 – 2013 [125]	110494	0	884	1.49	3.99
8	1888 – 2013 [125]	46152	–37626	370	2.37	5.19
9	1887 – 2014 [127]	24491	–2872	657	1.86	3.85
Σ		298018	–50797.7			

Explanation: 1 – Halčianska, 2 – Belianska, 3 – Evička, 4 – Bakomi, 5 – Large Kolpašská, 6 – Brennerštôľňanska, 7 – Large Richňavská, 8 – Small Richňavská, 9 – Vindšachta

Figure 2: Bathymetric maps of selected water reservoirs.

identical. We have identified various risk factors in this locality. From the point of view of volume change analysis period the average set speed of sedimentation of reservoir Evička seems fairly significant. We assume that intensive urban planning and development of town residential area Štiavnické Bane and numerous changes in the country's exploitation have shown on the last cascade stage of water reservoirs Bakomi, Vindšachta and Evička with mutual cumulative watershed. In Evička's watershed the urban area

has increased by 11.2%, in Large Kolpašská's watershed by 1% (nearby the water surface). Bank zones of water reservoirs, especially in the days of growing tourism (construction of new buildings for tourism purposes), are exposed to anthropogenic pressure resulting in sediment load because of the change in exploitation or removal of vegetation cover. It is mainly a matter of eroded banks with a short grass cover or built up areas. There is a probability that the tendency to progressive build-up and change of

Table 3: Selected characteristics of reservoir watersheds.

Reservoir	Average slope [°]	Average potential erosion [t.ha ⁻¹ .year ⁻¹]	Aspect [%]				The average altitude [m.a.s.l.]	Area [km ²]	Drainage divide [m]
			N	S	E	W			
			NE NW	SW SE					
1	15	104.1	33	21	20	26	643	9.12	12956
2	5	39.4	45	24	3	28	610	0.39	3033
3	5	33.7	33	51	5	11	741	1.37	5169
4	5	39.2	23	54	3	20	757	0.40	2624
5	20	99.9	32	41	15	12	699	1.97	5808
6	17	98.4	22	51	14	13	706	0.99	4151
7	5	38.9	30	50	5	15	750	0.97	4305

Explanation: 1 – Halčianska, 2 – Belianska, 3 – Evička, 4 – Bakomi, 5 – Large Kolpašská, 6 – Brennerštôľňanska, 7 – Vindšachta

the reservoir surrounding into urban area will continue in the watershed areas of water reservoirs Evička, Large Kolpašská, Belianska and Bakomi. Moreover, according to the geological map of Slovakia: State Geological Institute of Dionýz Štúr [52] most of the places of interest are located in the geological subsoil of deluvial sediments: mainly claystone (secondary stony-loam) slopes and debris.

Total storage capacity of the reservoirs has decreased from the original volume of 2673264 m³ to present 2226780 m³. That is the deposition of 298018 m³ of sediment load. It is necessary to state that the original design capacity of reservoir Small Richňavská (406656 m³) was by 325330 m³ larger than capacity in year 1888 (81326 m³). This capacity has never been reached due to dam leakage [51].

Outcomes of individual areas cannot be statistically definite and drawn into a single conclusion upon intensity of erosion-accumulation processes in the water reservoirs of Banská Štiavnica and its surrounding. Areas differ in watershed size, intensity and in a way of land exploitation or the landscape cover structure. We see a limiting factor in the missing data on erosion and sediment accumulation progress course over the time. The only available data are those from the time of reservoir constructing and current conditions. Great variability of the average sediment load transported to particular reservoirs per one year show significant differences. Reservoir Halčianska shows the most distinct changes. Indicators of these changes include maximum sediment thickness 4.45 m, average thickness 2.6 m, total reduction of water surface by nearly a third of its original area (–9373.6 m²) and the average sediment load per one year (352 m³/year). According to the data provided by Research Institute of Pedology and Soil Protection, reservoir Halčianska is located in subsoil with average poten-

tial erosion up to 104.1 t.ha⁻¹.year⁻¹. It is interesting to state that watersheds of reservoirs Large Kolpašská and Brennerštôľňanska are both located in the area with approximately identical rate of potential erosion that is 99.9 and 98.4 t.ha⁻¹.year⁻¹. Water reservoir Brennerštôľňanska shows significantly lower accumulation intensity of sediment load (in average 35 m³ per one year) than Large Kolpašská (in average 470 m³ per one year). The reason is that in the watershed of Brennerštôľňanska reservoir there is a more significant anthropogenic pressure (no building-up, little timber harvesting and no tourists). In water reservoir Large Kolpašská we can assume an intensive and fast sediment flow to the deepest parts of the reservoir as we have not observed reduction of water surface in the past 123 years. Greater sediment thickness in the deepest parts of the reservoir and a progressive depth reduction in offshore parts around weak tributaries prove our assumption.

Reservoirs Large Kolpašská and Evička experience great annual accumulation of sediment load (Evička: 273 m³ per one year, Large Kolpašská: 470 m³ per one year) on account of intensive landscape exploitation, changes in landscape structure of the watershed and anthropogenic activities in the nearest surrounding of water surfaces.

Water reservoirs in Banská Štiavnica and surrounding are included in UNESCO World Heritage list. Their original function – supplying water to mining mechanisms – has ceased to exist after the regression of mining. These reservoirs are still used for fishing, tourism and leisure, flood protection and they compose significant landscape-ecological and eco-stabilizing element. These are the binding reasons and they should lead to a more complex change in administration and management of these unique technical objects and their watersheds.

Table 4: Secondary landscape structure in 1949 and 2014.

Watershed	Meadow	Forest	Non-forest vegetation	Built-up areas	Agricultural land	Permanent grassland	Water surface
	%						
1*	22.26	73.53	1.39	0.26	2.16	-	0.40
1**	31.62	58.13	4.87	0.08	4.87	-	0.43
2*	59.52	19.64	10.02	3.52	-	3.02	4.28
2**	75.70	12.15	7.85	-	-	-	4.30
3*	41.8	37.4	4.1	11.4	-	0.1	5.2
3**	66.4	22.9	5.2	0.2	-	-	5.3
4*	37.14	43.14	4.42	8.38	-	-	6.92
4**	55.93	28.4	8.75	-	-	-	6.92
5*	15.27	67.6	7.5	1.02	2.89	1.31	4.41
5**	26.88	57.9	3.29	0.02	7.50	0	4.41
6*	34.54	57.97	4.44	0.33	-	1.21	1.51
6**	32.87	58.42	6.87	0.33	-	-	1.51
7*	37.6	35	5.2	12.8	-	3	6.4
7**	62.2	27.4	3.8	0.2	-	-	6.4

Explanation: 1 – Halčianska, 2 – Belianska, 3 – Evička, 4 – Bakomi, 5 – Large Kolpašská, 6 – Brennerštôľňanska, 7 – Vindšachta, * situation in 2014, ** situation in 1949

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