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Siltation of Small Water Reservoir under Climate Change: A Case Study from Forested Mountain Landscape of Western Carpathians, Slovakia

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Abstract: The effectiveness of small reservoirs in a mountain landscape continuously decreases over time due to the gradual siltation. We examined two hypotheses about the enhanced siltation rate and the constant relative contribution of unpaved roads to the siltation of a small water reservoir in the period 1990–2014, with pronounced climate change, compared to the reference period 1970–1989. Analysis was based on deposit volumes extracted from the reservoir in 1989 and detected at the reservoir bottom in 2014. The geographical information systems, image analysis and universal soil loss equation were applied to model the soil erosion according to the two sources—catchment area and roads—to study siltation processes in depth. Despite expectations, rates of siltation were almost unchanged in compared periods. The positive changes in vegetation cover (the forest expansion and changes in forest management practices) offset the enlarged rain erosivity. On the other hand, road erosion increased by 41% from 1990 and became twice as much a contributor to sediments compared to 1970–1989. The intensity of erosion from roads was from 13 to 29 times greater than from other areas. Therefore, proper maintenance of road networks could rapidly decrease reservoir siltation. Moreover, we recommend continuous cover forestry as a critical measure for central Europe's forested regions to prevent growing erosion pressures.

Keywords: water reservoir; erosion control; climate change; mountain watershed; forest management; road maintenance

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1. Introduction

Soil degradation and reservoir siltation are two of the significant current environmental, scientific, and engineering challenges [1]. The small water reservoirs in mountain regions perform various essential functions in the landscape. For example, small water reservoirs can slow down the water runoff and change the landscape microclimate, dampen the peaks of flash floodings, facilitate erosion control, accumulate the water in the landscape and filtrate the wastes. Small dams can be an important local source of drinking/industrial water; they are utilizable for energy or fish production and provide habitat for water plants and animals [2]. They can be utilized for biodiversity promotion and represent an essential element of landscape beauty. People also use them frequently as recreation and as a sports facility [3].

The effectivity of reservoirs for water management and other tasks continually decreases over time due to the gradual siltation of water reservoirs by deposits continually emerging in watersheds [4]. The siltation of small water reservoirs is a natural phenomenon that has, however, significantly changed in recent years. Several authors in different parts of the world have registered that the siltation of water reservoirs was increased at an unprecedented pace [2,5]. The siltation has developed to a great extent, resulting in a considerable volume of accumulated sediments, practically in all the reservoirs in Europe [6]. Some authors estimate that the accumulation space of European reservoirs was reduced by one-third within the last 50 years [7,8]. The siltation is closely related to soil erosion which mainly depends on rain erosivity, soil erodobility, vegetation cover, topographic properties of land and protection measures against soil erosion [4,9]. The rain erosivity, vegetation cover, and protection measures can rapidly change in response to climate change and changes in land cover/land use. Subsequently, the siltation of water reservoirs can be highly affected by climate, agriculture, forestry or societal changes [10]. As stated, siltation has become a severe threat in recent years. Among the main reasons are adverse effects of climate change (CC), which emphasizes the importance of proper water management in the landscape on the one hand and of accelerated siltation processes on the other hand [11,12]. Climate change projections in central Europe are characterized by the mean annual temperature increase from 2 to 4 °C until 2100 compared to the pre-industrial period. The temperature increase will be combined with enlarged winter (+5 to +15%) and decreased summer (from −5 to −10%) precipitations accompanied by changes in its distribution within the vegetation period [13–15]. Central Europe has the highest projected increase in temperature variability among all Europe's regions—up to 100% [16], causing increased weather variation within the year. Due to climate change, Europe faces more extreme weather, such as more frequent and intense heatwaves, flooding, droughts, and storms [17]. Extreme precipitation events and sudden snow melting enlarge the bank abrasion when a large water volume enters watercourses during short periods [18]. Intensive precipitation increases the number and intensity of erosion-effective events, which can be a problem in agricultural areas and forest landscapes with a negative ecological status [19]. The higher precipitation intensity almost undoubtedly causes the enlarged production of erosion deposits in most watersheds. Moreover, the warning changes the biological activity of living organisms leading to the acceleration of internal sedimentation [20]. Thus, the siltation of (small) water reservoirs has become a severe environmental and economic problem in recent years [5,21].

In Slovakia, instrumental measurements already confirmed these expectations. From 1881 the mean annual temperature increased by 1.6 °C, and the mean yearly increments decreased by 24 mm (5.6%) on average [22]. At the same time, the weather has become more extreme. Increasingly frequent and prolonged dry periods alternate with short periods of very intensive rainfall in the warmer part of the year. The intensity of extreme rain events is projected to increase by 20–40% by 2100 [23,24].

The main goal of the presented work was to assess the changes in erosion processes in a small catchment in the western Carpathians' mountain landscape and related modifications in the siltation intensity of the small water reservoir situated in the catchment. Two distinct periods—1970–1989 and 1990–2014—were studied. The later period was characterized by rapid climate change (manifested in the rise of air temperature, and frequency and intensity of extreme precipitation events) and by fundamental changes in agriculture practices and forest management (effects of political changes after the fall of communism and transfer to a market economy).

Concerning the primary goal, we formulated a hypothesis on the increased rate of siltation due to the negative adverse effects of climate change in the period 1990–2014. We expected that increased rain erosivity would cause accelerated soil erosion, sediment yield, and reservoir siltation. Moreover, the relative contribution of two primary erosion sources—catchment areas and unpaved roads—was supposed to be constant over time (assuming the same quality of road maintenance in the studied periods). Two interesting research questions closely related to research hypotheses were: (i) will the reservoir cleaning interval be shortened due to climate changes in the future? (ii) is the need for thorough road maintenance becoming increasingly important?

The study's minor goal was to evaluate the accuracy and practical utility of two measurement methods (sonar and measuring rod) to detect the reservoir bottom state for quantification of sediment volumes.

The study results can serve as an example for mountain regions of Europe and potentially add new information to the ongoing general discussion about the soil loss offset capacity of reforestation against the effects that could arise from increases in storm intensity. Furthermore, the role of forest road networks and maintenance will be highlighted to find proper general mitigation actions against the adverse climate change effects on soil loss.

2. Materials and Methods

2.1. Study Area

The catchment area of inlet streams defined the study area for the selected water reservoir (local name Hnusno II). The catchment is in a mountainous landscape covering the southern slopes of the Low Tatras mountain range, Western Carpathians (Figure 1, location of dam wall N 48.83703, E 19.56300). The area's lowest point is the reservoir bed 532.5 m above sea level (a.s.l.), and the highest point is the top of the Baba mountain with an altitude of 1617 m a.s.l. The area is a moderately cool mountain zone, with mean annual precipitation between 800–1200 mm, mean air temperature in July between 12–16 °C and in January minus 5–6 °C [25].

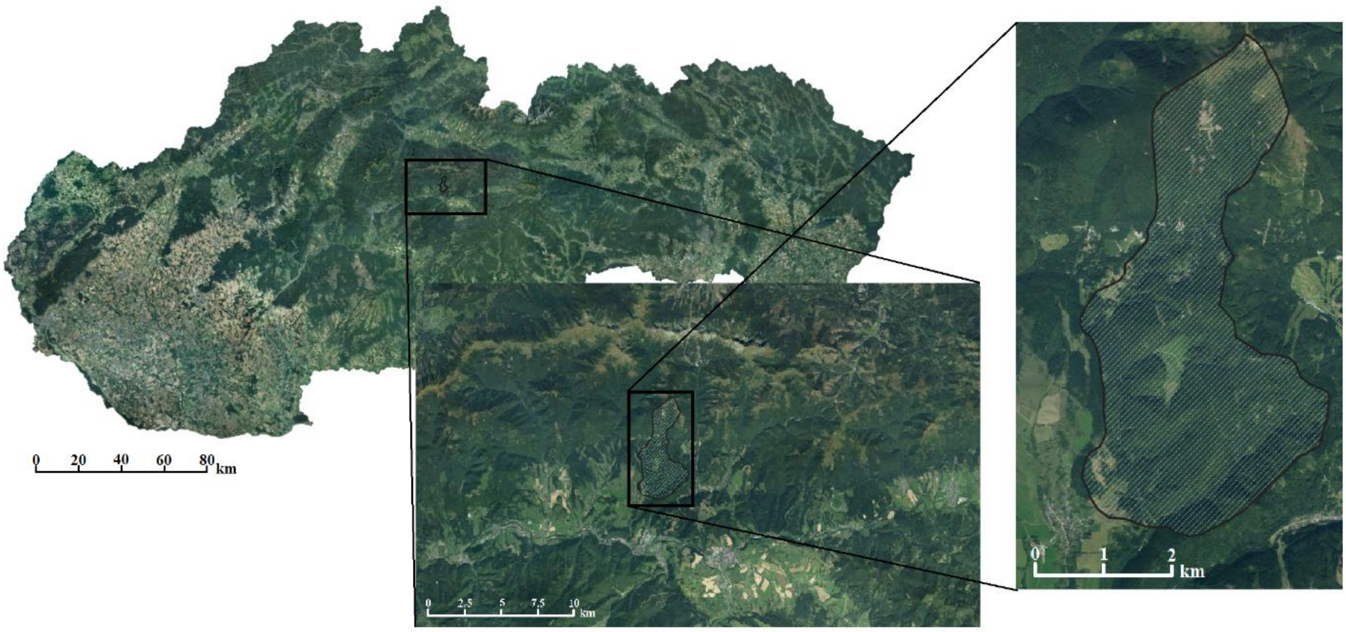

Figure 1. Location of catchment area.

The geologic structure is composed of Mesozoic rocks of the Inner Carpathians combined with the early Paleozoic period (shales, sandstones, dolomites, limestones, metapsammites, meta-pelites and granitoides). Strongly dissected hill, upland, and highland form the terrain morphology. The main soil types are the leptosols, cambisols and podsols, and the soils have loamy, loamy-sandy, or sandy grain structures.

Forests now dominate the landscape (95%), combined with meadows, pastures, and other typical landscape elements. The forest stands are even-aged, mixed, and conifers slightly prevail (app. 60%). The health status is good, and most forest stands are fully stocked with a full canopy cover. The age class structure of forest stands is even—almost all age classes have roughly the same representation. The most represented species are Norway spruce (37%), European beech (30%), Dwarf Mountain pine (11%), Silver fir (9%) and Sycamore (6%).

2.2. Catchment and Water Reservoir Characteristics

The studied reservoir is part of a system of two reservoirs located at the confluence of two streams. The catchment area of the streams is situated at the southern foot of the Low Tatras and has the character of a very narrow valley with steep slopes. The waterwork is a small water reservoir with a low swell level, built-in to protect the storage space of the lower, more extensive reservoir Hnusno I. from siltation in 1970 [26]. The larger reservoir serves as a source of industrial water for the Podbrezová Steelworks. Engineers designed a combined dam, the stabilizing part of which was built of waste cinder from Siemens-Martin furnaces, and the sealing part was constructed of clay.

The water level in the reservoir is usually maintained at 539.30 m a.s.l. At the maximal flood, the elevation of 540.00 m is reached. The minimum height of the reservoir bottom is 532.56 m a.s.l., and the height of the dam dike is 540.45 m a.s.l. The length of the flooded space is about 300 m (see also Table 1).

Table 1. Catchment, streams and reservoir parameters.

Catchment			Stream			Reservoir		
Total area	ha	1364.4	Spring—altitude	m a.s.l.	1200	Total volume	m^3	55,000
Border length	m	21,086	Spring of the highest inlet—altitude	m a.s.l.	1500	Maximum flooded area	m^2	21,000
Length of watercourses	m	17,112	Length	m	10,250	Length of the flooded area	m	300
Average slope length	m	395	Average annual discharge	l/s	330	Dam length	m	94.4
Average slope inclination	%	35.45	Maximal discharge Q_{100}	m^3/s	18.0	Dam width	m	4.6
Altitude range	m	1037.7	Annual rainfall	mm	890	Dam height	m	8.0

2.3. Methods

The research approach consisted of the following steps:

1. Finding the archive information on sediment volumes (SV) accumulated in 1970–1989, extracted from the reservoir during the maintenance in 1989, and visual inspection of the roads, inlet streams and vegetation state.
2. The measurement of the current state of the reservoir bottom (two measuring methods) including the inlet part and specification of SV accumulated in the period 1990–2014.
3. Calculating the sediment yield (SY) as an essential measure of siltation intensity based on estimated reservoir trap efficiency (TE) and measured SV for both periods.
4. Utilization of Universal Soil Loss Equation (USLE, [9]) to estimate the gross soil erosion (SE) in total and distinctively according to the main possible sources—catchment and roads. The climate and vegetation changes were included in calculations through the determination of USLE inputs for each period individually (rain erosivity and vegetation cover factors).
5. Comparison of the amount and intensity of soil erosion and sediment yield in total between studied periods and assessment of relative contributions of primary sources (including error analysis).
6. Evaluation of the effects of the pronounced climate change in 1990–2014 and formulation of future recommendations for managing this mountain landscape.

The information on the volume of sediments extracted from the water reservoir in 1989 was obtained from the technical report engineering handbook for Hnusno I and Hnusno II Reservoirs [27] stored in the enterprise archive of the Podbrezová Steelworks.

The investigators controlled the category, state and maintenance quality of road solids and surfaces, the state of watercourses and their banks, management practices, and density and health of forest cover within the visual assessment.

2.3.1. Water Reservoir Siltation

Determination of sediment volume SV for the period 1990–2014 was performed by mapping the current shape of the reservoir bottom and its comparison with the original state known from the project documentation. Measurements of the current state were made at fixed points evenly distributed over the six transverse profiles over the water surface (Figure 2). Profiles from the original project documentation gave the location of the measurement profiles. At measurement, each profile was established on both sides of the water reservoir by stretching a nylon line with measuring points marked every 5 m [28]. The measurements themselves were performed from a non-powered vessel.

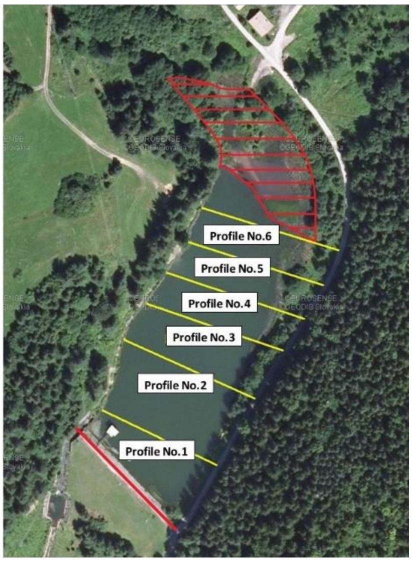

Figure 2. Measurement profiles of water reservoir Hnusno II.

The measurements of the reservoir bed were conducted by two methods: (i) probing rod and (ii) sonar method. The probing rod method was applied in line with the instructions of Slovak technical standards STN ISO 3454. The telescopic rod was 6 m in length with a measuring accuracy of 10 mm, equipped with a level tube and steel plate at the rod base against immersion (30 × 30 cm).

The sonar method is a technique that uses the propagation and reflection of sound to detect the bottom, or objects below the water's surface. Sonar allows direct reading of the thickness and calculation of the deposit volumes at the bottom of the reservoir. An Eagle SeaFinder 480DF sonar equipped with a measuring probe was used for the measurement. The measurement was performed using a cone with an angle of 35° at a frequency of 50 kHz. The results provided by two measurement methods were statistically examined by paired difference t-test with a confidence level of 0.05 [29].

Cross-sectional profiles (current and past) were plotted in the Microstation software environment [30], which then calculated surface areas of deposits and sediment volumes for both measurement methods. At the reservoir's inlet, extensive deposition of sediments did not allow the use of the boat (Figure 2, the area marked with a hatch). The volume of deposit in this part was calculated by the batigraphic curve method based on the planimetry of the area identified from the original terrain map.

Measured and quantified deposit volumes were used to calculate the reservoir's annual sedimentation rate (in m^3/year), serving as a base for the calculation of area-specific sediment yield (in t/ha/year) from the whole catchment. Sediment yield *SY* was estimated by Formula [31]:

$$SY = 100\left(\frac{SV \times dBD}{TE \times A}\right) \tag{1}$$

where *SY* is area-specific sediment yield (t/ha/yr), *SV* is the annual sedimentation rate in the reservoir (m^3/yr), and *dBD* represents the dry sediment bulk density (t/m^3)—the value determined from eight sediment samples taken from a reservoir bed in a laboratory. *TE* is the sediment trap efficiency of the reservoir (%), and *A* is the catchment area (ha).

Trap efficiency of the water reservoir (*TE*) was estimated using three empirical models/equations. First, Brown [32] developed a curve that relates *TE* to a capacity-watershed area ratio (C/W):

$$TE = 100\left(1 - \frac{1}{1 + D\frac{C}{W}}\right) \quad (2)$$

where *C* is the reservoir storage capacity in m^3, *W* is the catchment area in km^2 and *D* values range from 0.046 to 1 (with a mean value of 0.1), and they are dependent on the technical characteristics of the reservoir (we used the mean value according to Brown's suggestion).

Second, the use of a C/W ratio has been discussed by Brune [33], who stated that reservoirs with the same C/W ratio could have completely different TEs if their catchments produced different runoff volumes due to other hydrological characteristics. He replaced the C/W ratio and used a capacity-annual inflow ratio (C/I) to predict TE, where the letter I denotes stream inflow to reservoir inlet. TE for our study by Brune's method was determined using a published diagram.

Third, the method developed by USDA forest service [34] was also applied:

$$TE = 124 - 6.59\, abs\left(ln\left(\frac{C}{I}\right)\right)^{1.52} \quad (3)$$

The resulting *TE* estimate was calculated as the arithmetical mean of three distinct *TE* values provided by three different methods (Table 2).

Table 2. Trap efficiency estimation.

Brown			Brune			USDA		
Inputs	**Units**	**Values**	**Inputs**	**Units**	**Values**	**Inputs**	**Values**	**Average**
Storage capacity C	m^3	55,000	Inflow I	$l.s^{-1}$	330			
Catchment area A	km^2	13.7811	Inflow I	$m^3\ yr^{-1}$	10,406,880			
Coefficient D	$km^2\ m^3$	0.1	C/I		0.005285	C/I	0.005285	
Trap efficiency		0.456			0.400		0.422	0.426

Besides the estimation of *SY*, the errors associated with calculated *SY* values and inputs of Formula (1) were estimated to support the reliability of comparisons statistically (Table 3).

Table 3. Estimation of sediment volume and yield standard errors.

Sediment Volume				**Dry Bulk Density**		**Trap Efficiency**	
Source: Measurement		**Source: Sampling**		**Source: Sampling**		**Source: Estimation**	
Measurement rounding in cm	0.5	Mean deposit thickness in cm	40	Mean in kg/m^3	901.6	Mean value	0.426
Rounding in %	1.20	Number of measurement	99	Number of measurement	8	Number of methods	3
St. error of rounding in %	0.50	St. deviation in cm	20.2	St. deviation in kg/m^3	588.2	St. deviation	0.028
Measurement st. error (estimation)	0.50	St. error in cm	2.0	St. error in kg/m^3	208.0	St. error	0.016
Total measurement error ME_{SV} in %	**0.71**	**St. error SE_{SV} in %**	**5.1**	**St. error SE_{dDB} in %**	**23.1**	**St. error SE_{TE} in %**	**3.8**
Final st. an error of SY in %	**23.9**						

The classic error propagation formula calculated the final estimate of SY standard error (23.9%):

$$SE\%_{SY} = \sqrt{ME\%_{SV}^2 + SE\%_{SV}^2 + SE\%_{dBD}^2 + SE\%_{TE}^2} \quad (4)$$

Based on the assumption of the independence of detected SV, dBD and TE serving as inputs for SY calculation, Equation (4), only with the first two components, provides information about the estimated standard error of sediment volume measurement—5.15%. It should be noted that the combined SE of SV is a conservative estimate neglecting uncertain error caused by the unknown configuration of post-dredging depths after the bed maintenance in 1989.

2.3.2. Quantification of Soil Erosion

Four fundamental sources of reservoir siltation exist: (i) soil erosion in the catchment, (ii) soil erosion from unpaved ground roads, (iii) erosion of inlet streams watercourses and (iv) natural sedimentation of biological material in the reservoir. Sediment volume caused by the first pair of sources can be modelled by the universal soil loss Equation USLE [9,35]:

$$SE = R \times K \times L \times S \times C \times P \quad (5)$$

where:

SE—soil loss by water erosion (t/ha/year),
R—rain erosivity (MJ/ha/cm/h) derived from the frequency, volume, and intensity of rain events in a particular year,
K—the soil erodibility (t/ha/year) per unit of R from a standardized land parcel with a length of 22.13 m and inclination of 9% maintained as a permanent loose outfield cultivated in the direction of tilt) given by the content of clay, silt, sand and humus in the soil, soil structure and its water infiltration ability,
L—ratio of soil loss from real land with a certain length and inclination of slope to the soil loss from a standardized parcel,
S—ratio of soil loss from real land with the inclination and shape of the longitudinal slope profile to the soil loss from a standardized parcel,
C—ratio of soil loss from real land covered by vegetation to the soil loss from standardized parcel depending on the type, coverage and density of vegetation,
P—ratio of measures against the water erosion efficiency related to agricultural or forestry activities.

To quantify soil loss for a larger area and more extended periods, SE in t/ha/year must be multiplied by land area size in hectares and by the number of calendar years composing the period.

In our study, the potential erosion SE and its change were quantified for the catchment area of the water reservoir and unpaved road surface, respectively, in both considered periods. The inputs for the USLE equation were measured or estimated. The quantification was performed according to the logic, procedures and equations recommended by Wischmeier & Smith [9]. The input factors that significantly vary in time had to be estimated for each period. Moreover, the different values of input variables were detected for catchment and roads in cases where the difference can be expected logically.

All input variables were divided into two categories: (i) static factors changing only in very long periods (e.g., hundreds or thousands of years) as they are variables K, L, S and P (they were quantified only once, assuming their constancy in both periods), (ii) dynamic factors manifesting inter-annual or at least inter-decadal variation like a factors R and C that had to be quantified or estimated twice, separately for both considered periods.

Rain Erosivity R and Its Change

Only one factor/input in USLE is climatically sensitive—erosion efficiency of rains R. The R values for a particular period are calculated as:

$$R = \left(\sum_{i=1}^{n} E_i \right) I_{max}^{30} \tag{6}$$

where $\sum_{i=1}^{n} E_i$ is the sum of kinetic energies (J/m^2) of n individual erosion-effective rain events (influential erosion event is rain with a total of over 12.5 mm and maximal intensity of over 24 mm per hour) and I_{max}^{30} is maximal 30-m rain intensity (cm/h) that occurred within the most extreme rain event over the monitored period. The kinetic energy of individual rain is given by:

$$E_i = (206 + 87 \log I_i) H_i \tag{7}$$

where I_i is the rain intensity (cm/h) and H_i is the precipitation sum during the particular event (cm).

As we can see, the mean annual erosion efficiency of rains depends on the number, magnitude and intensity of rain events occurring in the defined area in the monitored period. If the changes in frequency, total amount and intensity of rain events between 1970–1989 and 1990–2014 are assessed, the alteration of R and mean annual soil loss G by water erosion can also be modelled, and climate change effects can be exposed.

Therefore, to obtain information about the climate changes between considered periods in the defined catchment area, the mean monthly temperatures and monthly precipitation sums from 1970 to 2006 were interpolated by two regression models published by Bošela et al. [36]. The regression models were parametrized on data from 116 meteorological stations of the Slovak Hydro-meteorological Institute covering the whole area of Slovakia. The models interpolate the values of mean monthly temperatures (model I, the adjusted R-square 0.991) and monthly precipitation sums (model II, the adjusted R-square 0.660) for each month of the calendar year in the period 1961–2006 for any spatial point (with known coordinates and altitude) on Slovak territory. In our case, the regular grid of spatial points (46 points, step app. 500 m) with altitudes determined from the digital elevation model systematically covering the catchment area was used. Final values of interested climate variables for the whole catchment area in the month of a particular year were calculated by averaging the sampling point's records.

Subsequently, the temperature and precipitation time series provided by regression models for 1970–2006 was prolonged to 2014 using the mean monthly observations of CRU TS3.21 (0.5° × 0.5° grid interpolated points) available at KNMI Climate Explorer ([37]; http://climexp.knmi.nl, accessed on 31 July 2020). The KNMI source provided the climate information for the entire period 1970–2014: the data from 1970–2006 were used to quantify biases between the regression and KNMI data, and bias-corrected KNMI data for the period 2007–2014 were used for time series augmentation.

The average annual precipitation for each year of the investigated periods was calculated from monthly data, and the relative change of annual precipitation sums between the investigated periods was revealed. Whereas the assumption that the annual precipitation sums are proportionally related to precipitation totals H_i of each rain event and to $\sum Ei$ sums exist, the relative change of annual precipitations can be regarded also as the relative change of the first component needed for calculation of R.

The temperature data were needed to estimate the relative change of the second component—maximal 30-m rain intensity I_{max}^{30}. The identified temperature rise in the catchment area can be recalculated to estimate of relative change (increase) of maximal rain intensity I_{30}. Here, several scenario simulations by authors Lapin et al. [24] projected the increase of precipitation totals during extreme events up to 50% if the mean temperatures rise by 3.5 °C by 2075. This fact suggests that the rate of extreme precipitation rises by approximately 15% with each one °C of warming. The maximal 30-m rain intensity change was estimated based on quantified temperature change.

The value of rain erosion efficiency for the period 1970–1989 was published by Janeček [38], who calculated the R values using the actual precipitation measurements from 86 meteorological stations (measurement period consisting of 15 to 64 years) distributed over Slovakia. The value R = 24.53 MJ/ha/cm.h for the period 1970–1989 measured on the nearest meteorological station Jarabá situated app. 10 km away from our study area was applied.

Subsequently, an updated R-value for 1990–2014 was obtained using the known absolute R-value for 1970–1989 and its estimated relative change. The total relative change of R for the period 1990–2014 was calculated easily as the simple multiplication of relative changes of both components of R calculation in ratio for the sum of kinetic energies of individual erosion-effective rain events $\sum E$ and maximal 30-m rain intensity I_{max}^{30}. The changes in both components were estimated with the aid of quantified temperature and precipitation changes in the given area (Table 4).

Table 4. Changes in mean annual temperatures and annual precipitation sum in the period 1990–2014.

Period	Temperatures in °C	Precipitations in mm
1970–1989	5.36	773.8
1990–2014	6.19	906.1
Change	+0.83	132.3 (17.1%)

Whereas the reasonable assumption that a 1 °C increase in mean annual temperatures will be reflected in a +10% increase in rain intensity during extreme precipitation events [19], the registered increase in mean annual temperatures by 0.83 °C allows estimation of the relative increase in maximal intensity ΔI_{max}^{30} = 8.3%. At the same time, the relative increase $\Delta\sum E\%$ can be equated with detected relative change of annual precipitation totals +17.1%. Subsequently, a combined relative increase of R can be derived by multiplication of individual component changes $\Delta R\% = ((1.083 \times 1.171) - 1) \times 100 = 26.3\%$. The final updated value of R for the period 1990–2014 was calculated as $R_{1990–2014} = 24.53 \times 1.263 =$ 31.02 MJ/ha/cm/h. As was expected, the rain erosivity after 1989 increased.

The value of soil erodibility K was estimated using data from the Research Institute of Soil Assessment and Protection for a representative soil site class unit. Identification of representative soil site class unit for our case study area was based on detecting prevailing soil types. The soil site-class unit on the map is freely available on the information site of the Research Institute of Soil Assessment and Protection [39].

The estimated K was considered constant in time, i.e., the same value was used in both analyzed periods. Moreover, the exact value of R and K was used for catchment and road water erosion calculations. The soil erodibility K in t/ha/year per unit of R from a standardized land parcel (with the length of 22.13 m and inclination of 9% maintained as a permanent loose outfield cultivated in inclination) was obtained from a map of soil site-class units of the Slovak republic. According to the map, the value K = 0.26 corresponding to the prevailing soil site class unit (sandy-clay subvariant) represents the considered area.

The other input variables of USLE were determined or estimated either with GIS analysis support or based on the assessment of the catchment state obtained during the visual inspection. The morphological terrain characteristic of catchment and roads (mean length and inclination of slopes, slope profile form) were identified and quantified through GIS analysis in the ArcGis 10.0 environment [40]. Terrain characteristics were analyzed using the digital elevation model (DEM) provided by software DMR 5.0 (digital model of terrain relief) with a resolution of 1 m. The DMR 5.0 is a software product provided by Geodesy, Cartography and Cadastre Authority of the Slovak Republic from the ground class of Lidar point cloud using linear interpolation. Source point cloud had a minimal point density of 5 points per m^2.

Based on terrain characteristics, the ratios of L and S were calculated by the formulas proposed by Wischmeier & Smith [9] separately for catchment and roads. They are used as constants for both periods. The ratio of soil loss L from real land with the specific average length and inclination of slopes to the soil loss from standardized parcel was calculated as:

$$\text{Catchment } L = \left(\frac{\bar{l}}{22.13}\right)^{p} = \left(\frac{395}{22.13}\right)^{0.5} = 4.22 \text{ Roads } L = \left(\frac{\bar{l}}{22.13}\right)^{p} = \left(\frac{274}{22.13}\right)^{0.5} = 3.52$$

where $\bar{l}$ is mean inclination of slopes in catchment or roads (395 or 274 m, respectively) detected on DEM in ArcGis 10.0 environment and parameter p is dependent on mean slope inclination (the value p = 0.5 suggested for slopes with mean inclination over 5% was applied).

The ratio of soil loss S from real land with the inclination and shape of the longitudinal slope profile to the soil loss from a standardized parcel was obtained as:

$$\text{Catchment } S = \left(0.43 + 0.3I + 0.043I^{2}\right)6.613^{-1} = 9.834$$

$$\text{Roads } S = \left(0.43 + 0.3I + 0.043I^{2}\right)6.613^{-1} = 1.1$$

where I is the mean inclination of slopes and roads (35.45% and 9.6%) derived from the DEM of the study area.

Soil Loss Ratios C and P

Ratio C was determined by the approaches published by [41], which uses pan-European datasets (such as CORINE Land Cover), biophysical attributes derived from remote sensing, and statistical data on crops and agriculture practices.

The study area has two vegetation types: (i) forest and (ii) permanent grasslands and pastures. The identification of vegetation type and its change in time was made by the method of image regression in software ENVI [42]. Detection of forest and pasture extent was based on pair of ortho-photo images of the study area from 1970 and 2014. The area and mutual proportion in the analyzed periods were significantly changed. Therefore, two different C values were estimated for two periods. The different C values were also used for catchment and roads (C_{roads} = 1), whereas the roads have no vegetation cover.

The C value for catchment was calculated as the weighted average of predefined C values determined by [38] for two types of vegetation cover existing in the study area—forest and meadows. Due to a significant change in vegetation type representation over time (detected on ortho-photo maps), the different C values were calculated for both periods (Table 5).

Table 5. Determination of soil loss correction for vegetation cover.

Vegetation Type	Value Panagos (2015)	Proportion	Final Value
		1970–1989	
Meadow	0.0395	0.15	0.00703
Forest	0.0013	0.85	
		1990–2014	
Meadow	0.0395	0.05	0.00321
Forest	0.0013	0.95	

The results indicate that the high vegetation protection against erosion was even enlarged in 1990–2014 due to natural afforestation of abandoned pastures (evidence of a decreased intensity of agricultural land use). The C ratio for roads was set to 1 in both periods due to the absence of any vegetation cover.

The value of P (efficiency of management measures against the water erosion) was set to value 1 for catchment and roads in both periods because no specific technical or management measures against water erosion were performed in the case study area.

After obtaining the inputs, annual soil loss SE from catchment and roads was determined by USLE for two separate periods to quantitatively assess and explain the impacts of climate change on water reservoir siltation.

3. Results

3.1. Visual Observations and Assessments

The water catchment is characterized by high forest cover at the time of investigation (95%). The ecological state and density of forest stands are good, and wind or insect disturbances are clearly under management control. The final harvests are performed under a shelterwood management system; thus, the continuous cover of the forest is permanently maintained.

On the other hand, forest roads show signs of considerable erosion. The forest roads have ground or gravel surfaces, and transverse drainage devices shortening the water flow path and/or velocity are absent. During the flash rains, intensive erosion and material removal from the road body occur. Subsequently, many roads contain damaged parts that severely restrict transportation accessibility. Moreover, the watercourses and banks of inlet streams are not entirely stable and at least some sections evidence erosion processes.

3.2. Siltation of Water Reservoir before and after the Year 1989

The first important facts about the reservoir siltation was extracted from technical documentation stored in the archive of Ironworks Podbrezová. According to the data of the Engineering Handbook for Hnusno I and Hnusno II Reservoirs [27], during the first major planned maintenance of the water reservoir in 1989, app. 10,264 m^3 of sediments were removed from the reservoir bed. During that time, the reservoir storage space was reduced to 82% of its original capacity. The reduction has begun to negatively affect its protection efficiency concerning the downstream located main reservoir of industrial water. The intensity of reservoir siltation within the 19-year period achieved a level of 513 m^3/year or 0.933% per year from storage capacity.

The calculations of sediment volumes for the period 1990–2014 (Tables A1 and A2) revealed that the volume of sediments from the reservoir bed was 6369 m^3 and the volume of sediments in the inlet part was 6114 m^3. Total sediment volume was 12,483 m^3, which means a decrease of water storage capacity by 23% to 77% of the original capacity. The intensity of siltation in 1990–2014 was very similar to the previous period 1970–1989, whereas it was determined at 499 m^3/year level or 0.908% per year in relative terms. The difference in intensities between periods was just 13 m^3/year (or 0.025%), but despite expectation, the pace of siltation in 1990–2014 was a bit less. Similar results indicate area-specific and total sediment yields per year (Tables 3, 4 and 6).

Table 6. Deposited sediments and sediment yield.

Variable	Units	Period	
		1970–1989	1990–2014
Deposited sediment volume	m^3	10,264	12,483
Deposited sediment volume per year	m^3/year	513.2 ± 26.4 *	499.3 ± 25.7 *
Dry bulk density	t/m^3	0.902 ± 0.208 *	
Trap efficiency	Dimensionless	0.426 ± 0.016 *	
Watershed area	ha	1378.11	
Specific sediment yield	t/ha/year	0.788 ± 0.188 *	0.767 ± 0.183 *
Total sediment yield per year (mass/volume)	t/year/m^3/year	1086.6/1204.6	1057.2/1172.1
Total sediment yield (mass/volume)	t/m^3	21,733/24,094	26,431/29,303

* standard errors.

Specific sediment yield (SSY) and total sediment yield per year (TSY per year) for the period 1970–1989 differ from the period 1990–2014 by only 0.021 t/ha/year or 29.4 t/year, i.e., 2.74% from mean SSY/TSY and, surprisingly, the smaller value was registered in the later period. Total sediment yield was higher for the period 1990–2014 by about 21.6%, but the only reason was the more considerable length of the observed period compared to 1970–1989 (20 vs. 25 years). The sediment yield rate (expressed by specific sediment yield or total sediment yield per year) was essentially the same. Calculated standard errors provide statistical confirmation of this crucial finding. The relative differences of the SSY or TSV per year are marginal from the statistical, scientific and practical point of view—specific sediment yields are 0.767 vs. 0.788 and/or SY rate 1086.6 vs. 1057.2; thus, they differ by only 2.7%. The absolute and relative difference is smaller than the associated standard error of 23.9% so it will be within any larger confidence intervals derived from standard errors. That means that the registered difference will be statistically non-significant within formal statistical testing at a high probability level.

3.3. Soil Erosion before and after the Year 1989

After the determination of values of independent variables, the estimates of erosion and sediment volume from two critical sources—catchment and roads—and for the whole watershed were obtained from USLE (Tables 7 and 8).

Table 7. The potential soil erosion from catchment and roads.

Variable	**Units**	**Catchment**		**Roads**	
		1970–1989	**1990–2014**	**1970–1989**	**1990–2014**
USLE inputs					
Rain erosion efficiency R	MJ/ha/cm/h	24.53	31.02	24.53	31.02
Soil erodibility K	t/ha/year/R	0.26	0.26	0.26	0.26
Slope length ratio L	Dimensionless	4.22	4.22	3.52	3.52
Slope inclination ratio S	Dimensionless	9.84	9.84	1.10	1.10
Vegetation cover ratio C	Dimensionless	0.00703	0.00321	1	1
Technical protection ratio P	Dimensionless	1	1	1	1
Soil erosion					
Area	ha	1364.32		13.79	
Dry bulk density	t/m^3	0.902			
Specific soil erosion from USLE	t/ha/year	1.863	1.076	24.695	31.231
Specific soil erosion volume	m^3/ha/year	2.065	1.192	27.378	34.624
Total erosion volume per year	m^3/year	2817	1627	338	477
Total erosion volume for a period	m^3	56,344	40,671	7551	11,937

Table 8. Total erosion, sediment yield and sediment delivery ratio for watershed.

Variable	**Units**	**Period**	
		1970–1989	**1990–2014**
Total erosion volume per year	m^3/year	3155	2104
Total erosion volume for a period	m^3	63,895	52,608
Total sediment yield per year	m^3/year	1204.6	1172.1
Total sediment yield for a period	m^3	24,094	29,303
Sediment delivery ratio	Dimensionless	0.377	0.557

Although the share of roads is only 1%, the share of road erosion was 11.8% in 1970–1989 and up to 22.7% in 1990–2014. The main reason for disproportion is that the road erosion intensity was 13 times in 1970–1989 and up to 29 times in 1990–2014 greater than erosion intensity from remaining watershed areas. Potential road erosion increased by as much as 41% between 1990 and 2014, in line with the expectation that increased rain erosivity R must be reflected in increased erosion, assuming other factors are constant.

An interesting finding is that the increase in erosion in relative terms is greater than the expected relative increase in precipitation erosivity (41 vs. 26%).

Other watershed areas covered mainly by forests and meadows accounted for 88.2% of total erosion in 1970–1989 and only 78.3% in 1990–2014. In contrast to roads, the total potential erosion decreased significantly in 1990–2014 (by 42.2%). The increased erosivity of precipitation R was significantly outweighed by positive changes in land use when, after 1989, there was an increase in forest area and a decrease in the erosion of less efficient meadows by 10%, as a result of which the value of the correction factor *C* decreased by more than half (Table 6).

Total erosion for the period decreased considerably by 17.7% in 1990–2014, despite the period being longer. More objective comparison is made by comparing the values of total erosion calculated per year (i.e., erosion rate), where we see that the intensity of total erosion decreased by up to 33.3% in the period 1990–2014, primarily due to the increase in forest area in the study area.

However, the total sediment yield values derived from the sediment data stored at the bottom of the reservoir show a completely different picture. As already stated, the total sediment yield in the period 1990–2014 was 21.6% higher at approximately the same intensity of production due to the unequal length of the observed periods.

There must have been major changes in the process of transporting soil particles from the sites of release to watercourses and reservoirs. At a significantly lower total erosion per year (Table 7) in 1990–2014, deposited sediments per year (Table 6) and the total sediment yield per year (Table 7) were roughly the same in both periods. This fact was also numerically reflected in the sediment delivery ratio, which in the period 1990–2014 rose 47.7% from 0.377 to 0.557.

As shown in Figure 3, the most endangered locations are close to the Hnusno streams and its tributaries and locations at the upper part of the catchment (high altitudes at tree line), having the largest inclination. Thus, technical measures against water erosion should be focused here.

To identify the critical spatial zones that significantly contribute to reservoir siltation, slope inclinations were analyzed using the available DEM (Figure 3).

3.4. Comparison of the Measurement Methods of Sediment Volume

Two measurement methods—probing rod and sonar device—showed almost identical results (Table 9). The Student's t-test for paired measurement also confirmed the statistical non-significance of the method differences at confidence level of 0.05, i.e., the mean difference deviates from 0 only randomly in a statistical sense. Moreover, the mean absolute difference (4 cm) did not overcome the size of the measurement error: $m_{diff} = \sqrt{(1^2 + 5^2)} = 5.09$ cm, where inputs are the measurement accuracy of probing rod (±1 cm) and sonar (±5 cm).

Table 9. Measurement characteristics for water depth and sediment layer (N = 83).

Method/Statistic	Probing Rod	Sonar	Absolute Difference	t-Statistics	Sediment Thickness
Mean (m)	3.09	3.13	0.04	1.90	0.42
St. deviation (m)	1.19	1.26	0.20		0.04
St. error (m)	0.13	0.14	0.02	*p*-level	0.0045
Coef. of variation (%)	38.5	40.3	-	0.060948	9.2

The results prove the usefulness of the sonar method. The sonar method has comparable accuracy to the probing rod method but is much more comfortable and faster. Moreover, the sonar method provides not only information about water depth but is also able to measure the sediment thickness directly. Thus, the time consumption for analysis can be markedly reduced. Eventually, the direct measurements of sediment thickness can be used for the validity check of sediment calculations from project documentation.

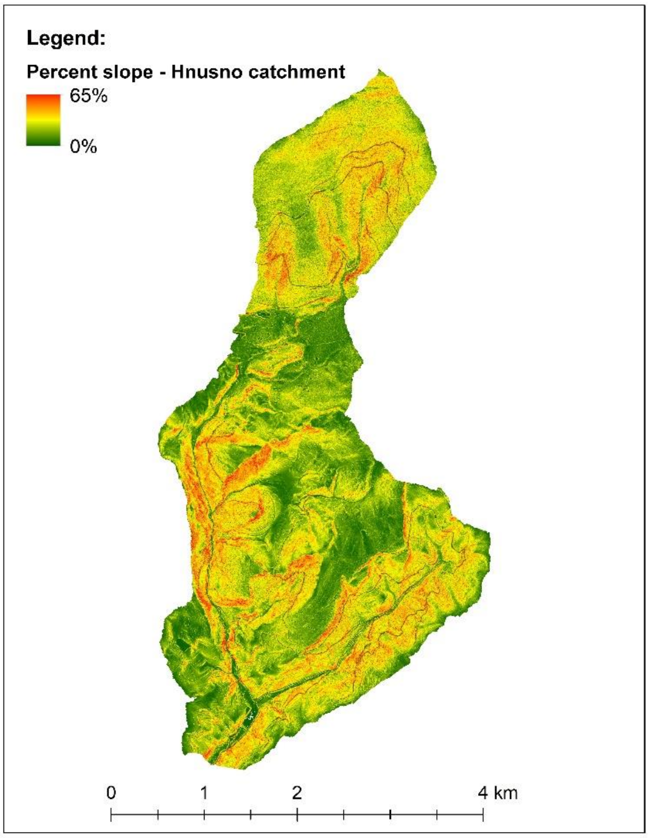

Figure 3. The slope inclinations in the catchment.

4. Discussion

4.1. Siltation and Climate Change

Soil erosion and siltation of small water reservoirs are complex processes affected by many factors and processes ongoing in the landscape. Sediment yield at the basin scale results from all erosion and sediment transport processes active within the basin [43].

Negative effects of climate change (CC) on soil erosion, sediment yield and siltation were expected in the mountains regions of Slovakia. Slovakia ranks among the countries where climatic change concerning erosion hits hardest [44]—the highest mean rise of erosivity caused by rain (>50%) was predicted [45]. The extremity of torrential rains is caused by the rise of more irregular rainfalls during the vegetation period, which is one of the main factors behind increased erosion on unpaved roads [46–48]. General conclusions of domestic research on extreme precipitation indicate that an increased number of extraordinary rainfall situations was registered during the last decennium. In addition, the more significant part of these was caused by climate change [49]. The climate in the case study area became significantly warmer (+15.5%) and wetter (+17.1%) in recent years.

The change in precipitation regimes is expected to impact soil erosion directly regarding rainfall amount, intensity, and spatial or temporal distributions [18]. Soil particles washed away by saturation excess runoff are mainly fine materials. Because of the easy transportability of fine particles, long-duration rainfall at low intensities (no more than 1.2 mm/min) can create small channels and thus contributes to total gully erosion [50]. Thus, if rainfall duration is long enough or rainfall amount is great enough, more soil particles will likely be eroded by saturation excess runoff because of the kinetic energy provided. Subsequently, increased siltation of small water reservoirs can be expected.

Despite these described facts, the first hypothesis about the promoted siltation rate of small water reservoirs in the mountain landscape of western Carpathians was not confirmed. Rates of sediment yields transported by watercourses and deposited in reservoirs were very similar in both periods, meaning that the expected adverse effects of CC were not manifested. The possible explanation lies in the trade-off between the rain erosivity, road maintenance and vegetational cover effects on erosion. More specifically, the negative effects of enlarged amount and intensity of precipitation and worsened maintenance of the existing road network were probably offset by the extended area and improved status of vegetational cover.

During the period 1990–2014, the ortho-photo image analyses indicate the spreading of the forest cover (+10%) instead of mountain abandoned pastures (−10%) which led to an apparent decrease in total erosion (−33%) [19]. The relatively small positive changes in land use ultimately outweighed the increased rain erosivity, the negative impact of which is still clearly observable on the increased overall erosion from forest roads.

The primary means of reduction has been the reduction of soil erosion at the sites of release. The better ground cover by more dense vegetation in forest land is very positive for soil erosion and/or sediment yield [51,52]. Expansion of forest cover decreases the kinetic energy of falling raindrops on the ground, absorbing part of the energy during fall on the leaves. This significantly retards sheet erosion during intensive rainfall [46,53–55]. Moreover, the forest directly impacts carbon sequestration, which is one of the effective methods for the fight against climatic change [56].

4.2. Siltation and Vegetation

As already stated, the ortho-photo image analyses indicate the spreading of the forest cover instead of mountain abandoned pastures. At the same time, visual inspections confirmed by management records and personal communication with local forest managers proved the relatively good health status and density of forest in the studied catchment. In this regard, some authors doubt if it is possible to determine from the long-term point of view whether climatic change contributes to increased erosion and faster siltation in the small water reservoirs or not. They stated that the increase in the temperature and precipitation contribute to the abundance of vegetation cover, which diminishes erosion, or that the extreme and unpredictable irregularity of intensive rainfalls will be the reason for increased erosion, despite better conditions for vegetation growth [18,57].

A denser and more vital forest can act as a very effective anti-erosion agent and significantly reduce erosion. According to [58], bare land had the highest soil loss, followed by cropland, orchard, grassland, shrubland and forestland. Indeed, in our territory, CC can support forest expansion and density, especially at the upper altitude limit of its distribution. However, this can only be expected from a long-term perspective of several decades to hundreds of years, and visual inspection of the upper tree line did not confirm the expansion of the forest to higher altitudes. Therefore, we assume that the decisive factor in our study area was the natural overgrowth of pastures in lower altitudes caused by the change in land use provoked by damping agricultural activities due to a profound change in the political and economic system in Slovakia after the year 1989.

In addition, a change in forest management approaches has also become an essential factor. The original framework based on small-area clear cuttings in conjunction with artificial forest regeneration was replaced by shelterwood cutting and natural regeneration of forest stands, maintaining the forested area's continuous cover almost permanently. In this context, the visual inspection of the area showed good health of the forest (with only a few calamities). Appropriate species composition and silviculture care of forest stand thus significantly contribute to a reasonably dense forest providing excellent soil cover.

It is also crucial that, on steeper slopes and at higher altitudes, forests are purposively managed in such a way as to prevent soil erosion primarily. It is necessary to maintain or strengthen this good practice in the future by applying modern procedures for payments for ecosystem services. We assume that higher locations on the tree line with more than 35% slopes will be the most endangered by erosion processes in the future (in line with [57,59]).

The latest IPCC report [60] mentions the increasing likelihood of pessimistic climate change scenarios. If we estimate that during the short 25-year period after 1990, the warming of 0.83 °C caused an increase in rain erosivity of up to 26%, then in the more pessimistic scenarios of climate development in Slovakia, which anticipates an increase in temperatures in Central Europe by 2–4 °C by the end of the century, rain erosivity can increase by up to 40–80%. At the same time, the potential for mitigating the negative impacts of CC by changing land use is practically exhausted in our case study area. The forest already covers 95% of the catchment area, so the importance of forest management and health care will grow enormously.

For these reasons, it would be highly appropriate for the owners of the Podbrezová Steelworks or water management enterprises to consider contributions from forest owners to support close-to-nature management, which could compensate for increased management costs and reduced income from wood harvests. Harvest restrictions and finer but more expensive forest management should be introduced, particularly near watercourses and spring zones at higher altitudes and on steeper slopes. Ultimately, this can lead to a significant reduction in the cost of maintaining water reservoirs in the long run and, in particular, to improving the quality of the industrial water for fishing or recreation.

4.3. Siltation and Road Network

Proper unpaved road network maintenance is an extremely important means of reducing soil erosion, sediment yield and siltation [61]. The results showed that, if the volume of sediments from this source could be reduced, the positive effects of vegetation change would be significantly enhanced. The negative effects of climate change on the rate of siltation could not only be offset but even significantly reduced.

Roads represent only 1% of the study area but account for 12% before 1990 and 23% after 1990 (roughly 1/5) of the total gross soil erosion. The road erosion intensity is 13–29 times higher than in the rest of the area. Such a proportion roughly corresponds to the results published in [47,62]. This finding concurs with [63], who claims that about 70–80% of the suspended sediment is supplied from unpaved roads. His study identified the lack of maintenance and excessive road network usage. Froelich's results can be seen as a demonstration of what can happen if things go in the wrong direction. In some areas, forest roads are recognized as major source of erosion. They can account for as much as 90% of all sediment production in forested watersheds [64].

Climate change impacts the sediment volume, as the soil erosion rate from the roads increased by up to 41% from 1990 to 2014. If we combine the increase in the volume of erosion from roads in 1990–2014 with the decrease in the total volume of erosion, the second hypothesis on the unchanged relative contributions of roads has to be rejected. Roads with a high probability began to function as gully channels, worsened the sediment delivery ratio SDR [65] and became twofold a contributor to sediments compared to 1970–1989.

At the same time, although the construction of new forest roads after 1990 was almost stopped, the visual check on existing roads revealed the serious lack of responsible maintenance manifested in clear signs of negative erosion effects. The maintenance of the forest road network was neglected. The main reason was a change in ownership and economic conditions from 1990–2014 when forest owners were not willing to invest enough funds for road maintenance and thus created an investment debt. The situation has reached a point at which the transport accessibility of the forest is currently endangered or reduced in many locations.

4.4. Siltation and Other Factors

The increase in SDRs was most likely due to two other factors. (i) Increased leaching of watercourses by extreme flows promoted by the bad technical status of roads. Water from the roads is clustered into the small channel, and over time it outgrows into the gully erosions, which are the main transport paths for sediment yields. Water in these paths accelerates [66] and ends in the watercourse, which causes promoted bank erosion. (ii) Increased sedimentation of biological material at the bottom of the reservoir caused by global temperature warming. However, both possible sources still needed to be thoroughly experimentally verified to assess their relative contribution more objectively to the total amount of sediments deposited in the reservoir.

Reducing the rate of siltation can be achieved by proper maintenance of the reservoir, roads and land use optimization and by additional technical measures. A technical solution could be to build a check dam on the Hnusno stream before entering the reservoir, which would be cleaned regularly every year. A storage volume of the check dam equal to the registered siltation rate of 520 m^3 per year would be sufficient.

Overall, the results show that the storage space of this Hnusno II reservoir is currently reduced by 23%. The deposit volume has been accumulated for 24 years since past maintenance (reduction of 0.96% per year). The ratio between the volume of settled sediments at the mouth of the inflow and in the reservoir space is approximately the same.

A similar, slightly smaller intensity of siltation of selected reservoirs in Slovakia is reported by several authors. For example, [67] report an average annual loss of storage volume of 0.03% for much the larger Liptovská Mara, and 0.76% for the Drahovce reservoirs. Ref. [68] state an average annual loss of storage volume of 0.45% for Malá Richňavská and 0.11% for Veľká Richňavská reservoirs. Worldwide annually, a range of between 0.5% and 1% of reservoir storage is estimated to loss due to sedimentation deposited [10].

At present, the need to remove these deposits does not seem acute, but this may change over the years. If the sedimentation process in the reservoir continued at the current pace, the entire storage space would be exhausted over the next 80 years. However, it can be assumed that this process will accelerate due to the increasing erosion pressure and overgrowth of the reservoir with aquatic vegetation. The time to complete siltation and the interval for regular cleaning of the reservoir can thus be significantly reduced.

The expected reduction in maintenance time makes it necessary to monitor and measure the rate of siltation and the total amount of sediment in the reservoir regularly. Modern reservoirs provide accurate timing because the onset of operation is well known. Chiefly, the topography before flooding is documented, allowing for determination of sediment volumes from later bathymetric surveys and isopach maps [69]. Alternatively, high-resolution seismic investigations may be performed, usually clearly showing the boundary between unconsolidated sediment infill of the reservoir and the bedrock surface [69].

In this context, measurements using sonar devices have proven to be very promising. The sonar method has comparable accuracy to the probing rod method, but it is much more comfortable, faster and has a broader utilization. Therefore, the reasonable assumption is that surveyors' reduced salary costs will refund the initial financial investments in sonar purchase.

5. Conclusions

Due to specific changes in land use in the study area, the rate of siltation of water reservoirs did not increase despite climate change. The adverse effects of enlarged volume and intensity of precipitation and worsened maintenance of the existing road network were probably offset by the extended area and improved status of vegetational cover.

Changing the land use has proven to be an essential means of mitigating the adverse effects of CC on erosion processes in the watershed. However, the potential of this measure in the studied area is practically exhausted. Therefore, it is necessary to change the objectives of forest management and promote more refined, but more expensive, forest management based on close-to-nature principles combined with strict health care to achieve permanent forest cover. The change in management approaches and strategies will be a necessary measure against the increasing erosion pressure due to the expected increase in the extremity and erosivity of precipitation in the mountainous regions of Central Europe. Management primarily aimed at erosion protection will be crucial in stands at the upper tree line, near watercourses and on slopes with a high inclination.

A significant finding of this work is the knowledge that investments in maintenance, reconstruction or improvement of the quality of forest roads could reduce erosion and sediment volumes. Reducing the volume of sediments can also be achieved by smaller technical measures to improve the current state of reservoirs and by improved care of watercourse beds, which, however, requires additional financial investment. For all the above reasons, water management and industrial enterprises interested in water utilization for commercial purposes should share in the costs of anti-erosion measures, which could ultimately positively affect their financial results and long-term competitiveness.

In addition, it will be highly desirable to continue experimental research and intensive monitoring of reservoir siltation. New research could improve anti-erosion measures' effectiveness and reduce or at least maintain the siltation intensity. Otherwise, soil erosion, sediment yield and siltation of water reservoirs could be a severe problem in the future, causing deterioration of many diverse and important functions fulfilled by small reservoirs in mountain landscapes today.

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Appendix A

Table A1. Calculations of bed-load sediment volumes (main part).

Profile	Mean Distance (m)	Sediment Profile Areas S (m^2)	Ss (m^2)	Sediment Volumes V (m^3)	∑ V (m^3)
End of dam body					0
profile No.1	15	31.3	31.3	470	470
profile No.2	50	33.4	32.35	1618	2088
profile No.3	31.75	31.8	32.6	1035	3123
profile No.4	24	30.08	30.94	743	3866
profile No.5	24	25.9	27.99	672	4538
profile No.6	24.5	24.96	25.43	623	5161
end of backwater	13	160.82	92.89	1208	**6369**

Table A2. Calculations of inlet part sediment volumes (inlet part).

Altitude of Layer (a.s.l.)	Difference of Contour Lines (m)	Sediment Area S (m^2)	Ss (m^2)	Sediment Volumes V (m^3)	∑ V (m^3)
536.65		0			0
537	0.35	173	87	30	30
538	1	2020	1097	1097	1127
539	1	4853	3437	3437	4567
539.3	0.3	5480	5167	1550	**6114**

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