Analysis of change of retention capacity of a small water reservoir

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Abstract. This study is focused on the analysis of the changes of retention capacity of a small water reservoir induced by intensive erosion and sedimentation processes. The water reservoir is situated near the village of Vrbovce in the Western part of Slovakia, and the analysis is carried out for a period 2008-2017. The data used to build a digital elevation model (DEM) of the reservoir’s bed came from a terrain measurement, utilizing an acoustic Doppler current profiler (ADCP) to measure the water depth in the reservoir. The DEM was used to quantify the soil loss from agricultural land situated within the basin of the reservoir. The ability of the water reservoir to transform a design flood with a return period of 100 years is evaluated for both design (2008) and current conditions (2017). The results show that the small water reservoir is a subject to siltation, with sediments comprised of fine soil particles transported from nearby agricultural land. The ability of the water reservoir to transform a 100-year flood has not changed significantly. The reduction of the reservoir’s retention capacity should be systematically and regularly monitored in order to adjust its operational manual and improve its efficiency.

1. Introduction
One of the biggest challenges in the operation of small water reservoirs is the problem associated with their siltation with sediments coming from agricultural land as a result of erosion and transport processes. The siltation of water reservoirs is a worldwide problem that significantly reduces their retention capacity, deteriorates their efficiency, and shortens the time of their operational use. In order to increase the lifespan of water reservoirs, to maximize their efficiency in terms of retention capacity, and their ability to maintain good quality of water, it is necessary to know the current state and the dynamics of the changes of their bathymetry. The quantification of sedimentation processes, and a regular monitoring of reservoir’s capacity and the volume of bed sediments plays an important role in the process of estimating the dynamics of their siltation, and their ability to meet the tasks for which they have been built. From the practical point of view the monitoring of this dynamics could be used in designing various mitigation measures aiming to reduce the amount of sediments eroded from the basin and deposited in the reservoir. The realisation of various management measures in the basin, as well as optimizing operation of water reservoir it is also possible to reduce the increasing costs of reservoir operation and maintenance. The problem of siltation of small water reservoirs is a very active research task both worldwide [1,2,3] and in Slovakia [4,5].

The main objective of this study was to monitor the bathymetry of a small water reservoir using an ultrasonic Acoustic Doppler Current Profiler (ADCP), and to compare the results with the survey from...
2008 in order to estimate the amount of bed sediments, and the intensity of its siltation. The results were also used to recalculate its actual retention capacity, and its ability to accommodate a 100-year design flood. Within the study the mean annual volume of soil loss from the reservoir’s basin was also evaluated.

2. Methodology

The area of the interest is situated in the western part of Slovakia in a cadastre of the Vrbovce village. A multipurpose water reservoir Vrbovce was built at the Zápasečník Creek in the southeast part of the village in 1966. The area of the basin contributing to the water reservoir is 3.24 km$^2$ with an altitude range between 342 and 587 m a.s.l. The parameters of a 100-year design flood were estimated using a SCS-CN method with a peak flow of 4.3 m$^3$s$^{-1}$ and a total volume of 17926.1 m$^3$ [6,7,8]. The basin of the reservoir is predominantly covered by arable land (42%), which is followed by meadows and pastures (31%), and broad-leaved forests (25%) (see figure 1). The predominant type of soil texture is loam with as much as 85% of the basin area belonging to this category. The area of interest is situated at the border between lowland and highland climate. The mean annual temperature in this region is 7.5 °C, with January and July being the coldest and warmest months respectively. The mean annual precipitation depth in this area ranges between 650 and 850 mm.

2.1. Determination of soil erosion

The effect of water erosion on the agricultural land is quantified by soil loss, which was estimated by the universal soil loss equation using the USLE2D model integrated in GIS environment. The method is based on the following equation proposed by [9]:

$$ G = R \cdot K \cdot LS \cdot C \cdot P $$

Each member of the equation represents a factor influencing the soil loss. For each factor a 10x10 m raster was created in GIS to account for its spatial variability. The area of interest is located near the city of Senica, for which the value of the rainfall-runoff erosivity factor ($R$) of 28 MJ.ha$^{-1}$.cm.h$^{-1}$ has already been estimated [10]. The values of the soil erodibility factor ($K$) were based on the soil texture classification (see [10]). The $LS$ factor, which takes into account the impact of slope length and steepness, was calculated as a mean value of the $LS$ factor estimated by three methods of these authors: Wischmeier-Smith, McCool – moderate, Nearing and McCool by the USLE2D model [11]. The cover-management factor ($C$) was estimated for various types of land use including: arable land ($C = 0.18$ for winter wheat), meadows and pastures ($C = 0.005$), and broad-leaved forests ($C = 0.001$), [12]. The support practice factor ($P$) was determined according to the steepness of the ploughed slopes (contour ploughing) [9].
The Williams’ model was used to estimate the quantity of transported sediments (soil yield), which is generally given in our physical-geographic conditions by the relationship:

\[ SDR = 1.366 \times 10^{11} F^{-0.0998} RP^{0.3629} CN^{5.444} \]  \( (2) \)

where: \( SDR \) is the sediment delivery ratio, \( F \) is the basin area (km\(^2\)), \( RP \) is the relief-length ratio (m/km) calculated as a ratio of the difference between mean and minimum elevations and the longest flow path, and \( CN \) is the weighted value of the SCS curve number (\( CN = 67.5 \)).

2.2. Monitoring of reservoir and data collection

In order to analyse the changes in the retention capacity of the water reservoir two monitoring surveys were conducted. The first one took place in 2008 when the reservoir was emptied and the sediments were removed. The second survey took place in 2017 during the full operation of the reservoir.

During the first monitoring in June 2008 a thorough geodetic survey of the reservoir and its near vicinity was conducted. The survey was focused on the obtaining of a precise location and elevation of the reservoir’s dam, bed, surrounding terrain, technical objects and buildings. The planimetric survey (see figure 2) was performed using the method of precise tachymetry utilizing the Leica’s TC 600 electronic total station. The crest of the reservoir’s dam is situated at an altitude of 349.85 m a.s.l. and the emergency spillway at 348.25 m a.s.l.

![Figure 2. Planimetric and hypsometric survey of the water reservoir in 2008.](image)

The second survey took place in April 2017 and was focused on the monitoring of the reservoir’s bed elevation and surrounding terrain. The geodetic survey of the planimetry and hypsometry of the terrain (green points) and water level (blue line) was conducted using a GPS station (see figure 3). In order to monitor and evaluate the extent of the reservoir’s siltation, 18 monitoring cross-sections were selected, each approximately 10 m apart. Within each cross-section an ADCP StreamPro, with a measuring range of 0.1 - 6 m, was towed from one bank of the reservoir to another to measure bathymetry. The interval of the measurements within each cross-section was set to 0.5 m. In order to reduce the measurement error two measurements were conducted for each cross-section. The end points of each cross-section (see figure 3 – red points) were fixed and geodetically surveyed using a GPS station (see figure 3). The elevation of the reservoir’s bed was calculated by subtracting the bathymetry data from the elevation of the water level at the time of measurement (348.1 m a.s.l.).

The geodetic data from both surveys were used to create a DEM with a raster resolution of 0.5 m, which were further used in the analysis of the changes in the reservoir’s retention capacity.

![Figure 3. Planimetric and hypsometric survey of the water reservoir in 2017.](image)
3. Results
The results of the calculation of the long-term annual soil loss and the corresponding volume of soil particles transported from the basin are shown in table 1. When converting the estimated soil loss from t.year\(^{-1}\) to m\(^3\).year\(^{-1}\) the bulk density of soil of 1800 kg.m\(^{-3}\) was used. The volume of sediments which could be deposited in the reservoir were estimated by multiplying the annual soil loss by SDR.

Table 1. Mean annual soil loss and a total volume of sediments washed out from the basin.

| Object  | SDR  | Area [km\(^2\)] | Average of soil loss [t.ha\(^{-1}\).rok\(^{-1}\)] | Volume of soil loss [m\(^3\)] | Sediment loss [m\(^3\)] | Degree of Erosion |
|---------|------|-----------------|---------------------------------|-----------------------------|------------------------|-------------------|
| Basin   | 0.425| 3.24            | 9.22                            | 1657.5                      | 705.4                  | moderate          |

The analysis of the changes in reservoir’s bed bathymetry between years 2008 and 2017 is shown in figure 4. The results show that most of the reservoir’s bed is a subject of deposition of eroded material (see figure 4 - red and yellow areas). The monitoring showed that the maximum depth of the sediments in was 2.25 m and was situated in the vicinity of the reservoir’s dam, as well as near the inflow to the reservoir. At some places it was also possible to observe that the reservoir’s bed was eroded with the maximum difference between its state in 2008 and 2017 of 1.5 m.

Figure 4. The depth of deposited and eroded particles in the reservoir’s bed.

The impact of the reservoir siltation on its retention capacity was also evaluated for various values of water level (see table 2).

Table 2. Changes in the retention capacity of the water reservoir under various values of water level.

| Year | Volume V (m\(^3\)) |
|------|-------------------|
|      | Water level (348.1 m a.s.l.) | Emergency spillway (348.25 m a.s.l.) | Dam crest (349.5 m a.s.l.) |
| 2008 | 17022.4           | 18309.1                         | 34515.8                        |
| 2017 | 16688.4           | 18064.4                         | 34469.5                        |
| Difference | 334.0 | 244.7                         | 46.3                           |
4. Conclusions
The results of the analysis of the siltation of the water reservoir showed that as much as 334.2 m$^3$ of eroded material was deposited in the reservoir between the years 2008 and 2017. The results also showed that the estimated retention capacity of the reservoir in 2017 has decreased by 2% compared to the state in 2008. The estimated volume of the reservoir with a water level at the elevation of emergency spillway was 18064.4 m$^3$, and at the water level at the elevation of dam crest it was 34469.5 m$^3$. Based on the volume of the 100-year design flood it is possible to conclude that the capacity of the reservoir in 2017 is sufficient to accommodate the whole volume of the design flood (17926.1 m$^3$). The mean annual soil loss from the basin of 9.22 t.ha$^{-1}$.year$^{-1}$ could be categorized as a moderate erosion intensity. In order to increase efficiency of the reservoir it is strongly recommended to apply erosion mitigation measures in some parts of the basin. The calculations showed that the total annual soil loss from the basin is 705.46 m$^3$.

The result of this study proved that the water reservoir Vrbovce is a subject to siltation. Therefore, in the near future a proper analysis of landscape structures as well as morphometric analysis of the basin will have to be performed. The observed reduction of its retention capacity calls for establishing a systematic and regular monitoring scheme, which would focus on observing the trends in its siltation. Only by implementing such monitoring schemes it will be possible to adopt and implement appropriate management measures, which would guarantee the functionality of the most important reservoir’s tasks, such as flood protection and water supply.

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