Monitoring and Assessment of Water Retention Measures in Agricultural Land

Roman Výleta [1], Michaela Danáčová [1], Andrej Škrinár [1], Róbert Fencík [1], Kamila Hlavčová [1]

[1] Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology, Radlinského 11, 810 05 Bratislava, Slovakia

roman.vyleta@stuba.sk

Abstract. One of the most interesting events, from the environmental impact point of view, is the huge storm rainfall at which soil degradation processes occur. In Slovakia, agricultural areas with a higher slope have been recently increasingly denudated by water erosion processes. Areas having regular problems with muddy floods and denudation of soil particles have been currently identified. This phenomenon has long-term adverse consequences in the agricultural landscape, especially the decline in soil fertility, the influence on soil type and the reduction of depth of the soil profile. In the case of storm rainfall or long-term precipitation, soil particles are being transported and deposited at the foot of the slope, but in many cases the large amounts of sediment are transported by water in the form of muddy floods, while putting settlements and industrial zones at risk, along with contamination and clogging of watercourses and water reservoirs. These unfavourable phenomena may be prevented by appropriate management and application of technical measures, such as water level ditches, erosion-control weirs, terraces and others. The study deals with determination of the soil loss and denudation of soil particles caused by water erosion, as well as with determination of the volume of the surface runoff created by the regional torrential rains in the area of the village of Sobotište. The research is based on the analysis of flood and erosion-control measures implemented in this area. Monitoring of these level ditches for protection against muddy floods has been carried out since 2015 using UAV technology and terrestrial laser scanning. Monitoring is aimed on determination of the volume of the ditch, changes in its capacity and shape in each year. The study evaluates both the effectiveness of these measures to reduce the surface runoff as well as the amount of eroded soil particles depending on climatological conditions. The results of the research point to the good efficiency of these measures; however, in conjunction with belt crops cultivation they could form a comprehensive flood and erosion-control protection to eliminate the muddy floods and protect the settlements from surrounding slopes.

1. Introduction

Flash and muddy floods and associated soil erosion occurring in Europe including Slovakia have been recently defined as one of the most widespread environmental impacts. These extreme events call for an urgent need to improve the current level of flood and erosion protection, and their occurrence is significantly influenced by land use and management of an agricultural land. The modelling of erosion-transport processes in the landscape during extreme rain events is an essential part of the research in this area. These processes result in surface or linear transport of soil particles from the upper soil profile, loss of organic matter and nutrients, reduction of soil fertility, clogging of watercourses, settlements endangerment, etc.

Modern advanced technologies combined with experimental fieldworks and data collection are currently being used for of modelling the natural processes (e.g. surface runoff, transport processes and changes due to soil erosion). Perhaps the greatest progress is currently associated with the use of terrestrial laser scanning and photogrammetric processing of aerial photography for the digital elevation model (DEM) creation. These techniques allow us to obtain various information, e.g. about the type of land use, terrain morphology or vegetation cover properties in a relatively short time. The quickness and easiness of such measurements means that they can be carried out repeatedly, allowing not only to monitor changes in degradation processes but also to determine the sedimentation dynamics of flood and erosion-control measures (e.g. after major rainfall events). A number of scientific teams in our country [1], as well as abroad (e.g. [2-5]), is currently dealing with utilizing such techniques in data collection.

The original character of the Slovak landscape was significantly altered after the political and social changes in the former Czechoslovakia in 1948 and subsequent collectivization, which has affected the soil degradation processes in large scale. Removal of the natural flora, elimination of the mosaic of the small fields and emergence of undivided large-scale agricultural fields has contributed to this phenomenon. The destruction of the levels of the original terraced fields, where the surface from the landscape perspective has been smoothed out, was the most notable intervention [6]. In the hydrological, water-management and ecological professional community, disputes about the potential and effectiveness of the so-called unsystematic flood and erosion-control measures are held in relation to occurrence of flash floods. The effectiveness of these measures to reduce flood runoff and erosion-transport processes varies, and therefore needs to be examined for the specific conditions of the particular physical-geographic environment. Requirements arose to better quantify the maximum volume of precipitation that can be received by the watershed before the significant runoff creation mechanisms (subsurface and surface runoff, reference flow) or eventually the flood event occur. Several authors [7], [8] have been dealing with the issue of modelling the surface runoff in relation to erosion transport processes.

The Kopanice region of western Slovakia (the Myjava basin), which includes the village of Sobotište, presents one of the areas significantly threatened by muddy floods. In 2010, the village was several times hit by a massive flash muddy flood. In its near vicinity, erosion-control and flood protection measures have been implemented [7] to capture or reduce the surface runoff and the removal of soil particles from the agricultural land. The aim of the study is to determine the soil loss and quantity of the transported particles and to calculate the amount of the surface runoff created at the occurrence of regional torrential rains in this area. The soil and vegetation play an important role in redistributing the water from precipitation and determines whether a surface runoff occurs. An analysis of the effectiveness of existing flood and erosion-control measures to reduce the runoff from the slopes in the area of interest has been continuously carried out by experimental field measurements since 2015. Modern advanced technologies such as terrestrial laser scanning and unmanned aerial vehicle (UAV) have been used to monitor the level ditches.

2. Methodology

The area of interest is located in the western Slovakia in the area of Sobotište municipality, which lies at an altitude of 220 - 568 m a.s.l. From a physical-geographic point of view, it belongs to the area of Slovak-Moravian Carpathians at the foot of White Carpathians and Myjava hills. The village of Sobotište is situated in a valley which the Teplica stream flows through, while an area of interest with level ditches is located in the northeast of the village in the part of Kubíny (Figure 1).

Important data on solving issues in the field of erosion-transport processes are, among other things, information about the height variability of the landscape and land use. According to the nature of the land use, the largest area in the Sobotište municipality is occupied by arable land (37%), meadows and pastures (21%) and deciduous forests (30%). The geological ground has a rich structure, with a large part of the territory forming a flysch substrate of sandstones, pudding stones and clay from the Paleocene-Eocene period (41%). Flysch type of rocks have a tendency to erode and are more susceptible to landslides. Loam, that occupies more than 90% of the Sobotište village, is the predominant soil type. According to the division of climatic and geographic types of Slovakia [10], the area of interest lies at the interface between lowland and mountain climates. The average annual temperature is 9.8 °C; with an average annual rainfall of 600-700 mm. January is the coldest month while July is the warmest.

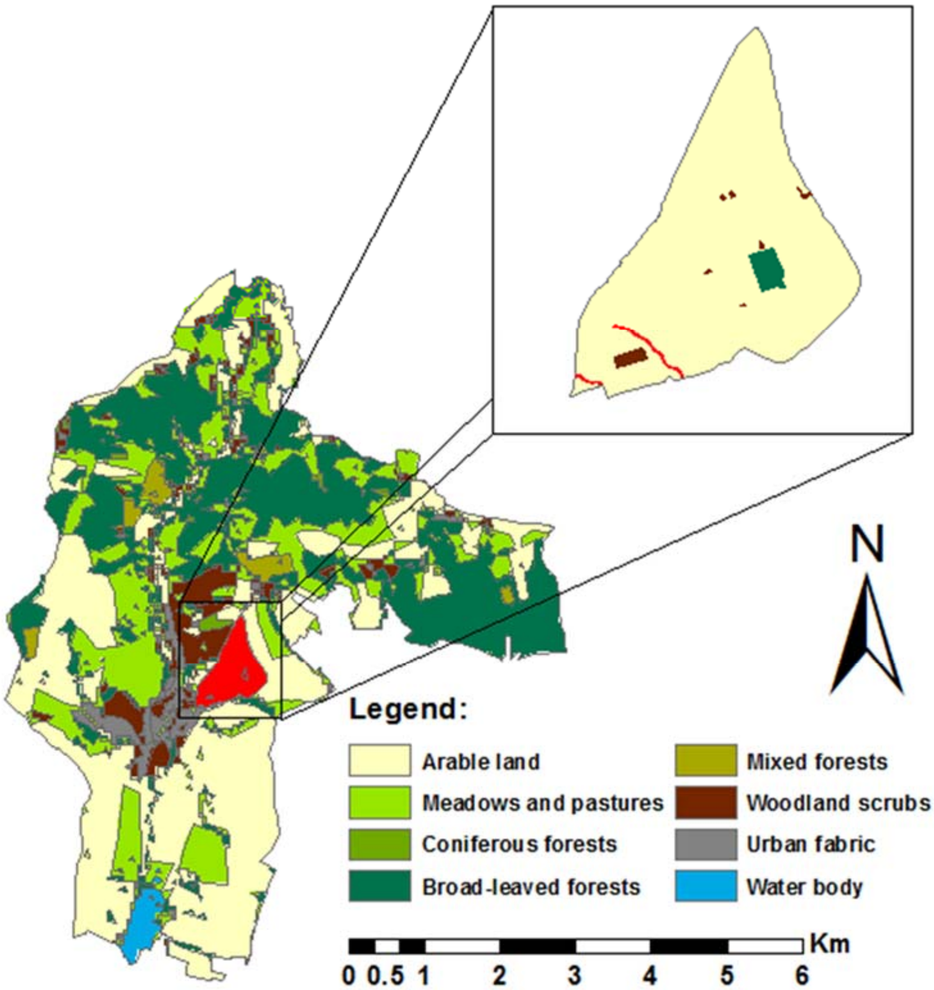

Figure 1. Localization of the area of interest (village part Kubíny within the Sobotište village) with the level ditches (red colour)

2.1. Determination of direct runoff and soil erosion

The height of the direct (surface and subsurface) runoff from the area of interest was determined by the SCS-CN method based on the rainfall sum with a certain time distribution. The area of interest has been divided into three territorial units separated by ditches to take into account the interruption of direct runoff and accumulation of water in ditches (Figure 2a). The longest runoff path (blue line) was then defined, taking into account the runoff concentration into the final profile (red dot). For the needs of the study, the concentration time (t_{kc}) was determined using the method of Hrádek [11], considering only the slope runoff as it is a sloping terrain used for agricultural purposes. Design precipitations (H_Z) were derived for the concentration time from a curve constructed from precipitation sums for various rainfall periods and $N = 10$ years at Myjava Station located near the area of interest [12]. They may therefore be considered representative.

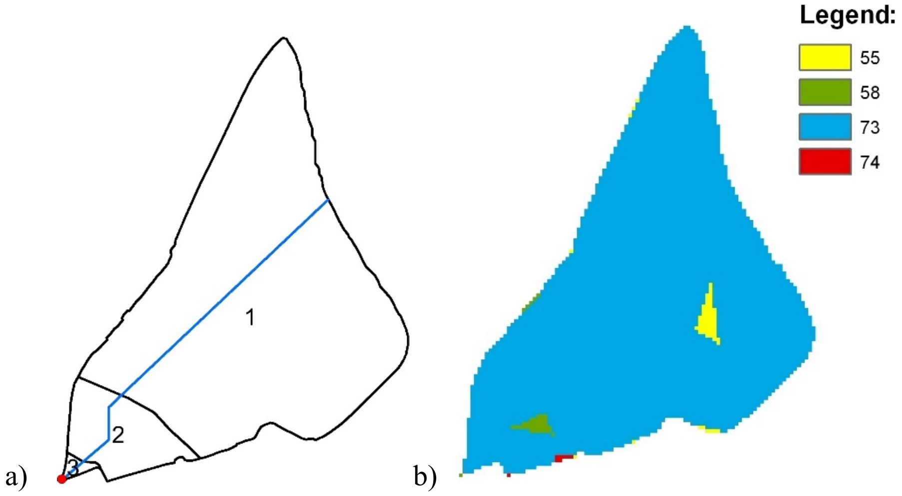

Figure 2. (a) The separation of the area of interest into 3 territorial units (Blue lines represent the longest runoff path and red dot represents the runoff concentration into the final profile), and (b) a map with the corresponding CN runoff curve numbers

The volume of precipitation was then transformed to the runoff volume using the weighted *CN* number of the runoff curve (Figure 2b) derived from hydrological groups of soils according to their use and management [13], ranging from 0 to 100. The maximum potential retention (*A*) was determined by relationship:

$$A = \frac{25400 - (254.CN)}{CN} \tag{1}$$

After its determination and known design precipitation, the representative height of the direct runoff was calculated according to:

$$H_0 = \frac{H_z^2}{H_z + A} \tag{2}$$

where:
H_o - height of the direct (surface and subsurface) runoff (mm),
H_z - height of the rain considered (mm),
A - maximum potential retention of the river basin (mm).

The initial retention was considered as $I_a = 0$. The calculation of the direct runoff volume (V) is determined as the product of the direct runoff height H_o and the area F. The maximum peak flow is expressed in equation (3) and the flood wave was designed in ratio $k = 1:2$, where k represents the ratio of the ascending part of the wave to the descending one.

$$Q_{max} = \frac{2V}{kt_{kc}} \Rightarrow \frac{2V}{3t_{kc}} \tag{3}$$

where:
Q_{max} - maximum peak flow ($m^3.s^{-1}$),

V - volume of the direct (surface and subsurface) runoff (m^3),
t_{kc} – runoff concentration time (s).

The impact of water erosion on agricultural land has been expressed by sediment yield, which has been determined using the universal soil loss equation by the USLE2D model in GIS according to the relationship [14]:

$$G = R.K.LS.C.P \tag{4}$$

The slope length factor L and the slope steepness S (LS factor) were defined as the mean value calculated by Wischmeier-Smith, McCool-moderate, Nearing and McCool by the USLE2D model [15]. The area of interest is located near Senica, with the value of the rainfall-runoff erosivity factor (R) for this area of 28 $MJ.ha^{-1}.cm.h^{-1}$ [16]. The soil erodibility factor (K) values for erosion were determined from the evaluated soil-ecological units (SEU), according to Alena [16]. After the consultation with the main agronomist of agricultural cooperative in Sobotište, the cover-management factor (C) for winter wheat and winter rapeseed production was defined (C = 0.12). There is a contour ploughing on the slopes in the area of interest, for which the support practice factor (P) was determined according to the steepness of the ploughing.

The Williams' model [17] was used to estimate the quantity of transported sediment (soil yield), which is generally given in our physical-geographic conditions by the relationship:

$$SDR = 1{,}366.10^{-11}.F^{-0{,}0998}.RP^{0{,}3629}.CN^{5{,}444} \tag{5}$$

where:
SDR - sediment delivery ratio,
F - river basin area (km^2),
RP - the relief-length ratio (m/km),
CN - the long-term average SCS curve number.

2.2. Monitoring and data collection

Monitoring and data collection for assessing the changes in level ditches at Sobotište was carried out over several time periods using two modern mapping techniques, namely unmanned aerial vehicle (UAV) and terrestrial laser scanning (TLS). There are two level ditches at the site (the upper one with the length of 310 m and the lower one with the length of 91 m).

In July 2015 and July 2016, a mapping of the lower ditch was carried out by the Trimble TX5 TLS device. It is a 3D scanner, which currently belongs to the most advanced technologies in the field of collecting the spatial information. Mapping by TLS generally involves two sub-tasks; (i) the object scanning directly in the field and (ii) post-processing (scan processing). A quick scan preview typically runs before scanning itself to check and adjust the scan settings. The adjustment of the terrain has been an important part of mapping of the change in the volume of the ditches, especially in the post-processing stage. This process consisted in removal of undesirable vegetation, respectively in mowing the plant cover in the vicinity and inside the ditch, as the scanner measures the spatial position of the points at the surface (point cloud) and the results would be considerably biased by unmowed vegetation.

The TLS process can be described by the following steps: The scanning of the level ditch itself preceded by the establishment of the triangulation points 5001, 5002, 5003 and 5004, coordinates of which were determined using the Leica GS15 GNSS system by the Real Time Kinematic (RTK) technique in the permanent SmartNet network (Figure 3). These points were necessary for determining the positions of the Leica FlexLine TS02 Total Station used for georeferencing of the model via the adequate number of control points (CP) deployed along the ditch. Subsequently, the scanner was placed in the vicinity of the ditch so as the marks at CP were visible from its position (min. 3 control points for one measuring location). The number of the triangulation points and the CP and their distribution within the area of interest in 2015 and 2016 is shown in Figure 3. After setting the parameters of the scanner affecting the duration and the final quality of the scan, as well as the point density of the cloud, the laser scanning itself has been started. After the completion, the scanner was transferred onto next position, so as the marks at CP were visible again (including at least one of the previous adjacent scan). The procedure was repeated until the scan has covered the entire area of the level ditch.

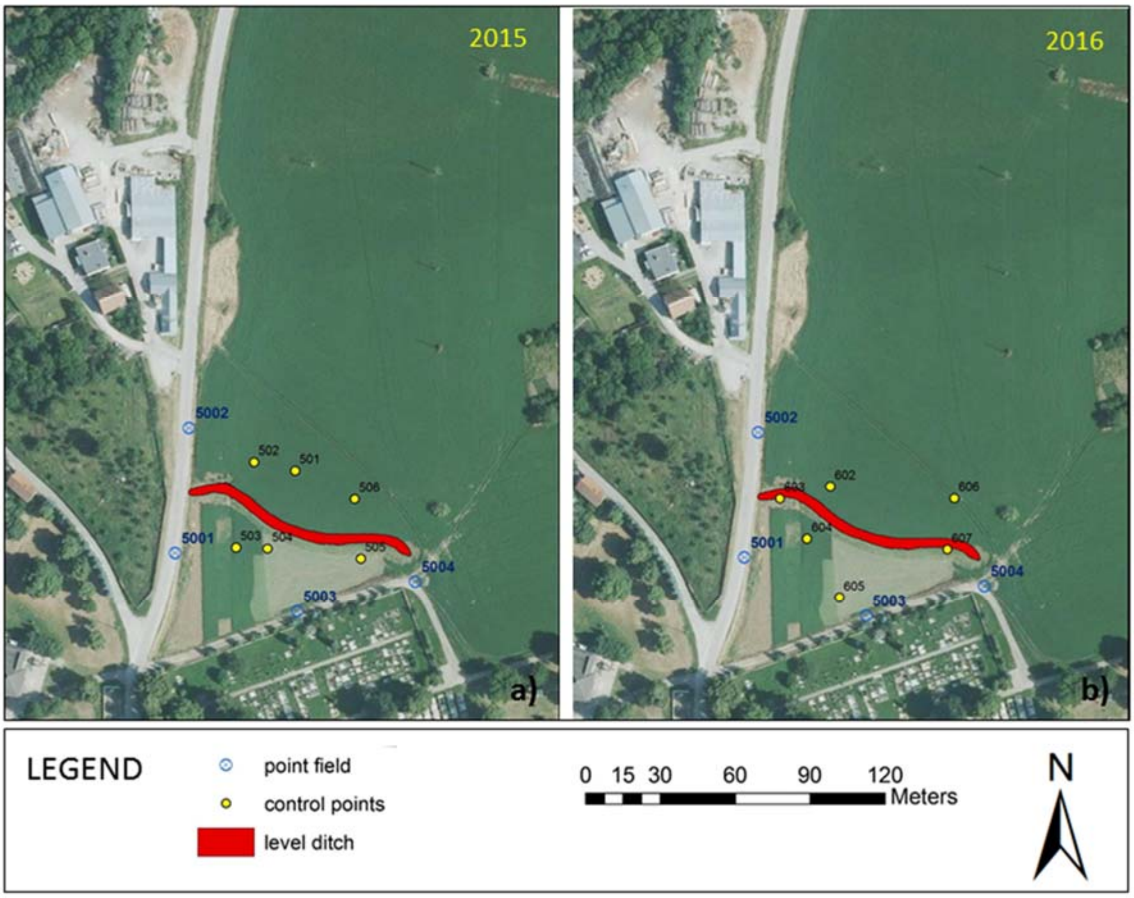

Figure 3. Diagram of works during the mapping using the terrestrial laser system with deployment of the triangulation points and the CP in the area of the lower level ditch: a) 15.07.2015, b) 06.07.2016

Figure 4. Mapping of the upper ditch by the AIBOTIX device in the area of Kubíny (03.11.2015)

In November 2015, the UAV technology has also been applied to map the upper ditch. The UAV technology is the modern and highly efficient mapping tool with the possibilities to create a 3D model and the orthophotos of the area of interest in one flight. For the study, the AIBOTIX UAV device was selected with a camera to create images of the given site (Figure 4). The process of mapping consisted in deploying and measuring the CP within the selected location (similar to TLS process described above), setting the flight plan of the UAV device followed by processing the aerial photography itself.

2.3. Post-processing data

The digital terrain models (DTM) from the TLS data from 2015 and 2016 were created in the FARO SCENE 6.2 and ESRI ArcGIS 10.2 software. First, the local cloud points from each scanner position (Chapter 2.2) were transformed from local coordinate systems into one joint point cloud in the S-JTSK coordinate system in the SCENE environment. It was necessary to eliminate the number of points because further work with such a big file would be impossible. The number of points has been reduced from 80 000 000 to 5 000 000. Finally, a point cloud has been imported in the ArcGIS environment using the "Create LAS Dataset" feature and the vector TIN DEMs from the TLS data from 2015 and 2016 were created using the "From Las to TIN" feature.

The Agisoft PhotoScan software was used to create a DTM from the 2015 UAV photogrammetry. After implementing the input data and calibrating the digital camera, the relative and external orientation of the frames of the imaging area using the CP was performed. After the model transformation into the S-JTSK coordinate system, a point cloud has been created. Subsequently, a 2015 raster DTM with a 3 cm grid has been generated from the point cloud.

3. Results and discussion

The results of the direct runoff calculation from the agricultural land using the SCS-CN method for the 10-year design precipitation in the area of Kubíny are shown in Table 1. From the table it follows that an estimated water volume of 2162 m^3 at a maximum runoff of 0.439 $m^3.s^{-1}$ will flow into the upper level ditch and 130 m^3 with a corresponding maximum runoff of 0.086 $m^3.s^{-1}$ will flow into the lower ditch at 10 years precipitation.

Table 1. The results of a direct runoff calculation on a slope in the area of interest.

Territorial units	*CN* [-]	*F* [km^2]	*A* [mm]	t_{kc} [s]	H_z [mm]	H_o [mm]	*V* [m^3]	Q_{max} [$m^3.s^{-1}$]
Part 1	72.8	0.523	95.1	3281	22.0	4.1	2162.0	0.439
Part 2	72.2	0.059	98.1	1003	15.9	2.2	130.0	0.086
Part 3	72.6	0.004	96.0	460.0	12.6	1.5	5.0	0.007

Notes *CN* is number of the runoff curve, *F* is river basin area of territorial unit, *A* is maximum potential retention of the river basin of territorial unit, t_{kc} is runoff concentration time, H_z is height of the rain considered, H_o is height of the direct runoff, *V* is volume of the direct runoff and Q_{max} is maximum peak flow.

Table 2 shows the annual soil loss from the various territorial units in the area of Kubíny. When converting the soil loss from $t.year^{-1}$ to $m^3.year^{-1}$, we considered the volumetric mass density of soil to be 1800 kg/m^3 at natural moisture. According to Zachar's degree of erosive sediment yield intensity [18], slight (0 - 4 $t.ha^{-1}.year^{-1}$), medium (4 - 10 $t.ha^{-1}.year^{-1}$) and even severe (10-30 $t.ha^{-1}.year^{-1}$) intensity in several places can be observed at the Kubíny site (Figure 5).

By multiplying the annual soil loss with the SDR, we have gained an idea of how much eroded particles are transported from the agricultural land in the area of interest (Table 2). Assuming the entire transported soil to be deposited in level ditches, it can be claimed that the clogging speed of the upper ditch will be 3.4 m^3 per year, which represents 6.139 tonnes of soil and in the case of the lower ditch the speed will be 0.204 m^3 per year representing 0.367 tonnes of soil. However, this scenario is unlikely, since during the muddy floods some soil particles are transported downhill in the form of bed load and trapped in ditches, but a considerable part of them is continuously deposited on a slope.

Table 2. Average annual soil loss and sediment yield in the area of Kubíny.

Territorial units	SDR [-]	River basin area [km^2]	Volume of soil loss [m^3]	Sediment loss [tonnes]	Degree of Erosion
Part 1	0.020	0.523	170.44	6.139	moderate
Part 2	0.022	0.059	9.28	0.367	no, slight
Part 3	0.030	0.004	0.25	0.014	no, slight

Notes *SDR* is sediment delivery ratio.

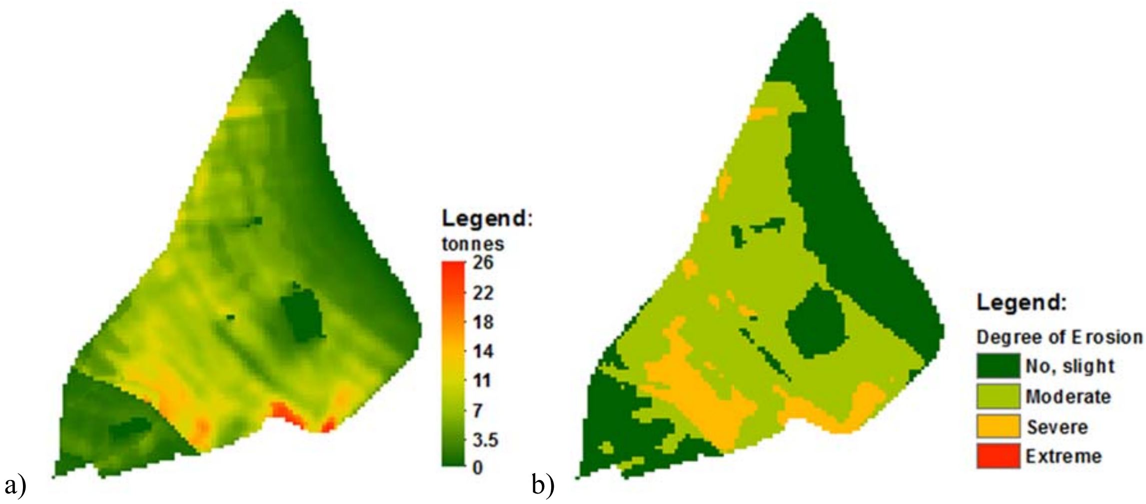

Figure 5. Average annual soil loss (a) and degree of erosion (b) in the area of Kubíny.

Outputs from field experimental measurements were used to determine the basic parameters of both ditches (shape and volume) in a GIS environment. The maximum altitude of the edge, respectively the highest contour, at which the ditch would still be able to retain water, was defined for both ditches (253.35 m a.s.l. for the lower ditch and 278.30 m a.s.l. for the upper one). Subsequently, polygons were created to characterize the points of the same height (i.e., the maximum water level in ditches). The volume was determined for both level ditches from the DEM and TIN generated as the outputs from the field measurements. Table 3 lists the lengths and volumes of the ditches after the influence of climatic factors on the area of Kubíny for 2011-2016.

Table 3. Resulting values of the volumes of the level ditches.

Object	Year	Method	Device	Length [m]	Total volume [m^3]	Reduction of volume [%]
Lower ditch	2011	Project	-	91.0	764.4	-
	2015	TLS	Trimble TX5	90.0	180.25	76.1
	1016	TLS	Trimble TX5	90.6	184.95	
Upper ditch	2011	Project	-	303.0	2545.2	-
	2015	UAV	AIBOTIX	301.2	449.09	82.3

The results show that during the monitoring period, the volume of the lower ditch was reduced by 76.1% and the upper one was reduced by 82.3%. This fact is true, however, only with the assumption that the ditches (after the implementation) had a height of 2 m and a width of 4.2 m, as stated in the pre-project documentation (which cannot be verified). However, it may be assumed that the clogging of these objects, especially the upper one, occurs, as they capture a significant part of the rainfall runoff. The shape and the volume of the bottom ditch have not changed significantly over the recent year (slight deviations in volume may be caused by measurement errors), since it may be regarded as a backup one within the area.

4. Conclusions

In order to assess the effectiveness of the level ditches over a certain period, we had to take into account their characteristics and the current state that was obtained through continuous monitoring.

Assuming the 10-year design precipitation occurrence, which would cause a direct runoff of 2162 m^3 into the upper ditch and 130 m^3 of water into the lower ditch; it may be assumed that the volume of both ditches in the current state is not sufficient. The average annual yield of soil from the Kubíny site is around 3.6 m^3 per year, with more than 90% captured by the top ditch. It would therefore be desirable to deepen the ditch and clean the accumulated sediments, since these line elements prevent the soil denudation and creation of the direct runoff, but also interrupt the movement of matter, thus eliminating the effects of water erosion. In order to increase the flood protection and erosion control in the Kubíny area, strip farming could be applied on an agricultural land (e.g. winter wheat changing with lucerne).

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