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Comparison of two concepts for assessment of sediment transport in small agricultural catchments

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Abstract: The erosion, transport and deposition of sediments in small valley reservoirs represent a significant impact on their operations, mainly with regard to reducing the volume of their accumulation. The aim of this study is a comparison and uncertainty analysis of two modelling concepts for assessment of soil loss and sediment transport in a small agricultural catchment, with an emphasis on estimating the off-site effects of soil erosion resulted in sedimentation of a small water reservoir. The small water reservoir (polder) of Svacenicky Creek which was built in 2012, is a part of the flood protection measures in Turá Lúka and is located in the western part of Slovakia, close to the town of Myjava. The town of Myjava in recent years has been threatened by frequent floods, which have caused heavy material losses and significantly limited the quality of life of the local residents. To estimate the amount of soil loss and sediments transported from the basin, we applied two modelling concepts based on the USLE/SDR and WaTEM/SEDEM erosion models and validated the results with the actual bathymetry of the polder. The measurements were provided by a modern Autonomous Underwater Vehicle (AUV) hydrographic instrument. From the sediment data measured and the original geodetic survey of the terrain conducted at the time of the construction of the polder, we calculated changes in the storage volume of the polder during its four years of operation. The results show that in the given area, there has been a gradual clogging of the bottom of the polder caused by water erosion. We estimate that within the four years of the acceptance run, 10,494 m^3 of bottom sediments on the Svacenicky Creek polder have accumulated. It therefore follows that repeated surveying of the sedimentation is very important for the management of the water reservoir.

Keywords: Soil erosion; Reservoir storage volume; Sediment; Bathymetry, Svacenicky Creek.

INTRODUCTION

Erosion and sediment transport and deposition are major environmental issues that affect society through soil loss, reduction of the capacity of reservoirs, and intensification of both water pollution and floods (Abril and Knight, 2004; Fasching and Bauder, 2001; Lane et al., 1997; Nelson and Booth, 2002; van Rompaey et al., 2001; Walling, 1983). The problem of soil erosion is closely related to flash floods and muddy floods which generally occur in small to medium-sized basins (Hlavčová et al., 2016).

Soil erosion by water causes the greatest loss of soil in Europe compared to other soil degradation processes. It is one of the most widespread forms of soil degradation (Boardman and Poesen, 2006; Bosco et al., 2015) and can lead not only to soil loss but also to other soil threats, such as the breakdown of soil structure, reduction of water-holding capacity (Hlaváčiková et al., 2018), and declines in organic matter and nutrient contents. During the past decade, the problem of soil erosion has become part of the environmental agenda in the European Union (EU) due to its impacts on food production, drinking water quality, ecosystem services, mud floods, eutrophication and biodiversity (Boardman and Poesen, 2006). It is listed in the Soil Thematic Strategy of the European Commission (EC, 2006) as one of the eight threats to soil. Recent policy developments formulated by the European Commission (the Soil Thematic Strategy, the Common Agricultural Policy, Europe 2020, and the 7th Environmental Action Programme) have called for quantitative assessments of soil loss intensity at the European level (Panagos et al., 2015a).

The processes of soil erosion by water consist of the detachment of soil particles by the kinetic energy of raindrops or overland flow, the transport of the detached soil particles by overland flow, and sediment deposition. The main kinds of water erosion are sheet, rill, gully and in-stream erosion. Sheet erosion induces a uniform detachment of soil, so that soil particles from the surface are evenly distributed across a slope (Hairsine and Rose, 1992). Rill erosion occurs when water flowing over a soil surface flows along preferential pathways and forms easily recognisable channels (Rose, 1993). Rills are small erosion channels which can be eliminated by tillage. The flow in rills is a transporting agent for the removal of sediment downslope from rill and interill sources, although if the shear stress in the rill is high enough, the rill flow may also detach significant amounts of soil (Nearing et al., 1994). Sheet and rill erosion can be considered as overland flow erosion; both processes are often analysed together in the modelling of erosion (Merritt et al., 2003). Gully erosion forms channels of concentrated flow that are too deep to be obliterated by cultivation (Rose, 1993).

The analysis and quantification of soil erosion processes and the assessment of their impact on soil loss and the quality of water on slope, catchment or regional scales are required by water managers and catchment stakeholders. Various erosion models have been developed to predict soil erosion intensities by water. These models differ greatly in terms of their complexity, inputs, and spatial and temporal scales, so that different modelling approaches can lead to significantly different soil erosion rates even when the same model is applied within the same region (Shen et al., 2009). The heterogeneity of the models also affects the processes they represent, the manner in which these processes are represented, and the types of output information they provide (de Vente et al., 2013). Therefore, research is needed to improve methods for estimating soil erosion rates using modelling approaches upon which mitigation strategies can be assessed and implemented (Bosco et al., 2015). Models for estimating the soil erosion of large areas, e.g., PESERA (Kirkby et al., 2008), that require input data with a sufficient degree of accuracy may not always be available for large spatial extents (Jones et al., 2003). A comprehensive review of erosion and sediment transport models was done by Merritt et al. (2003). He characterised various existing erosion models based on empirical, conceptual, and physical bases. Empirical models are usually based on an analysis of observations, and data requirements for such models are less than for conceptual and physically-based models. The parameters used in empirical models may be obtained by calibration, and they are often transferred from calibrations at experimental sites (Merritt et al., 2003). The most widely-used empirical erosion models for estimating long-term mean annual soil loss by sheet and rill erosion are the Universal Soil Loss Equation USLE (Wischmeier and Smith, 1978) and its revised versions, e.g., RUSLE (Renard et al., 1997).

Conceptual models (e.g., AGNPS, WaTEM/SEDEM) describe general catchment processes; because of the simplification of interactions between them, they do not require detailed catchment data. Various developed conceptual models have provided outputs in a spatially distributed way. Physically-based models (e.g., LISEM, TOPOG, WEPP) are based on the solution of fundamental physical equations describing runoff and sediment transport processes. The parameters used in physically-based models are measurable, but the large number of parameters means that these parameters must often be calibrated against observed data (Beck et al., 1995).

The rate of erosion and sediment transport from a catchment can also be determined by estimating sediment yields, which can be quantified in various ways, i.e., from reconnaissance methods through the use of catch pits for measurements of the flow and sediment loads or from the quantities of sediment trapped in water reservoirs. Many of the problems associated with sampling river sediments can be avoided when data derived from reservoir surveys are used to estimate sediment yields (Lawrence, 1996). Reservoir surveys are usually carried out to determine the rate at which storage is being lost due to sedimentation and to provide information on changes in the storage volume curve. But the data derived from surveys can also be used to estimate catchment sediment yields. This kind of survey can be performed by "dry survey techniques" (when a reservoir is dry) or "wet survey techniques" (hydrographical survey). Autonomous Underwater Vehicles (AUVs) have recently become available as an effective tool or device for hydrographical surveys which investigate the bathymetry of a reservoir in high resolution (Wynn et al., 2014).

The objective of this study is a comparison and uncertainty analysis of two modelling concepts for assessment of soil loss and sediment transport in a small agricultural catchment, with an emphasis on estimating the off-site effects of soil erosion resulted in sedimentation of a small water reservoir. The methodology for validation of both modelling approaches by comparing sediment transport from a catchment with sediment yields in a small water reservoir is developed. The possibilities for reducing erosion processes by land and crop management are discussed.

The paper is structured in the following way: A brief introduction of the problems studied is presented in Chapter 1. In Chapter 2 the methodology used is described. We characterise the USLE, SDR and WaTEM/SEDEM models for estimating the soil erosion and sediment transport on a catchment scale and the methodology for measurement of bed sediment loads in a small water reservoir using the AUV EcoMapper device. Chapter 3 describes the study area of the Svacenicky Creek catchment and the Svacenicky Creek polder and the input data for modelling the soil erosion and sediment transport and for modelling the bathymetry of the polder (mission planning). Chapter 4 contains the results of modelling the soil erosion and sediment transport by the USLE/SDR and WaTEM/SEDEM models and the results of the polder bathymetry. A comparison of the modelled sediment transport to the polder with the measured bed sediment loads is provided. Chapter 5 discusses the results and states our conclusions.

METHODS

Modelling of soil loss and sediment transport

Two modelling approaches were applied for quantifying the soil erosion by water on a catchment scale. First, the mean annual soil loss and sediment transport from the catchment were estimated by the Universal Soil Loss Equation (USLE) and the Sediment Delivery Ratio (SDR) model. The second approach was presented by the WaTEM/SEDEM spatially-distributed soil erosion and sediment delivery model.

The Universal Soil Loss Equation (USLE) is an empirical model which can be used to estimate soil loss with an emphasis on sheet and rill erosion, without taking into account the sediment transport and deposition. In the modified version of USLE with the LS topographical factor, the mean annual soil loss is calculated according to the equation:

$$E = R \cdot K \cdot LS \cdot C \cdot P \quad (1)$$

where E is the mean annual soil loss (t ha^{-1} year^{-1}); K is the soil erodibility factor (t ha^{-1} year^{-1} on one unit of R); R is the rainfall erosivity factor (MJ ha^{-1} cm h^{-1}); LS is the topographical factor (–); C is the vegetation cover factor (–); and P is the erosion control measure factor (–). The R factor represents the long-term value of rain erosivity on a yearly basis. The K factor depends on soil properties such as soil texture and structure, the content of organic matter, and soil permeability. The LS factor is a representation of the spatial variability of soil erosion caused by the topography. The L factor is a measure of slope length, and the S factor is proportional to the local slope.

The USLE2D methodology was applied to calculate the LS topographical factor. In the USLE2D the LS factor is derived for closed eroded units (parcels) based on a raster digital elevation model. The raster structure of the digital elevation model allows for taking into account a slope's variability in the separate cells of a square grid area, together with increasing the slope's length in the direction of the surface runoff. Increasing the slope length in the model is expressed by a unit contributing area, which is defined by several algorithms.

The basic expression of the relationship between the length and steepness of a slope was defined by Foster and Wischmeier (1974). The formula for the topographic factor of an irregular slope has the shape:

$$LS = \sum_{j=1}^{N} \frac{S_j \cdot \lambda_j^{m+1} - S_j \cdot \lambda_{j-1}^{m+1}}{\left(\lambda_j - \lambda_{j-1}\right) \cdot (22.13)^m} \quad (2)$$

where S_j – factor of the slope's steepness for the j-th element (m m^{-1}),
λ_j – the length between the lower boundary of the j-th element and the upslope field boundary (m),
m – the slope length exponent.

The equation can be expanded to a three-dimensional topography:

$$LS = \sum_{i,j} \frac{S(i,j)\cdot\lambda(i,j)_{outlet}^{m+1} - S(i,j)\cdot\lambda(i,j)_{inlet}^{m+1}}{\left(\lambda(i,j)_{outlet}^{m+1} - \lambda(i,j)_{inlet}^{m+1}\right)\cdot(22.13)^{m}} \qquad (3)$$

where LS – the topographical factor for one parcel or a whole river basin,
$\lambda(i,j)$ – the slope length at the input for the i-, j-th grid cell (m),
$\lambda(i,j)$ – the slope length at the output for the i-, j-th grid cell (m),
$S(i,j)$ – the slope factor for the i-, j-th grid cell,
m – the slope length exponent.

The factor of the slope's steepness for individual cells is expressed by several algorithms:

Wischmeier and Smith`s relationship (1978):

$$S(i,j) = 65.41 \cdot \sin^2 \theta_{i,j} + 4.56 \cdot \sin \theta_{i,j} + 0.065 \qquad (4)$$

McCool`s relationship (McCool et al., 1989), which was used in RUSLE:

$$S(i,j) = 10.8 \cdot \sin \theta_{i,j} + 0.03 \text{ where } \theta_{i,j} \le 9\% \qquad (5)$$

$$S(i,j) = 16.8 \cdot \sin \theta_{i,j} - 0.5 \text{ where } \theta_{i,j} > 9\% \qquad (6)$$

Gowers`s expression (Desmed and Govers, 1996):

$$S(i,j) = (\tan \theta_{i,j} / 0.09)^{1.45} \qquad (7)$$

Nearing`s formula for a slope`s steepness is expressed in the form:

$$S = -1.5 + \frac{17}{\left(1 + \mathrm{e}^{\left[2.3 - 6.1\cdot\sin(\theta)\right]}\right)} \qquad (8)$$

The USLE model does not take into account the sediment transport and deposition. Therefore, the sediment transport was estimated using the Sediment Delivery Ratio (SDR) model by Wiliams (1977). The SDR calculates the percentage of total soil loss that is delivered to a catchment outlet by the equation:

$$SDR = 1.366\cdot 10^{-11} \cdot A^{-0.0998} \cdot S_r^{0.3629} \cdot CN^{5.444} \qquad (9)$$

where A – the catchment area (km^2),
Sr – the relief ratio (m km^{-1}), it is the ratio between the difference in elevations in a catchment divide and outlet, and the longest route of the flow path,
CN – the average SCS curve number of the catchment.

The mean annual sediment transport is then estimated by multiplication of the mean annual catchment's soil loss and the catchment's SDR value (Janeček, 2007).

The second modelling approach is represented by the WaTEM/SEDEM spatially distributed soil erosion and sediment delivery model developed at the Physical and Regional Geography Research Group of KU Leuven (Van Oost et al., 2000; Van Rompaey et al., 2001; Verstraeten et al., 2002). The model consists of two submodels that calculate water and tillage erosion, including sediment delivery to rivers, using proportional, multiple-flow calculations of transport capacity. In the first submodel the soil loss is estimated by the RUSLE equation (Renard et al., 1991, 1994). Unlike RUSLE, WaTEM/SEDEM works with a 2D approach to the topographical factor. The algorithm (Desmet and Govers, 1996) uses a digital elevation model and a parcel map and was adjusted by Takken et al. (2001) so that the direction of the tillage is taken into account. The location of roads is also included, i.e., water on a road will always follow that road to the lowest point. Both topographical parameters are derived from a DEM (Verstraeten and Poesen, 2001).

The second submodel of WaTEM/SEDEM is the calculation of the sediment transport and sedimentation. It calculates the amount of sediments that is exported towards surface water. This is done by routing the sediments towards the surface water and taking into account the possible deposition of sediments. This deposition is controlled by the transport capacity (*Tc*), which is calculated for each pixel. The transport capacity is the maximal amount of sediments that can pass through one pixel. WaTEM/SEDEM has two ways of calculating the *Tc*, i.e., proportional and non-proportional. All the versions of the model except for WaTEM/SEDEM 2005 assume that the transport capacity is proportional to the volume of the potential gully erosion (Van Rompay et al., 2001):

$$Tc = ktc \cdot Eprg = ktc \cdot R \cdot K \cdot \left(LS - 4.12 \cdot Sg^{0.8}\right) \qquad (10)$$

where ktc – transport capacity coefficient,
$Eprg$ – potential gully erosion,
Sg – local slope (m m^{-1}),
R, K and LS are the factors from the RUSLE equation.

The values of *ktc* should be calibrated and validated to use the model. Several sets of calibrated parameters are available. For each land use type, transport capacity can be different. Using sediment yield data for 26 catchments in the Belgian Loess Belt, Van Rompaey et al. (2001) calibrated a transport capacity coefficient for arable land and for non-erodible land surfaces such as pastures or forests. These values are respectively 75 and 42. However, since the first calibration phase of WaTEM/SEDEM, some changes have been made to the model, and a new calibration points out that the values are 200 and 100 respectively for the following PTEF and parcel connectivity values (PTEF arable land: 0; forest & pasture: 75; parcel connectivity arable land: 10; forest & pasture 75). For other areas, new values of *ktc* need to be calibrated first. In WaTEM/SEDEM, a threshold C-factor value needs to be given to indicate for which areas the high *ktc* needs to be used. This threshold is set at 0.1. A transport capacity map will then be created using the C-factor map. Roads are given a very high *ktc* such that no sediment deposition is modelled on road surfaces.

Measurement of the sediment yields in the water reservoir
The bathymetry measurement of the polder

For the hydrographic research and data mapping of the Svacenicky polder, the Autonomous Underwater Vehicle (AUV) EcoMapper device was used. AUVs represent devices which are currently used in a wide range of hydrographic research, marine geoscience, and the military, commercial, and policy sectors. In general, they have the shape of a torpedo and were originally developed for military purposes. The first AUV was developed at the Applied Physics Laboratory at the University of Washington as early as 1957. The vehicle was used to study diffusion, acoustic transmissions and submarine wakes (Vijay, 2011). During the 1980s, AUVs were also used for water exploration and hydrographic surveys. One of the most significant instruments is IFREMER L'Epaulard, which was built by ECA Group in association with the French Oceanology Research Institute in the 1980s. IFREMER L'Epaulard was used for oceanographic surveys with a depth range of up to 6000 m. In subsequent years the research and development of new AUV devices have allowed for their use in inland conditions and have also increased the range of the measurements of biological and geochemical parameters.

EcoMapper represents a device which is capable of moving on surface and subsurface water levels independently and performing data logging. This device is ideal for coastal and shallow water applications such as hydrographic surveys and spatial environmental monitoring. A survey mission by EcoMapper can be performed in water with a depth of more than one meter, and it is fully capable of subsurface operations down to 100 m. EcoMapper was developed by YSI Company (USA) and is designed for the quick and easy collection of bathymetric, sonar, and water quality data.

The EcoMapper device consists of a hardware part (Fig. 1) and the Vector Maps software program, which is designed for mission planning and for the partial analysis of measured data. Physically, the vehicle can be divided into 3 distinct parts. The bow section contains water quality sensors that interact with the aquatic environment and a Dopler Velocity Log (DVL) for navigation under water. The middle section includes an onboard computer, electronic components, batteries, and weights to balance the vehicle. The tail section contains a propulsion system and GPS antennas for navigating on the water's surface (YSI, 2009).

While it is measuring (its mission), the Ecomapper collects predetermined parameters every second; they are automatically associated with geographic coordinates (latitude, longitude). Water quality measurements include information such as the water temperature, dissolved oxygen, turbidity, pH, chlorophyll, salinity, etc. Measuring the depth of the bottom (bathymetry) is carried out by an integrated single beam echo-sounder. The device uses a frequency of 500 kHz and has a range of measurement depth from 1 to 100 m and a measurement accuracy ± 0.003 m.

Mission planning

The EcoMapper follows a predefined mission plan created by the user. This mission plan is created in the graphic user environment of the Vector Map Software. Mission planning starts by downloading available geo-referenced charts, maps or satellite images into the Vector Maps planning software and then clicking the position of waypoints for the vehicle's navigation (Fig. 4).

The mission planning includes set points for each leg to a waypoint, speed, depth or undulate for data collection. Additionally, operators can click and drag any waypoints to edit a mission. This simple but powerful tool lets you program the vehicle and sensor parameters for each leg or for a complete survey.

The programme output is an ASCII mission file that is uploaded to the EcoMapper via a wireless interface prior to the mission's start. Once the vehicle has started its mission, it operates independently and uses GPS waypoints and DVL navigation to complete its programmed course. Throughout the course, the vehicle constantly steers toward the line drawn in the mission planning software (VectorMap) and essentially follows a more accurate course of coordinates instead of transversing waypoint-to-waypoint. Upon completing its mission, the vehicle uses Windows® Remote Desktop to relay the collected data via a WiFi connection, which is facilitated by the Communications Box, to the user's computer (YSI, 2009).

DESCRIPTION OF THE CATCHMENT AND INPUT DATA

The catchment of the Svacenicky Creek with its area of 8.61 km^2 is located in the Myjava River basin (Korbeľová and Kohnová, 2017; Valent et al., 2016) in Western Slovakia (Fig. 2a). The creek has a length of 5.4 km and is a right-hand tributary of the Myjava River, which it joins near the Turá Lúka site at an altitude of 308 m a.s.l. The spring of the creek lies on the boundary between the White Carpathian Mountains and the Myjava Hill Land, eastward to a ground elevation of 507.9 m a.s.l. and northward to the Zimovci settlement at an altitude of 460 m a.s.l. The Svacenicky Creek flows into the Myjava River at 69.0 river km, close to Turá Lúka.

For modelling the erosion and sediment transport, the catchment's outlet at the Svacenicky Creek polder was considered. The area of the catchment to the polder is 626.32 ha, with 513.32 ha of arable land (81.96% of the area), 46.45 ha of forest (7.42%), 46.78 ha of urban areas (7.47%), 9.01 ha of roads (1.44%) and 10.76 ha of water bodies/rivers (1.72%).

The Svacenicky Creek polder is a part of the flood protection measures in Turá Lúka and is located near the outlet of the Svacenicky Creek (Fig. 2b). The Svacenicky Creek polder, which was built in 2012, can reduce a 100-year maximum design flood of 16.00 m^3 s^{-1} to 0.21 m^3 s^{-1}. The volume of the polder according to the project is 215,808 m^3, and it is able to retain a flood wave of 207,330 m^3. The levee of the polder has been constructed as a homogenous embankment dam built from impervious clay soils. The embankment dam is 147 m long and has a width of 4.5 m. The shape of the dam has an upstream slope inclination of 1:2.5 and a slope gradient of 1:3.0 on the downstream slope. The close vicinity of the polder is covered with oak-beech woods, beech-oak woods and alder woods.

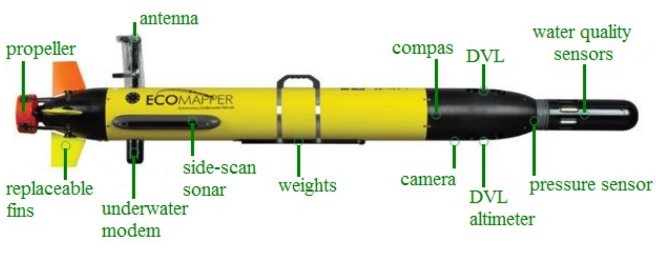


Fig. 1. YSI EcoMapper side view (YSI, 2009).

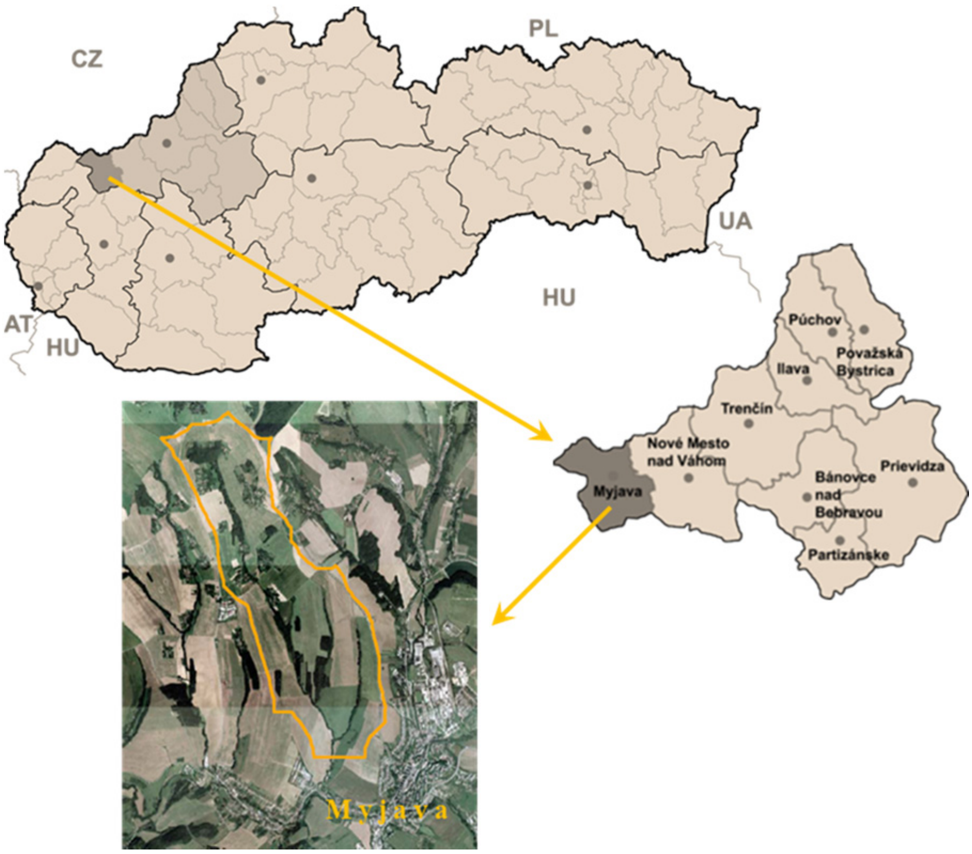
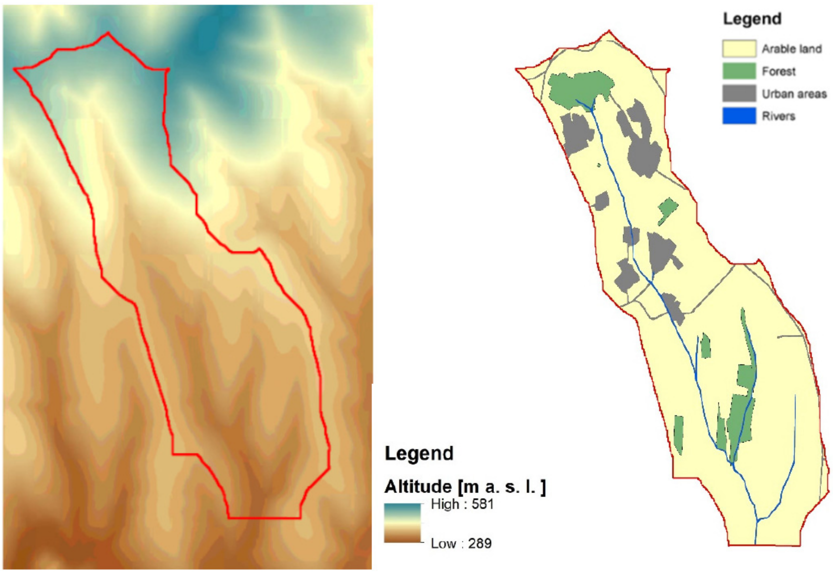


Fig. 2a. Locations of the the Svacenicky Creek basin.

Fig. 2b. The Svacenicky Creek polder and flooded area.

Input data for modelling the soil erosion and sediment transport

For modelling the soil erosion and sediment transport, the morphological, hydrological, land use and soil data were prepared. The morphological data were represented by a digital elevation model with a raster size of 10 m x 10 m (Fig. 3a). The precipitation data were represented by the rainfall erosivity factor R (MJ ha^{-1} cm h^{-1}) = 30 (Malíšek, 1990). The soil data were represented by a map of the soil erodibility factor, which was developed from a soil texture map with values of K (t ha^{-1} year^{-1} on one unit of R) = 0.45 for loamy soils and K = 0.60 for clay-loamy soils (Alena, 1991). The land use data was entered into the modelling in the form of vegetation factor C (–) with values of C = 0 for forested areas and grasslands and different C values for the various crops considered: C = 1 for bare soil, C = 0.72 for maize for silage, C = 0.61 for maize for grain, C = 0.12 for winter wheat and C = 0.22 for winter rapeseed (Alena, 1991). For modelling the soil erosion using the WaTEM/SEDEM model, a map of parcels with arable lands, roads and a generated river network was created from the land use map (Fig. 3b).



a) b)

Fig. 3. The Svacenicky Creek catchment a) Digital elevation model b) Land use map.

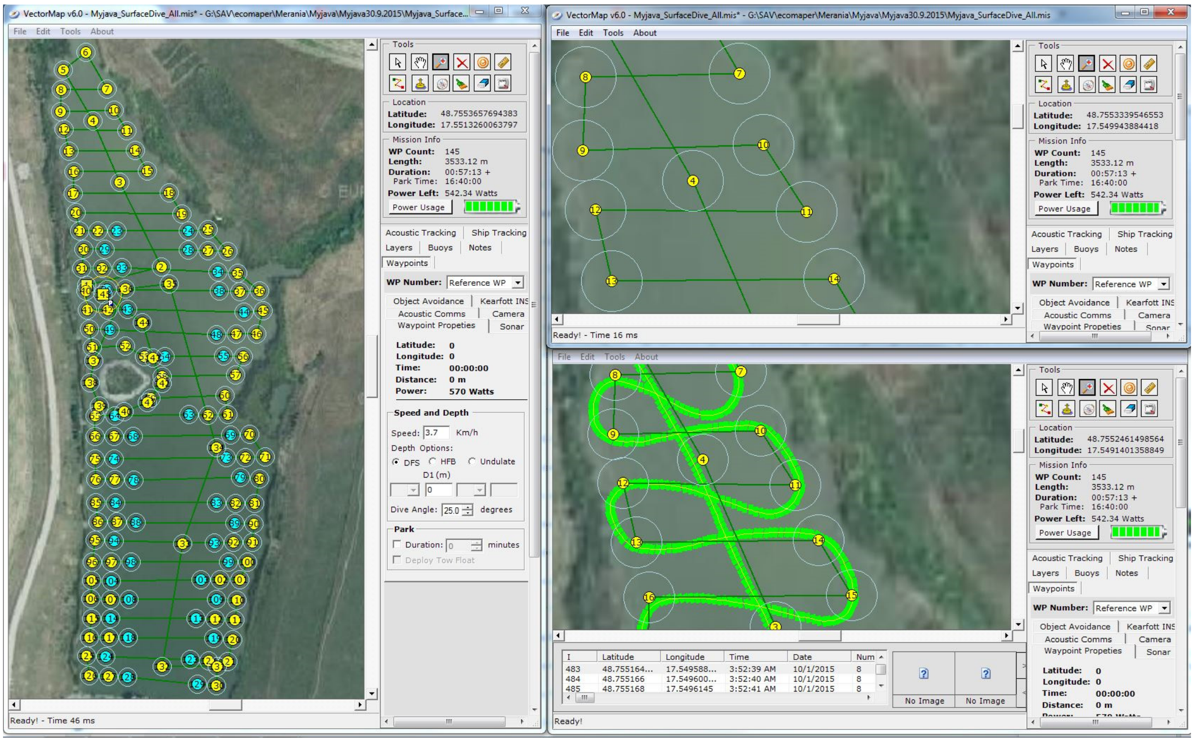


Fig. 4. Mission planning using the VectorMap software program.

Data for the polder bathymetry – mission planning

The hydrographic survey of the Svacenicky Creek polder was carried out in two stages. In the first stage, on 22.09.2015, a preliminary survey of the polder using the EcoMapper device was conducted; the measurements were only taken on the water surface of the polder. In the second stage (30.9.2015) more detailed research was carried out by where the measurements took place alternately from the water surface and from a depth of 0.5 meters below the surface. The aim was to obtain in-depth data, water quality parameters, and images of the polder's bottom to create a database of this information. Water level during measurement was of 316.45 m. a.s.l.

The mission represents 84 navigation points (Fig. 4). During the first measurement a certain distance had to be kept from the polder's shore, due to the dense vegetation and shallow depth, especially in the northern part of the polder. After entering the navigation points, cross sections at distances of 10–12 meters were created. The total length of the measurement was 2878.97 m. The EcoMapper velocity was set at 3.7 km h^{-1}, wherein one measurement took about 47 minutes. The collecting intervals of the qualitative and depth data were set at 1 second. The total amount of data collected during the measurement of the water level was 3004 values for each parameter. Based on the evaluation of the first phase of the measurement, the navigation points in the second mission were extended to a total of 145. This amount includes the points used during the underwater measurements. The total length measured during the second stage was 3533.12 m; the velocity remained at 3.7 km h^{-1}. The mission lasted 57 minutes, and the total amount of data collected was 3413 values for all the parameters measured.

RESULTS

Modelling the soil erosion and sediment transport from the Svacenicky Creek basin

The results of modelling the erosion and sediment transport from the Svacenicky Creek catchment (to the outlet of the polder) are presented in the form of erosion/sediment deposition maps (WaTEM/SEDEM) and in tables with the total mean annual soil loss in (t ha^{-1} $year^{-1}$) and (t $year^{-1}$) and the total mean annual sediment transport to the catchment outlet (polder) in (t $year^{-1}$). The erosion/sediment deposition maps for the bare soil and the winter wheat are shown in Figs. 5 and 6. The maps illustrate the spatial distribution of the erosion (soil loss) and sediment deposition in (t ha^{-1} $year^{-1}$) calculated by the WaTEM/SEDEM model and the various algorithms for estimating the LS factor.

Tables 1 and 2 present the results of the mean annual soil loss for the selected crops and the bare soil in (t ha^{-1} $year^{-1}$) and (t $years^{-1}$), respectively. The comparison shows that the greatest intensities of soil loss were achieved by the bare soil without vegetation and from the planting of maize for silage. The lowest values were achieved from the planting of winter wheat.

In both tables "WS" is the LS algorithm developed by Wischmeier-Smith; "Mc Cool-l", "Mc Cool-m" and "Mc Cool-h" are algorithms developed by Mc Cool low, Mc Cool moderate, and Mc Cool high; "Nearing-WS" is the LS algorithm developed by Nearing and Wischmeier Smith; and "Nearing-Mc" is the LS algorithm developed by Nearing and Mc Cool.

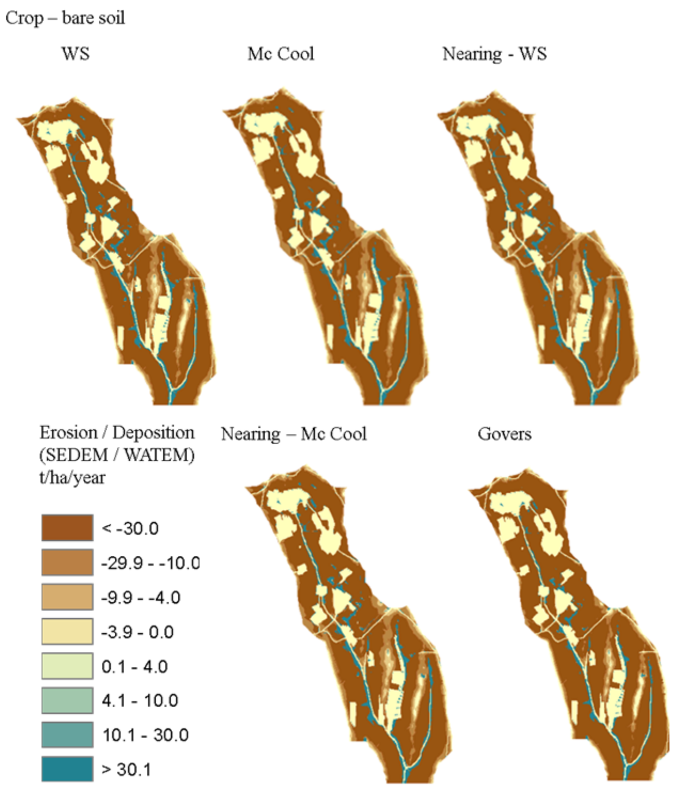


Fig. 5. The erosion/sediment deposition maps for the bare soil (t ha^{-1} $year^{-1}$).

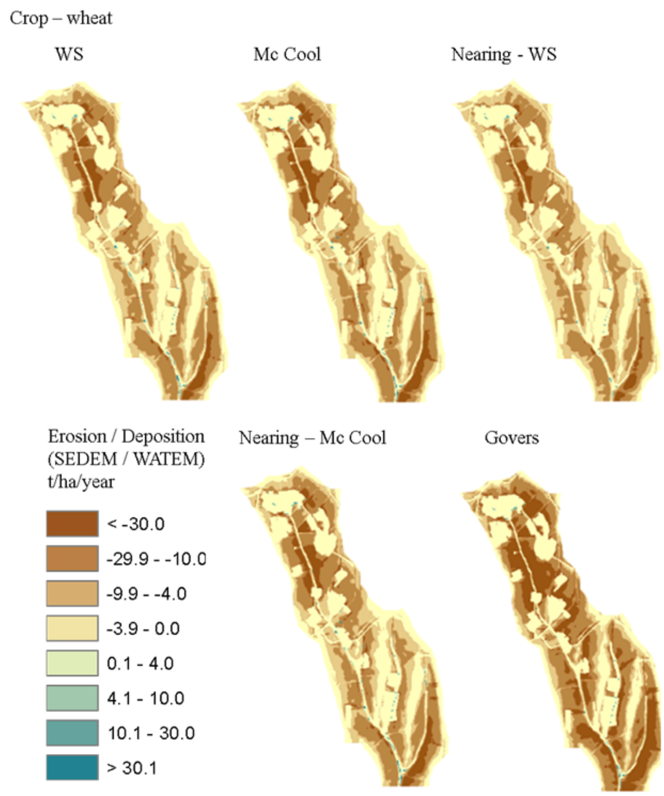


Fig. 6. The erosion/sediment deposition maps for the winter wheat (t ha^{-1} $year^{-1}$).

Table 1. Comparison of the mean annual soil loss (t ha^{-1} $year^{-1}$) according to the USLE and WaTEM/SEDEM models and various LS algorithms.

Model	LS algorithm	Soil loss (t ha^{-1} $year^{-1}$)				
		Winter wheat	Winter rapeseed	Maize for corn	Maize for silage	Bare soil
USLE	WS	8.93	16.38	45.41	53.60	74.45
USLE	Mc Cool-l	6.17	11.32	31.37	37.03	51.43
USLE	Mc Cool-m	9.74	17.85	49.49	58.41	81.13
USLE	Mc Cool-h	14.79	27.11	75.18	88.74	123.24
USLE	Nearing-WS	7.86	14.41	39.97	47.18	65.52
USLE	Nearing-Mc	9.43	17.29	47.95	56.60	78.61
WaTEM/SEDEM	WS	11.15	20.35	54.77	63.70	84.95
WaTEM/SEDEM	Mc Cool	12 .44	22.73	61.35	71.53	95.66
WaTEM/SEDEM	Nearing-WS	9.78	17.87	48.03	55.82	74.05
WaTEM/SEDEM	Nearing-Mc	12.06	22.03	59.44	69.30	92.64
	Mean value	**10.29**	**18.76**	**51.30**	**60.19**	**82.17**

Table 2. Comparison of the total mean annual soil loss (t year^{-1}) according to the USLE and WaTEM/SEDEM models and various LS algorithms.

Model	LS algorithm	Total soil loss (t year^{-1})				
		Winter wheat	Winter rapeseed	Maize for corn	Maize for silage	Bare soil
USLE	WS	5998.18	10996.66	30490.75	35989.08	49984.84
USLE	Mc Cool-l	4143.78	7596.93	21064.22	24862.68	34531.50
USLE	Mc Cool-m	6535.93	11982.54	33224.31	39215.58	54466.08
USLE	Mc Cool-h	9929.27	18203.66	50473.78	59575.61	82743.89
USLE	Nearing-WS	5278.79	9677.79	26833.87	31672.76	43989.95
USLE	Nearing-MC	6333.40	11611.23	32194.79	38000.40	52778.34
WaTEM/SEDEM	WS	6980.55	12747.10	34300.43	39896.88	53206.72
WaTEM/SEDEM	Mc Cool	7793.53	14234.29	38425.35	44798.68	59911.48
WaTEM/SEDEM	Nearing-WS	6128.32	11193.59	30084.17	34963.18	46379.28
WaTEM/SEDEM	Nearing-Mc	7552.26	13794.84	37231.19	43406.48	58020.42
	Mean value	**6667.40**	**12203.86**	**33432.29**	**39238.13**	**53601.25**

The mean annual amount of sediments transported from the catchment of the Svacenicky Creek to the catchment's outlet (polder) was estimated by the USLE and the "Sediment Delivery Ratio" (SDR) models (USLE/SDR) and by the WaTEM/SEDEM model.

The SDR was calculated as a function of the CN values, the catchment area, and the relief ratio (Table 3). It presents the ratio of the total soil loss from the catchment area which can be transported to the outlet of the catchment.

Table 3. Values for estimation of SDR.

	RP	CN	SDR (–)
Winter wheat	16.76	72.94	0.45
Maize	16.76	77.04	0.60
Bare soil	16.76	82.78	0.89

The values of the mean annual amount of the sediments transported to the catchment outlet estimated by the USLE/SDR and WaTEM/SEDEM models and various algorithms for the estimation of the LS factor are presented in Table 4.

Table 4. Total sediment transport to the catchment outlet (polder) in (t year^{-1}).

Mean annual sediment transport (t year^{-1})				
Model	Algorithm	Winter wheat	Maize	Bare soil
USLE/SDR	WS	2684.36	18374.76	44536.2
USLE/SDR	Mc Cool-l	1854.46	12694.01	30767.36
USLE/SDR	Mc Cool_m	2925.02	20022.09	48528.96
USLE/SDR	Mc Cool-h	4443.64	30417.21	73724.32
USLE/SDR	Nearing-WS	2362.42	16171.00	39194.79
USLE/SDR	Nearing-Mc	2834.38	19401.67	47025.19
WaTEM/SEDEM	WS	3771.95	11269.06	12834.55
WaTEM/SEDEM	Mc Cool	4173.95	12122.90	13897.52
WaTEM/SEDEM	Nearing-WS	3425.74	11150.58	13003.83
WaTEM/SEDEM	Nearing-Mc	4031.43	11676.03	13326.17
	Mean value	**3250.74**	**16329.93**	**33683.89**

From the results of estimation of mean annual and total soil loss presented in the Tables 1 and 2 we can conclude, that the results by Mc Cool-h provide always the highest values compared to other methods which have comparable results. The lowest values were achieved using the Mc Cool-l algorithm. The greatest intensities of soil loss were achieved by the bare soil without vegetation (from 51.43 to 123.24 t ha^{-1} year^{-1}) and from the planting of maize for silage (from 37.03 to 88.74 t ha^{-1} year^{-1}). The lowest values were achieved from the planting of winter wheat (from 6.17 to 14.79 ha^{-1} year^{-1}).

The total mean annual sediment transport to the polder for the soil without vegetation varied from 12,834 to 73,724 t year^{-1} and for the winter wheat from 1,854 t year^{-1} to 4,443 t year$^{-1,}$ (Table 4).

Measurement of the sediment yields in the polder

The geodetic points measured during the polder´s construction were first used for the creation of a digital terrain model to characterize the original morphology of the polder bed. The geodetic points of the dike and regulated river above and below the dike were then measured in December 2010. The geodetic points of the road and the polder's bed were measured in May 2011.

The polder's bed was only modelled in the flooded area during the bathymetry measurement on September 22, 2015, when a water level height of 316.45 m. a.s.l. was estimated. A resolution of 1 square meter per cell of the digital terrain model was chosen. The digital terrain model created is shown in Fig. 7.

The network of points determing the current bed with sediments is the output that came from the bathymetry measurements (Fig. 8). This network was used for creating the actual morphology of the polder bed after the process of sedimentation. During the creation of the digital terrain model of the sediments, it was nevertheless difficult to define the morphology in the areas without any measured points. Those areas had a water depth lower than 20 cm, but measuring equipment cannot be used when the water level is so low. In this case, the same resolution of the raster was chosen. The final version of the digital terrain model of the sediments is shown in Fig. 9.

The final analysis was based on calculating the differences in height between the digital terrain model of the polder bed and the digital terrain model of the sediments. The results of this analysis are shown in Fig. 10. In the flooded area, a maximal height of the sediments of 1.74 m was identified. This maximal height of the sediments was localized near the dike. The maximal depth of the terrain decreased by erosion was identified to be around 0.54 m. It is evident from Fig. 10 that sedimentation areas clearly dominate over the areas of polder bed erosion.

The results confirmed our theories about the on-going sedimentation processes in the Svacenicky Creek polder. According to the analysis with the ArcGis 10.1 software – the function Surface Volume, it was determined that during the last 4 years, over 10,474 m^3 of sediments were deposited on an area above 32,444 m^2 at a water level of 316.45 m. a.s.l.

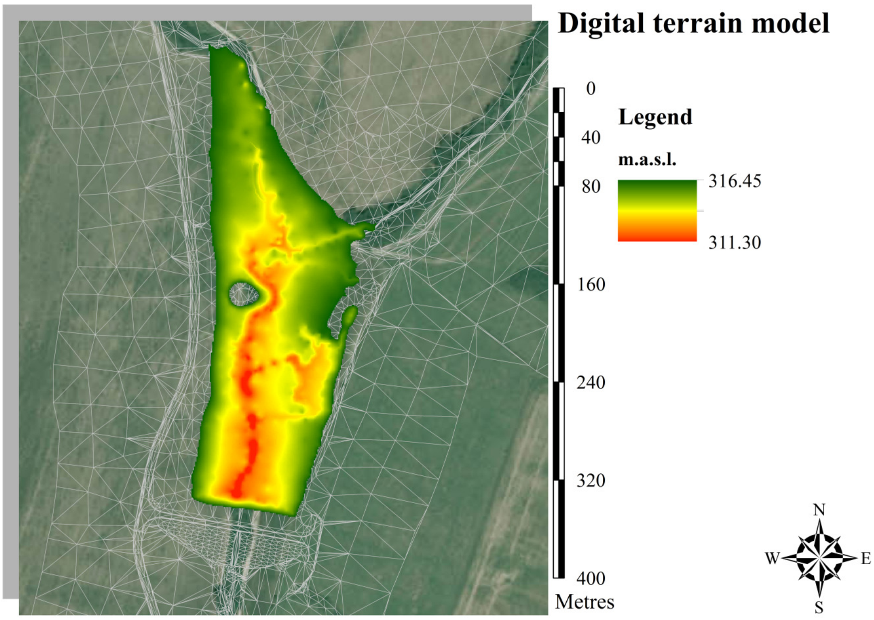


Fig. 7. Digital terrain model of Svacenicky Creek (ArcMap 10.1).

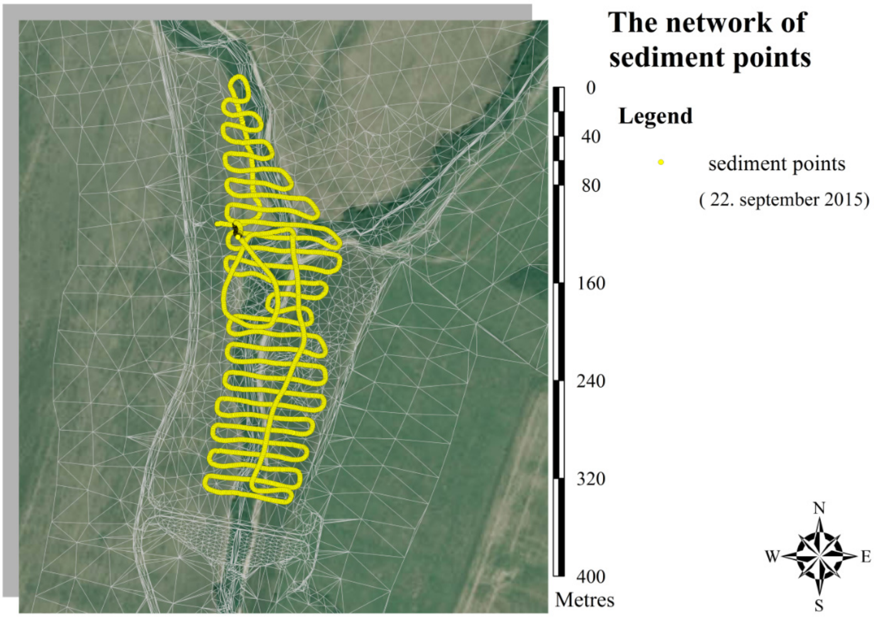


Fig. 8. The network of sediment points using the ArcMap 10.1. software program.

Subsequently, we compared the values of the mean annual sediment transport calculated using the USLE/SDR and WaTEM/SEDEM models with measurements of the sediment yields in the polder using the AUV EcoMapper for the period of four years after the polder´s construction. The estimation of the mean annual value of the measured sediment yields in tons is presented in Table 5. We assumed the bulk density of the bed sediments to be 1.9 t m^{-3}.The results presented confirmed our theories about the on-going sedimentation processes in the Svacenicky Creek polder. According to the analysis presented, we determined that during the last four years, over 10,474 m^3 of bed sediments on the area of the Svacenicky Creek polder have accumulated, i.e., a mean annual value of 2,618 m^3 or 4,975 t.

Table 5. The mean annual measured sediment yields in the polder of Svacenicky Creek.

Measurement	Method	
Sediment yield in 2015	AUV EcoMapper	10,474 m^3
Annual average of sediment yield in tons		4,975.15 t

The modelling results for the winter wheat are comparable with the measurements, i.e., the estimated mean annual sediment transport is 4,174 t according to the WaTEM/SEDEM model and Mc Cool LS algorithm, and 4,444 t according to the USLE/SDR model and the Mc Cool high LS algorithm.

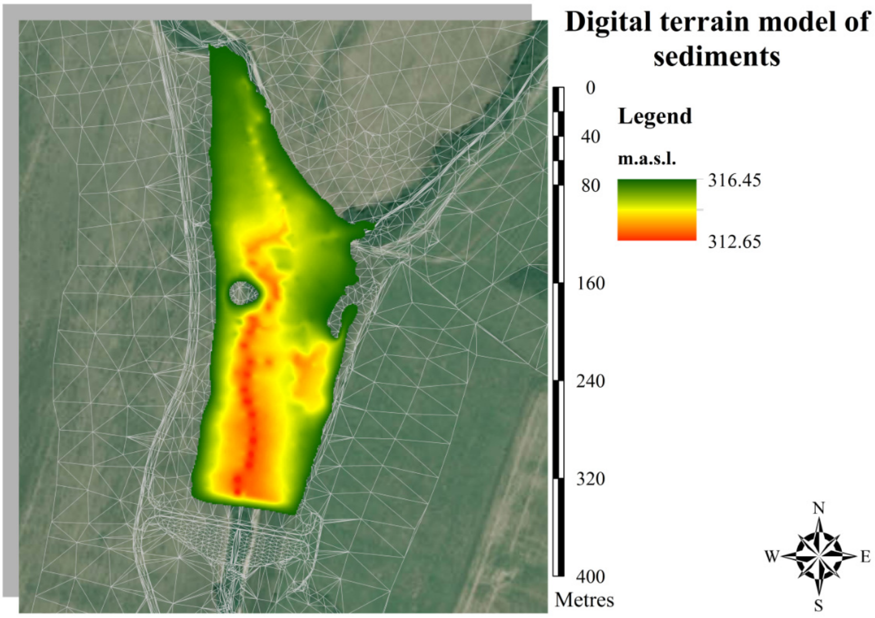


Fig. 9. Digital terrain model of sediments using the ArcMap 10.1. software program.

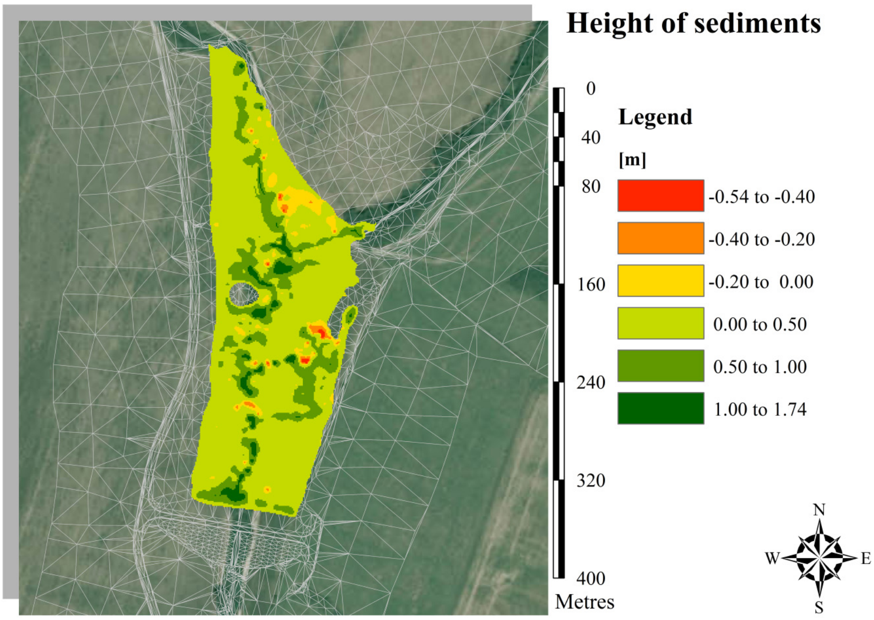


Fig. 10. Height of sediments using the ArcMap 10.1.software program.

DISCUSSION AND CONCLUSIONS

The main objective of this study was to quantify both the soil loss from agriculturally arable lands and the transport of sediments to the dry water reservoir (polder) of the Svacenicky Creek. The estimation was mainly focused on the off-site effect of soil erosion processes that result in the sedimentation of a small, flood protection water reservoir in the catchment outlet. In contrast to the on-site effect of soil erosion, which directly affects the people who control the source of the erosion, off-site impacts affect neighbouring areas where the people affected have little or no influence on source of the erosion (Renschler and Harbor, 2002). The import of sediments and nutrients causes changes in nutrient budgets, sediment loading, and the eutrophication of surface water bodies with impacts on the protective function of water reservoirs and water quality.

For estimating the mean annual soil loss and sediment transport from the catchment, empirical (USLE/SDR) and conceptual (WaTEM/SEDEM) approaches were applied. The USLE and SDR represent empirical models which are often criticised for employing simplified assumptions about the physics of the catchment system, i.e., they ignore the heterogeneity of catchment inputs and characteristics such as rainfall and soil types, as well as ignore the inherent non-linearities in the catchment system (Merritt, 2003). However, empirical models are frequently used in preference to more complex models as they can be applied in catchments with limited data and parameter inputs and are particularly useful as a first step in identifying sources of sediment and nutrient generation. The USLE belongs among the widely-used prediction equations in the world (Kinnell, 2010). Although it was designed to predict long-term average annual soil loss, it has the capacity to predict event-based soil losses reasonably well at some geographic locations. Its lack of capacity to predict event-based erosion is highly influenced by the fact the event-based rainfall–runoff factor used in the USLE and its revisions (RUSLE, RUSLE2) do not explicitly consider runoff.

Most of the empirical parameters of the models applied in this study originate from the original or modified members of the USLE equation; only the rainfall erosivity factor R is a physically based parameter, which is estimated from measured rainfall data. There have been many efforts to estimate and develop these parameters at the European level (e.g., Panagos, 2015a, b). Therefore, in the paper we did not focus on the calibration of the parameters but rather on their validation by comparing results of the modelled and measured sediment yields at the river basin outlet. We are aware of many uncertainties in this approach but on the base of the models validation we tried to recommend the most applicable model for engineering practice in our conditions. The best results, in terms of comparing the sediment yields, were achieved by the combination of USLE/SDR model and LS factor calculated by Mc Cool-h and Watem/SEDEM with McCool algorithm of LS.

The impact of land use and management was parameterised by the vegetation (cover-management) factor C. The C-factor is among the five factors that are used to estimate the risk of soil erosion within the Universal Soil Loss Equation (USLE) and its revised versions. The C-factor is perhaps the most important factor with regard to policy and land use decisions, as it represents conditions that can be most easily managed to reduce erosion (Panagos, et al., 2015b). The vegetation factor was parametrized with values of $C = 0$ for forested areas and grasslands and different C values for the various crops considered: $C = 1$ for bare soil, $C = 0.72$ for maize used for silage, $C = 0.61$ for maize used for grain, $C = 0.12$ for winter wheat, and $C = 0.22$ for winter rapeseed.

From the results of the estimated the mean annual soil losses in Table 1, the effect of various crops on reducing soil erosion is evident despite some differences in the modelling approaches used. The greatest intensities of soil loss were achieved by the bare soil without vegetation (from 51.43 to 123.24 t ha^{-1} year^{-1}) and from the planting of maize for silage (from 37.03 to 88.74 t ha^{-1} year^{-1}). The lowest values were achieved from the planting of winter wheat (from 6.17 to 14.79 ha^{-1} year^{-1}). The total mean annual sediment transport to the polder for the soil without vegetation varied from 12,834 to 73,724 t year^{-1} and for the winter wheat from 1,854 t year^{-1} to 4,443 t year^{-1}.

Next, the results of the sediment transport were compared with the results of the actual bathymetry of the polder. The AUV EcoMapper was used to gather the data on the Svacenicky Creek polder in September 2015. Based on the field measurements of the polder bottom's bathymetry, the current status of the clogging of the reservoir was evaluated. The results confirmed our theories about the on-going sedimentation processes in the Svacenicky Creek polder. According to the analysis with the ArcGis 10.1 software, it was determined that during the last 4 years, over 10,474 m^3 of sediments were deposited on an area of more 32,444 m^2 at a water level of 316.45 m. a.s.l. The sediment transport modelled from the Svacenicky Creek catchment to the polder for winter wheat is comparable with the measurements, i.e., the estimated mean annual sediment transport is 4,174 t according to the WaTEM/SEDEM model and Mc Cool LS algorithm, and 4,444 t according to the USLE/SDR model and the Mc Cool high LS algorithm.

Finally, it can be stated that public awareness of the problem of reservoir sedimentation and its relation to the sustainability of reservoirs should be increased by a more appropriate transfer of knowledge from researchers to the entities responsible and to the general public. It is necessary to pay more attention to soil conservation and erosion control on agricultural land. Approaches to soil conservation on cultivated lands are based on agronomic measures, soil management or mechanical methods. Agricultural and management practices play an important role in controlling soil erosion. For instance, soil loss rates decrease exponentially as vegetation cover increases (Gyssels et al., 2005). Besides vegetation cover, several other land use and management factors affect soil loss, such as the type of crop, tillage practice, etc. In this paper agronomic measures for soil conservation based on the protective effect of plant covers to reduce soil erosion were tested. The simplest way to combine different crops is to grow them consecutively in rotation or in strips. With strip-cropping, row crops and protection-effective crops are grown in alternating strips aligned on the contour. Erosion is limited to the row-crop strips and soil removed from these strips is trapped within and behind the next strip downslope.

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