Comparison of the Curve Number Method (SCS-CN) Modifications and the Application of Measures for Soil Erosion Reduction and Flood Protection in Small Ungauged Catchments in the White Carpathian Mountains in Slovakia

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Abstract. Knowledge of soil erosion and runoff processes leads to changes in attitudes towards a rational use of soil. Agricultural practices have a wide range of negative environmental impacts, including accelerated soil erosion, degradation, and increases in the volume of surface runoff. It is, therefore, necessary to investigate these negative influences on arable land. The study area is the municipality of the village of Vrbovce. It is situated in the north-western part of Slovakia in the White Carpathian Mountains. Due to its specific geological (heterogeneous rock masses of flysch) and geomorphological conditions (hilly country, uplands), that part of Slovakia is prone to accelerated soil erosion and mud flood formations. Nevertheless, a significant part of the municipality of Vrbovce is classified as agricultural land. The aim of this study is the soil erosion and runoff volume modelling that is focused on changes in the land cover/land use. We calculated soil loss with the Universal Soil Loss Equation (USLE) for agricultural parcels in the cadastral area of the village of Vrbovce. We are offering a set of suitable measures and agricultural procedures for this area as a result of our research. We estimated the direct runoff for the Teplica River basin up to the Teplica water gauge and five ungauged subcatchments in the cadastral area of the village of Vrbovce (Haluznikov creek, Lulovský creek, Zahutník creek, Zápasečník, and an unnamed creek). The Teplica river is poorly gauged with only a 10-year observation period. That length of hydrological measurements is not enough for the required period for calibrating a hydrological model. We used 3 modifications of the curve number (CN) method for estimating the volume of the direct runoff with various return periods, i.e., the standard CN method with values for the current land use, the worst land use and an alternative, and the DesQ program method. We also applied the Pearson Type III distribution for the estimation of the peak flow with a higher frequency of occurrence for the Teplica gauging station. The results of the specific runoff were compared with the values of the specific runoff calculated for the Sobotište water gauge, which is situated downstream of the Teplica river. The results show that the most suitable modification of the CN method is the standard CN method with the use of the values for the current land use. The predictions of the long-term average annual rate of erosion on each parcel from the land parcel identification system (LPIS) were calculated by the Universal Soil Loss Equation (USLE).
1. Introduction
The study of changes in the characteristics of runoff caused by human activities plays an essential role in understanding the effects of changes in land use on hydrological processes [1]. Hydrological modelling is a powerful tool for simulating runoff generation and erosion processes as a consequence of land use changes. These models simulate the hydrological processes on a watershed that occur as a result of precipitation. Simulation models are divided according to the degree of representation of the physics of the rainfall-runoff processes into three categories, i.e., physically-based models, conceptual models, and black box models. The selection of the most suitable model usually depends on the availability of the required input data. The complexity of the model enhances demands for spatial and temporal resolutions and the complexity of the data inputs, especially the hydrological measurements. This broad range of data required is usually unobtainable in the conditions of the Slovak Republic, because most small water catchments are ungauged. Applications of empirical models are the only way to estimate direct runoff in this case.

The most popular empirical model among engineers is the Soil Conservation Service Curve Number (SCS-CN) method. It is not demanding when it comes to input data; it requires a land use map, a map of the hydrological properties of the soils, the time of the runoff concentration, and the intensity of the design rainfall. The main weaknesses of this method are that the SCS-CN method does not consider the impact of the rainfall’s intensity; it works with lumped CN parameters and is ambiguous when considering the effect of antecedent moisture conditions [2]. Because we had data measured from the Teplica-Vrbovce gauging station, we decided to use statistical calculations of the peak flows with the wavelet-based Gaussian method (WGM).

The kinetic energy of rain water, runoff energy, and complex regional geomorphic factors are active erosive agents, which influence the volume and type of soil erosion sub-processes. Very important factors in the occurrence of soil erosion are the slope of the hill and the type of soil. The resistance of soil to erosional processes plays an important role in the water erosion process on a hillslope. Soil erosion processes are mainly divided into three basic groups, i.e., sheet erosion, rill erosion and gully erosion. The criteria for the boundary between these process groups are different, based on each author’s approach. The Soil Science Society of America has defined “gully erosion”, which occurred in the pilot area (figure 1), as channels too deep to easily ameliorate, that typically range from 0.5 m to as much as 25 to 30 m [3].

Figure 1. Gully and sheet erosion in the basin of the Haluznikov creek, Vrbovce
Gully erosion is a very dangerous subtype of erosion process, because as a result of gully erosion, a large amount of the soil eroded from a catchment is redistributed and delivered to water courses [4]. Soil loss rates from gully erosion are in a range between 10 to 94% of the total sediment yield caused by water erosion [5]. The Universal Soil Loss Equation (USLE) method used in this study is not intended for the calculation of gully erosion rates. Standardized procedures are not available for the calculation of sediment yield caused by gully erosion [5]. Nevertheless, design technical and agricultural measures should have a significant impact on the reduction of the formation of gully erosion.

The topographical factor is one of the factors of the USLE equation that we modified through design measures. The land use pattern of dispersed settlements, which was created in the period of the “Kopaničiar” colonization in Slovakia, was changed by collectivization during the Socialist era. In this process former small private plots were merged into large fields; a dense network of linear landscape elements was removed; and terraces were levelled to create large fields that could be used for mechanized tilling. These interventions to the land cover and land structure had a negative impact on the volume of peak flows [6]. In our scheme, we are trying to restore the linear landscape elements back to large areas of arable land, thereby reducing the surface runoff and accelerated soil erosion.

2. Methodology

2.1 The CN methodology

The SCS-CN method is a rainfall-runoff model developed for the United States by the U.S. Soil Conservation Service, now called the USDA in 1956. In this method, the relationship between a watershed’s characteristics and antecedent rainfall is described by the Curve Number parameter. With this simple parameter, the rainfall depth can be transformed into the runoff depth. The tables and figures for estimating the CN parameter for the soil cover complexes of the USA are available in a Natural Resources Conservation Service (NRCS) publication (2004) [7]. These CN numbers were empirically derived from locally observed data to fit the conditions of the eastern, midwestern, and southern parts of the United States. The CN is assumed to be constant for a given land use and type of soil class in a watershed, but the CN number actually differs due to storm events, which are the result of changes in the antecedent conditions and the variability of a storm’s morphology. Although the CN was developed based on the empirical data of the USA, this method is widely used in engineering hydrology in many countries all over the world. The SCS-CN method works with mean values, which leaves even more room for uncertainty.

The SCS – CN method is based on the following formula:

\[ Q = \frac{(P-I_a)^2}{S + (P-I_a)} \]  

(1)

In the original methodology, a classification of the antecedent moisture condition (AMC) was developed that classifies rainfall-runoff events into the AMC I, II and III classes. They correspond to low, medium, and high soil moisture conditions.

where \( I_a \) is the initial abstraction [mm]; \( S \) is the potential maximum retention [mm]; \( Q \) is the direct runoff depth [mm]; \( P \) is the rainfall depth [mm]; and \( CN \) = the curve number [-]. The relation between \( S \) [mm] and \( CN \) [-] has the form:

\[ S = 25.4 \left( \frac{1000}{CN} - 10 \right) \]  

(2)

While \( I_a \) can be expressed as \( \lambda.S \) (in the original form \( \lambda=0.2 \)), the original formula can be in the form:
Q = \frac{(P-\lambda S)^2}{S+(P-\lambda S)}  \tag{3}

The desQ model is a deterministic “black-box” model, based on the SCS-CN method, which was developed by Hradek in 1997 in the Czech Republic to predict peak flows in ungauged basins.

2.2 Estimation of design discharges
For the design of the estimation, a statistical analysis was applied, which is based on the DVWK/101 (1999) methodology supported by the HQ-EX statistical computer program (version 3.0, Wasy Gmbh.).

Using this methodology, the plotting positions of the annual maximum discharges are calculated according to Cunnane, WMO (1989) [8] as:

\[ P = \frac{m - 0.4}{n + 0.2} \tag{4} \]

where \( n \) is the sample size, and \( m \) is the rank of the observations in descending order.

To estimate the parameters of the theoretical distribution functions, three methods can be used alternatively, i.e., the method of moments, the maximum likelihood method, and the method of probability weighted moments.

The following theoretical distribution functions have to be tested for their applicability: Gumbel, Generalized extreme value, Rossi, 3-parameter lognormal, Pearson 3, log-Pearson 3, and 3-parameter Weibull distribution. All the theoretical distribution functions use the three above-mentioned methods of estimating parameters.

To select the most appropriate fitted distribution a combined statistical test is recommended. The testing criterion is computed from the relationship:

\[ D + n\sigma^2 + (1 - r_p) \tag{5} \]

where \( D \) is the value of the Kolmogorov test; \( \sigma^2 \) is the value of the omega squared test; and \( r_p \) is the correlation coefficient between the values of the descending sorted discharges and their distribution quantiles. The best fit gives the lowest values of \( \sigma^2 \) and the highest values of \( r_p \), by minimizing the value of equation (5).

2.3 Universal Soil Loss Equation
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:

\[ E = R \cdot K \cdot LS \cdot C \cdot P \tag{6} \]

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 the 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) [9]. The formula for the topographic factor of an irregular slope has the shape:

$$LS = \sum_{j=1}^{N} \frac{S_j \lambda_j^{m+1} - S_j \lambda_{j-1}^{m+1}}{(\lambda_j - \lambda_{j-1})(22.13)^m}$$  \hspace{1cm} (7)

where

- $S_j$ - the factor of the slope’s steepness for the j-th element (m$^{-1}$),
- $\lambda_j$ - 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:

$$LS = \sum_{i,j} S(i,j) \lambda(i,j)^{m+1} - S(i,j) \lambda(i,j)^{m+1}_{\text{inlet}} \frac{\lambda(i,j)^{m+1}_{\text{inlet}} - \lambda(i,j)^{m+1}}{(\lambda(i,j)^{m+1}_{\text{inlet}} - \lambda(i,j)^{m+1})} \times (22.13)^m$$  \hspace{1cm} (8)

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, including McCool’s relationship [9], which was used in RUSLE:

$$S(i,j) = 10.8 \sin \theta_{i,j} + 0.03 \quad \text{where } \theta_{i,j} \leq 9\%$$  \hspace{1cm} (9)

$$S(i,j) = 16.8 \sin \theta_{i,j} - 0.5 \quad \text{where } \theta_{i,j} > 9\%$$  \hspace{1cm} (10)

3. Description of the study area and inputs

The study area, i.e., the village of Vrbovce, is situated in western Slovakia, the district of Myjava, near the Slovak-Czech boundary. The researched area is in the Western Carpathians province and the White Carpathians unit according to the geomorphological regionalization of Slovakia. The geological structure of the subsoil is composed of flysch sediments. This type of subsoil is characterized by low permeability and a low accumulation capacity. The alluvium of the Teplica River is covered by fluvial sediments [10]. The relief of the area is characterized by medium slopes, with the infrequent occurrence of steep slopes at the bottom parts of the valleys.

The land use was formed by dispersed settlements, where small groups of settlements were formed outside the built-up areas of the villages. A significant part of the area is used as agricultural land. Due to its specific geological (heterogeneous rock masses of flysch) and geomorphological conditions (hilly country, uplands), this area is prone to accelerated soil erosion and mud flood formations [11]. Nevertheless, a significant part of the endangered slopes of the hills is used as arable land.

We selected five subcatchments of the Teplica River basin, which are potentially endangered on account of the high amounts of runoff, i.e., the basin of the Haluznikov creek (9.31 km$^2$), the Lulovský creek (3.36 km$^2$), the Záhutník creek (2.34 km$^2$), the Zápasečník creek (3.29 km$^2$) and the basin of an unnamed creek (1.06 km$^2$). In each of these sub-basins, we set the critical point on the boundary of the Vrbovce municipality, according to an analysis of the accumulated runoff. These points were selected as the watershed outlets (figure 2).
The main GIS inputs for calculating the average annual soil loss were a digital elevation model, a land use map, and a map of the soil’s hydrological properties. We used a vectorised map of the river network for estimating the peak flow.

The current land use map was created using the zonal plan of the village of Vrbovce, an agricultural land map based on the Land Parcel Identification System (LPIS), an orthophoto map, and a land use map. The map of the soil’s hydrological properties (figure 3) was created according to the classification system of Bonited Soil-Ecological Units (BSEU) [12]. Every parcel of agricultural land is characterized by a set of the parameters of the soil-ecological properties.

We can extract information from the BSEU about many characteristics of the soil, including information about the soil type, which is important for predicting the annual soil loss.
4. Results and discussions
The calculations were performed in five sub-basins of the Teplica river basin, i.e., Haluznikov Creek, Lulovský Creek, Záhutník Creek, Zápasečník Creek, and an unnamed Creek basin. The watersheds of these five creeks were delimited by using the digital elevation model and the analysis in the Geographical Information System (GIS). The most distant point of the basin was defined for each of these basins, and the time of concentration was calculated using the Heinige method (1995). The design peak flows were calculated for the current land use map for the return periods of 5, 10, 20, 50 and 100 years from the values of the rain intensity computed by the simple scaling. We used three modifications of the CN method for the estimation of the direct runoff volume. We used the CN values for the current land use (ACT) and for the worst alternative of the land use (WORST) in the standard CN method and we also applied the DesQ program method. The results of the calculations with a return period of 100 years are shown in Figure 4. In the worst alternative of the land use, we considered that the whole area characterized in the LPIS as agricultural land that could be used as arable land in the future.

Because the results from the DesQ model are too low to represent the actual situation, we decided that the DesQ method should be excluded from our further calculations. We also calculated the peak flow for the subcatchments of the Vrbovce-Teplica gauging station. The Teplica river basin, from its source up to the Vrbovce water gauge, is poorly gauged with only a 10-year observation period up to the water gauge. That length of hydrological measurements is not enough for the required inputs for calibrating the hydrological model. Therefore, we used two variations of the standard CN method for calculating the peak flows and selected statistical methods for estimating the peak flows for the return periods of 5, 10, 20, 50 and 100 years (figure 5). We compared the results from the statistical methods with the results from the two alternatives of the standard CN method. The results show that a 10-year time series is not too long to predict a peak flow in the outlet of a basin. The volumes of the peak flows were too small to represent the actual situation. The outputs of the hydrological modelling without any calibration of the model with the measured data cannot be fully guaranteed as to their accuracy in comparison with the modelling of the runoff processes from the data measured in the catchment area.
Figure 5. A comparison of the results from the direct runoff prediction methods for the selected return periods (5, 10, 20, 50 and 100 years) at the Vrbovce-Teplica water gauge

The results of the specific runoff in the Teplica-Vrbovce subcatchment were compared with the values of the specific runoff calculated for the Sobotište water gauge. The Teplica - Sobotište water gauge is situated 10 kilometres from the Vrbovce water gauge. The area of its basin is two times larger than the area of the Vrbovce water gauge subbasin. At that station, there are 20 years of time series of hydrological characteristics. The comparison of the results shows that the most suitable modification of the CN method is the standard CN method with using the CN values for the current land use (figure 6). Figure 6 shows a strong correlation between the standard CN method, the ME – MLM, and the WB3-WGM methods. On the other hand, the results from the LN3-MLM modelling method slightly overestimate the 100-year return period. One of the possible explanations is that the Log-Pearson distribution 3 type is not able to predict a 100-year return period based on 20 years of observations at the Sobotište water gauge.

Figure 6. A comparison of the results from the specific runoff calculation methods for the selected return periods (20, 50 and 100 years)

The predictions of the average annual soil loss were calculated by the Universal Soil Loss Equation (USLE). The values of the soil erodibility factor of the soils (K) were derived from the Bonited Soil-Ecological Units numbers, according to Ilavska [12]. The topographic factor (LS) was calculated by the Usle2D model; we used the equations developed by McCool [13], with a moderate setting. The cropping factor values are derived from the land use map according to Heinige (1995) [14]. The rainfall erosivity index value of R = 40 MJ.ha⁻¹.year⁻¹ is defined based on the regionalization of the Czech Republic. The conservation practice factor (P) is 1, because the measures for reducing the erosion have not yet been implemented in the area of research. The results of the calculations show that 96.19 % of the agricultural land is endangered by accelerated soil erosion, with the values of the average annual soil loss greater than 10t/ha⁻¹*a⁻¹ (figure 7).
4.1 Designed measures
We designed two types of measurements on the area, which is characterized in LPIS as agricultural land; our task is to reduce surface runoff from the watersheds and thereby contribute to the reduction of the soil loss. In each creek, we designed a polder, the function of which is to accumulate water in a flooded state in the creek. A drainage ditch was designed for parts of the arable land, especially the land most endangered by accelerated soil erosion, i.e., the Haluznikov creek basin and Lulovsky creek basins (figure 8).

5. Conclusions
The prediction of the direct runoff from ungaged catchments is a frequently discussed problem concerning the conditions of Central Europe. It is very difficult to find a suitable tool to predict the hydrological response of ungaged or poorly gauged basins and minimalize uncertainties when there are no possibilities for the direct calibration. Although the best matching model does appear to be the standard CN method and the CN values derived from the current land use, these results need further review. The aim of the research was to denote the possible solutions to the hydrological problems in the area of the ungaged basins. Additional technical and hydraulic calculations are needed to realize the proposed design measures.

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