

A multicriteria approach to different land use scenarios in the Western Carpathians with the SWAT model

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Abstract: Water erosion in mountainous areas is a major problem, especially on steep slopes exposed to intense precipitation. This paper presents the analysis of the topsoil loss using the SWAT (Soil and Water Assessment Tool) model. The SWAT model is a deterministic catchment model with a daily time step. It was designed to anticipate changes taking place in the catchment area, such as climate change and changes in land use and development, including the quantity and quality of water resources, soil erosion and agricultural production. In addition to hydrological and environmental aspects, the SWAT model is used to address socio-economic and demographic issues, such as water supply and food production. This program is integrated with QGIS software. The results were evaluated using the following statistical coefficients: determination (R^2), Nash–Sutcliffe model efficiency (NS), and percentage deviation index ($PBIAS$). An assessment of modelling results was made in terms of their variation according to different land cover scenarios. In the case of the scenario with no change in use, the average annual loss of topsoil (average upland sediment yield) was found to be $14.3 \text{ Mg}\cdot\text{ha}^{-1}$. The maximum upland sediment yield was $94.6 \text{ Mg}\cdot\text{ha}^{-1}$. On the other hand, there is an accumulation of soil material in the lower part of the catchment (in-stream sediment change), on average $13.27 \text{ Mg}\cdot\text{ha}^{-1}$ per year.

Keywords: catchment area, land use, soil erosion, SWAT model, Western Carpathians

INTRODUCTION

Under climate change and increasing anthropopressure, the frequency of extreme, meteorological, hydrological, as well as geomorphological events is increasing (Kostrzewski, 2001; Kundzewicz and Jania, 2007; Lorenc *et al.*, 2009; Majewski, 2020). Extreme events are often local, and poorly developed meteorological monitoring makes them difficult to record (Starkel *et al.*, 1997; Majewski, 2020).

Extreme phenomena intensify erosion processes, especially in mountainous areas. Factors that affect erosion are precipitation, slope of the land surface, and its vegetation cover (Lipski and Kostuch, 2005). Particularly important is the intensity of rainfall, which causes large surface runoff. Mountain areas tend to have higher precipitation than other parts of the country (Banasik and

Górski, 1990; Lorenc *et al.*, 2009; Stach, 2009; Majewski, 2020). Moreover, in Poland, extreme events are more often recorded in the south, mainly in the Carpathians (Gil, 2009; Święchowicz, 2009; Święchowicz, 2010; Kijowska, 2011) and in the upland range (Ziemnicki, 1956; Maruszczak and Trembaczowski, 1958; Buraczyński and Wojtanowicz, 1971; Czyżowska, 1997; Ciupa, 2001; Michalczyk *et al.*, 2008; Majewski, 2020).

A large forest cover on slopes in mountainous areas has a protective role against water erosion of soil. Therefore, under natural conditions, the water erosion of soil in mountainous areas is negligible (Gil, 2009). However, as a result of human interference, such as poor land use and poor alignment of paths and access routes along the slope, erosion processes can increase.

Soil erosion is a complex and dynamic process associated with topsoil detachment and it causes several adverse environ-

mental changes (Jain *et al.*, 2001; Mularz and Drzewiecki, 2007). Its intensity depends on the physiological and hydrological characteristics of the catchment area. In mountainous areas, it can be a serious problem. It causes the depletion of nutrients from soil, it is a source of surface water pollution, and it causes landslides hazardous to roads and buildings (Verstraeten and Poesen, 2001; Halecki, Kruk and Ryczek, 2018).

In Poland, intense soil erosion during torrential rains and snowmelt is one of the most important geomorphological extreme events. An average intensity greater than 0.5 mm·min⁻¹ and daily total precipitation greater than 30 mm and 100 mm are considered threshold values (Zwoliński, 2008; Jania and Zwoliński, 2011). Similar values were proposed by Lorenc, with daily totals greater than 50 mm and 70 mm (Lorenc *et al.*, 2009; Majewski, 2020).

According to the Joint Research Centre of the European Soil Data Centre (ESDAC), soil loss caused by water erosion is expected to increase by 13–22.5% in the EU and UK by 2050, mainly because of increased rainfall intensity. This soil loss is expected to be larger in Central and Northern Europe, where losses could be as high as 100% in some areas (Panagos *et al.*, 2021).

The study by Cerdan *et al.* (2006) showed that soil loss in Europe is 0.54 Mg·ha⁻¹·y⁻¹, while the study by Borrelli *et al.* (2017) for a forest area in Italy demonstrated that the modelled annual average soil loss rate was 0.54 Mg·ha⁻¹·y⁻¹ as predicted by a long-term study.

The Panagos *et al.* (2020) reported that the average rate of soil erosion in Europe in 2016 was estimated at 2.45 Mg·ha⁻¹·y⁻¹, which was close to the 2010 value (2.46 Mg·ha⁻¹·y⁻¹). The highest erosion rate was shown in Italy (8.59 Mg·ha⁻¹·y⁻¹), Spain (4.0 Mg·ha⁻¹·y⁻¹), whereas Greece (4.19 Mg·ha⁻¹·y⁻¹) shows an increase in average rates of at least 1.5% compared to 2010.

Two main approaches can be distinguished in the modelling of erosion processes. The first one assumes that there is no limit to the amount of soil material that can be transported by water flowing down the slope. It follows that the erosion rate is determined only by the detachment of soil particles, without taking sedimentation and deposition into account. Popular erosion models of this type are USLE and RUSLE (Drzewiecki and Mularz, 2008).

The second type assumes that there is a limit to the transport capacity of surface runoff and where it is exceeded, deposition of soil material occurs (Schmidt, 1991; Drzewiecki and Mularz, 2005). Examples of such models are modifications of the USLE – the USPED model (Unite Stream Power-based Erosion/Deposition) (Mitasova *et al.*, 1998) and SWAT (Soil and Water Assessment Tool) (Arnold, Williams and Maidment, 1995).

The SWAT model is used to assess the amount of soil material. The model is among the most widely used catchment areas in the world. It has the advantage of open-source code, which is modified by users to suit their own needs, and a user-friendly GIS interface. The model also includes a comprehensive set of options for testing basin management scenarios. The SWAT is one of the most widely used catchment models in the world (Piniewski and Okruszko, 2011).

The SWAT model is a powerful tool for predicting the impact of climate change and agricultural practices on water resources, soil erosion, and yield over long periods and in areas with diverse natural conditions (Neitsch *et al.*, 2002). The SWAT

models, for example, water balance, surface and infiltrating water quality, nitrogen and phosphorus cycling, pollutant transport, soil erosion, sedimentation, and crop yields, but also to predict flood risk, climate change and weather simulations. The SWAT model uses detailed data on land location and land use, including spatial, agrotechnical, and climatic information. Some of it is necessary to run the modelling process, while others can be introduced to improve the model performance or can be replaced with default values. Such a solution allows for flexible application of the program. In cases of data shortages, approximate results can be obtained. On the other hand, in catchments with continuous monitoring and measurement of many parameters, it is possible to obtain accurate data based on modelling (Śmietanka, Śliwiński and Brzozowski, 2009). The model has been tested in hundreds of locations on all continents and virtually in all climatic and soil conditions. In Poland, it has been used for several years for various catchments (Bogdanowicz *et al.*, 2010; Brzozowski *et al.*, 2011; Majewski and Walczykiwicz, 2012; Piniewski, 2012; Piniewski *et al.*, 2015; Berezowski *et al.*, 2016). The model is physical (deterministic) in its nature, and due to its high computational efficiency, it allows for continuous simulations for long time intervals (Gassman *et al.*, 2007; Gudowicz and Zwoliński, 2017). The SWAT model is a continuous-time model in which calculations are performed with a preset time step on the scale of a river basin. The model requires basic inputs: a digital elevation model, a soil map, a land cover, and land use map, and meteorological data.

The aim of the study was to model appropriate types of management in mountainous areas where succession (emergence of forests in place of grazing land) or over-intensive use may occur without introducing appropriate use recommendations. Spatial data were used for this purpose. Long-term monitoring of topsoil losses can be used to assess the environmental effects of water pollution, water bodies, etc.

MATERIALS AND METHODS

CATCHMENT FEATURES

Study area

The research and modelling results refer to a mountain catchment of the Grajcarek stream located in the Lesser Pieniny Mountains in the Polish Carpathians (Fig. 1, Photo 1). The catchment area is the border between the Pieniny Mountains and Beskid Sądecki (Kowalczyk and Twardy, 2018). Long-term studies indicate that the area is prone to soil erosion (Kowalczyk and Twardy, 2007; Wężyk *et al.*, 2012; Halecki, Kruk, and Ryczek 2018). The catchment area is 84.9 km², the length from the sources to the mouth is approximately 15 km, and the average slope is 3.5%. The structure of land use (Fig. 2) is dominated by mixed forests (SWAT code FRST) and coniferous forests (SWAT code FRSE), whereas pastures account for 13.76 km² (SWAT code WPAS).

Climatic conditions and soils characteristics

The climate in the mountainous areas is characterized by high variability in local weather conditions. In 2018 to 2021, the average annual precipitation amounted to 910.9 mm. The driest year was 2019 with a total of 979.3 mm. In 2021, the total

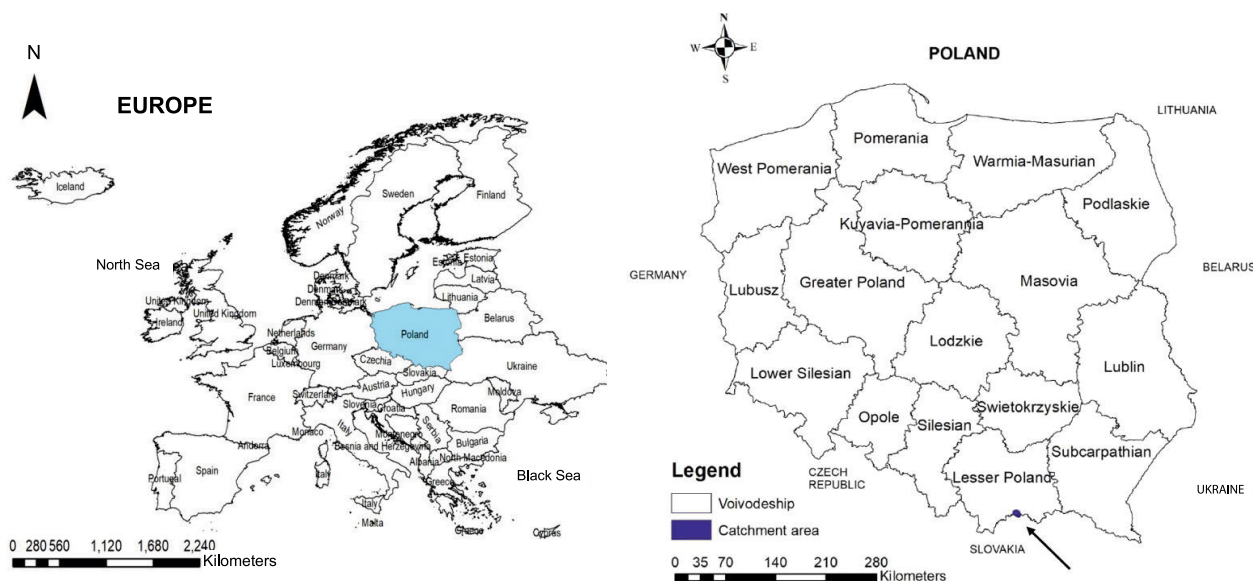


Fig. 1. Location of the research area in Poland; source: own study



Photo 1. Research area (phot.: M. Kopacz)

precipitation was 1068.1 mm. Very low precipitation (up to 1 mm) prevailed, which accounts for 66.7% of all rain, whereas low precipitation (1–5 mm) accounted for 18.2% of all precipitation days. Precipitation with a flood risk (30–50 mm) accounted for 0.8 % of all precipitation events, precipitation that poses a serious flood risk (50–70 mm) was 0.1 % of all rainfall events, and flood precipitation (>70 mm) occurred only once (Kruk, 2017). The distribution of total precipitation by season is

shown in the graph below (Fig. 3). In 2018–2021, the average annual air temperature was 7.7°C. The warmest year of the period was 2019 with an average annual temperature of 8.3°C. Meteorological data were taken from Jaworki station (49°24'31.3" N, 20°33'36.0" E). The following measurement data were used: precipitation (mm) (daily total), air temperature (°C) (daily minimum and maximum), wind speed ($\text{m}\cdot\text{s}^{-1}$) (daily average), total solar radiation ($\text{MJ}\cdot\text{m}^{-2}$) (daily total).

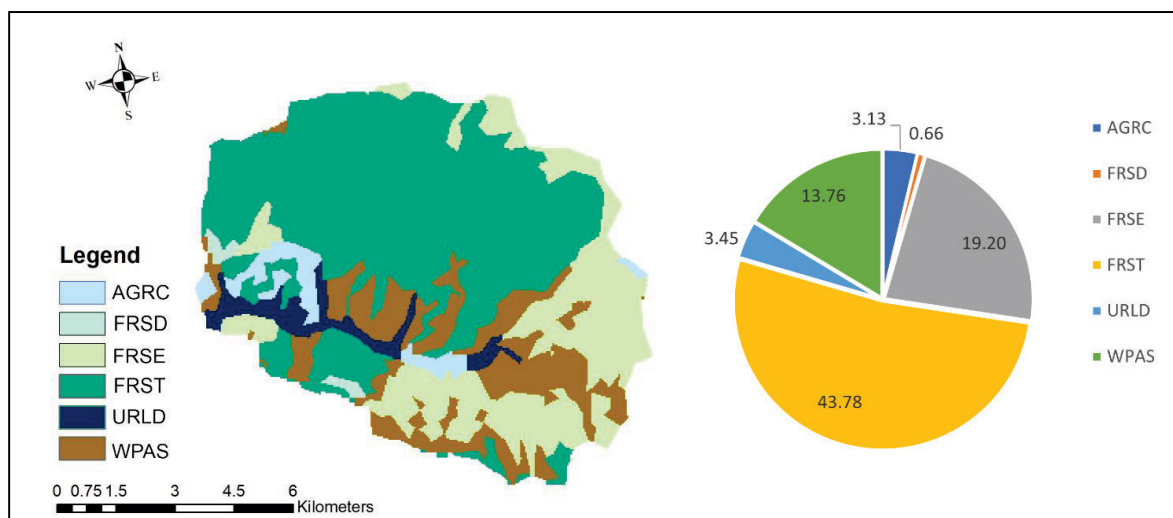


Fig. 2. Map and percentage of land use structure according to the map used in the SWAT model; URLD = low density residential, AGRC = Agricultural Land-Close-grown, WPAS = winter pastures, FRSD = deciduous forest, FRSE = coniferous forest, FRST = mixed forest; source: own study

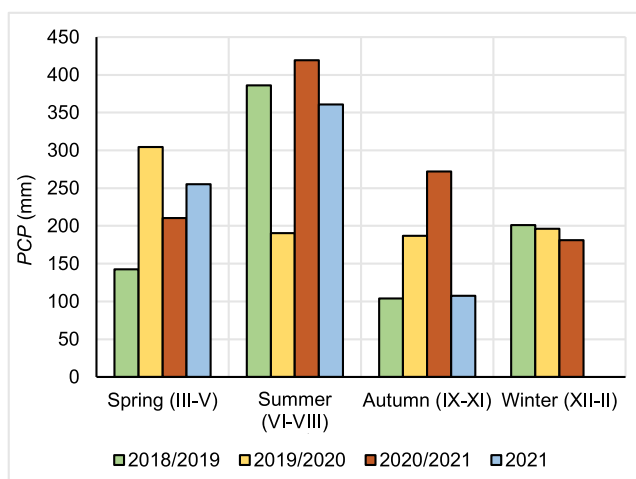


Fig. 3. Distribution of total precipitation (PCP) by season for 2018–2021; source: own study

The catchment is dominated by leached brown and acid brown soils (Bw), which occupy 69.9% of the catchment, and F (mud) – 3.1% of the area of the considered catchment. Brown soils (B), leached brown soils and acid brown soils formed from sedimentary rocks with a carbon binder (Bwow), and those formed from sedimentary rocks with a noncarbon binder (Bow) were assigned to Bw. In contrast, gleyic muds (FG), muds subject to fluvial flooding (Fzal), as well as brown swards (Rb) and swards with an undeveloped profile (R) account for about 1.8% of the catchment to F (Fig. 4a).

STUDY METHODS

The 2012 version of the SWAT model integrated with QGIS software was used for the calculations (Neitsch *et al.*, 2005; Dile, Srinivasanand and George, 2020). Among the methods implemented in the model were the Soil Conservation Service Curve Number (SCS-CN) effective precipitation estimation method

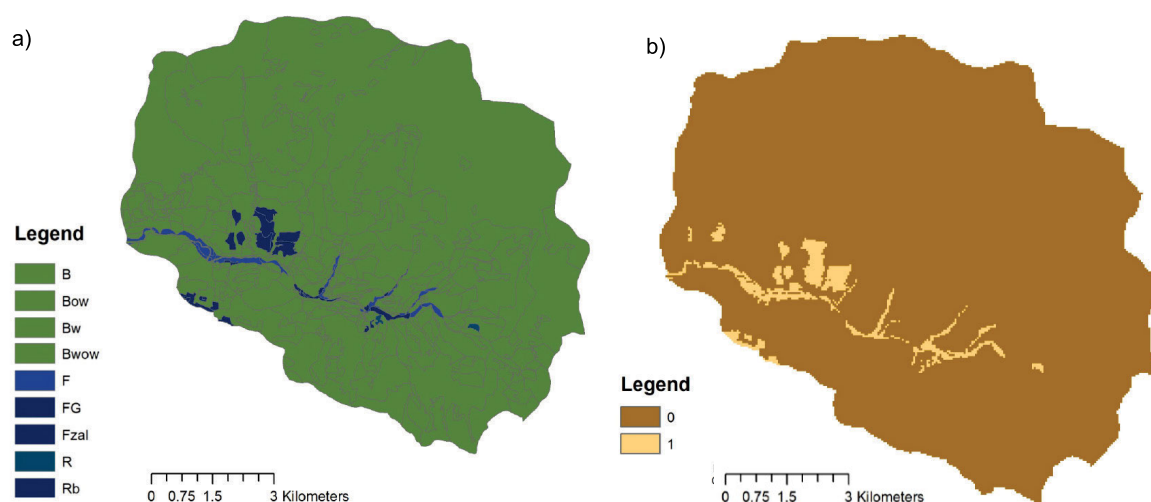


Fig. 4. Maps: (A) soil and (B) map of reclassified soil for SWAT; symbols in legend as in the text above; source: own study

(USDA, 1972), the Penman–Monteith evapotranspiration estimation method and the Muskingum method to calculate the flow of water in the river bed (Neitsch *et al.*, 2002). These methods are used in the SWAT model as standard (Neitsch *et al.*, 2005, Gudowicz and Zwoliński, 2017).

Sediment transport in a riverbed depends on the simultaneous action of two processes, deposition and degradation. Previous versions of SWAT used stream intensity to estimate deposition/degradation in the bed (Arnold, Williams and Maidment 1995). Bagnold (1977) defined stream power as the product of water density, flow rate, and water surface slope. Williams (1980) used Bagnold's definition of stream power to develop a method for determining degradation as a function of slope and channel/bed velocity.

The SWAT 2012 version uses four alternative sediment estimation methods, and a detailed description can be found in the SWAT User's Manual.

All sediment transport equations have the same route in the sediment stream (sediment transport capacity is directed in the main sections/channels) but calculate the maximum sediment transport capacity (maximum transportable sediment concentration) differently (Yen *et al.*, 2017).

According to the SWAT model flowchart (Fig. 5), the model requires basic input data: a digital elevation model, a soil map, a land cover, and land use map, and meteorological data (Tab. 1). Based on the DEM data, delimitation of watercourses and subcatchments was performed using the D8 algorithm (O'Callaghan and Mark, 1984; Winchell *et al.*, 2011).

The preparation at good resolution of map background is essential for the quality of the output data obtained. The researcher confirms that the implementation of spatial data with the highest resolution allows to obtain model data most similar to reality (Gudowicz, 2015).

A soil map was then prepared and reclassified to SWAT (Fig 4b). The predominant leached brown and acid brown soils (Bw) were designated as (Soil1, and F – soils – Soil2). The following soil parameters were entered according to the Soil & Water Assessment Tool- Input/Output Documentation. Two hydrological groups (D and C) were defined in the Grajcarek catchment area, organic carbon content 1.61% (SWAT code

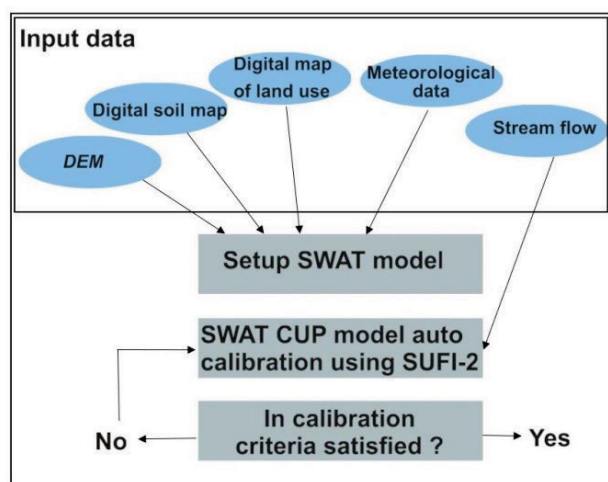


Fig. 5. Diagram of the SWAT model; source: own elaboration based on Neitsch *et al.* (2002)

Table 1. Overview of entities, sources and description of SWAT input data in the study area

Entity	Source
DEM	Copernicus (no date b), resolution 25 m
Digital soil map	Provincial Center for Geodetic and Cartographic Documentation in Krakow
Digital map of land use	CORINE Land Cover (Copernicus no date a) for 2018, resolution 100 m
Meteorological data	Institute of Technology and Life Sciences – National Research Institute, Jaworki station (2018–2021)

Source: own elaboration.

SOL_CBN), clay percentage 10.4% (SWAT code SOL_CLAY) were entered; slit 58.8% (SWAT code SOL_SILT), sand 30.8% (SWAT code SOL_SAND) (IUNG, no date), the soil erodibility coefficient (SWAT code USLE_K) was 0.16 Mg·ha⁻¹·y⁻¹, determined using Wischmeier and Smith (1978) and Arnold *et al.* (2012).

Three land use scenarios were introduced, i.e. the zero scenario – land use structure following Figure 2. In scenario 1, it was assumed that pasture land (SWAT code WPAS) would be converted to a mixed forest (SWAT code FRST), in scenario 2 pasture land was converted to Agricultural Land-Close-grown (SWAT code AGRC).

The study area was divided into 39 subcatchments ranging from 0.01 km² to 9.2 km². The baseline variant involved a total of 797 hydrological response units (HRUs).

The obtained results of topsoil loss were compared with the classification presented by Marks *et al.* (1989).

RESULTS AND DISCUSSION

The average annual loss of topsoil (average upland sediment yield) from the catchment in the baseline scenario was 14.3 Mg·ha⁻¹. The maximum soil loss (maximum upland sediment yield) is 94.6 Mg·ha⁻¹. In contrast, there was an accumulation of soil material in the lower part of the catchment (in-stream sediment change) and averaged 13.27 Mg·ha⁻¹ per year.

The first scenario of the model proposed no maintenance of pastures, which would result in succession and conversion of these areas to forests (FRST). The average annual loss of catchment topsoil in this scenario was 9.02 Mg·ha⁻¹.

In the second scenario, all pastureland was defined as Agricultural Land Closely Grown (AGRC). The annual loss of topsoil from the catchment for this type of land use was 13.58 Mg·ha⁻¹. According to the classification (Marks *et al.*, 1989), the land was classified as erosion class IV (Tab. 2).

The study by Halecki, Kruk and Ryzek (2018) in the catchment area of the Mątna stream, located in the Western Carpathians region, presented similar losses of topsoil depending on the scenarios of surface management. For the scenario in which no changes in land use were made, the loss of topsoil was 8.01 Mg·ha⁻¹. In the area where the entire catchment area was covered with grassland, the loss was 6.02 Mg·ha⁻¹. In the scenario that assumed spring oat replaced by potato cultivation, the loss of topsoil was 16.99 Mg·ha⁻¹. Another study conducted in the

Table 2. Calibrated parameters

Parameter	Input file	Unit	Description
CN2	.mgt	–	SCS runoff curve number f
ALPHA_BF	.gw	days	baseflow alpha factor
GW_REVAP	.gw	–	groundwater “revap” coefficient
SURLAG	.bsn	–	surface runoff lag coefficient
CH_N2	.rte		Manning’s n value for the main channel
GW_DELAY	.gw	days	groundwater delay time
GWQMN	.gw	mm H ₂ O	threshold depth of water in the shallow aquifer for return flow to occur
REVAPMN	.gw	mm H ₂ O	threshold depth of water in the shallow aquifer for revap or percolation to the deep aquifer to occur
SOL_Z	.sol	mm	depth from soil surface to bottom of layer

Source: own study.

Parsęta River basin (Gudowicz, 2015) showed that the loss of topsoil in subbasins was in the range of 0–5 Mg·km^{−2}·y^{−1}, while monthly average values were characterised by values in the range of 0.0–0.3 Mg·km^{−2}·y^{−1}.

Catchments in mountainous areas are known to have significant differences in topography, vegetation species, soil and climatic conditions, and hydrological regime. To test the model fit to the measured data for the two study catchments (Fig. 6), calibration was required.

This study aimed at evaluating the performance of the SWAT model in simulating sediment flow, as well as to investigate models uncertainty in the watershed areas of mountainous regions. The study used the Sequential Uncertainty Fitting ver. 2 (SUFI-2) algorithm to assess the uncertainty and calibrate the model (Abbaspour, 2015).

To evaluate the sensitivity of input parameters, we used SWAT calibration uncertainty program (SWAT-CUP) parameters, including GW_REVAP, CN2, SOL_Z and GW_DELAY (Tab. 2) for all scenarios.

For the subsequent calibration, the above-mentioned parameters have been selected, i.e. CN2, ALPHA_BF, GW_REVAP, SURLAG, CH_N2, GW_DELAY, GWQMN, REVAPMN, SOL_Z (Marcinkowski *et al.*, 2013; Dile *et al.*, 2016; Singh and

Saravan, 2022), and since they did not affect the model during the first calibration, they were rejected.

The entire period (2018–2021) was simulated, and the first year considered a warm-up period, followed by calibration. During the simulation, iterations were run with 50 simulation numbers for each catchment I and catchment II (Fig. 6). The degree to which SUFI-2 accounts for all uncertainties is evaluated using a formula defined as p and r coefficients. They are the proportion of the calculated data in the 95% predicted uncertainty (95PPU) bracket and the average bandwidth of 95PPU divided by the standard deviation of the calculated results. If the acceptable values of the p -factor and the r -factor are met, the parameter uncertainties must be the ranges of corresponding parameters.

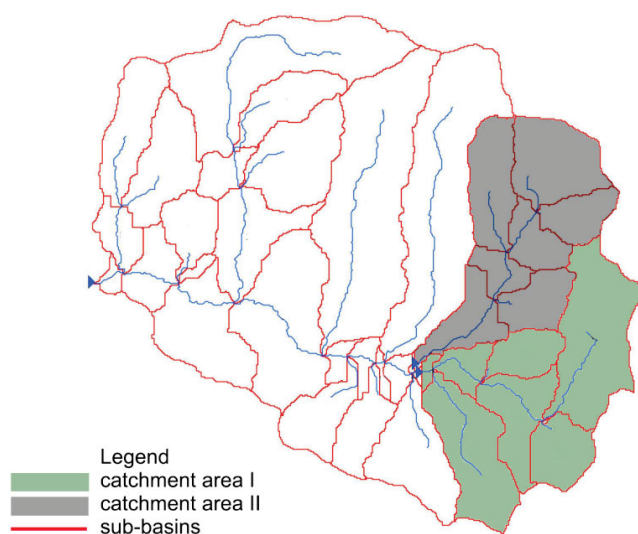
Calibration reliability and prediction uncertainty are determined by similarity of the p -factor to 100%, while at the same time having an r -factor close to zero. The SUFI-2 algorithm is adopted to identify sensitive parameters.

The sensitivity and uncertainty were evaluated using several regression analyses. The results of the global sensitivity analysis show the ranking of various parameters with a p -value and a t -test. A large p -value and a small t -value indicate greater sensitivity of the parameter (Neitsch *et al.*, 2005) – Table 3.

Table 3. Sensitivity rank for the discharge of three watersheds using SUFI-2 (scenario 0)

Parameter for catchment area	t -star	p -value
Parameter I (catchment area I)		
GW_REVAP	1.52	1.36
CN2	−36.49	0.00
SOL_Z	1.76	0.09
GW_DELAY	0.16	0.87
Parameter II (catchment area II)		
GW_REVAP	0.79	0.43
CN2	−34.69	0.00
SOL_Z	1.77	0.08
GW_DELAY	0.53	0.60

Source: own study.

**Fig. 6.** Map with catchment area I and catchment area II; source: own study based on SWAT model

The statistics of simulated values in catchment I and catchment II were determined using statistical indicators such as the Nash–Sutcliffe (*NS*) efficiency measure, the ratio of the observations of the root mean square error (*MSE*) to the *SD* ratio (*RSR*), which is derived from the *RMSE*, and the percentage loading (*PBIAS*) (Abbaspour, 2015).

$$NS = 1 - \frac{\sum_i (Q_m - Q_s)_i^2}{\sum_i (Q_{m,i} - \bar{Q}_m)^2} \quad (1)$$

where: Q = discharge, m = measured values, s = simulated values stands, $\bar{Q}_m$ = average measured discharge, i = successive stages of equation interaction.

If there is more than one variable, then the objective functions g are defined as:

$$g = \sum_j w_j NS_j \quad (2)$$

where: w_j = weight of j^{th} variable.

The *NS* varying between $-\infty$ and 1.0 and its optimal value is 1.0. The value from 0.50 to 1.0 is generally acceptable importance of performance, and 0 value indicates unacceptable performance, which means observed data is an enhanced predictor than simulated data. The percent of bias (*PBIAS*) is a numerical error-index that is commonly used to assess model output performance.

The results showed that in the case of p -factor, the model reflected the values in 69% for catchment area I and 47% for catchment area II. In the case of the root mean square error (*RSR*) for catchment II, a better fit of the model was shown. However, for the *PBIAS* parameter, the model was overestimated relative to the observations (Tab. 4).

To meet these demands, the following statistics for model evaluation were used: standard regression (R^2), dimensionless statistic (*NS*) and several error indices (*MAE* – mean absolute error; *RMSE* – root mean square error; *PBIAS* and *RSR* – ratio of *RMSE* to standard deviation of measured data).

Figure 7 compares the experimental data and the data obtained from the tested model. Differences were observed between the observed and simulated flow data. The largest differences occurred after a major snowfall in March each year. This was due to the increase in air temperature. The average

Table 4. Summary of model performance for calibration periods Scenario 0

No. of catchment	Evaluation of statistics of parameters					
	<i>p</i> -factor	<i>r</i> -factor	R^2	<i>NS</i>	<i>RSR</i>	<i>PBIAS</i>
I	0.69	0.86	0.22	−0.32	1.15	−44.4
II	0.47	0.79	0.39	0.25	0.87	−6.1

Explanations: p -factor = the percentage of observations covered by the 95PPU, r -factor = the thickness of the 95PPU envelop, R^2 = coefficient of determination, *NS* = Nash–Sutcliffe efficiency, *RSR* = the standardizes the *RMSE* using the observation standard deviation, *PBIAS* = percent bias measures the average tendency of the simulated data to be larger or smaller than the observations.

Source: own study.

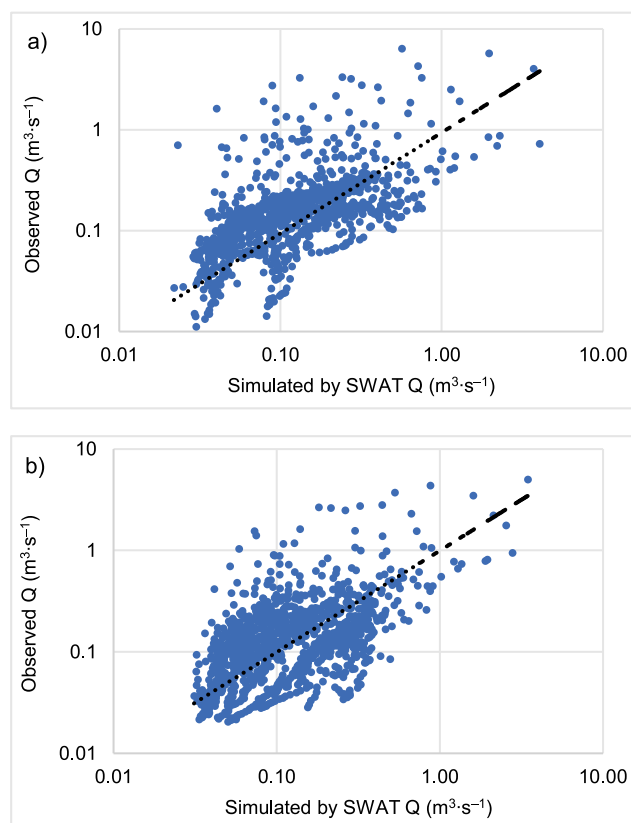


Fig. 7. Summary of experimental data and continuous data obtained from the model studied for the discharge: a) catchment area I, b) catchment area II; source: own study

temperature in March ranged from 3.6°C (in 2019) to 0.35°C (in 2021), while the maximum temperatures were respectively: 9.5°C, 7.4°C and 10.9°C for 2019, 2020 and 2021.

CONCLUSIONS

Water erosion in the mountains is a major problem as it results from steep slopes and intense precipitation. Therefore, there has been a pronounced loss of topsoil. To assess it, the study used the SWAT model integrated with QGIS software. The study area was divided into 39 subcatchments ranging from 0.01 km² to 9.2 km².

The average annual loss of topsoil in scenario 0 (average sediment yield) from the catchment was 14.3 Mg·ha^{−1}. The maximum soil loss (maximum upland sediment yield) was 94.6 Mg·ha^{−1}. In contrast, there was an accumulation of soil material in the lower part of the catchment (in-stream sediment change) and it was 13.27 Mg·ha^{−1} on average per year.

In the first scenario, the average annual loss of topsoil of the catchment was 9.02 Mg·ha^{−1}. In the second, the annual loss of topsoil from the catchment for this type of land use was 13.58 Mg·ha^{−1}.

The model calibration performed in SWAT-CUP used the following parameters: GW_REVAP, CN2, SOL_Z and GW_DELAY. Sensitivity analysis of SWAT model parameters based on flow simulations suggested that CN2 were the most sensitive parameters in the catchment under consideration.

The results showed that in the case of the p -factor, the model reflected observed values in 69% for catchment I and 47%

for catchment II. In the case of the root mean square error (RSR) for catchment II, a better fit of the model was shown. For the PBIAS parameter, the model was overestimated relative to the observations.

In conclusion, analysis with the SWAT model allows for a proper assessment of erosion risks in mountainous areas. This, in turn, provides an opportunity to better adjust the utility structure in these areas to implement a pro-retention and anti-erosion measures.

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