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Loss of topsoil and soil erosion by water in agricultural areas: A multi-criteria approach for various land use scenarios in the Western Carpathians using a SWAT model

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ABSTRACT

Erosion by water is a major problem in agricultural areas, especially in mountainous zones. In this context, the mass of detached soil clods is affected by surface run-off. In this paper, the utility of simulated data has been assessed toward various land use scenarios and soil erosion. The aim of the research was to model relevant management options in agriculture areas using spatial data. Long-term monitoring of sediment yield in top-soil loss dynamics models can be applied to evaluate the environmental effects of water pollution. In our study, we used data from 1995 to 2014 to analyze erosive events. The SWAT (Soil and Water Assessment Tool) was selected to assess the rill and inter-rill erosion. The investigations were carried out in an agricultural mountain catchment of the Mątny stream, located in the West Carpathians. Model calibration indices showed satisfactory adjustment of the model to the experimental data. Three scenarios of the catchment land use were distinguished (basic, first and second): the basic involved the actual structure of the land use, including a spring oat crop; in the first, the spring oat crop was replaced with potato crop; and in the second, it was assumed that the entire catchment area was covered by grassland. In the basic scenario, mean annual top-soil loss was 8.01 Mg ha^{-1}, in the first it was 16.99 Mg ha^{-1}, and in the second, 6.02 Mg ha^{-1}. Thus, land management options can provide powerful constraints on predictions of sediment budget (Suspended Sediment Concentration). The management options simulated by SWAT model were important to effectively reduce top-soil loss in agricultural catchments.

1. Introduction

Soil erosion by water is a complex and dynamic process connected with detachment of topsoil and causing a number of unfavorable changes in the environment (Jain et al., 2001; Mularz and Drzewiecki, 2007). For instance, eroded soil is a source of river pollution in agricultural areas (Niazi et al., 2015), and is a significant issue in mountainous areas. Intensity of soil erosion is determined by physiographic and hydrological characteristics of a catchment area (Verstraeten and Poesen, 2001; Restrepo et al., 2006; Zabaleda et al., 2007).

In mountainous areas in Central Europe the main important erosion factor seems to be a slope steepness and the spatial pattern of land-use change, for example in catchments in the Czech Republic (Kliment et al., 2008). In Southern Europe, chemical denudation is a bigger factor, in accordance with climatic conditions, at intermediate physical erosion rates (Barbayiannis et al., 2011). This discrepancy at first sight is caused by vascular plants in crop land (Borrelli et al., 2014).

Hydrologic models can be used to help quantify the hydraulic effects that govern flow conditions in small-sized catchments (Gül and Rosbjerg, 2010). For instance, the Soil and Water Assessment Tool (SWAT) provides sediment yield data under fluvial process in stream (Wang et al., 2015). The SWAT model indicates, with high sensitivity, temporal dynamics for three groundwater parameters (groundwater time delay, baseflow recession constant and aquifer fraction coefficient) and applies a soil evaporation compensation factor for parameter sensitivity (Guse et al., 2014).

The SWAT model is capable of computing hydrologic models (Vazquez-Amábile and Engel, 2005), which are dependent on spatial modelling as well as temporal factors such as rainfall seasonality and spatio-temporal factors such as land use and land use changes. In a spatial sense, modeling of hydrologic processes is sensitive to the raster cell size (scale) resolution. Calibration of monthly run-off volume, and slope may be reduced when 1:250,000 DEM (Digital Elevation Model) is used as input data. SWAT has the potential to simulate over the

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long-term the rainfall run-off process using monthly satellite rainfall data (Dessu and Melesse, 2012). Land-use changes implies soil loss in response to chemical denudation and soil erosion (Bakker et al., 2008).

The multisite calibration method of SWAT was simulated with more accuracy for hydrologic modeling in a mountainous watershed (Noor et al., 2014a). SWAT identified quality of hydrologic processes by predicting river flow regimes under agricultural management (Gebremariam et al., 2014). The Revised Soil Moisture Index (SMI), which is sensitive to land-use and land-cover features, was used for the calculation of curve numbers in SWAT based on hydrometeorological data (Jajarmizadeh et al., 2014). A large number of input files from sub-basins and Hydrologic Response Unit (HRU) required optimization methods to promote containing spatial and computational units. SWAT-G is applied towards changes in soil properties (top soil layer, bulk density, saturated hydraulic conductivity). Consolidated SWAT (C-SWAT) is utility to store numerous data and exhibite auto-calibration of watershed (Yen et al., 2014). Intensity of erosion may by supported by spatial distribution of erosion (Dabral et al., 2008; Bahadur, 2009) and GIS – Geographic Information Systems (Lee and Choi, 2010; Rathjens et al., 2015).

Our investigation attempted to denote a calibration procedure of sediment delivery yield. Hence, we focused on: (i) using spatial data based on land cover and physical properties; (ii) modelling the soil loss integrated with fluvial sediments at the agricultural system; (iii) using Hydrologic Response Units (HRUs) for ArcGIS-SWAT to assign the best management practice in agriculture structure; (iv) measuring Suspended Sediment Concentration at various calibration points to determine the water erosion for different scenarios of catchment management.

As we were interested in the important effects of land use in mountainous areas on soil erosion, the investigations were carried out in an agricultural mountain catchment of the Mątny stream, located in the West Carpathians. Three different scenarios of the catchment land use were distinguished (basic, first and second): the basic involved actual structure of the land use, including a spring oat crop; in the first, the spring oat crop was replaced with potato crop; and in the second, it was assumed that the entire catchment area was covered by grassland.

2. Materials and methods

2.1. Study area

The study was carried out in Mątny mountain catchment (Fig. 1), located on the border of Beskid Wyspowy and Gorce (Małopolska, Poland) – a geomorphological province that forms the western part of the Carpathian Mountains and is prone to soil erosion (Wężyk et al., 2012). Mean elevation above sea level of the catchment was 582.66 m. Slope distributions were as follows: < 5%, 4.08%; 5–10%, 18.37%; 10–18%, 45.58%, 18–27%, 21.09%; and > 27%, 10.88%. The weighted average slope for the entire catchment was 16.28%. The research area included mountains with a deep, or relatively deep soil profile. The length of the main watercourse was 2.37 km, and its average slope was 5.7%. River network density amounted to 2.96 km km^{-2}. The land use structure was dominated by grassland (73.5%, SWAT code PAST). Arable lands constituted 14.3% and included the following crops: spring oats 7.3% (SWAT code OATS), potatoes 4.3% (POTATO), and wheat 2.7% (SWHT). Forests (FRST) accounted for 9.5% and urban areas (URLD) for 0.7% of the catchment land.

2.2. Experimental design

Calculations implementing the SWAT model algorithm were performed using the ArcSWAT 2012.10_2.13 interface of ArcGIS 10.3.1 software. The spatial data were obtained based on the Polish State Surveying Coordinate System (PUGW) 1992. Thematic layers and climatic data were developed using the sources specified in Table 1. The

Fig. 1. Location of research area in Poland.

general monthly breakdown of the climatic statistics included in WGEN_user file of the SWAT model is presented in Table 2. The necessary soil classification was developed based on Table 3 and soil samples collected from 43 sites in the catchment area. The time period of the harvest and grazing seasons were collected from local farmers. The SWAT analysis was performed for three assumed crop variants, i.e. the basic, first and second variant (input datasets subjected to optimum range of parameters). The basic variant described experimental data throughout site inspection (July 2015), and it was a benchmark for the simulations involving different land use structure (first and second variant). The study investigated the catchment response to the presented assumptions.

2.3. Climatic conditions and soils of the experimental area

The mountain and sub-mountain climate is characterized by large contrasts of local weather conditions with a considerable amount of rainfall (Woś, 1993; IUNG, 2005). In the period from 1995 to 2014, the annual average total precipitation was 960.7 mm. The driest year of the study period was 2008, with a total precipitation of 728.5 mm. In 2010, total precipitation was as high as 1309.7 mm. Days with very low (up to 1 mm) or low (1–5 mm) precipitation prevailed and accounted for 74.6% of all days with precipitation. Precipitation with risk of floods (30–50 mm) accounted for 1% of all precipitation events, and those creating serious flood risks (50–70 mm) occurred 10 times in the study period. Flood-causing precipitation (> 70 mm) occurred five times, and catastrophic precipitation ≥100 mm was recorded once (Kruk, 2017). Distribution of total precipitation in individual seasons is presented in Fig. 2. The growing season in the research area was initiated in April. The snow cover stayed for 80–90 days in each year (Institute of Meteorology and Water Management, 2005). Mean annual air temperature in the years 1995–2014 was 6.3 °C. The warmest year of this period was 2014 with mean annual temperature of 7.4 °C. The meteorological data implemented into the model are shown in Table 4.

2.4. Statistical analysis

Conformity assessment of the measurement data with a normal distribution was based on the Kolmogorov-Smirnov test using Statistica 12.0 software. Uniformity of the measurement sequences for the investigated properties was conducted with non-parametric Kruskal-