THE APPLICATION AND VALIDATION OF PHYSICALLY-BASED EROSION AND EMPIRICAL MODEL IN CENTRAL POLAND

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ABSTRACT

The general problem of an appropriate erosion modelling can be seen in a lack of available data and in the validation and verification of the methodologies applied. The article includes two significant and challenging topics, i.e. the evaluation of the sediment amounts in a catchment and the validation of the methodologies used. The importance of the sediment estimation can be found not only in the modelling and prediction fields but also in the terms of engineering practice. The significance of erosion model validation lies in the confidence in the model itself and in the detection of its applicability and relevance. In this study, results obtained from the physically-based EROSION-3D model was compared with the sediment yield of a small agricultural catchment in central Poland. The estimation of sediment yield from the agricultural catchment has been conducted using the empirical method (USLE) coupled with a sediment delivery ratio (USLE-SDR) and verified by reservoir measurement. Firstly, the application of a physically-based EROSION-3D model has been done based on a continuous rainfall series for the selected period and afterwards the results have been compared with the sediment yield obtained by the empirical methods in order to test a model´s performance. The results of the paper point to the comparison of the results obtained by two different approaches, i.e. the physically-based and empirical methods together with the validation of the methods through the acoustic depth measurements.

Keywords: *erosion modelling, physically-based model, sediment estimation, rainfall events, empirical model*

INTRODUCTION

Among the different soil degradation processes, the water erosion represents the most serious position and about 55% of the eroded land is caused by soil water erosion [1]. The growing and critical global problem of soil degradation represent the natural process, but it is strongly accelerated by inappropriate human activities and is directly linked to climate change. The research of a connection between climate change and soil erosion have been started since the 1940s [2] Leopold, 1951). However, the consequences of climate change include direct and indirect impacts. The direct effects include changes in rainfall characteristics, i.e. rainfall amount [3], [4], rainfall intensity [5] and temporal and spatial distribution of rainfall patterns [6]. In reverse, the indirect impacts are linked to the rising temperature and warming climate which affects soil erosion through changes in vegetation cover and soil moisture [4]. Due to climate change, the number of intensive rainfall events is expected to increase in the future [7], [8], [9]. The role of such events directly impacts soil erosion rate and maybe worse under a changing climate. Based on the facts mentioned above, the understanding of soil erosion processes and developing assessment methods have an important meaning in the sense of soil protection as a fundamental source to ensure basics human needs, i.e. to provide food.

The importance of soil erosion prediction together with the sediment yields prognosis from the small catchments lies in the requirement to provide relevant information for engineering hydrology and for environmental modelling and forecast. The estimation of sediment yields can be conducted using a variety of methods but choosing a suitable method is still a very complex and intricate issue. Many models suffer from a different kind of problems (overestimation, the uncertainty of the models, lack of input data) because the modelling of a natural system is always restricted by many factors, such as spatial and temporal scales, spatial heterogeneity, and very unstable input data [10].

In the contribution, the amount of sediments have been calculated for a small lowland agricultural catchment using physically-based Erosion-3D model and using the empirical Universal Soil Loss Equation together with a sediment delivery ratio (USLE-SDR) and the modelled results were confronted with the amount of sediment deposited in a reservoir at the catchment outlet.

MATERIALS AND METHODS

Physically-based EROSION-3D model

The physically-based EROSION-3D model represents event based method which can be applied for calculating the amount of surface runoff generation, the amount of soil loss, sediments, the volume and concentration of eroded sediments and deposition processes on agriculture land produced by intensive rainstorms [11]. The model has been developed since 1995 by Michael von Werner at the Department of Geography at the Free University of Berlin and consists of two main submodels, i.e., the infiltration and the erosion model. The erosion submodel describes the soil erosion processes in three steps, i.e., the detachment of soil particles from the impact of raindrops and their transport and deposition. The submodel includes the processes of rainfall infiltration, the generation of surface runoff, the detachment of soil particles involved by the kinetic energy of raindrops and surface runoff. The infiltration submodel uses the Green-Ampt approach to define the process of infiltration and considers the soil as a rigid and homogeneous soil matrix (vertical changes in the physical soil properties, dynamic processes or changes in soil structure due to biological activity are not considered).

As mentioned previously the EROSION-3D model has been predominantly established as an event based model but thanks to the long-term simulation submodel are possible to perform long-term simulations. In the contribution the long-term simulation is based on a continuous rainfall series consists of a series of single rainfall events that occur within the period evaluated. Each rainfall event requires its own soil data set whose parameters account for the individual soil conditions and the stages of crop growth as of that date.

Study area

The Zagożdżonka catchment (Figure 1) represents a small lowland agricultural catchment, situated in central Poland, about 100 km south of the capital city Warsaw. The watershed area up to the Płachty gauging station is 82.4 km^2. The whole catchment is characteristics by topography specific for this part of Poland with the minimum altitude 148 m a. s. l. and the maximum altitude 185 m a. s. l. The mean annual temperature is about 8°C and the mean annual relative humidity is about 79-81%, which indicates low spatial distribution. The mean annual precipitation in the catchment ranges from 414 mm to 941 mm (1963-2015). Nowadays, the main part of the catchment area is formed by forest (about 60% of total area) and arable land (about 25%), and the rest of catchment area belongs to the pastures (Figure 1B) and Figure 3 [12]. Hydrological research in the upper part of the Zagożdżonka River has been conducted by the Warsaw University of Life Sciences since the 1960s. All measurements are done according to the standard methodology recommended by the Polish Institute of Meteorology and Water Management-National Research Institute.

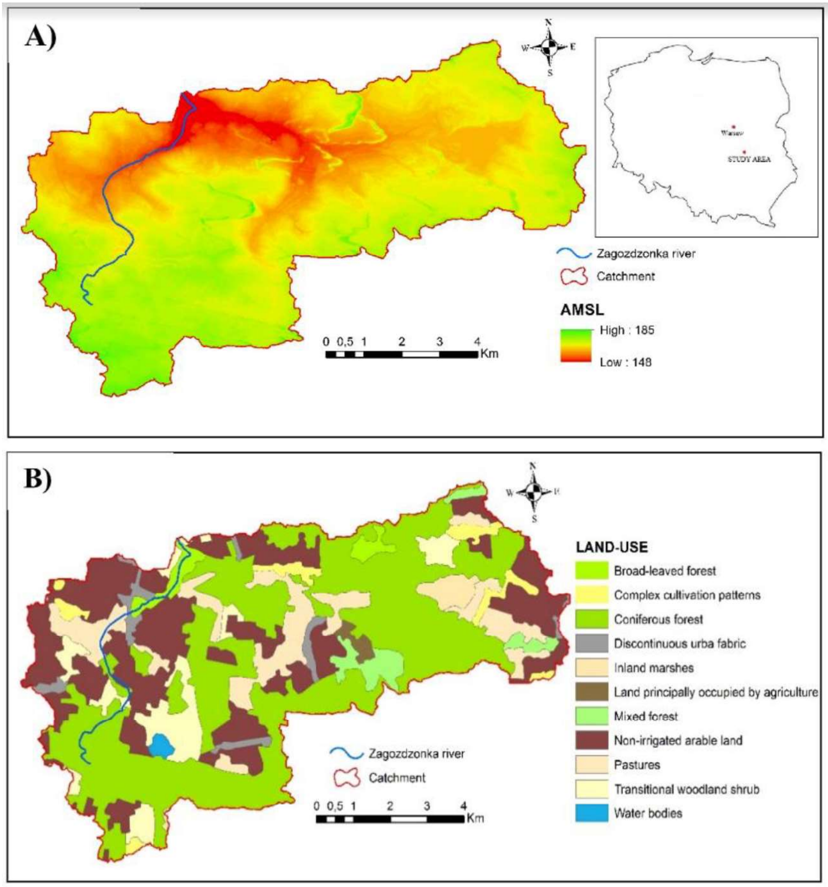

Figure 1. *The characteristics of the* Zagożdżonka *catchment study area: A) Relief and location in Poland; B) Land use characteristics of the study area (Corine Land cover, 2018).*

Input data

Physically-based Erosion-3D model

The physically-based Erosion-3D model requires three input data, i.e. terrain characteristics in the form of a square grid (digital elevation model), rainfall characteristics (duration and intensity) and soil input data (eight soil characteristics). The rainfall events (a ten-minute step) were recorded at the Plachty gauge station during the period selected (III.2013-X.2014). The model´s runs were conducted for the rainfall events, which have been occurred during the years 2013 and 2014. The characteristics of the rainfall events with the dates of occurrence are introduced on Figure 2. The soil input parameters were set according to the dates of individual rainfall events.

Empirical model USLE-SDR

Amount of sediments estimated by empirical equation USLE together with the sediment delivery ratio SDR was conducted using the formula [15]:

$$Yr = SDR \cdot E \cdot AE \qquad (1)$$

where:

Y_r annual sediment yield from the catchment of reservoir ($Mg \cdot year^{-1}$),
SDR sediment delivery ratio (-)
E annual soil loss per unit area ($Mg\ ha^{-1} year^{-1}$)
AE the active area of the catchment (ha)

The proper application of USLE requires to determine regionally sensible parameter, e.g. the rainfall and runoff erosivity R which had been done for Polish condition in the studies [13] and [14].

Reservoir Staw Gorny

The Staw Górny Reservoir within the Zagożdżonka catchment was built in 1976 with the area of 14 ha and the original volume of 252 000 m^2. Because the construction of the reservoir has caused sediment deposition within the reservoir as well as in the area above the reservoir, the estimation of sedimentation intensity and reservoir surveys are crucial for a different reason and are considered as the most reliable technique established for sedimentation intensity determination. The first survey was done during the period 1979-1980 using the range line method, and then in the years 1991, 2003 and the last survey was conducted in 2009 [15]. The survey reservoir undertaken in 2003 and 2009 were done using a survey vessel equipped with a hydrographic system comprising an echo-sounder unit and a Global Positioning System (GPS) receiver.

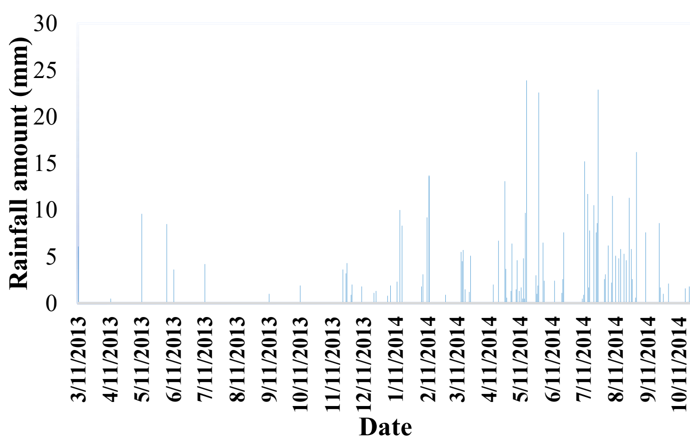

Figure 2. *Total rainfall amounts and date of occurrence of rainfall events during the two time periods: (a) March 2013 - December 2013; January 2014 - October 2014*

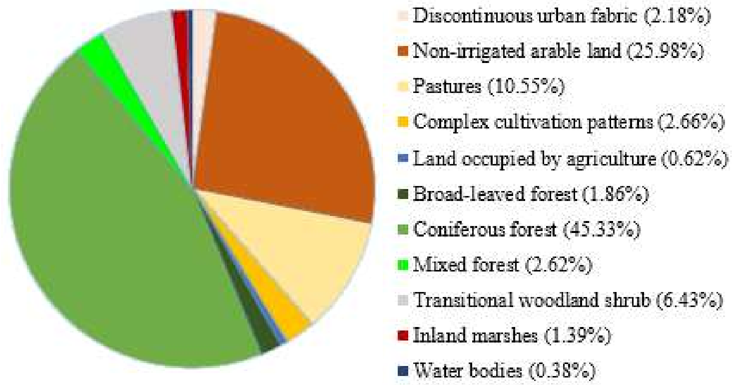

Figure 3. *Percentual representation of landscape elements in the investigation territory*

RESULTS AND DISCUSSION

The article deals with the estimation of sediments amount by the physically-based EROSION-3D model and empirical model USLE together with a sediment delivery ratio (USLE-SDR) and with the confrontation of results modelled with the sediment amount deposited in a reservoir at the catchment outlet. According to the reservoir survey average annual volume of sediment deposits is 1080 m^3. It must be noted that the total sediment input to the reservoir consists of bed load and suspended load as well while the sediment amounts calculated by physically-based EROSION-3D model consider only suspended sediments. When compared the EROSION-3D model and empirical model USLE-SDR the results show, the empirical model USLE-SDR are more close to the measured amount of annual deposition than the Erosion-3D model (Table 1). Based on the results, it is clear that the Erosion-3D model represents a more appropriate and satisfactory approach to determine the spatial localization of places endangered by water erosion (Fig. 4). The intensity of the erosion is higher in the second period evaluated (Fig. 4B) since the period has been richer in rainfall amount that the first period, which made the soil more vulnerable to the erosion processes (Fig. 4B).

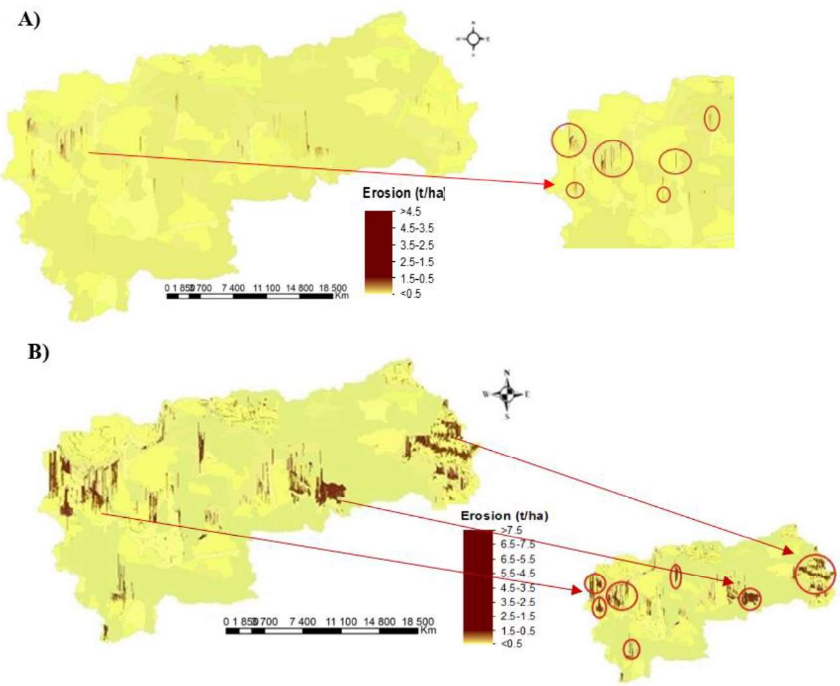

Figure 4. *Results obtained from the physically-based EROSION-3D model (calculated for a period evaluated): A) March 2013 - December 2013; B) January 2014 - October 2014*

Table 1. *Comparison between the measured data and modelled data of the sediment volume*

METHOD FOR THE DETERMINATION OF SEDIMENTS	SEDIMENT VOLUME (m^3)
USLE-SDR	708
RESERVOIR (total amount of sediments)	1080
EROSION-3D model (Period A)	508
EROSION-3D model (Period B)	678

CONCLUSION

The physically-based EROSION-3D model was applied to simulate the erosion processes and to simulate the amount of sediments in the catchment located in central Poland. The model helps to identify the most sensitive erosion and deposition zones within a catchment (Fig. 4). The calculations were performed using long-term simulations and were done for two periods selected; (March 2013 - December 2013; January 2014 - October 2014). The difference can be found in the total number of rainfall events because the second period (I. 2014-X.2014) was richer in the rainfall amount than the first period (III. 2013-XII. 2013), which made the soil more vulnerable to the erosion process. In reverse, the second period resulted in higher values of the erosion process as reflected in Figure 4.B). In the case of predicted (modelled) and measured sediment volume in the Zagożdżonka catchment, the physically-based Erosion-3D model calculated a lower amount of sediments for both period evaluated (March 2013 - December 2013 and January 2014 - October 2014) (Tab. 1.) in comparison with the empirical model USLE-SDR and with the observed sediments amounts as well. It is important to mention that results obtained from USLE represent averaged suspended sediment load and the reservoir deposits cover annual volume of suspended load together with the bed load. The possible errors in the predicted amount of sediments estimated by the Erosion-3D model are associated with the model parameters, especially in the case of soil moisture which is highly variable before each rainfall event. The parameters of the EROSION-3D model were chosen from the Parameter Catalogue for EROSION-3D, which contains their tabularized values by the type of soil, land use and the specific crop and its growth phase in different months within the year. This inaccuracy has to be improved for further work with the model to provide high-level results. At the end can be concluded, the Erosion-3D model reflects a useful tool for identification of areas prone to erosion processes.

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