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THE RAINFALL-RUNOFF MODEL FOR THE CARPATHIAN FLYSCH CATCHMENT USING THE SWAT+ HYDROLOGICAL SOFTWARE

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ABSTRACT

Aim of the study
The goal of this study was to apply SWAT+ tools to estimate the water shortage in the Smugawka catchment.

Material and methods
The use of the area was documented in the form of an orthophotomap with GIS layers superimposed, which was provided by CORINE Land Cover 2018. A soil and agricultural map, supplemented with lithological content from a detailed geological map, was used as the input layer for QGIS ver. 3.16. In the next stage, multiannual meteorological data (1991–2020) were added to the SWAT+ model, which included: minimum and maximum daily air temperature, daily rainfall, average daily radiation and average daily wind speed. Full integration of the SWAT+ model with QGIS facilitates the procedure of iterative generation and modification of the model input parameters. The calculation of continuous simulations for average extended periods of time is presented in the manuscript.

Results and conclusions
The application of GIS-based approaches and modelling techniques are crucial in the quest for optimal methods for calculating the water balance today. Our findings also contribute to a better understanding of the hydrological processes at work in the flysch catchment.

Keywords: flysch catchment, soil, water retention, SWAT+ model, water balance

HIGHLIGHTS

The SWAT+ is a promising method for understanding water balance in a small mountain catchment.

In sub-catchment evaporation can be measured by the simulation approach.

Available soil water content was the highest in the forest area.

A rainfall-runoff model should be assessed by the SWAT+ tool.

Implementation of hydrological modelling is crucial for effective watershed management.

INTRODUCTION

Disturbances in the stability of water conditions pose a threat to the functioning of forest ecosystems, and the assessment of water availability has recently become an urgent issue (Kowalczyk et al., 2019). In the scientific literature, prognostic models are quite commonly used to determine the water balance.

Simulating runoff in catchments remains an integral part of current hydrological research. Rainfall-runoff modelling describes climatic processes. ‘Runoff’ refers to rainwater being transformed and

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depleting behind drainage basins (outlet) or infiltrating into the soil profile (Szalińska, et. al., 2014). The inclusion of these components is used to decide the catchment area's water supply and loss (Wang et. al., 2022).

The easiest way to capture these relationships is to analyze them spatially using GIS software with the SWAT deterministic model (Soil and Water Assessment Tool), intended for hydrological calculations (Panhalkar, 2014). Modelling with a GIS program and SWAT support the quantification of the character between the soil participle and the load of the transported material carried by water in the stream (Hülsmann et al., 2014; Mutlu and Arslan, 2021). The rainwater is partially drained by gravity, and its direction depends on the slope of the terrain. On unvegetated slopes, soil particles may be washed away during heavy rainfall, which may cause significant soil degradation (Wu et al., 2016). The SWAT model was created to forecast the impact of changes in the catchment development on the water balance, the concentration of sediments in the watercourse and quasi-spatially distributed nutrients (Arnold et al., 2005). The inhibited infiltration mechanism increases the released and transported soil particles, resulting in a loss of the necessary nutrients for trees (Hao et al., 2019). In this paper, a model based on a Geographic Information System (GIS) to calculate the accuracy of the simplified water balance of the forest catchment in the flysch Carpathians was used. SWAT has been applied to hydrological modelling and water erosion assessment for an exceptionally long time. SWAT+ model is innovative approach to hydrological assessment that requires basic input data, such as: numerical terrain model, soil map, land cover and land use map, and meteorological data. SWAT+ is a revised GIS – based model for hydrological processes within the catchment area.

It is a novel work since it calculates the rainfall-runoff model considering new parameters in the SWAT+ configuration. These options include splitting sub-catchments into landscape units (LSUs), which could not be generated in the earlier SWAT version. The goal of this study was to apply SWAT+ tools to estimate the adjusted water balance in the forested catchment. Moreover, the suitability of the new feature set for simulating mountain catchment runoff was also examined.

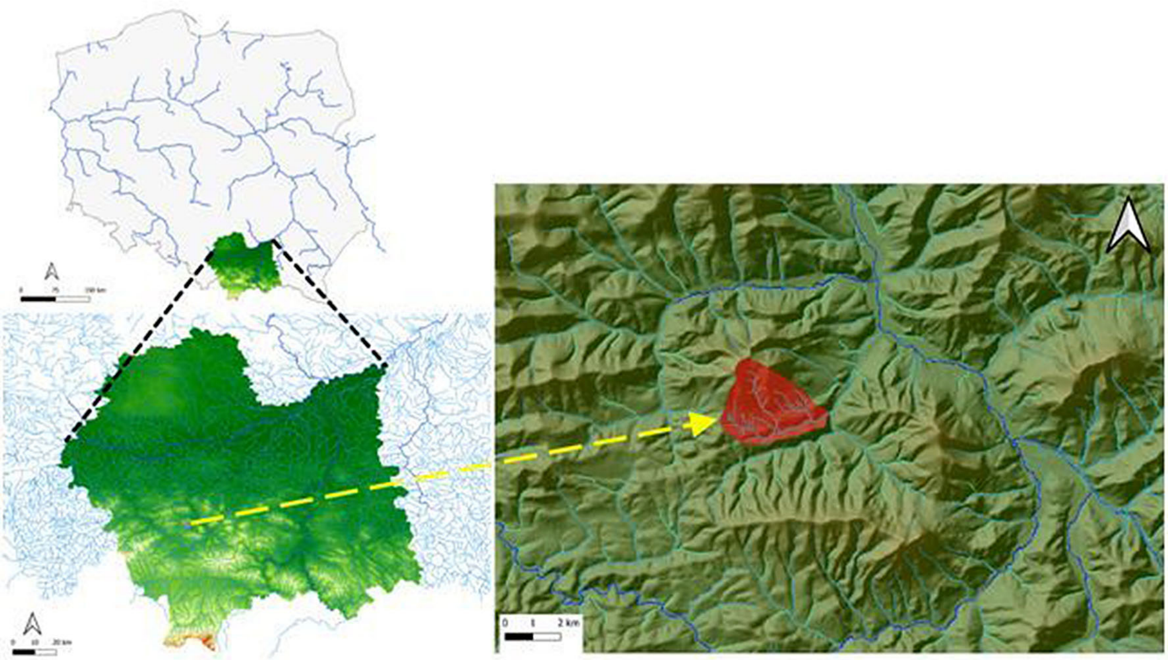

Fig. 1. Location of research area

RESEARCH AREA

The research area was the Smugawka catchment (49°41'33.6"N, 19°56'45.24"E). This stream flows through the Lubień commune and is a part of the Lubieńka stream, the right-bank tributary of the Raba River (see: Fig. 1). Physico-geographically, it belongs to the Carpathian mesoregion in the Western Carpathians province and the Outer Western Carpathians (flysch) sub-provinces (Kondracki, 2011). Luboń Wielki rises above its valley – 1022 m above sea level with an eminence of 512 m.

The land management of studied catchment, which is a part of "Beskid Wyspowy" mountain was subordinated to extensive agriculture – grassland and arable land. Some areas, mainly in the valleys, have also been built up. However, the remains of semi-natural forest communities in the foothills and lower mountain ranges, typical of the Carpathians with their high natural values, have survived. Well preserved, dense forest complexes are found in this area only above the altitude of 700 m above sea level. The tree species in the catchment area are characteristic of sub-mountain and mountain deciduous, and mixed forests. The dominant forest species here are silver fir (*Abies alba*) and common beech (*Fagus sylvatica*). The stands also include the sycamore maple (*Acer pseudoplatanus*) and the Norway spruce (*Picea abies*). Northern beech fern (*Phegopteris connectilis*) was found at the forest edges. The slopes of mountains are also covered with rowan (*Sorbus aucuparia*). The trees near the streams are mainly gray alder (*Alnus incana*) and black alder (*Alnus glutinosa*). Numerous sites of pink butterbur (*Petasites hybridus*) of deserve attention by the streams. The most common monocotyledonous plant species in pastures and meadows in this area are timothy grass (*Phleum pratense*), meadow fescue (*Alopecurus pratensis*), grassland fescue (*Festuca trachyphylla*), meadow grass (*Poa pratensis*), and narrow-leaved meadow-grass (*Poa angustifolia)* for dicots: white clover (Trifolium repens), common dandelion (*Taraxacum officinale*) and chamomile (*Matricaria chamomilla*). These plant species have been identified in the studied catchment.

METHODOLOGY

The SWAT+ numerical approach is a multidimensional (deterministic) physical model which can compute hydrological balance, covering an exceptionally substantial number of parameters. Its high computational efficiency makes it possible to perform the water balance and study various scenarios for hydrogeological processes in the river network and biogeochemical processes in the catchments. Creating a hydrological model consists of repeatedly generating and changing the model's input parameters in order to obtain simulation results at an acceptable level of compliance with real data (see: Fig. 2). The quality of the simulation results largely depends on the input data used. The calibrated and validated SWAT+ model makes it possible to calculate the components of the water balance of the catchment area; it depends on the input data for the model and the adopted time step of the calculations.

A basic data digital elevation model for the Smugawka catchment (DEM) with a resolution of 10 m was ordered from Head Office of Geodesy and Cartography. Meteorological data were obtained from the Institute of Meteorology and Water Management in Warsaw. The use of the area was documented in the form of an orthophotomap with GIS layers superimposed, which was provided by CORINE Land Cover 2018 (CLC). A soil and agricultural map, supplemented with lithological content from a detailed geological map, was used as the input layer for QGIS ver. 3.16. The arable land use map was reclassified to categories supported by SWAT+. The water permeability of the topsoil is important for forest species as it determines their harmonized development. The required physical properties of the soil were entered into the model ac-

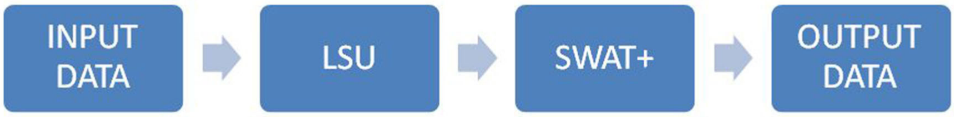

Fig. 2. Block diagram of the stages of water balance modeling for the studied Carpathian catchment

cording to the grain size composition. Determination of the yield point of the material depends on the soil moisture, which finds the stability of the mountain slope. Based on the DEM, the delineation of the main watercourses and sub catchments were made. The raster format data has been implemented in the model.

In the next stage, multiannual meteorological data (1991–2020) were added to the SWAT+ model, which included: minimum and maximum daily air temperature, daily rainfall (see: Fig. 3), average daily radiation and average daily wind speed. The input data was calibrated by the SWAT-CUP4 software using the Sequential Uncertainty Fitting (SUFI2) procedure. Input variables used to develop the water balance based on surface water runoff (see: Fig. 4), evaporation (see: Fig. 5) and available soil water (see: Fig. 6). The most optimal parameters of the model structure were selected for the analysed physical and geographical conditions and visualized on the maps. In developing the input data, each individual parameter was showed as output data in the final modelling. Evapotranspiration by Penman Monteith's method was estimated from the forest hydrology approach and implemented in the model. Full integration of the SWAT+ model with QGIS facilitates the procedure of iterative generation and modification of the model input parameters. The calculation of continuous simulations for average extended periods of time is presented in the manuscript. The availability of water in the soil was assessed by seeing rainfall and soil moisture content (retention). We recognized runoff and evaporation from the sub-catchment as a source of water loss. A discussion is provided in the section that explains the components of this water balance.

Hydrological models themselves are distorted by many factors. Among the model's limitations is the absence of anthropogenic influence. Moreover, the continuous measurements that are included in the variable model may be constrained by the dynamic nature of weather processes; therefore, a simplified rainfall-runoff model was used to analyse the water balance to minimize this impact. In addition, we could reduce the influence of random hydroclimatic phenomena on output results by using LSUs (see: Fig. 2).

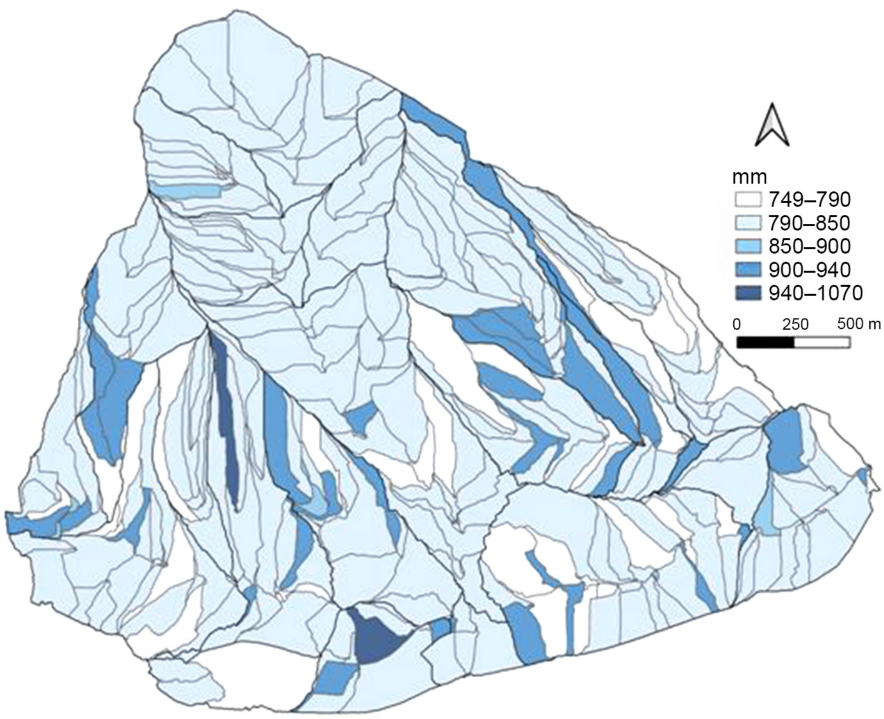

Fig. 3. Mean annual rainfall in the catchment

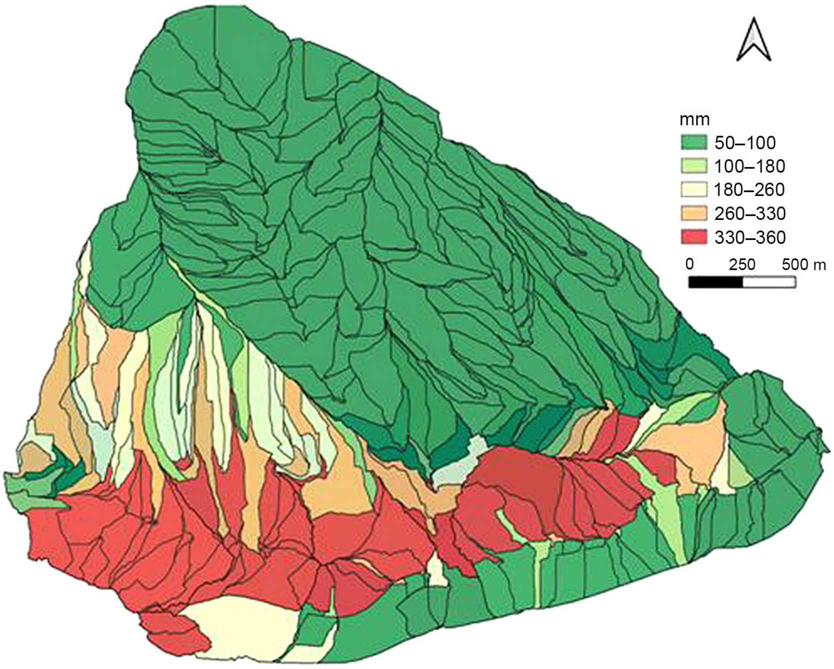

Fig. 4. Mean annual surface run-off in the catchment calculated with SWAT+

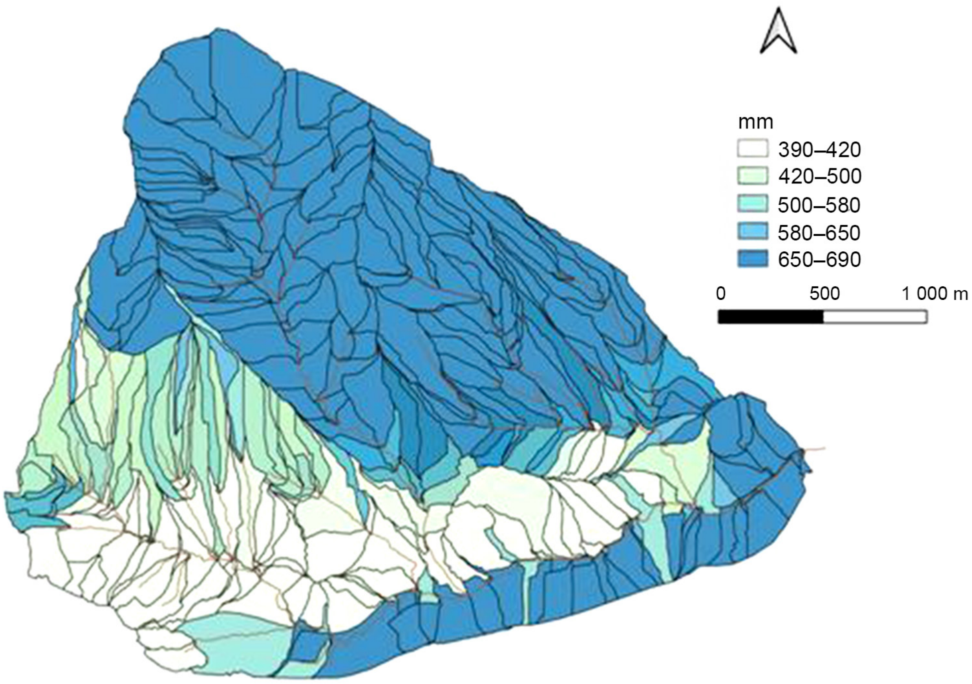

Fig. 5. Mean annual surface evaporation in the catchment simulated by SWAT+

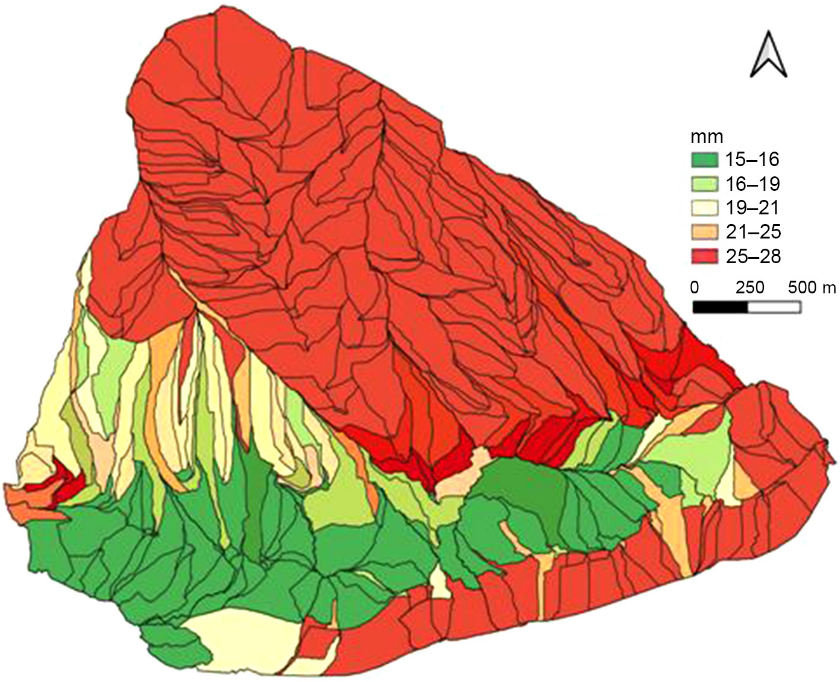

Fig. 6. Results of SWAT+ modelling for available soil water content in the root zone (mean annual)

RESULTS

The studied catchment area was characterized by the domination of forests in the structure of land-use (see: Table 1). The forests in this part of the Beskids have been preserved fragmentarily, on the less accessible and steeper slopes.

In the conducted analysis and modelling, it was shown that the Smugawka catchment has a high surface runoff into the main watercourse, especially in the forested part.

On average, the catchment receives 790–850 mm of rainfall per year, although locally the amount may exceed 1000 mm per year (see: Fig. 3).

The presence of forest areas as compared to permanent grasslands and arable land in the catchment area was characterized by lower surface runoff (see: Fig. 4). Approximately 389 to 690 mm of water evaporated per year. The lowest evaporation rate was seen in the catchment area influenced by human activity, which was partly built-up (see: Fig. 5).

The content of available soil water content in the years 1991 to 2020 was higher in areas with forest use, ranging from 21–25 mm per year. As shown by our results, the greatest amount of water is found in the foothills and in areas where there is a local accumulation of water (see: Fig. 6).

Table 1. Land use structure in the Smugawka catchment

Land use type	Share in the catchment structure	Unit
Forests	42	%
Arable lands	31	%
Permanent grasslands	16	%
Others	11	%

DISCUSSION

1. Supply of rainwater to forest soils (water gain)

In small mountain catchments, a water deficit risk assessment should be considered on the basis of parameters determining what amount is supplied from precipitation and what is transported through the surface runoff (Zabaleda et al., 2007). The credibility of the results will be ensured when the surface erosion process in mountain catchments is captured and the appropriate frequency of the measurement series is conducted (Halecki et al., 2019). Hydrological research can be implemented from the theoretical and mathematical points of view (Panagos et al., 2015). The SWAT model also allows for the generation of sub-catchment units (Li et al., 2014).

The SWAT+ simulation results concerned water retention, which is shown in the Figure 6 in the partial catchments of the Smugawka stream in cartographic form. The highest levels of available soil water were found in the forested areas of the studied stream, while satisfactory results were found for simulated and observed values for plants on permanent grasslands. Measures to increase the retention in the catchment area should be constantly introduced and improved in order to better understand and forecast quantitative and qualitative changes in the forest ecosystem (Zhang et al., 2010).

2. Surface water runoff from the catchment area (water losses)

Leaching and transport down the slope by rainfall depends on the roughness of the surface of soil aggregates (Zhang et al., 2015). A decrease in water infiltration poses a risk of rain ablation. As a consequence, there is a deficit of water in the forest soil. Theoretical methods are used to determine the flow rate of river material (Izmaiłow et al., 2008, Starkel, 2011, Comino et al., 2016). It is worth noting that computer simulated technical solutions are dedicated to generating real data (Halelcki et al., 2018). In mixed forests, the level of evaporation was higher in analysed sub catchments (see: Fig. 5). This is crucial in interpreting the hydrological situation of the heterogeneous catchment (Wang et al., 2010).

Rainwater causes a washout of the topsoil in the Carpathian catchment areas on arable land (Borek and Kowalik, 2022). This may result from the roughness of soil particles, which in the Smugawka catchment area was the highest in the valleys. Therefore, it is important to show the water balance for the entire forest complex in a catchment. The SWAT model is helpful in solving water shortage problems. However, the presented model requires laborious calibration (Abeysingha et al., 2015), especially for surface runoff (Hoang et al., 2017). An appraisal of water shortages in the flysh catchment is useful to show hydroclimatic changes and the availability of water resources (Halecki and Łyszczarz, 2021).

The demonstrated research allowed us to assess that evaporation can serve to estimate water losses in the catchment area (see: Fig. 5). In this method, a simplified technique was used. Our runoff model (see: Fig. 4), despite these limitations, is well constructed for the scale of the entire catchment. It is imperative to consider the input data for the micro-catchment in later studies in order to show more exact data. The article correctly showed the results for runoff, which suggests the possible structure of the water balance of the entire catchment area (Moosavi et al., 2022) and for the verification of hydrometeorological data (Młyński et al., 2020). In other studies, more effort should have been focused on the selection of factors for the input data (Ai et. al., 2022), and the reliability of the results. It is necessary to quantify the impact on predicting anthropogenic factors, which should be proposed in watershed modelling (Wang et al., 2022).

CONCLUSION

The article presents the rainfall and surface runoff estimation for forest sub catchments in the Outer Carpathian. The calculations were made with the average annual time step from the 30-year period. A correctly constructed and verified model made it possible to study various scenarios for the development of the hydrological situation. For adequate forest hydrology management, spatial planning and proper land use are needed. Further study of this numerical model may explain its direction in climate change research. In addition, it can help in figuring out the water balance of forested catchments. Using the model output, it was decided that forest areas have more available soil water content. The results suggest that small mountain forested catchments increase water retention. The application of GIS-based approaches and modelling techniques are crucial in the quest for best methods for calculating the water balance today. Our findings also contribute to a better understanding of the hydrological processes at work in the flysch catchment. Moreover, in the case of future research anthropogenic factors should also be examined in the data structure during the proceeding of the model.

ACKNOWLEDGMENTS

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A LIST OF ACRONYMS

CLC – CORINE Land Cover
DEM – Digital Elevation Model
GIS – Geographics Information System
LSU – Landscape Unit
SWAT+ – Soil & Water Assessment Tool

REFERENCES

Abeysingha, N.S., Singh, M., Sehgal, V.K., Khanna, M., Pathak, H., Jayakody, P., Srinivasan, R. (2015). Assessment of water yield and evapotranspiration over 1985 to 2010 in the Gomti River basin in India using the SWAT model. Curr. Sci., 108(12), 2202–2212.

Ai, P., Song, Y., Xiong, C., Chen, B., Yue, Z. (2022). A novel medium-and long-term runoff combined forecasting model based on different lag periods. Journal of Hydroinformatics, 24(2), 367–387.

Arnold, J.G., Fohrer, N. (2005). SWAT 2000: Current capabilities and research opportunities in applied watershed modelling. Hydrol. Process., 19, 563–572. https://doi.org/10.1002/hyp.5611

Borek, Ł., Kowalik, T. (2022). Hydromorphological Inventory and Evaluation of the Upland Stream: Case Study of a Small Ungauged Catchment in Western Carpathians, Poland. Land, 11(1), 141. https://doi.org/10.3390/land11010141

Comino, J.R., Iserloh, T., Lassu, T., Cerdà, A., Keestra, S.D., Prosdocimi, M., Brings, C., Marzen, M., Ramos, M.C., Senciales, J.M., Ruiz Sinoga, J.D., Seeger, M., Sinoga, J.R. (2016). Quantitative comparison of initial soil erosion processes and runoff generation in Spanish and German vineyards. Sci. Total Environ., 565, 1165–1174. https://doi.org/10.1016/j.scitotenv.2016.05.163

Izmaiłow, B., Kamykowska, M., Krzemień, K. (2008). Geomorfologiczna rola katastrofalnych wezbrań w transformacji górskiego systemu korytowego na przykładzie Wilszni (Beskid Nicki). W: B. Izmaiłow (red.). Przyroda – Człowiek – Bóg, Kraków.

Halecki, W. (2019). Erozja wodna – przyczyna odpływu związków biogennych ze źródeł rolniczych do cieków powierzchniowych (Water erosion – the trigger of biogenic compounds transport through surface run-off from agricultural area to surface watercourses). Aura. Ochrona Środowiska, 1(19), 6–11.

Halecki, W., Łyszczarz, S. (2021). Examination of Susceptibility to the Deficiency of Soil Water in a Forested Agricultural Area. Earth, 2(3), 532–543. https://doi.org/10.3390/earth2030031

Halecki, W., Kowalik, T., Bogdał, A. (2019). Multiannual Assessment of the Risk of Surface Water Erosion and Metal Accumulation Indices in the Flysch Stream Using the MARS Model in the Polish Outer Western Carpathians. Sustainability, 11, 7189.

Hoang, L., Schneiderman E.M., Moore K.E.B., Mukundan, R., Owens, E.M., Steenhuis, T.S. (2017). Predicting saturation-excess runoff distribution with a lumped hillslope model: SWAT-HS. Hydrol. Process., 31, 2226–2243 https://doi.org/10.1002/hyp.11179

Hülsmann, L., Geyer T., Schweitzer C., Priess J., Karthe, D. (2014). The effect of subarctic conditions on water resources: initial results and limitations of the SWAT model applied to the Kharaa River Basin in Northern Mongolia. Environ. Earth Sci. 73(2), 581–592. https://doi.org/10.1007/s12665-014-3173-1

Kondracki, J. (2011). Geografia regionalna Polski. Warszawa: Wydawnictwo Naukowe PWN.

Młyński, D., Wałęga, A., Książek, L., Florek, J., Petroselli, A. (2020). Possibility of using selected rainfall-runoff models for determining the design hydrograph in mountainous catchments: A case study in Poland. Water, 12(5), 1450.

Moosavi, V., Fard, Z.G., Vafakhah, M. (2022). Which One is More Important in Daily Runoff Forecasting using Data Driven Models: Input Data, Model Type, Preprocessing or Data Length? Journal of Hydrology, 127429.

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., Alewell, C. (2015). The new assessment of soil loss by water erosion in Europe. Environ. Sci. Policy, 54, 438–44. https://doi.org/10.1016/j.envsci.2015.08.012

Panhalkar, S.S. (2014). Hydrological modeling using SWAT model and geoinformatic techniques. Egypt. J. Remote. Sens. Space Sci., 17(2), 197–207. https://doi.org/10.1016/j.ejrs.2014.03.001

Starkel, L. (2011). Złożoność czasowa i przestrzenna opadów ekstremalnych – ich efekty geomorfologiczne i drogi przeciwdziałania im. Landform Analysis, 15, 65–80.

Szalińska, W., Tokarczyk, T., Jełowicki, J., Chorążyczewski, A., Michalski, A., Tiukało, A., Ostojski, M. (2014). Środowisko obliczeniowe operacyjnego modelu typu opad-odpływ. Monografie Komitetu Gospodarki Wodnej PAN, XX, 293–306.

Wang, J., Haining, R., Cao, Z. (2010). Sample surveying to estimate the mean of a heterogeneous surface: reducing the error variance through zoning. Int. J. Geogr. Inf. Syst., 24, 523–543. https://doi.org/10.1080/13658810902873512.

Wang, Z., Xu, M., Liu, X., Singh, D.K., Fu, X. (2022). Quantifying the impact of climate change and anthropogenic activities on runoff and sediment load reduction in a typical Loess Plateau watershed. J. Hydrol. Reg. Stud., 39, 100992.

Wu B., Wang, Z., Shen, N., Wang, S. (2016). Modelling sediment transport capacity of rill flow for loess sediments on steep slopes. Catena, 147, 453–462. https://doi.org/10.1016/j.catena.2016.07.030

Zabaleta, A., Martinez, M., Mriarte, J.A., Antiguedad, I. (2007). Factors controlling suspended sediment yield during runoff events in small headwater catchments of the Basque country. Catena, 71(1), 179–190. https://doi.org/10.1016/j.catena.2006.06.007

Zhang, Q., Wang J., Zhao, L., Wu, F., Zhang, Z., Torbert, A.H. (2015). Spatial heterogeneity of surface roughness during different erosive stages of tilled loess slopes under a rainfall intensity of 1.5 mm min 1. Soil Tillage Res., 15, 95–103. https://doi.org/10.1016/j.still.2015.05.011

Zhang, X., Wu, B., Ling, F., Zeng, Y., Yan, N., Yuan, C. (2010). Identification of priority areas for controlling soil erosion. Catena, 83, 76–86. https://doi.org/10.1016/j.catena.2010.06.012

MODEL OPAD-ODPŁYW PRZY WYKORZYSTANIU OPROGRAMOWANIA HYDROLOGICZNEGO SWAT+ W KARPACKIEJ ZLEWNI FLISZOWEJ

ABSTRAKT

Cel pracy

Celem pracy było zastosowanie narzędzia SWAT+ do oszacowania niedoboru wody w zlewni Smugawka.

Materiał i metody

Użytkowanie terenu udokumentowano w postaci ortofotomapy z nałożonymi warstwami GIS, którą pobrano z CORINE Land Cover 2018. Jako warstwę wejściową do QGIS w wersji 3.16, w kolejnym etapie do modelu SWAT+ dodano wieloletnie dane meteorologiczne (1991–2020), które obejmowały: minimalną i maksymalną dobową temperaturę powietrza, dobowe opady, średnie dobowe promieniowanie oraz średnią dobową prędkość wiatru. Pełna integracja modelu SWAT+ z QGIS ułatwia procedurę iteracyjnego generowania i modyfikacji parametrów wejściowych modelu hydrologicznego. W artykule przedstawiono obliczenia ciągłych symulacji dla okresów z wielolecia.

Wyniki i wnioski

Wykazano, że obecne użytkowanie badanego obszaru górskiego sprzyja retencji wody. Zastosowanie podejścia systemowego i technik modelowania odgrywa obecnie istotną rolę w poszukiwaniu optymalnych metod obliczenia bilansu wodnego.

Słowa kluczowe: zlewnia fliszowa, retencja wody glebowej, model SWAT+, bilans wodny