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Analysis of precipitation and runoff in Carpathian catchments using the soil and water assessment tool model

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ABSTRACT

The aim of this study was to evaluate the relationship between precipitation and runoff in an exemplary Carpathian catchment using sublime analysis methods with the SWAT model. The results apply to a mountain catchment – the catchment of the Grajcarek stream located in the Małe Pieniny Mountains in the Polish Carpathians. The period 2019–2021 was studied. During the simulations, iterations were carried out with 50 simulations for Biała Woda and Czarna Woda catchments each. The following statistics were used to compare the model results: MAE, NSE, PBIAS, r, and RMSE. The analysis showed multilevel parameter relationships between land use changes and their causal factors. The aforementioned methods of analysis highlighted the essence of these relationships. An important conclusion is that transformation towards arable land is practically non-existent. The influence of river sediment and surface runoff prevails here, which naturally links these two influencing factors. The statistical analyses performed showed that the multiplicity and variability of the influence factors on structural transformation vary strongly. Methods of analysis (MAE, NSE, PBIAS and RMSE) showed that changes in use indicate natural or anthropogenic afforestation of arable land as grasslands, the main restructuring factors are sedimentation applied to the catchment, evapotranspiration, and water infiltration. This indicates a structural change towards a broadly greening of the catchment, resulting primarily from the extensification of agricultural production.

Keywords: Western Carpathians, rainfall-runoff, SWAT model, MAE analysis, NSE analysis, PBIAS analysis, RMSE analysis.

INTRODUCTION

Water resources are primarily created by precipitation. Their accumulation in the environment determines in the catchment the amount of surface and groundwater runoff [Lach et al., 2023; Kopacz et al., 2024]. The most important factors influencing water are land relief, land use, and geological and soil conditions. Vegetation and soil cover play an important role. Forests, trees and shrubs, as well as grasses slow surface runoff, which improves water retention [Kopacz, 2011; Baran-Gurgul and Rutkowska, 2024], and can limit the flow of pollutants into surface waters [Jakubiak and Bojarski, 2021; Lach et al., 2023]. The water resources of Poland are mainly natural and quite small. The average specific outflow is smallest in the central lowland belt, larger in the uplands, and largest in the mountains. Therefore, the volume of unit outflow from the Polish territory is on average 5.5–7.0 $dm^3 \cdot s^{-1} \cdot km^{-2}$, which is only about 60–70% (9.6 $dm^3 \cdot s^{-1} \cdot km^{-2}$) compared to the European average. Unfortunately, the relationship between precipitation and runoff in Poland is not satisfactory. The average annual precipitation (about 600 mm), assuming that 50–60% of the precipitation is retained in the catchment and an outflow of 5.7 $dm^3 \cdot s^{-1} \cdot km^{-2}$, gives an average theoretical proportion in the precipitation-outflow system for Poland of about 82%. This is, of course, an estimated value and averaged for the whole country, but it represents the hydrological risk for Poland [Ozga-Zieliński and Walczykiewicz, 2022; Demaree et al., 2024]. Studying runoff from mountain catchments is very important because it allows determining the dynamics and intensity of hydrological processes, which are crucial for water resource management, flood protection and to assess climate change.

Modeling such catchments is challenging due to their varied relief, rainfall variability, as well as the complex interaction between vegetation, soil, and groundwater.

Small mountain catchments, in contrast to large lowland catchments, are characterized primarily by varied relief. In mountain areas, precipitation is higher, whereas its spatial distribution and variation over time is very high. The mountain climate is also sharp and "unstable", there are large amplitudes of air temperature between day and night and between seasons. This also results in a shorter growing season for plants, and translates into complex interrelationships between the climate in general and the development of vegetation. This is further compounded by soil conditions. As a rule, the soils here are of poorer quality, lacking such a well-developed sorption complex and proper fertility. The soil profile in the mountains, as a rule, is shallower, and the soil structure is poorer. This directly affects the retention capacity of the catchment area. Adding to this varied orography, including steep slopes, the area is exposed to many extreme hydro-meteorological phenomena. These are mainly flash floods but also, among other things, soil drying that occurs during the periods without rain. Hence, the quantitative and qualitative characteristics of groundwater in this type of catchment area are specific and highly variable. It follows that the relationship between precipitation and runoff is complex and results from the conjunction of a great many different environmental factors.

The purpose of this study was to assess the relationship between precipitation and runoff in an exemplary Carpathian catchment using sublime analysis methods with the SWAT model. This allowed a preliminary identification of factors influencing hydrological variability in relation to change in land use.

In turn, the research problem of the paper was to identify and parameterize environmental factors, mainly orographic, edaphic and utility factors, and relate them to hydrological factors in the precipitation-drainage relationship using model tools in the SWAT framework. Identifying and parameterizing these parameters should at least partially bridge the research gap in this area.

The SWAT model is designed to predict the effects of changes in the catchment area, such as climate and land use, and their impact on water resources or soil erosion, among others. With its extensive modules, it is often used for modeling agricultural catchments. Thus, the SWAT model (soil and water assessment tool) allows modeling of water balance (precipitation, surface runoff, infiltration, and evapotranspiration), as well as climate change, weather simulations, and land use changes. The SWAT model also has some limitations. It requires the input of many parameters, which makes its calibration and validation time-consuming and requires a lot of experience. Some of the model's parameters are particularly sensitive to changes, which can make modeling difficult when data are incomplete, uncertain or of low quality. The model can also have difficulty simulating some complex ecological processes, such as nutrient migration and bioaccumulation [Srinivasan et al., 2006].

Despite the shortcomings of the model, and after comparing its capabilities with the stated goal and research problem of the work, it was concluded that it would be the best tool to carry out the work because the SWAT model allows for more accurate runoff forecasting, water quality assessment, and the impact of different water management scenarios on the catchment. The model is particularly valuable in analyzing the effects of climate change, urbanization, and changing land use [Kowalczyk et al., 2023; Barno, 2024; Puche et al., 2025; Bouslihim et al., 2025].

STUDY MATERIALS AND METHODS

Study area

The presented results of the study and modeling concern a mountain catchment – the Grajcarek stream catchment located in the Małe Pieniny Mountains in the Polish Carpathians (Figure 1). The catchment forms the border between Pieniny and Beskid Sądecki [Kopacz, 2011; Kowalczyk and Twardy, 2018]. Many years of research indicate that the area is prone to soil erosion [Kowalczyk and Smoroń, 2007; Wężyk and Gęca, 2013]. The catchment area is 84.9 km², the length from source to mouth is approximately 15 km, and the average gradient is 3.5%. The individual gradient distributions are: 0–5%, 5–12%, 12–18%, 18–27%, and above 27%.

The climate in mountainous areas is characterized by a high variability of local weather conditions. From 2018 to 2021, the average annual rainfall amounted to 910.9 mm. The driest year was 2019 with a total rainfall of 979.3 mm. In 2021, the total rainfall was 1068.1 mm. The predominant days were those with very low (up to 1 mm) rainfall, i.e. 66.7% of all rainfall or low (1–5 mm) rainfall, which accounted for 18.2% of all days with rainfall. Precipitation with flood risk (30–50 mm) accounted for 0.8% of all precipitation events, precipitation posing a serious flood risk (50–70 mm) was 0.1% of all precipitation events, and precipitation with flood risk (> 70 mm) occurred once [Kruk, 2017]. The distribution of rainfall totals by season is shown in the graph (Figure 5 and Figure 6). The mean annual air temperature from 2018 to 2021 was 7.7 °C. The warmest year of the period was 2019 with an average annual temperature of 8.3 °C. Meteorological data were implemented from the Jaworki station (49°24’31.3 ‘N 20°33’36.0 ’E). The following measurement data were used: precipitation [mm] (daily sum), air temperature [°C] (daily minimum and maximum), wind speed [$m \cdot s^{-1}$] (daily average), total solar radiation [$MJ \cdot m^{-2}$] (daily sum).

Data collection

The following input data to the SWAT model were used in this study, i.e.:

- digital elevation model (DEM), resolution 30 m (Figure 2);
- digital soil map – obtained from the Centre for Geodetic and Cartographic Documentation of Cracow (Figure 3). The catchment is dominated by leached brown and acid brown soils (B_w), which occupies 69.9% of the catchment area, and F (silts) – 3.1% of area Brown soils (B), leached brown soils and acid brown soils formed from carbonaceous sedimentary rocks (B_{wow}), formed from noncarbonate sedimentary rocks (B_{ow}), were assigned to B_w. On the other hand, gleyic muds (FG), muds subject to fluvial flooding (F_{zal}), as well as brown muds (R_b) and undeveloped profile muds (R) account for approximately 1.8% of the catchment to F;
- digital map of land use obtained from CORINE Land Cover for 2018, resolution 100 m (Figure 4);
- meteorological data obtained from the Institute of Technology and Life Sciences – National Research Institute in Falenty, Jaworki station (2018–2021).

The land use pattern is dominated by mixed forest (SWAT code FRST) and coniferous forest

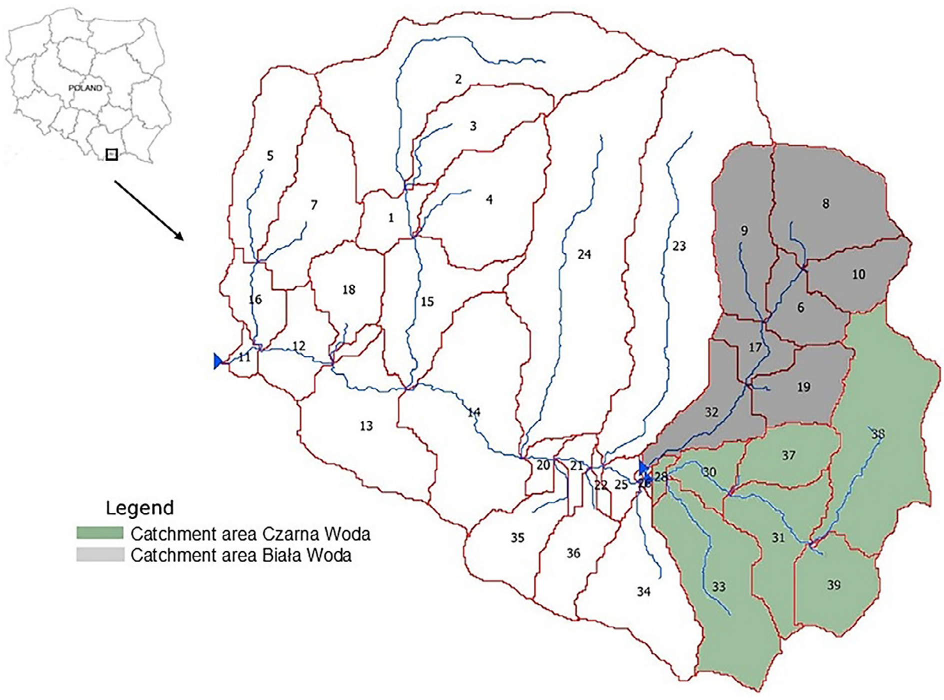

Figure 1. Location of the research area in Poland with the marked Biała Woda and Czarna Woda rivers and subcatchments division according to the SWAT model

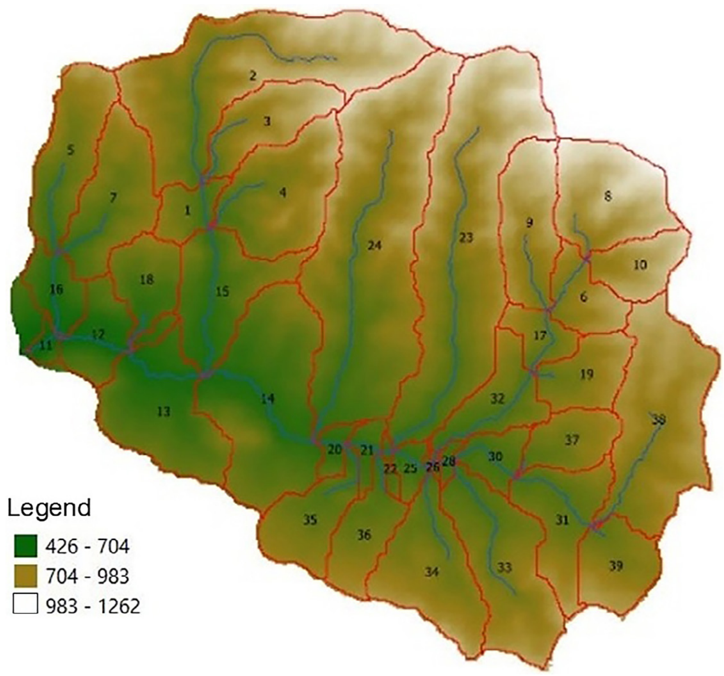

Figure 2. Digital elevation model (DEM) [m a.s.l.]

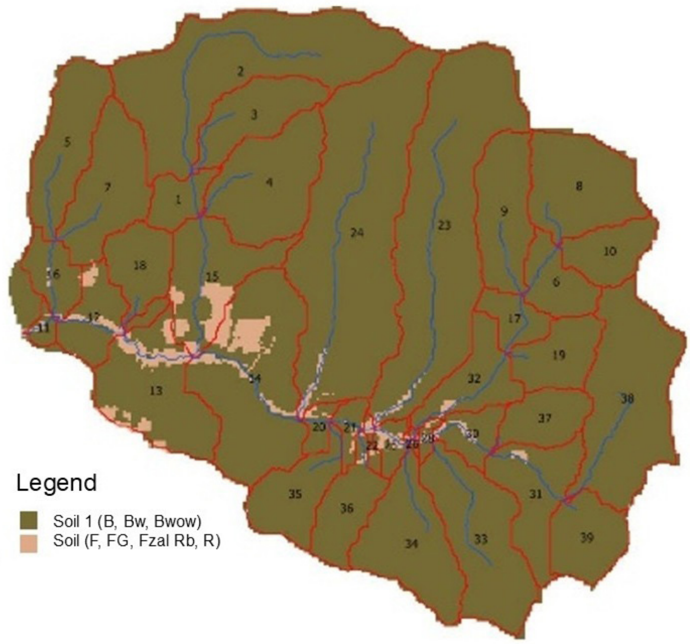

Figure 3. Map of the reclassified soil for SWAT. URLD – residential low density, AGRC – agricultural land-close-grown, WPAS – Winter pastures, FRSD – deciduous forest, FRSE – coniferous forest, FRST – mixed forest

(SWAT code FRSE), and pastures account for 13.76 km^2 (SWAT code WPAS).

SWAT model

For calculations, the studies conducted with the SWAT model version 2012 integrated with QGIS software were used [Neitsch et al., 2011]. Among the methods implemented in the model were the Soil Conservation Service Curve Number (SCS-CN) effective precipitation estimation method [SCS, 1972], the Penman-Monteith evapotranspiration estimation method and the Muskingum method for calculating water flow in the riverbed [Neitsch

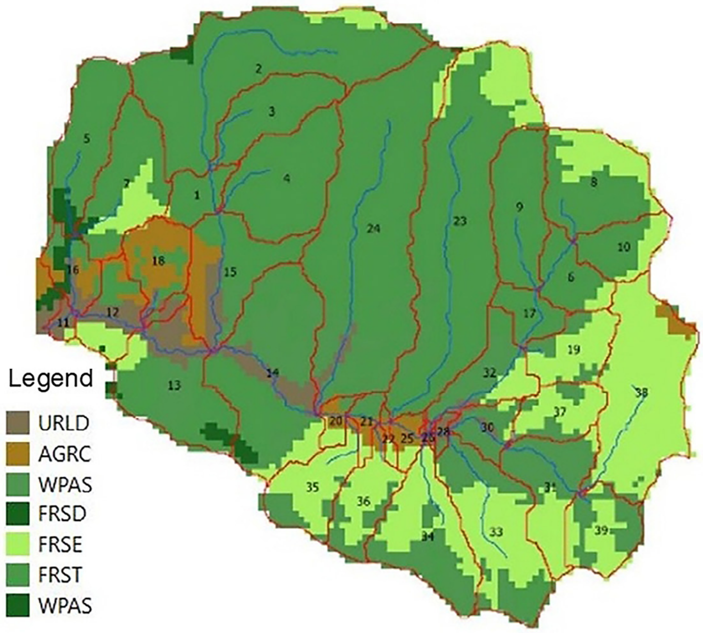

Figure 4. Land use map

et al., 2011]. These methods are standardly used in the SWAT model [Gudowicz and Zwoliński, 2017]. Three land use scenarios were introduced, i.e.:

- Scenario zero – land use structure consistent with Figure 4,
- Scenario one – pastureland (SWAT code WPAS) was assumed to be converted to mixed forest (SWAT code FRST),
- Scenario two – it was assumed that pastureland would be converted to agricultural land (SWAT code AGRC).

The study area was divided into 39 sub-catchments, ranging from 0.01 km^2 to 9.2 km^2. A total of 797 homogeneous hydrological response units (HRUs) were involved in the baseline. The water balance was calculated individually for the sub-catchments separated, and some of the balance elements are also calculated for homogeneous hydrological response units (HRUs) representing individual combinations of soils, slope and land use.

The model calibration was performed in SWAT-CUP, where the Sequential Uncertainty Fitting ver.2 (SUFI-2) algorithm was used, parameters) for all scenarios were included:

- GW_REVAP (Groundwater 'revap' coefficient,.gw, [-]),
- CN2 (SCS runoff curve number f,.mgt, [-]),
- SOL_Z (Depth from soil surface to bottom of layer,.sol, [mm]),
- GW_DELAY (Groundwater delay time,.gw, [days]).

The entire period (2018–2021) was simulated, with the first year considered as a warm-up period, followed by calibration. During the simulation, iterations were carried out with 50 simulation numbers for each Biała Woda catchment and Czarna Woda catchment.

Statistical analysis

The following statistics were used to compare model performance: MAE, NSE, PBIAS, RMSE, and r.

- MAE (mean absolute error) is a very common metric used to assess differences between series of variables. MAE, on the other hand, is a linear function, and no weights are used here, making it intuitive in analyses. The square in the formula exposes large differences very well. MAE has a range from 0 to infinity [Schneider and Xhafa, 2022].
- NSE (Nash-Sutcliffe Efficiency) is the criterion that is one of the most widely used indicators in hydrology and related sciences. It is calculated as one minus the ratio of the error variance of the modelled value divided by the variance of the observed value. NSE has a range from 1 to minus infinity, with values closer to 1 being better [Duc and Sawada, 2023].
- PBIAS is the percentage BIAS (deviation) of the Percented bias, which is a typical parameter used in the analysis of results from SWAT

models. It measures the average tendency of the simulated data to be larger or smaller than the values from the other model. The optimal PBIAS value is 0.0, small values indicate an accurate simulation of the model. Positive values indicate the model underestimation error and negative values indicate the model overestimation error [Moriasi et al., 2007, Ansari et al., 2019].
- RMSE, or root mean squared error - together with MEA is the standard for assessing modelling results. An important assumption of RMSE is that the values calculated with it have no outliers (BIAS) and a Gaussian distribution. RMSE has a range from 0 to infinity, and lower values are better (more fit) [Chai and Draxler, 2014].

R, on the other hand, is Pearson's linear correlation coefficient. The Pearson correlation coefficient r is not considered a good comparative statistic, so it has been used as an auxiliary indicator. Its properties are well known and easy to interpret; It takes values from -1 to 1, where 1 indicates full positive linearity [Rahman and Zhang, 2015; Bocianowski et al., 2023].

The package environment used here was CRAN R with the R Studio front-end. As part of the analysis, naming abbreviations were created for the individual parameters and so:
- SUB, YEAR, MON, AREAkm^2, PRECIPmm – catchment area, year, month, area [km^2], precipitation [mm],
- SNOWMELTmm – amount of melting snow, ice [mm],
- PETmm, ETmm – potential evapotranspiration, actual evapotranspiration [mm],
- SWmm – amount of water in soil [mm],
- PERCmm – amount of water percolated through the root profile [mm],
- SURQmm – amount of surface runoff in river flow [mm],
- GW_Qmm – proportion of groundwater (aquifer I) in river flow [mm],
- WYLDmm – net amount of water that leaves the catchment [mm],
- SYLDtha – amount of sediment from the catchment [Mg·ha^{-1}],
- ORGNha, ORGPha – organic N and organic P [kg·ha^{-1}],
- NSURQkg_ha – NO_3 transported by surface runoff [kg N·ha^{-1}],
- SOLPkg_ha – P transported by surface runoff [kg Pha^{-1}],
- SEDPkg_ha – mineral P transported with sediment by surface runoff [kg Pha^{-1}],
- LAT_Qmm – surface runoff [mm],
- LAT_Q_NO3kg_ha – Nitrate load in surface water [kg NO_3·ha^{-1}],
- GWNO3kg_ha – Nitrate load in groundwater [kg NO_3·ha^{-1}].

In addition, abbreviations for the land use structure in [%] were created:
- agrc – arable land area,
- frst – forest areas,
- raw (current use) – grasslands, mainly pastures.

RESULTS

The highest flow values were recorded in both catchments in late spring and summer, in the months of May, June and August. On the other hand, low-flow periods were characterized by low flows in the late autumn and winter months (November, February). Due to the spatial proximity of the two catchments, the area average precipitation on both catchments was the same. However, there were some differences in the seasonal pattern of runoff on the two catchments. (Figure 5, Figure 6). Slightly higher flow values were recorded throughout the hydrological year in the Biała Woda stream. This is due, among other things, to the different use structure of the two studied catchments. The Biała Woda catchment is less forested, as other studies indicate reduces its retention capacity [Twardy and Kopacz, 2012]. On the basis of the analyses above, Figure 5 and Figure 6 summarize the flow data, the actual precipitation, and the data obtained from the model tested. Differences were observed between the observed and simulated flow data. The largest differences occurred after a large snow melt in the month of March each year. This is due to the increase in air temperature. The average temperature in the month of March ranged from 3.67 °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, 2021.

SWAT model parameters

The following is a graphical breakdown of the most important modeled parameters: actual evapotranspiration (ETmm) (Figure 7) and

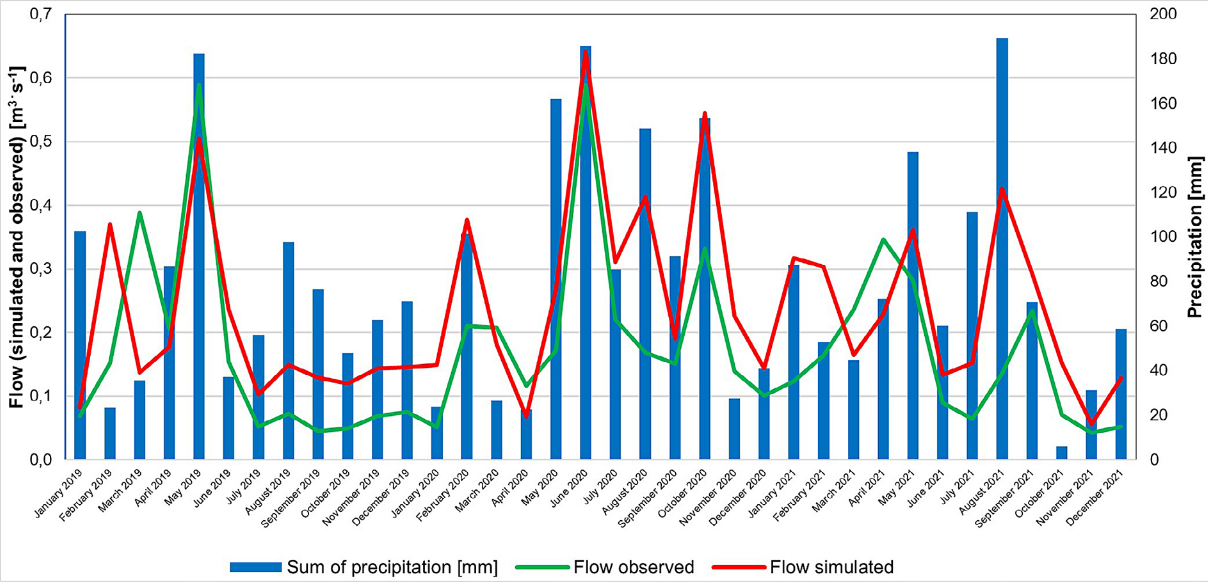

Figure 5. Actual and simulated flow and precipitation in the Biała Woda catchment area; source: own study

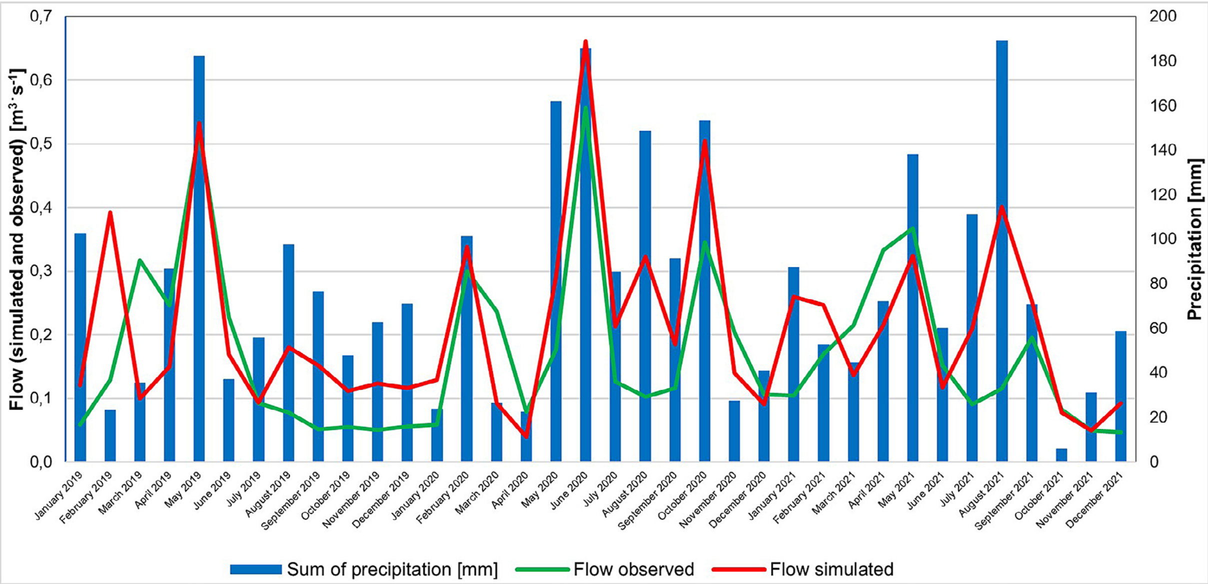

Figure 6. Actual and simulated flow and precipitation in the Czarna Woda catchment area; source: own study

the proportion of groundwater in the river flow (GWQmm) in [mm], the amount of water seeping through the root profile (PERCmm), the amount of surface runoff in the river flow (SURQmm) and the net amount of water that leaves the catchment (WYLDmm) (Figure 8).

All the listed parameters correlate quite well spatially. Evapotranspiration levels are lower in the upper parts of the catchment (Figure 7). The share of surface runoff in the flow of the river is greater in the southern sub-catchments, and the amount of water flowing out of the catchment predominates in the upper parts of the sub-catchments. The northern sub-catchments record higher groundwater levels and less seepage through the root system (Figure 8).

Statistical analysis of scenarios

The purpose of the statistical analysis was to compare the results of the three simulations and to check the differences between them. A pairwise comparison of scenarios was used: scenario zero – scenario 1 (raw-frst), scenario zero – scenario 2 (raw-agrc), scenario 1 – scenario 2 (agrc-frst). MAE, NSE, PBIAS, and RMSE statistics were

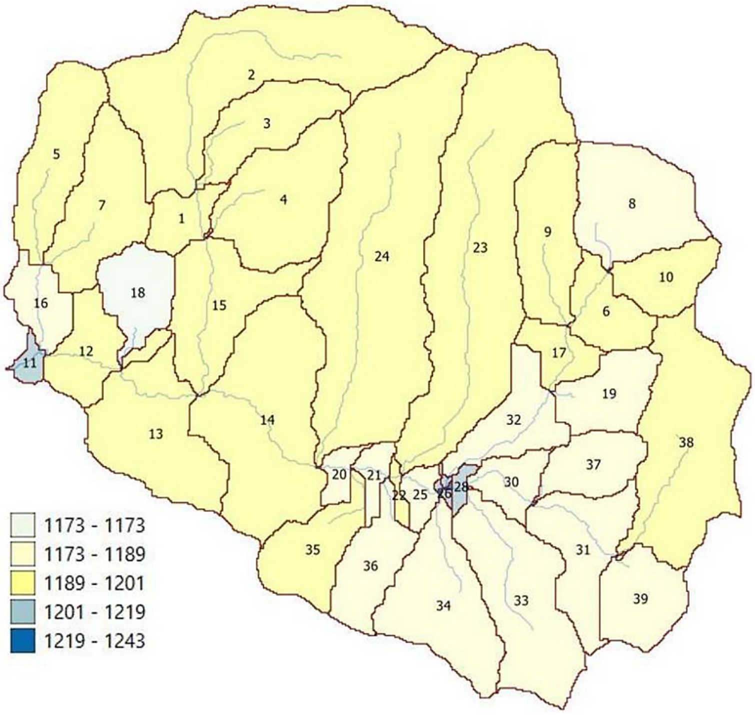

Figure 7. Real evapotranspiration (SWAT code ETmm) in [mm]

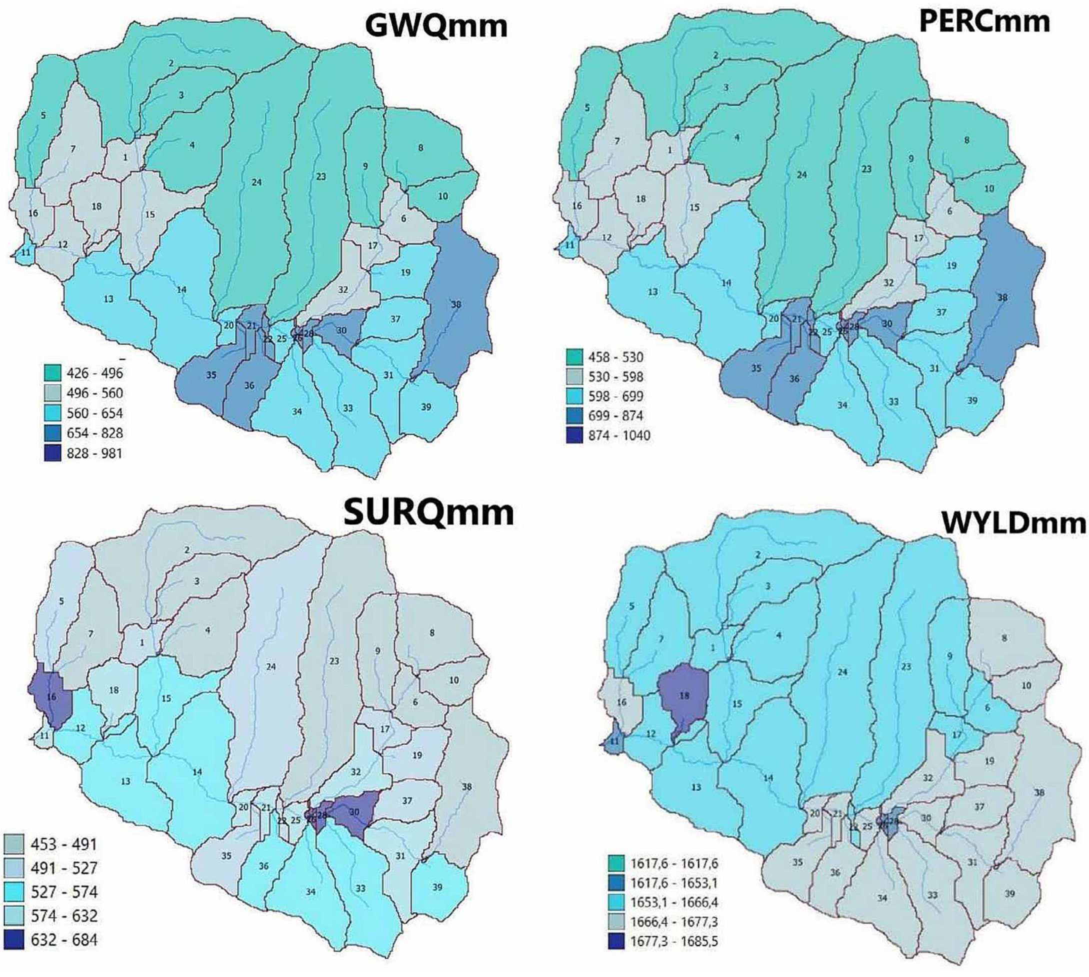

Figure 8. GWGmm, PERCmm, SURQmm, WYLDmm in [mm]

used for the analysis. A summary of the results of the statistical analysis of the model variants is shown in Figure 9.

In general, there are no significant differences between the models. The MAE index reaches a maximum value of 0.5 once for the SYLD parameter. The amount of sediment (SYLD) is the model parameter that shows the largest variation; it reaches it in comparisons with scenario 1, for both the baseline and agricultural models, the comparison with the model that introduces forests gives the largest discrepancies (PBIAS -20 and 30 respectively, NSE approaching 0, RMSE 1.5). Surface runoff (SURQ) was another parameter showing variation, mainly between the model based on scenario 1.

The MAE index reached a value of 0.4 for both the comparison of Scenario 1 with Scenario 0 and Scenario 2. The NSE and PBIAS indices did not indicate differences and again the RMSE indicated differences in the same cases at the level of 1.0. An analogous assessment took place for the parameters PERC, ORGN, LAT_Q, GW_Q, ET, differences between Scenario 1 and the others were discernible through the MAE and RMSE statistics.

DISCUSSION

The analysis revealed multilevel parameter relationships between land use changes and their causal factors, which were mentioned in the previous chapter. The listed methods of analysis highlighted the essence of these relationships.

The spatial variability of individual parameters seems logical. The lower level of evapotranspiration in the upper parts of the catchment is due to differences in altitude above sea level. In the upper parts, lower air temperatures are registered, which reduces evaporation. There are also higher gradients, which accelerates surface runoff, so less water remains in the catchment (Figure 7). The share of surface runoff in river flow (SURQmm) is greater in the southern sub-catchments, which

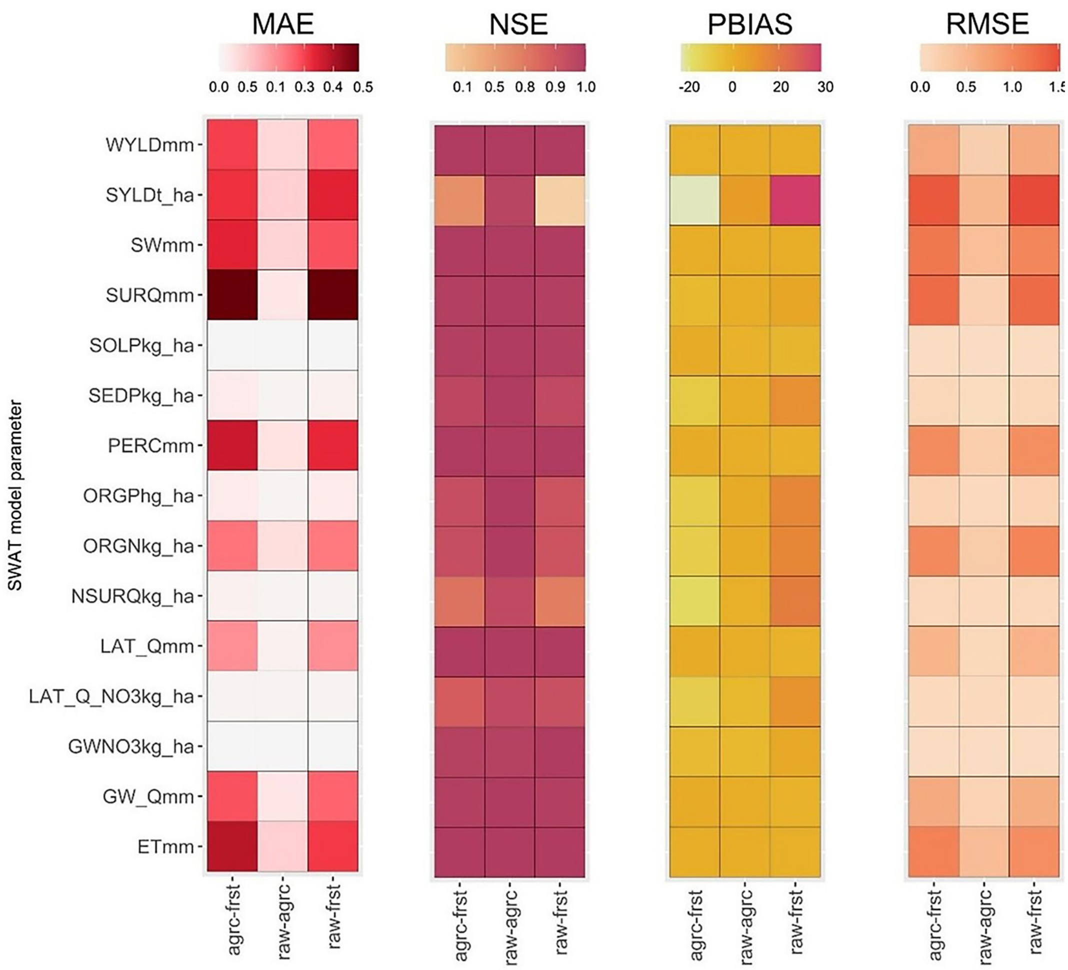

Figure 9. Influence of individual parameters on structural changes using MAE, NSE, PBIAS, RMSE methods

is also due to the slope of the terrain, as these catchments are shorter and their average slope is much greater than the northern catchments (Figure 8). Similarly, the amount of water flowing out of the catchment (WYLDmm) predominates in the upper parts of the sub-catchments, which is also related to the gradient of the terrain. The PERCmm and GWQmm parameters correlate closely, as they relate to water leaching from the groundwater table (Figure 8).

In the MAE method (Figure 9) (mean total error representing the difference between the parameters under study), the largest relationships were in the pattern of changes between grassland, arable land, and forest areas. The amount of surface runoff in the river flow expressed in [mm] was the important influence. In the same pattern of relationships, evapotranspiration and the amount of water percolated through the root profile [mm] were equally important, as was the amount of sediment lifted from the catchment [$Mg \cdot ha^{-1}$].

This means that forests, as areas strongly linked to field evaporation, are sensitive to the water runoff from the soil profile, contrary to the common opinion that they are the most stable in terms of retention. This applies not only to grassland transformation but also to arable land.

The analysis using the NSE method, which indicates a criterion for the hydrological efficiency of the catchment, showed that the correlations were no longer so pronounced. In fact, only the amount of sediment from the catchment, measured in Mg per hectare, meant that the transition of grassland (partly arable land) to woodland is most noticeable here. NO_3 transported by surface runoff [$kg\ N \cdot ha^{-1}$] is also associated with this sediment, so there is a logical link between the influence of river sediment containing mineral components, mainly nitrogen, and water status and the intermediate and long-term impact on the change in land use in the catchment (Figure 9).

The PBIAS method, as mentioned, measures the average tendency of the simulated data to be greater or less than the values from the other model, i.e. by the nature of this parameter, the values will be secondary. Therefore, the amount of sediment in the catchment [$Mg \cdot ha^{-1}$] is extremely represented here for the changes towards forested grasslands and arable land. This is indirectly due to the transport of nitrogenous forms through surface runoff. The correlations presented are not entirely clear and should be regarded as estimates. A recent analysis of the data associated with the RMSE method (i.e., the root of the mean squared error, which indicates an objective assessment of the modelling results) indicates that evapotranspiration, the amount of sediment from the catchment and surface runoff determines the aforementioned structural changes in the forested direction (Figure 9).

An important conclusion of the analyses is that the transformation towards arable land is practically nonexistent. The influence of fluvial sediment and surface runoff, which naturally (through surface erosion) links these two influencing factors, prevails here. Three groups of parameters are altered: ORGPhg, ORGNkg, NSURQkg; parameters related to water circulation: SURQmm, GW_Qmm, ETmm and SYLD_ha related to sedimentation. The others do not show a statistically significant difference, a known SWAT problem when modeling small catchments when converting part of an area to forest, regardless of its type and climate zone [Baker and Miller, 2013; Oliveira et al., 2020; Potić et al., 2022].

Changes in the type of use are known to affect surface runoff, depending on the area occupied by the forest annual changes in surface runoff can be from a few to several percent [Lin et al., 2022; Paiva et al., 2023]. In the case of the study carried out in the catchment, the runoff decreased by about 5% in relation to the original and agricultural variants. The parameter ETmm (evapotranspiration) remained at a similar level not exceeding 1%, as can be found in the literature [Danielescu et al., 2022; Mekonnen and Manderso, 2023; Ware et al., 2024]. However, it should be remembered that evapotranspiration in the SWAT model is highly dependent on the assumptions made and the submodel used [Earls and Dixon, 2008].

The discharge to surface water in the raw and agrc variants is at the same level, in the case of the frst variant, it increases by 1.2%. This is not a high value, but is close to the value of 1.3% in an experiment conducted by authors from South Korea or Ethiopia [Wonjin et al., 2022; Mekonnen et al., 2023]. However, values can sometimes be much higher even above 4% [Lee et al., 2023].

The change in use and impact on nutrients of ORGPhg, ORGNkg, and NSURQkg sometimes varies. Apart from a few cases, the share of forests has a positive effect on the retention of nutrients in the catchment [Feller, 2009]. This is most evident in the case of phosphorus, where the decrease is almost 15% with respect to adrc and raw. The contribution of N ammonium is low in all options. In the context of phosphorus, the decrease is 12% for the frst variant and almost 4% for the agrc variant. The values obtained can be considered almost textbook and in line with classical assumptions [Rast and Lee, 1983].

CONCLUSIONS

The statistical analyses that have been carried out have shown that the multiplicity and variability of the influencing factors on the structural transformation are highly variable. The analysis of the rainfall-runoff system here appears indistinct, on the contrary. The flows indicated in Figure 5 and Figure 6 were taken into account in later analyses (Figure 9), where non-hydrological elements shaping structural relationships were already taken into account. The methods of analysis (MAE, NSE, PBIAS and RMSE), as sophisticated methods for the statistical evaluation of relationships between structural parameters, showed, among other things, that:

- changes in use condemn natural or anthropogenic afforestation of both arable and grassland land,
- the main restructuring factors, mainly due to surface run-off, are sedimentation of the catchment, evapotranspiration and infiltration of water through the soil profile.

This indicates a structural change towards a broad greening of the catchment, resulting mainly from the extensification of agricultural production (disappearance of arable land and transformation of the remaining forms of use into forest land). These changes, from the point of view of sustainability and climate change, appear to be beneficial, both locally and regionally.

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