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Analysis of water regime modification induced by long-term development of vegetation cover

Abstract

The monitoring of air temperature and precipitation has been used as the input for the modelling of the rainfall-runoff process for three catchments with up to 100-year series. This monitoring has been used for the re-assessment of the long-term courses of evapotranspiration demand. The oscillations and random changes of vegetation cover are pursued as an indication of fluctuations in the resulting evapotranspiration. The intention is to appraise this complicated time series on the scale of decades. The modified computer implementation of the conceptual SAC-SMA model enables quicker simulation, and it facilitates other requisite and efficient procedures. It also allowed proper conditions for an automatic calibration of parameters in the used model, in which the genetic algorithm is used. That process (i.e., actual evapotranspiration) is to be simultaneously identified with the optimal parameters of the model. The resulting evapotranspiration is represented as the modelling outputs, when values could be hardly gained as measured or computed values (e.g., from only other meteorological observations).

Keywords: evapotranspiration land-use, optimization, rainfall-runoff modelling, vegetation cover

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Introduction

The actual aims of rainfall-runoff modelling are to use such tools for the evaluation of different changes in the water regime: first, during complex climatic variability and, second, due to natural land-use changes, which is an urgent matter within the previous long periods. In this context, the desirable information concerning vegetation cover is to be compensated by evapotranspiration as optimal monthly values. The intention is to decrease uncertainties in the water regime due to different oscillations. It requires the evaluation of the naturally appearing fluctuations and the abrupt, seemingly random changes in the basin. This sequential variability of the water regime is usually influenced through changes in vegetation cover in the annual cycle.

The goal of the implementation of the rainfall-runoff process is to reach the precision of modelling outputs, when some abrupt or continual abnormal situation appears in the differences between monitored and simulated discharges 1This approach may provide insight at the development of the water regime in different interactions in the basin. The development of the water system can include the changes in vegetation cover and consecutive evapotranspiration, unexpected water storages, etc. Agricultural production (e.g., increased yields of grain) has been considered a forceful phenomenon for water balance for some time.[2] The desirable attention to the higher variability of evapotranspiration demands is supported by the expectation that its connection with solar radiation is correlated with solar activity;[3] such fluctuations are to be considered and are in several figures herein. The length of the evaluated time series is significant in many circumstances. This allows following and ascertaining the influences of vegetation development. It affects evapotranspiration demand when daily series are available for several decades, for example. It could be significant for the runoff influence. The role of the ensuing deforestation has been viewed positively because it provides more water for the overall water supply (e.g., in Great Britain or Hamburg).[4]

The interactions between the evapotranspiration demand and the soil water content are to be adequately considered, especially during model calibration for a long-term time series. These interactions are significant and recognised when hydrological data series up 100 years are analysed. The precise information about the forest cover is not available. Thus, several natural phenomena require evaluation to explain the influences of the variability of runoff. Such situations are primarily the following:

1. The periodic and regular climatic oscillation. In addition, certain phenomena include the precipitation and evapotranspiration determining the water consumption, while[3] clearly shows the correlation between solar activity and climate variability. Some similar fluctuations have also been pursued quite recently.[5]
2. Long-term evolution of vegetation cover, including its possible abrupt changes (i.e., the extraordinary wind disasters and even devastations by insects) were events in central Europe during the second half of the nineteenth century.[6]
3. Significant and flexible geomorphological conditions or the seemingly random diverse events caused by increasing agricultural production.[7]

These are the primary processes for the activity of evapotranspiration. Moreover, infiltration and surface simulations of runoff processes in small catchments are frequently described (e.g., [8]), and these are the primary methods for the right notion of evapotranspiration activity.[9] However, various modelling tools can be used.[10,11] The process is also influenced by the developments on the scale of decades, during which some other natural events have occurred (e.g., wind disasters in the forests and other damage in such regions). The changes of vegetation cover and the desirable appraisals of the subsequent interactions between evapotranspiration demand and sub-surface water storage seem to be important processes.

This whole matter may appear important, both at the local as well as at the regional scales.[12] The rainfall-runoff models are based on mathematical and physical natural systems. Nevertheless, these system processes are not well understood in hydrology. Model parameters should be well adjusted so that model outputs provide practical and useful information. However, it is specifically for a modelled basin because it is very difficult or impossible to measure some of the model parameters. There are several approaches concerning how to estimate model parameters. The two primary methods rely on theoretical and empirical relationships between a model and the natural processes, such as soil and vegetation properties, a catchment topology, and more. The other instrument for the model calibration is using historical data or data from a similar watershed. The result of this effort is a calibrated model that approximates the observed values using model outputs. Unfortunately, these approaches are very complicated because they are designed only as estimates of the real world.

All these methods make it impossible to calculate the exact value of model parameters or to create a universal procedure of a model calibration. Frequently, the models are calibrated by trial and error, which is very time-consuming.[13] Therefore, a third approach for the parameter estimation is a heuristic method that, in simpler terms, tries to a solution of the model calibration because the correct estimate is not possible. The heuristic approach culminates in a lower error, which describes a difference between the observed and simulated values. The genetic algorithm (GA) is one of the heuristic methods that is widely used in hydrology.[14] The GA is a mathematical model with a broad range of applications and is very effective in applications where local optimisation methods fail.[15] Holland JH[16] developed the first applicable GA. The GA utilises elements of evolution that have been described in Darwin's evolution theory, such as populations, generations, crossovers, mutations, etc. This article does not focus on the theoretical background of the GA, but the algorithm is used as a tool to improve the calibration of the rainfall-runoff model. A detailed description of the GA is in.[17–19] From the viewpoint of hydrology, the optimising criteria are an important part of the GA because the criteria determine the quality output of the calibrated/optimised model. The optimising criteria are also called fitness or objective functions. A variety of statistical indicators determines the deviation between the measured and modelled outputs.[11]

The most frequently used indicators are the mean squared error and its variation,[20] the Nash-Sutcliffe model efficiency, or correlation coefficient (R).[21] Unfortunately, the mentioned indicators are not applicable for our purposes because they do not provide satisfying model outputs. Therefore, a practical object function should be determined. Modelling of the rainfall-runoff process used in these experiments provides the possibility to discover the diverse flow appearing in the simulations. The vegetation change influences the evapotranspiration needs and, consequently, the complex water regime.[11] The aspects of the evapotranspiration development in simulations for small forested catchments could be found. A rough look is possible in several of the relevant phenomena, along with the optimisation of model parameters. The manual calibration of the conceptual rainfall-runoff model and automatic optimisation of its parameters enable its use in the identification of the starting values of the monthly averages of evapotranspiration, giving 12 annual values.[22,23] The expression of the evapotranspiration demand is used in this context with the expectation that this value is between ET_{actual} and ET_{demand}. The criteria in the experiments for automatic optimisation have several statistical characteristics, similar to elsewhere.[24] Two simultaneous tasks are to be considered in the preparation stage (i.e., evapotranspiration long-term changes and its automatic optimisation).

Material and method

Data and approaches used in the analyses

The input time series contains daily values of precipitation and air temperature. Table 2 summarises modelled periods of the Elbe River. The time series, which is a bit longer than 100 years, is at the disposal for modelling the Czech part of the Elbe River. The area of this basin is $P = 51,000$ km^2. Moreover, the simulation outputs are complemented with the results from the following forested experimental basins for two small catchments: Liz (P = 1 km^2), near the borders with Germany and Austria, and Raztoka M (P = 2.1 km^2) in the Beskydy Mts. Each series for the model is nearly 40 and 60 years long, respectively. Modelled periods of the experimental basins are the same as the Elbe periods. The long-term time series is desirable and primarily useful for appraisals of the water regime variability. It is advisable to obtain information on vegetation cover development. Diverse aspects of runoff changes due to the climatic oscillation could also be partially explained with the implementation of modelling.[5] Differences between observed and simulated runoff ($dQ = Q_{obs} - Q_{sim}$) have been used to appreciate the fluctuations or tendencies in the water regime.

Rainfall-runoff model

The tools and approaches implemented to ascertain the processes in evapotranspiration include the Sacramento hydrological rainfall-runoff model for soil moisture accounting (SAC-SMA).[23] The SAC-SMA model has been used in simulations with Anderson's snow model.[22] The SAC-SMA software has been modified so that it enables a long-term continual simulation and a presentation of crucial components of the rainfall-runoff process. It also creates desirable conditions for an automatic calibration of this conceptual model. Such a condition can be, for instance, partial time intervals with supposed diverse evapotranspiration. The evapotranspiration may be identified simultaneously during the identification of optimal model parameters.[25] These procedures implemented in the given connection mean the modelling outputs represent the resulting evapotranspiration (ET_{demand}). The outputs are difficult to gain using the monitored process or the computed values.

The SAC-SMA parameter calibration

A manual calibration of the SAC-SMA model is time-consuming. The total number of calibrated parameters is more than 40 because the investigated watersheds require the use of the supporting models SNOW17 and UNIT-HG. Model users need to have sound knowledge of hydrology and the calibrated basin. Usually, an automatic calibration is utilised for fine-tuning of model parameters after the manual calibration is complete.[26] It also depends on a lot of experience and intuition. The model calibration is more an art than a science.[27] It is necessary to calibrate models in an efficient way to be usable in practice. The predictive ability of models is determined by indicators that define a degree of difference between the observed and simulated values. The full range of statistical data and techniques is used for model performance. The following enumeration represents the most fundamental indicators: root mean square error (RMSE), bias, coefficient of efficiency (Nash-Sutcliffe model efficiency coefficient), and correlation coefficient. Modified forms of these equations are used for a different time scale (e.g., monthly or daily RMSE).[9]

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The SAC-SMA parameter optimisation

Simulation results should correspond to the reality as much as possible. The way to identify the best indicator for a validation of the calibrated model is ambiguous and very difficult. The selection of the validation technique depends on several factors, such as the following:

1. Applicability concerning the model and weather conditions
2. Commonly used methods known from the literature
3. Identification based on its model validation[9]

We mentioned that the objective function determines the quality of the model output. The statistical indicators validate the model calibration. The primary task is to design and test an efficient object function that produces the highest quality results of the SAC-SMA model. More precisely, the RMSE value will be as low as possible, and the R value will be as high as possible. Column 3 of Table 1 shows the results of the SAC-SMA validation when using monthly volume RMSE (MVRMSE) as the objective function. Most of the indicators report orders of magnitude of improvement. On the other hand, R and Nash-Sutcliffe report a slight worsening but not the order of magnitude. Therefore, MVRMSE has been selected as the objective function for the optimisation of the SAC-SMA model. The MVRMSE is defined as follows:

$$MVRMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\frac{1}{30}\left(MQ_i - MS_i\right)^2} \quad (1)$$

where MQ: Observed monthly discharge; MS: Simulated monthly discharge; n: Number of monthly events

Table 1 The matrix of the statistical indicators by using different objective functions

Statistic indicator	Objective function				
	Rmse	Mvrmse	Nash	Bias	R
AVG ABS Monthly vol error (mm)	7,087	0,017	12,408	11,401	44,36
Monthly volume RMS error (mm)	32,221	0,073	51,453	46,251	160,776
Correlation	0,8851	0,8281	0,8763	0,8708	0,8939
Nash-Sutcliffe	0,7329	0,6652	0,7613	0,7437	0,6583
Monthly ABS volume error (mm)	400,372	0,0946	700,946	644,091	2,506,056
RMSE (mm)	0,0411	0,0508	0,0429	0,0444	0,0513
Percent bias (%)	-6,311	-0,001	-11,863	-11,099	-44,36
Monthly bias (mm)	-35,65	-0,005	-67,017	-62,703	-250,606
Time (sec)	464	291	622	532	589
Number of the best cases	1	5	1	0	1

Strategy of rainfall-runoff modelling

The long period cannot be calibrated at once because there are many different periods that need a different model calibration. The oscillations and random changes of the vegetation cover cause this diversity. Therefore, the long period has been divided into smaller parts. Each part describes a significant diversity (e.g., wind disasters, massive floods, or insect damage of vegetation cover). Output calibration of one period is input into the next period and so on. This approach assures a connection of calibration and thereby increased quality of the model output. Results of each sub-period are merged and provide a comprehensive view of the long period of the simulated basin.

Results

Modelling of the rainfall-runoff process and optimisation of its parameters

The preliminary results of manual calibrations of the Elbe River are presented in Table 2. The comparison with the optimisation is presented for the same periods. These results indicate that the optimisation of parameters helps visibly improve the modelling outputs. The smoothness of discharges by large water reservoirs in the period 1965-2000 provides additional relatively proper simulation. It is surprising and is nearly similar to the automatic optimisation. The massive floods in 1940 and 1941 indicate furthermore that the RMSE provides the apparent precision of the flows during just these periods. It means that the accuracy of the root square error is meaningful in the comparison with the correlation coefficient of Q_{obs} and Q_{sim}. The long-evaluated time series is usually desirable for the reliability of parameters in modelling tools. That may enable the assessment of the influences of the vegetation development, which affects the evapotranspiration demands.[28] Daily series, for several available decades, have been used for the basins with the various development of vegetation cover. They have been used with a different length of observation, which could enable the evaluation of such changes. Floods, as frequently surprising situations, require data with visible flexibility for improvement of some parameters in the rainfall-runoff modelling. It is first in the connection with natural land-use changes. The results after optimisation for identification of model parameters are illustrated in (Tables 2)(Table3). The manual calibration of the model could be considerably improved. The starting point for implementation of automatic identification values of parameters has been favourably accomplished (i.e., manual calibration is perceptible in this case for the Czech part of the Elbe River). Table 3 indicates that some situations anticipated in the context of vegetation cover could be the reason for the changes in evapotranspiration. The slight change in the parameters of the conceptual rainfall-runoff model might indicate

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the existence of other processes due to other related land-use changes (e.g., the density of the root relationship with the infiltration). Table 3 is possibly the illustration for such conditions. It is evidence that each period requires different values of the model parameter, which defines a SAC-SMA zone for the best model output. Figure 1 provides graphs with distinct shapes of monitored differences: monitored and simulated discharges (dQ) and accumulated values (sum dQ). All of this indicates the possible land-use changes at roughly the first decade and after 1965, when several relatively large water reservoirs existed in the catchment. However, the results are the outputs, including the period 1895-1915, mentioned in Figure 1. The relatively large system of weirs has been mostly built during this time for ship transport. The changing water levels due to the inundations along the river stream thus likely affect water storage. Some circumstances mentioned above, in connection with Table 3, are at least slightly illustrated in Figure 1. It provides the large differences in the period 1895-1915, already obtained during the calibration of the rainfall-runoff model and the optimisation of the model parameters. The disparate tendency indicates the visible respective assumed land-use activity.

Table 2 Characteristics of rainfall-runoff simulations with a manual parameter calibration and with parameters based on an automatic optimisation

Elbe periods	Q [m³/s]		ΔQ= Qobs- qsim		Daily error		Monthly error [mm]		Correl. coef.
	qsim	qobs	(%)	[m³/s]	rms[%]	abs.[m³/s]	Abs. values	rmse	
optimal 1895-2000	312.8	311.6	0.05	27.6	9.3	86.4	1	12.8	0.867
1915-1965	308	308.5	0.03	27.2	8.6	83.8	1.3	11.8	0.881
1990-2000*)	282.6	281.5	0.07	24.2	8.2	68	3.1	11.3	0.899
manual 1895-2000	276	311.6	-11.4	30.3	9.7	94.4	11.4	140.3	0.82
1915-1965	289	308.5	6.1	29	9.4	89.5	7.1	72.4	0.836
1990-2000	231	281.4	-15.7	25.1	8.5	72.4	15.7	69.2	0.856

*), favourable system effects of large reservoirs

Partial periods	Daily Abs. error Q [m³/s]	Monthly error [mm]	Rmse	Correl. coef.
1915-40	80.8	2.8	4	0.908
1915-25	83.5	2.8	4.3	0.911
1925-35	74.1	2.6	3.8	0.912
1935-45	115 *2)	4.3	6.2	0.841
1945-56	80	3	4.2	0.884
1938-45	95	6.5	16.3 *1)	0.88

*1), Dry period (1933–1935)

*2), Massive floods in 1940 and 1941

Table 3 Optimal parameters of SAC-SMA model for the Elbe River during different periods

Sac-Sma [mm] Zone	Period		
	1915-1938	1938-1945	1960-1970
ZPERC	105	105	133.8
LZTWM	268.5	259.7	245
LZFSM	127.8	158.2	208.6
LZFPM	375.2	347.9	318.5
UZTWM	48.3	26.6	26.3
UZFWM	173.4	173.4	183.8

ZPERC, Maximum Percolation Rate Coefficient; LZTWM, Lower Zone Tension Water; LZFSM, Lower Zone Supplemental Free Water; LZFPM, Lower Zone Primary Free Water; UZTWM, Upper Zone Tension Water; UZFWM, Upper Zone Free Water

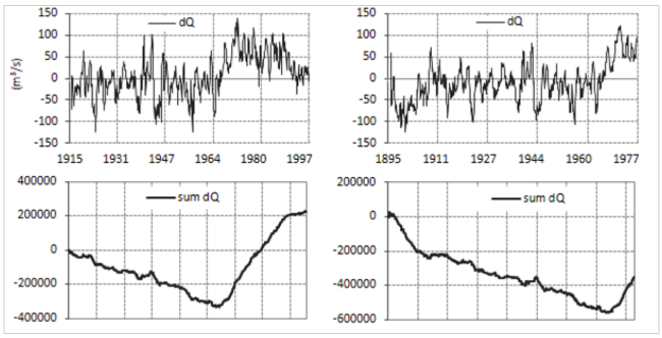

Figure 1 Time series of differences between observed and simulated long discharge of the Elbe River for unequal intervals from various periods.

Simulations of evapotranspiration

The evolution of evapotranspiration as a long-term process in the

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water regime of basins with meaningful vegetation cover is displayed in Figures 2-5, and the results could be conclusive. In most of these presentations, the outputs of the simulation are included, in which the optimisation of the parameter model is entirely included in the assessments of this phenomenon. The evapotranspiration is identified as part of the optimisation approach, assuming that the balance between precipitation and runoff is further ensured with the relevant correction factors, as a separate parameter to the rainfall-runoff model.

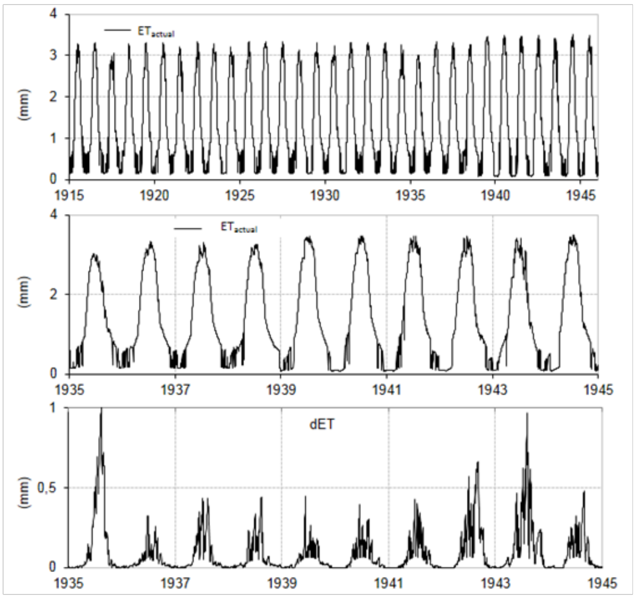

Figure 2 Evapotranspiration of Czech Elbe River (ET_{actual}) and ΔET as a complement to $ET_{demand.}$

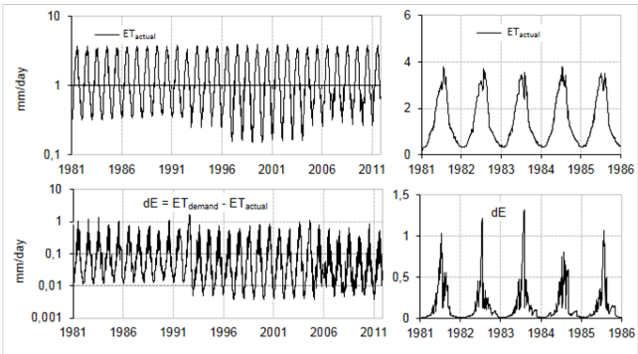

Figure 3 Actual evapotranspiration during several periods of different durations in the Liz basin.

Discussion

The actual evapotranspiration in the Elbe basin, as a process in the long-term period, is visible in Figure 2. It can be considered in the presented period as a nearly stable process. Still, the upper graph in Figure 2 indicates higher peaks of ET_{actual} in the summer periods at the turn of the 1930s and 1940s. Its character is comprehensively valid for the clear expressive annual cycle in the middle graph. The differences of expected evapotranspiration demand (ET_{demand}) and actual evapotranspiration (ET_{actual}) (i.e., $\Delta ET = ET_{demand} - ET_{actual}$) are in the lower graph. The semi-logarithmic scale showed that this quantity also appears as a phenomenon with the apparent annual and visible long-term variability.

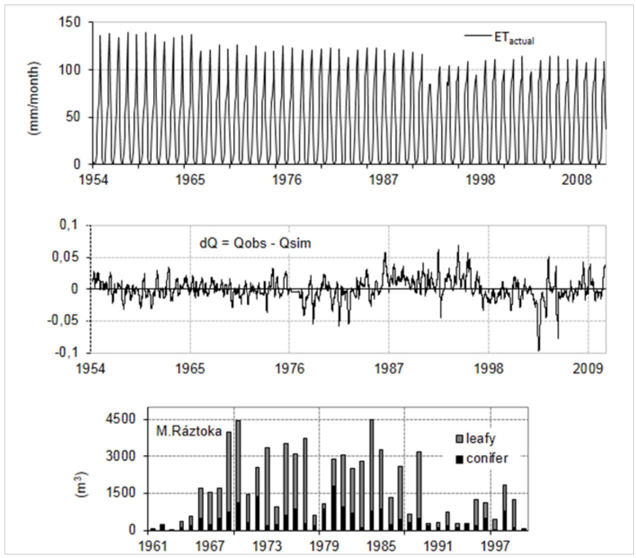

Figure 4 Evapotranspiration demand and actual evapotranspiration for Raztoka basin as the optimal output of rainfall-runoff modelling.

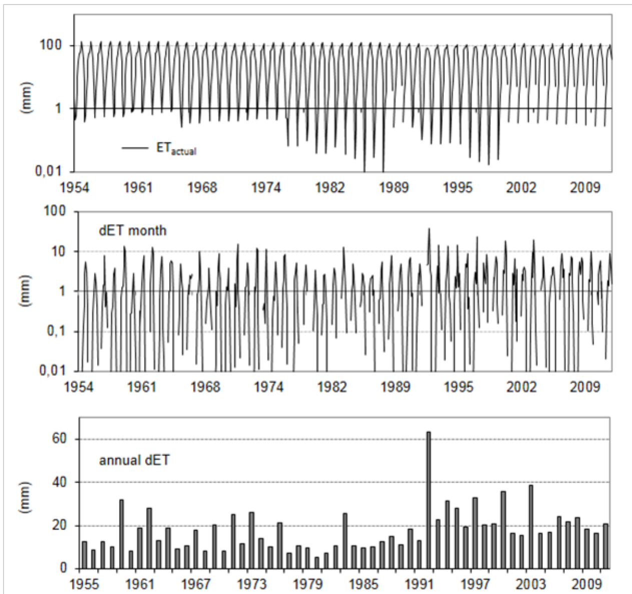

Figure 5 Long-term course of actual evapotranspiration and the differences $\Delta ET = ET_{demand} - ET_{actual}$ in M Raztoka.

Evapotranspiration in the forested catchment

The aspects of the evapotranspiration development in the rainfall-runoff simulation are to be pursued as an addition for the small forested catchment. Scales show seemingly different courses of evapotranspiration in the span of the three decades in the graphs. The random partial damage by insects in the forested catchment creates natural annual or abnormal long-term evolutions. Some graphs show a comparison of obtained actual evapotranspiration in an annual cycle. It is for the large basin of the Elbe River at the experimental Liz catchment. It could be an indication of the attention that should be required regarding water consumption. The vegetation activity probably caused consumption during the different parts of warmer periods of the year. The Liz basin in the Sumava Mts. is shown in

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Figure 3. Some natural damage by insects occurred between 1984 and 1998. The modelling of the rainfall-runoff process has provided evapotranspiration for the partial periods ET_{actual} and ΔET. The decreases of ET_{actual} and annual minimums with some tendencies are interesting as illustrated in the surprising shape of this variability. Figure 5 is the illustration of the evapotranspiration development in the situation of the forested catchment in Raztoka M in Beskydy Mts. However, the deforestation has been carried out during the monitored period, and young trees have consequently appeared in the last decades. The resulting actual evapotranspiration exhibits apparent decreasing tendencies as the response to the conditions of the trees, inclusive of afforestation. The modelling for this forested Raztoka basin also provides similar results, illustrated in Figure 5. An average monthly evapotranspiration shows a surprising view of the long-term annual cycle course of ET_{actual} monthly amounts for several partial periods. It is presented on the semi-logarithmic scale. The ET_{actual} minimums exhibit a surprising course during winters. It is caused in response to the cutting of the trees. The ascertaining of evapotranspiration along with the optimisation of the model parameters may be a useful approach for precise simulations, which is desirable. Figure 4 provides another look at the differences in ΔET, which confirm the strongly assumed influence of forest changes. The similar assumption connected with the differences between discharges observed and simulated in the lowest graph in Figure 5 could be complemented with the monthly fluctuations in differences of $\Delta ET = ET_{demand} - ET_{actual}$ in the semi-logarithmic scale in (Figures 4) (Figures 5). It could be considered a response to the deforestation and a distinct tendency in the annual amounts of the ΔET. It may also be valid as the distinct response on the initial deforestation and the following growth of trees. The distinct variability and tendencies in these graphs could permit some interpretation of the rainfall-runoff modelling. This document likely details quite diverse situations (i.e., the phenomena requiring attention regarding water uses).[29]

Conclusion

Vegetation evolution is one of the natural causes for the usual annual oscillations in water resources. However, the significant reason for the fluctuations could also be the development on the scale of decades. This might affect the long-term evapotranspiration variability, which is also due to the large wind disasters causing damage to the vegetation cover and/or the increase of wood volume in forests. One of the three evaluated basins with forest cover has gradually been entirely reforested. The modelling of the rainfall-runoff process appears helpful in the efforts to decrease uncertainties in the water regime due to the usual emerging natural fluctuations and/or the seemingly random abrupt changes due to forest disasters. The optimisation process used in this context appears to be an efficient tool to appreciate the decreased or increased evapotranspiration. The MVRMSE has been used as the objective function in the GA. This feature provides the best results for the observed watersheds. The course of differences between the observed and simulated discharges helps evaluate the variability in the current changes. It enables us to identify the intervals for which the evapotranspiration needs could be expected to be a stable process. Then, the model implementation and simulations, with newly optimal values of the model parameters and of the evapotranspiration, could be reached for partial time intervals within the whole period. The changes in vegetation cover and the resulting changed evapotranspiration could be connected with the infiltration. It means that, after optimisation, the model parameters have other values for different periods, and this has been ascertained mainly in the basin with the reforestation of its cover.

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Conflict of interest

Authors declare there is no conflict of interest in publishing the article.

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