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Multi-model climatic water balance prediction in the Zala River Basin (Hungary) based on a modified Budyko framework

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Abstract: Providing information on the impacts of climate change on hydrological processes is becoming ever more critical. Modelling and evaluating the expected changes of the water resources over different spatial and time scales can be useful in several fields, e.g. agriculture, forestry and water management. Previously a Budyko-type spatially distributed long-term climate-runoff model was developed for Hungary. This research includes the validation of the model using historical precipitation and streamflow measurements for three nested sub-catchments of the Zala River Basin (Hungary), an essential runoff contributing region to Lake Balaton (the largest shallow lake in Central Europe). The differences between the calculated (from water balance) and the estimated (by the model) mean annual evapotranspiration varied between 0.4% and 3.6% in the validation periods in the sub-catchments examined. Predictions of the main components of the water balance (evapotranspiration and runoff) for the Zala Basin are also presented in this study using precipitation and temperature results of 12 regional climate model simulations (A1B scenario) as input data. According to the projections, the mean annual temperature will be higher from period to period (2011–2040, 2041–2070, 2071–2100), while the change of the annual precipitation sum is not significant. The mean annual evapotranspiration rate is expected to increase slightly during the 21st century, while for runoff a substantial decrease can be anticipated which may exceed 40% by 2071–2100 relative to the reference period (1981–2010). As a result of this predicted reduction, the runoff from the Zala Basin may not be enough to balance the increased evaporation rate of Lake Balaton, transforming it into a closed lake without outflow.

Keywords: Evapotranspiration; Runoff; Budyko-model; Water balance; Climate change.

INTRODUCTION

One of the most significant effects of climate change in Hungary and the Carpathian Basin region is its impact on the water cycle through the change in precipitation and evapotranspiration patterns at multiple scales (Kohnová et al., 2019; Labudová et al., 2015; Nováky and Bálint, 2013; Pongrácz et al., 2014; Rončák et al., 2019; Szilágyi and Józsa, 2008). The global hydrological cycle has accelerated in recent decades (Cui et al., 2018; Lugato et al., 2013; Troch, 2008), and according to climate projections, this will probably continue (IPCC, 2019). This acceleration may cause more frequent and severe hydrological extremes with possible negative impacts on ecosystems, human health, water system reliability and operating costs (Bates et al., 2008; Kundzewicz and Matczak, 2015).

The frequency of climatic extremes (e.g. the number of consecutive dry days, the number of heavy precipitation days, the number of hot days, the number of hot nights) has increased in the Carpathian Basin region by the end of the 20th century (Pogačar et al., 2019; Pongrácz and Bartholy, 2006; Spinoni et al., 2015). Increasing average air temperature and decreasing summer precipitation are projected for the region (Anders et al., 2014; Kohnová et al., 2019; Nováky and Bálint, 2013). These will probably lead to increased evapotranspiration and decreased runoff. As a result, less water will be available to meet various demands, especially irrigation. A significant reduction of water resources is expected, which may cause a considerable decrease in the inflows of the Lake Balaton, the largest shallow lake in Central Europe.

Information on local or regional climate change impacts on hydrological processes is becoming increasingly significant (Karamouz et al., 2013; Stagl et al., 2014). Modelling and evaluating the expected changes in water resources over different time scales is important for water management, agriculture and forestry in the Carpathian Basin region (Hlásny et al., 2014; Mátyás et al., 2018; Škvarenina et al., 2009).

Several water balance models/frameworks have been developed, which are based on the relationship between an aridity index (e.g. the ratio of annual potential evapotranspiration to precipitation) and the evapotranspiration ratio (e.g. the ratio of actual annual evapotranspiration to precipitation) (e.g. Budyko, 1974; Fu, 1981; Mezentsev, 1955; Ol'dekop, 1911; Pike, 1964; Parajka et al., 2004; Porporato et al., 2004; Schreiber, 1904; Turc, 1954; Wang and Tang, 2014; Zhang et al., 2004). They are often used to estimate the long-term hydrological impacts of climate change (e.g. Arora, 2002; Jiang et al., 2015; Lv et al., 2019; Ning et al., 2018; Renner and Bernhofer, 2012; Shen et al., 2017; Teng et al., 2012; Wang et al., 2016), as catchment scale (lumped) models. Based on these frameworks, the elasticity of climate change impacts has also been tested in numerous studies (Andréassian et al., 2016; Gao et al., 2016; Konapala and Mishra, 2016; Liang et al., 2015; Tian et al., 2018; Wang and Hejazi, 2011; Zhang et al., 2016; Zhou et al., 2015).

The frameworks, as mentioned above, have also been used for hydrological studies in the Carpathian Basin region. Water balance estimations based on the Turc (1954) model were completed in Slovakia by Danihlik et al. (2004) for the upper part of the Hron river basin and Hlavčová et al. (2006) for the whole country. Nováky (1985, 2002) developed a Budyko-type spatially distributed (grid-based) empirical climate-runoff model for the Zagyva catchment in Hungary. This model has also been applied for the Lake Balaton basin (Nováky, 2008) and the Bácsbokodi-Kígyós catchment (Keve and Nováky, 2010).

There are many areas in the Carpathian Basin where the long-term mean annual actual evapotranspiration exceeds the long-term mean annual precipitation, that is, an additional amount of water is available for evapotranspiration above that which the area receives from local precipitation. These are mainly water bodies or storages with allochthone inflow, such as lowland rivers, lakes, wetlands and groundwater exfiltration areas. The additional incoming water can originate from surface or groundwater inflows (we use the term additional water here). The Budyko framework is not valid for these areas. A limited number of previous studies deal with the extension of the framework for conditions with additional water (Chen et al., 2013; Greve et al., 2016; Zhang et al., 2008). Csáki et al. (2014, 2018) extended the Budyko framework-based Nováky (1985, 2002) model to handle the areas (grid clusters) with additional water in Hungary. However, a detailed assessment of the accuracy, as well as the validation of the spatially distributed model, has not yet been performed.

Thus, an objective of this study was a validation of the spatially distributed climate-runoff model (Csáki et al., 2014, 2018), including areas with additional water. Further, based on the validation, hydrological predictions for the 21st century were performed in order to analyze the possible climate change impacts in the Zala River Basin (Hungary), which is the most important water supply region of Lake Balaton.

We structured the paper in the following manner. After the “Introduction”, the “Material and methods” section describes the spatially distributed climate runoff model, its calibration and validation methodology as well as the procedure of the model application for the hydrological predictions. The description of the pilot basin and the data used are included here, too. “Results and discussion” contain the model validation, the prediction of the hydrological balance under climate change and the discussion of the results. The following “Conclusions” complete the study.

MATERIAL AND METHODS

Long-term mean annual climate-runoff model

Previously a Budyko-type gridded climate-runoff model (Nováky, 2008) was developed by Csáki et al. (2014, 2018) for estimating the long-term mean annual actual evapotranspiration and runoff in Hungary. The model employs two parameters, α and β mapped in grids. These parameters aggregate all of the factors affecting evapotranspiration, the most dominant of them being the land cover (Keve and Nováky, 2010).

The α parameter follows the Budyko framework (Budyko, 1974), more precisely, the Schreiber equation (Fraedrich, 2010; Schreiber, 1904) and a pan-evaporation equation for the “class U” evaporation pan according to Nováky (1985, 2002).

The long-term mean annual potential evapotranspiration, as proposed by Schreiber, is estimated as:

$$ET_P = -P\left(\ln\left(\frac{P-ET_A}{P}\right)\right), \tag{1}$$

where ET_P is the long-term mean annual potential evapotranspiration (mm yr^{-1}), P is the long-term mean annual precipitation (mm yr^{-1}), and ET_A is the long-term mean annual actual evapotranspiration (mm yr^{-1}).

Long-term mean annual potential evapotranspiration can also be expressed as a function of the “class U” (with 3 m^2 water surface area, 0.5 m depth) pan evaporation, according to a general relationship valid for Hungary (Nováky, 1985, 2002), as:

$$ET_P = f\left(E_{pan}\right) = \alpha E_{pan} = \alpha\left(36400\frac{T}{P}+104\right), \tag{2}$$

where E_{pan} is the long-term mean annual pan evaporation (mm yr^{-1}), T is the long-term mean annual air temperature (°C), and α is a regional calibration parameter. Note that the long-term mean annual pan evaporation equation $\left(36400\frac{T}{P}+104\right)$ was developed for Hungary by Nováky (2002), using data from several “class U” evaporation pans (Nováky, 1985). We may consider these pan evaporation rates as close to the wet environment evapotranspiration rates (Priestley and Taylor, 1972); therefore, they are more appropriate for climate change modelling than the “class A” pan-based potential evapotranspiration rates, which are very sensitive to the local environmental conditions (e.g. the dryness of the area surrounding the pan).

The parameter α can be calculated from the Equations (1) and (2) as:

$$\alpha = \frac{ET_P}{E_{pan}} = -\frac{P\left(\ln\left(\frac{P-ET_A}{P}\right)\right)}{36400\frac{T}{P}+104}. \tag{3}$$

Under local conditions where additional water is available for actual evapotranspiration to that of the local precipitation, the Budyko model cannot be valid, thus the α parameter in Eq. (3) is not defined. For these areas, another local/regional calibration parameter β, which relates E_{pan} to ET_A (McMahon et al., 2012), can be proposed as:

$$\beta = \frac{ET_A}{E_{pan}} = \frac{ET_A}{36400\frac{T}{P}+104}. \tag{4}$$

For such conditions, we assume in our model that the actual evapotranspiration is not water-limited, therefore it depends only on the land cover type of the given grid(s). The parameter β is similar to the crop coefficient as used by Allen et al. (1998), which is the ratio of crop evapotranspiration (in our model represented by ET_A for an area with additional water) to reference potential evapotranspiration (in our model represented by E_{pan}). The β parameter integrates the specific local conditions of that area with additional water. The actual evapotranspiration (ET_A) of such area (grid) in our model is calculated by multiplying the estimate of the “class U” pan evaporation (E_{pan}) by the value of β.

The spatially distributed values of the parameters α and β in our model are derived using Eq. (3) and Eq. (4), (with map algebra in a GIS) from maps of ET_A, P and T with a spatial resolution of 1 km^2. These parameter maps can be used for evaluating ET_A in a spatially distributed manner, for which only spatial estimates of T and P are required as gridded inputs.

Actual evapotranspiration (ET_A) in grids, where the Budyko hypothesis holds, the model calculations are based on α:

$$ET_A = P\left(1-\exp\left(-\frac{\alpha\left(36400\frac{T}{P}+104\right)}{P}\right)\right), \tag{5}$$

whereas in grids with additional water ET_A is calculated using β as:

$$ET_A = \beta E_{pan} = \beta\left(36400\frac{T}{P}+104\right). \qquad (6)$$

The study area and input data

The Zala River provides the most significant inflow of water to Lake Balaton (Virág, 1997), which is the largest shallow lake in Central Europe (Dokulil et al., 2010). The Zala River Basin flows through the western part of Hungary (Fig. 1). The basin covers an area of 1520.7 km^2, the length of the main channel is 104 km. The long-term (1980–2008) mean discharge is 4.6 m^3 s^{-1} at the “Zalaapáti” gauging station.

The altitude ranges from 100 m a.s.l. to 334 m a.s.l. The basin has a moderately cool and moderately humid climate with a mean annual temperature of 10.4°C. The mean monthly temperature varies from about −1.7°C (West) and −0.9°C (East) in January to 19.5°C (West) and 20.5°C (East) in July. The long-term mean annual precipitation is 800 mm in the west and 660 mm in the eastern part of the basin.

The hydrological balance of the basin was studied in three nested sub-catchments, with increasing basin area. The three sub-catchments are labelled by the names of the cities/towns of the respective gauging stations: 1 - “Zalaegerszeg”, 2 - “Zalabér” and 3 - “Zalaapáti” (Fig. 1). According to the CORINE Land Cover database (CLC, 2006; Table 1), agriculture is the dominant land use of the Zala Basin (57.5% of the total area). “Forests and semi-natural areas” cover 36.5% of the area, while “Artificial surfaces” (which include urban areas, roads, mines, and similar categories) cover 5.1% of the surface. The categories “Wetlands” and “Water bodies” are rather insignificant, comprising 0.3% and 0.6% of the total area, respectively.

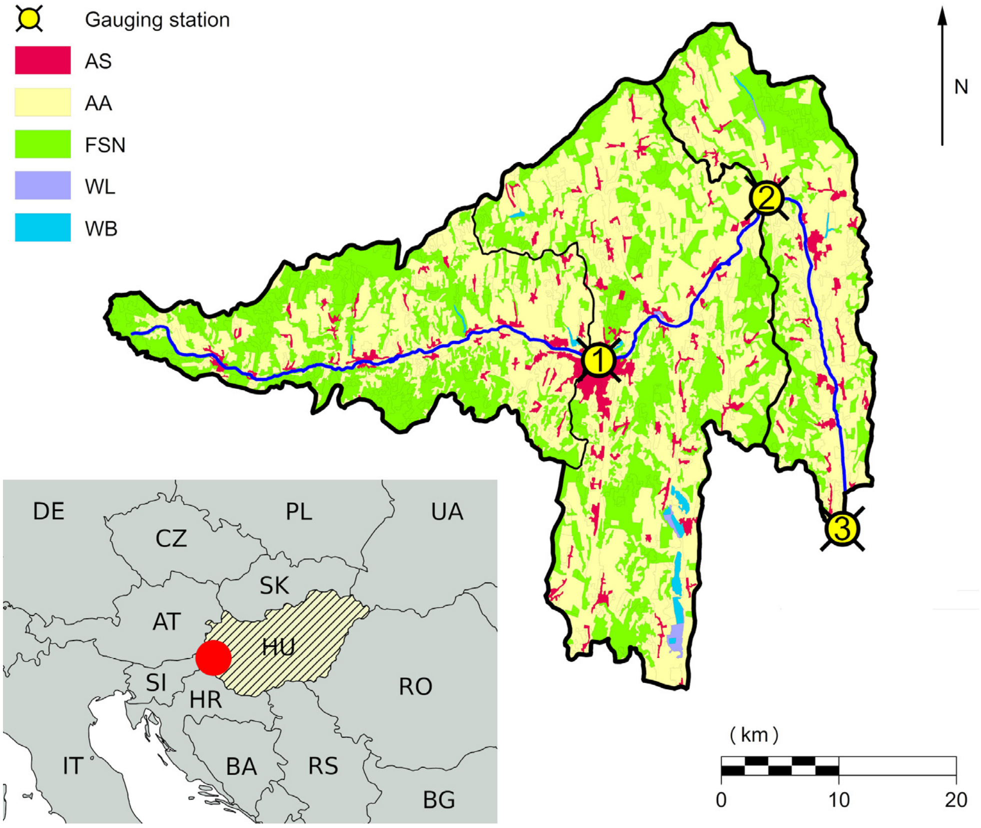

Fig. 1. Location of Hungary (hatched lines) and the Zala River Basin (red) within Europe, the three nested sub-catchments, their land cover and location of the gauging stations. CORINE Land Cover (CLC, 2006) categories are labelled as: AS - Artificial surfaces, AA - Agricultural areas, FSN - Forest and semi-natural areas, WL - Wetlands, WB - Water bodies. The sub-catchments are labelled by the names of the cities/towns of the respective gauging stations: 1 - “Zalaegerszeg”; 2 - “Zalabér”; 3 - “Zalaapáti”.

Table 1. The proportions of the respective land cover categories within the three nested sub-catchments: AS - Artificial surfaces, AA - Agricultural areas, FSN - Forest and semi-natural areas, WL - Wetlands, WB - Water bodies.

Corine land cover categories	Sub-catchment					
	1 - “Zalaegerszeg”		2 - “Zalabér”		3 - “Zalaapáti”	
	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)
AS	21.3	4.7	61.9	5.3	78.0	5.1
AA	228.3	49.7	654.7	56.1	874.2	57.5
FSN	207.9	45.3	439.1	37.6	554.9	36.5
WL	–	–	3.8	0.3	4.3	0.3
WB	1.4	0.3	8.6	0.7	9.3	0.6
Catchment area (km^2)	458.9		1168.1		1520.7	

For the Carpathian Basin, a gridded database of climate data was made available in the frame of the "CarpatClim" project (Lakatos et al., 2013; Szalai et al., 2012). The database includes gridded precipitation and air temperature data (P, T) with a spatial resolution of 0.1° (8 km × 12 km) for the period 1961–2010, estimated using the MISH (Meteorological Interpolation based on Surface Homogenized data basis) interpolation method for gridding (Szentimrey and Bihari, 2007) from climatological observations. As part of the EU-national project "Agroclimate" (Gálos et al., 2015) the "CarpatClim" precipitation and temperature data were further downscaled to a finer resolution of 1 km × 1 km, using a GIS software module developed by Czimber and Gálos (2016).

Monthly actual evapotranspiration (ET_{Am}) rates for the period of 2000–2008 have been mapped (in 1 km × 1 km spatial resolution) by Szilágyi and Kovács (2011) with the CREMAP (complementary-relationship-based evapotranspiration mapping) model, which is an established method in Hungary. Using their grid-based monthly maps, we prepared the long-term mean annual actual evapotranspiration (ET_A) map for the same nine-year period, which was used in this study.

Validation methodology of the CREMAP model outputs and the parameters maps of α and β

As for the validation of the CREMAP model data, we simply compared the estimated nine-year mean annual actual evapotranspiration (as estimated by CREMAP) with their water balance-based values (calculated using discharge data).

For the validation of our model (the parameters maps of α and β), 20 years (1980–1999) from the downscaled observed precipitation and temperature gridded data (based on the "CarpatClim" database) and observed streamflow (runoff, R) data were used for the Zala Basin's three nested sub-catchments. The runoff data, which was provided by the West-Transdanubian Water Directorate ("NYUDUVIZIG"), was estimated for each of the nested sub-catchments using rating curves and the measured water levels. For validation, the data was divided into three 10-year, partially overlapping, periods: 1980–1989, 1985–1994, and 1990–1999. For each of the periods and each of the sub-catchments, the long-term mean annual actual evapotranspiration values were calculated from the simplified water balance equation (Eq. (7)) and were also estimated by our model (with the α and β maps created by Eq. (5) and Eq. (6)).

$$ET_A = P - R, \tag{7}$$

where ET_A is the long-term mean annual actual evapotranspiration (mm yr^{-1}), P is the long-term mean annual precipitation (mm yr^{-1}), and R is the long-term mean annual runoff (mm yr^{-1}).

Then, we determined the difference (bias) between the water balance-based and the modelled values of the actual evapotranspiration.

Data for model predictions for future water balance estimations

For estimating the future long-term mean annual actual evapotranspiration, besides the Budyko-type α and β parameter maps (which were estimated using Eq. (3) and Eq. (4) on the data from the instrumental period), projected air temperature and precipitation data for the changing climate were required. They were obtained from outputs of 12 regional climate models (RCMs) using the SRES A1B (moderate) emission scenario (ENSEMBLES project: van der Linden and Mitchell, 2009; IPCC, 2007; Table 2). The original grid size of the RCM data was 25 km × 25 km. They were disaggregated (downscaled) to the resolution of 1 km × 1 km, using a GIS software module developed in C++ by Czimber and Gálos (2016), in the frame of the "Agroclimate" project (Gálos et al., 2015).

Table 2. The used regional climate models (RCMs) from the ENSEMBLES project (van der Linden and Mitchell, 2009), and the respective original General Circulation Models (GCM).

Nr.	RCM	GCM
1.	RCA3	HadCM3Q16
2.	REMO	ECHAM5
3.	CLM	HadCM3Q0
4.	RACMO2	ECHAM5-r3
5.	HIRHAM5	ARPEGE
6.	HIRHAM5	ECHAM5
7.	RCA	BCM
8.	RCA	HadCM3Q3
9.	RCA	ECHAM5-r3
10.	HadRM3Q0	HadCM3Q0
11.	HadRM3Q3	HadCM3Q3
12.	HadRM3Q16	HadCM3Q16

In the predictions of the future climate Eq. (5) and Eq. (6) were used for estimating the spatially distributed (gridded) future long-term mean annual actual evapotranspiration. The predictions of the long-term mean annual runoff on sub-catchment scale were calculated from the long-term water balance equation (Eq. (7)) as the difference between the areal average of the long-term mean annual precipitation and the estimated future actual evapotranspiration over each sub-catchment.

We made such estimates for three time periods (2011–2040, 2041–2070, 2071–2100) and determined the expected changes in the water balance components relative to the reference period (1981–2010) for each sub-catchment.

RESULTS AND DISCUSSION

Evaluation and validation of the CREMAP model data over the period 2000-2008

Table 3 contains the meteorological data (temperature, precipitation), the measured runoff data and the results of the CREMAP actual evapotranspiration validation over the 2000–2008 period for the three sub-catchments of the Zala River Basin (as the nine-year mean annual rates, averaged for the sub-catchment areas). For the CREMAP validation, the nine-year mean annual actual evapotranspiration was calculated for the sub-catchments using the simplified long-term water-balance equation (Eq. (7)).

The western sub-catchment (1 - "Zalaegerszeg") was colder and wetter than the two larger sub-catchments (2 - "Zalabér" and 3 - "Zalaapáti") in the validation period. The nine-year mean annual (water balance-based) actual evapotranspiration of the total area examined (3 - "Zalaapáti") was 555 mm yr^{-1}, 89.7% of the mean annual precipitation. The mean annual measured runoff was 64 mm yr^{-1}, the 10.3% of the mean annual precipitation.

Table 3. Validation of the CREMAP model actual evapotranspiration against the water balance equation in the 2000–2008 period in the three nested sub-catchments. T is the mean annual air temperature ("CarpatClim"), P is the mean annual precipitation ("CarpatClim"), R is the mean annual measured runoff ("NYUDUVIZIG"), ET_{WB} is the mean annual actual evapotranspiration from water balance calculation ($ET_{WB} = P - R$), ET_{CREMAP} is the estimated mean annual actual evapotranspiration (CREMAP model), and ET_{diff} is the difference between the water balance-based and the estimated evapotranspiration ($ET_{diff} = ET_{WB} - ET_{CREMAP}$). ET_{WB}/P and R/P represent the proportions of actual evapotranspiration to precipitation and runoff to precipitation, respectively.

Sub-catchment	T	P	R	ET_{WB}	ET_{CREMAP}	ET_{diff}		ET_{WB}/P	R/P
	(°C)	(mm yr^{-1})	(mm yr^{-1})	(mm yr^{-1})	(mm yr^{-1})	(mm yr^{-1})	(%)	(%)	(%)
1 - "Zalaegerszeg"	10.7	640	63	577	567	10	1.7	90.1	9.9
2 - "Zalabér"	10.8	629	67	562	566	−4	0.6	89.4	10.6
3 - "Zalaapáti"	10.9	619	64	555	569	−14	2.4	89.7	10.3

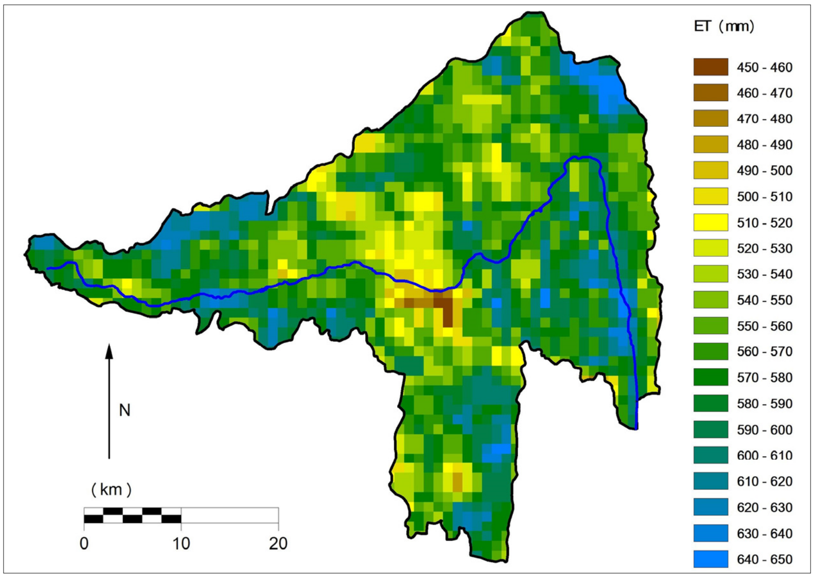

Fig. 2. The nine-year (2000–2008) mean actual annual evapotranspiration over the Zala River Basin based on CREMAP model data (spatial resolution 1 km^2).

The differences between the nine-year mean annual water balance-based and the mean estimated (CREMAP model) actual annual evapotranspiration are: 1.7% (10 mm yr^{-1}) for the 1 - "Zalaegerszeg" sub-catchment, 0.6% (−4 mm yr^{-1}) for the 2 - "Zalabér" sub-catchment, and 2.4% (−14mm yr^{-1}) for the total area examined (3 - "Zalaapáti"). These results verify that the CREMAP spatially distributed gridded evapotranspiration data can be used for water balance modelling in the Zala River Basin and as a basis for the estimation of the two parameters of our model.

The spatial variability of the nine-year (2000–2008) mean actual annual evapotranspiration (ET_{CREMAP}) based on the CREMAP data is depicted in Fig. 2. Brown and yellow grids show lower rates (e.g. the city Zalaegerszeg and its surroundings in the centre of the basin), green and blue grids show higher evapotranspiration rates (mainly in the western, north-eastern and south-eastern parts of the basin).

Evaluation and validation of the proposed climate-runoff model parameters

The α and β parameter maps, as estimated by Eq. (3) and Eq. (4) using the CREMAP model data, for the Zala Basin can be seen in Fig. 3. The α values cover 89% of the basin, and only 11% belongs to β (additional water-affected areas). In the case of α, violet and blue grids show higher, red and orange grids show lower parameter values. In the case of β, the parameter values are growing from light blue to the direction of dark blue. The validation process of the model parameters was done according to the method described in the previous chapter using data from the partially overlapping decades 1980–1989, 1985–1994, 1990–1999. Table 4 contains the results of the validation.

The differences (ET_{diff}; i.e. model bias) between the calculated (from the water balance, ET_{WB}) and the estimated (by the proposed model, ET_{model}) mean annual evapotranspiration are 0.7% (4 mm yr^{-1}), 1.2% (7 mm yr^{-1}) and 3.6% (22 mm yr^{-1}) in the 1 - "Zalaegerszeg" sub-catchment, and 0.5% (3 mm yr^{-1}), 1.0% (6 mm yr^{-1}) and 3.3% (20 mm yr^{-1}) in the 2 - "Zalabér" sub-catchment. In the case of the total basin area (3 - "Zalaapáti") the differences are 0.4% (2 mm yr^{-1}), 0.7% (4 mm yr^{-1}) and 2.7% (16 mm yr^{-1}). In the period 1990–1999 the model bias is a bit higher (but still relatively low) for all three sub-catchments. One possible explanation of it is that this period was relatively wet (compared to the other two periods) and therefore the areas with additional water probably expanded during these years. In consequence, the number of model grids with the β parameter (Eq. (6)) was underestimated using the information of the calibration period (2000–2008). A larger number of grids with β would increase evapotranspiration, and this cannot be followed by the model based on the 2000–2008 period, so for the period 1990–1999 the model slightly underestimates ET.

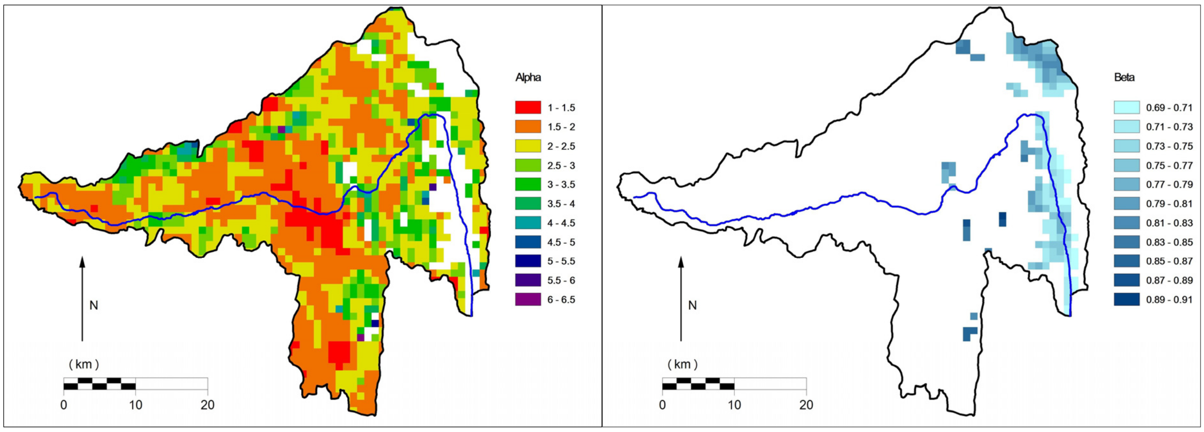

Fig. 3. The spatial variability of the α (left) and β parameters (right) of the proposed climate-runoff model over the Zala River Basin (spatial resolution 1 km^2).

Table 4. Validation results of the proposed climate-runoff model for the sub-catchments of the Zala River Basin in the three validation periods. *P* is the mean annual precipitation (“CarpatClim”), *R* is the mean annual measured runoff (“NYUDUVIZIG”), ET_{WB} is the mean annual actual evapotranspiration from water balance calculation ($ET_{WB} = P - R$), ET_{model} is the mean annual estimated actual evapotranspiration and ET_{diff} is the difference between the water balance-based and the estimated evapotranspiration ($ET_{diff} = ET_{WB} - ET_{model}$) in absolute values and in percentages.

Sub-catchment	Period	*P*	*R*	ET_{WB}	ET_{model}	ET_{diff}	
		(mm yr^{-1})	(mm yr^{-1})	(mm yr^{-1})	(mm yr^{-1})	(mm yr^{-1})	(%)
1 - “Zalaegerszeg”	1980–1989	698	131	567	571	4	0.7
	1985–1994	684	117	567	574	7	1.2
	1990–1999	716	108	608	586	22	3.6
2 - “Zalabér”	1980–1989	687	112	575	572	3	0.5
	1985–1994	676	107	569	575	6	1.0
	1990–1999	713	104	609	589	20	3.3
3 - “Zalaapáti”	1980–1989	680	114	566	568	2	0.4
	1985–1994	671	103	568	572	4	0.7
	1990–1999	706	106	600	584	16	2.7

Table 5. The average of the long-term changes of mean annual temperature (*dT*), precipitation (*dP*), actual evapotranspiration (*dET*), runoff (*dR*) predicted by 12 RCMs, and the standard deviations (*SD*) of *dET* and *dR*. Reference period: 1981–2010.

Sub-catchment	Period	Change (relative to 1981–2010)			
		dT	*dP*	*dET (SD)*	*dR (SD)*
		(°C)	(mm yr^{-1})	(mm yr^{-1})	(mm yr^{-1})
1 - “Zalaegerszeg”	2011–2040	0.9	0	7 (16)	−8 (27)
	2041–2070	2.1	8	22 (21)	−14 (23)
	2071–2100	3.2	−12	20 (36)	−31 (29)
2 - “Zalabér”	2011–2041	0.9	1	8 (15)	−7 (27)
	2041–2071	2.0	9	22 (21)	−14 (23)
	2071–2101	3.2	−11	20 (35)	−31 (28)
3 - “Zalaapáti”	2011–2042	0.9	1	10 (14)	−9 (30)
	2041–2072	2.0	10	25 (21)	−16 (26)
	2071–2102	3.2	−9	27 (36)	−36 (35)

Evapotranspiration and runoff predictions for future climates

Modelling the possible climate change impacts in the Zala River Basin and its sub-catchments was performed according to the previously described methodology. We estimated the long-term mean annual actual evapotranspiration (ET_A) and runoff (*R*) for three time periods (2011–2040, 2041–2070, 2071–2100) with downscaled data from the 12 RCMs (Table 1) and evaluated the expected changes relative to the reference period 1981–2010. The average of the respective long-term means of the changes predicted by the RCMs (relative to the reference period) of mean annual temperature, precipitation, evapotranspiration and runoff are summarized in Table 5.

According to the RCMs’ projections, in the case of the long-term mean annual temperature, an increasing trend is expected during the 21st century. It is projected to be more than 3°C higher in the period 2071–2100 relative to the reference period in all three sub-catchments. However, the change in the long-term mean annual precipitation (*dP*) is not significant; a small increase (8–10 mm yr^{-1}) is projected for 2041–2070, and a slight decrease (9–12 mm yr^{-1}) for 2071–2100, when compared to the time period of 1981–2010. In consequence, an increase can be detected in the long-term mean annual actual evapotranspiration rates for all sub-catchments during the 21st century. A smaller increase (7–10 mm yr^{-1}) is expected for the first, and higher increases (20–27 mm yr^{-1}) for the second and third periods. Due to this, in the case of long-term mean annual runoff, a significant decrease can be detected. The highest decrease is estimated for the third period (31–36 mm yr^{-1}), compared to the reference period. The highest standard deviation values belong to the last period for both cases.

Figs. 4 and 5 illustrate the expected changes of long-term mean annual actual evapotranspiration and runoff in percentages across the ensemble of the 12 RCMs as box and whiskers plots (Venables and Ripley, 1999). The spread – based on the simulation results of the ensemble of 12 RCMs – shows the uncertainty in the predictions, which grows from period to period (in the 21st century). For the middle of the century (2041–2070), on average, a higher evapotranspiration increase is predicted (3.3–4.2%, Fig. 4). In the case of 3 - “Zalaapáti”, 1.6%, 4.2%, and 4.4% increases in the averaged long-term mean evapotranspiration can be detected in the first, second, and third time period, respectively, compared to the reference period (1981–2010). The maximum increase can exceed 12.0% by the end of the century. The decrease in the averaged long-term mean runoff may exceed 40.0% by the end of the century, compared to the reference period, for all sub-catchments (Fig. 5). For the examined total basin area (“Zalaapáti”), the averaged long-term mean values may decrease by 21.2%, 33.2% and 53.4%, respectively. The estimated overall increase in the long-term evapotranspiration and the significant decrease in long-term runoff can lead to possible serious consequences, such as the risk of the severe deterioration of the local wetlands (e.g., Little-Balaton wetland area) no excluding a drying out. According to the predictions, the water supply to Lake Balaton may significantly decline.

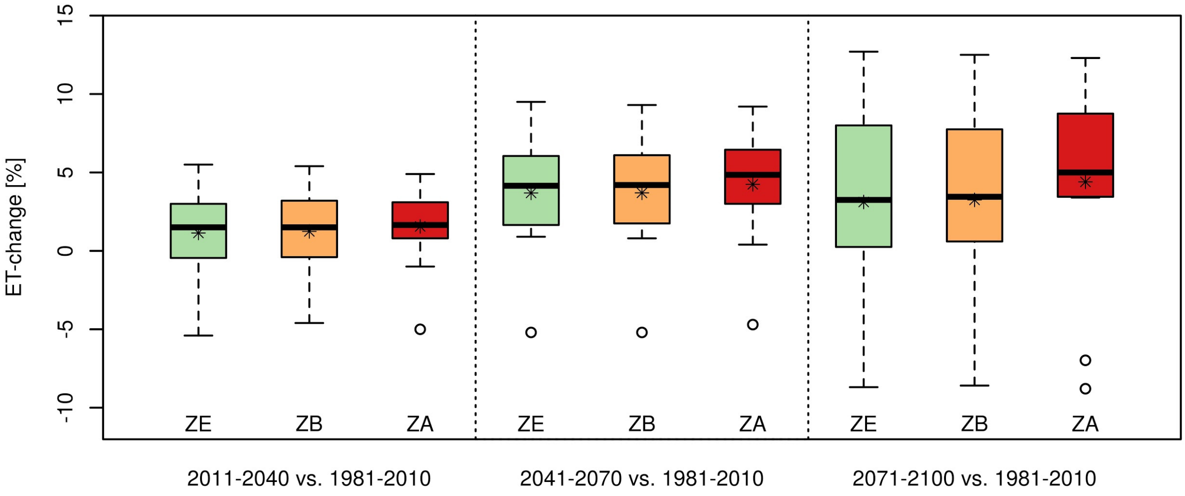

Fig. 4. The predicted changes in long-term mean annual actual evapotranspiration (*ET*) rates across the RCM ensemble. Reference period: 1981–2010. ZE: 1 - “Zalaegerszeg”, ZB: 2 - “Zalabér”, ZA: 3 - “Zalaapáti”.

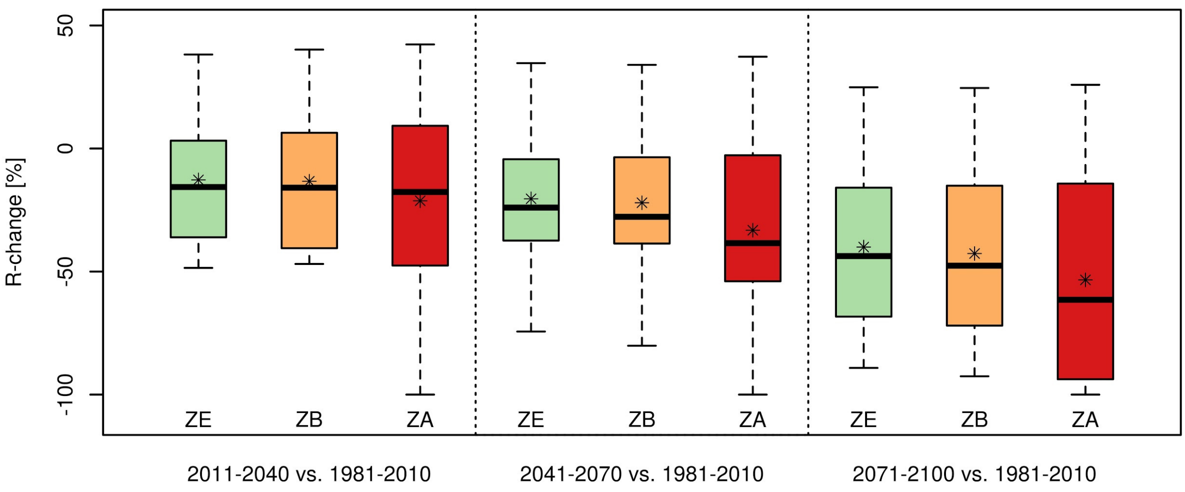

Fig. 5. The predicted changes in long-term mean annual runoff (*R*). Reference period: 1981–2010. ZE: 1 - “Zalaegerszeg”, ZB: 2 - “Zalabér”, ZA: 3 - “Zalaapáti”.

The uncertainties of the presented model predictions stem from the following sources: uncertainty of the CREMAP model evapotranspiration and the interpolated "CarpatClim" meteorological data (used for calculating the presented climate-runoff model parameters), and the spread of the downscaled climate projections (the regional climate models). Further, although an increase in the frequency and duration of the dry periods are expected, the proposed climate-runoff model cannot handle the reduction of the number of β-type grids (areas with additional water) for such scenarios in the future. In its present version, we cannot change the β-type grids to α-type ones, since during the model calibration period (2000−2008) these grids were affected by additional water, where the Budyko hypothesis (used for calculating the α model parameters) was not valid. Thus, our future aim is to solve the β to α transformation of a given grid in the development of the next version of the model.

Comparison with other model predictions for the Carpathian Basin

In order to examine the credibility of the results obtained, we compared them with other predictions made for the region. For Hungary and the Carpathian Basin, relatively few long-term hydrological climate change predictions have been published. Comparing hydrological predictions achieved by different models is not a simple task. The predictions were made for diverse areas, with various time steps (daily, monthly, seasonal, annual, long-term), reference and predicted time periods. In order to underpin the plausibility of our results, a comparison of the tendencies of the different predictions is attempted.

Nováky (2008) examined the possible effects of climate change on the water balance of Lake Balaton, until the middle of the 21st century. The runoff from the basin of the lake was calculated with the Budyko-type spatially distributed empirical climate-runoff model. The conclusions of the analysis are supporting our results: the drying climate is very likely to lead to worsening of the average water balance of the lake. By 2050 the decreasing runoff and inflow may not be enough to balance the increasing rate of evaporation from the lake, which could degrade into a closed lake without outflow (which is feeding the Sió River in present climatic conditions).

Keve and Nováky (2010) also used the Budyko-type spatially distributed empirical climate-runoff model for the Bácsbokodi-Kígyós watershed (South Hungary), under different climate scenarios. According to their results, by the period 2021–2040, the average decrease of the mean annual runoff may be 43%, compared to the reference period (1977–1998). Based on the most pessimistic climate scenario, the decrease can reach 61%.

The expected changes of runoff for the watershed of Zagyva-Tarna (North Hungary) were modelled in Kis et al. (2015) by the DIWA (Distributed Watershed hydrological model, Szabó, 2007), on daily and annual time steps. By the period of 2070–2099, much lower annual runoff rates appeared than in the reference period (1976–2005). However, floods may become more intense and more frequent. Kis et al. (2017) also examined the Upper Tisza Basin by the DIWA model. They concluded that the yearly average of the runoff values is estimated to decrease during the 21st century. On a seasonal scale, decreasing runoff is predicted for spring, summer, and autumn, while a substantial runoff increase in winter.

Herceg et al. (2016) developed a Thornthwaite-type monthly water balance model, which is also based on the CREMAP evapotranspiration rates as reference values. They examined the possible future changes of actual evapotranspiration and soil moisture for two study areas in Northwest Hungary (a forested catchment and an area with mixed land cover). Although the model is not spatially distributed and it uses a monthly time step, the analysis arrived at similar tendencies like our results here. According to their estimates, the long-term monthly average evapotranspiration may increase by 11% for both areas by the end of the 21st century, compared to the 1980–2010 reference period. In addition, sharply decreasing values of the soil moisture minimum (i.e. the minimum soil moisture available for the plants) are predicted: −48% and −32%, for the area with mixed land cover and the forested area, respectively. The soil water resources may decrease drastically in the summer periods because of the increasing evapotranspiration and declining recharge from precipitation.

Danihlik et al. (2004) evaluated the potential impact of climate change on river runoff in the upper part of the Hron River in Slovakia. For long-term predictions an empirical grid-based model (Parajka et al., 2004; based on the Turc (1954) model), while for monthly predictions a conceptual spatially-lumped water balance model was used (Hlavčová et al., 2002). They examined the possible changes for the time horizons 2010, 2030 and 2075 compared to a reference period (1951–1980), using data from four climate change scenarios. A decrease in the long-term mean annual runoff is expected in the upper Hron River basin, according to all scenarios and time horizons (−5% to −16% for the time horizon 2010, −5% to −27% for 2030, and −13% to −45% for 2075). They concluded that the effects of an increase in temperature would be decisive for these changes, even in cases when an increase in precipitation is expected. According to the seasonal analysis, the basin could become vulnerable to drought in the summer and early autumn, and the intensity of the changes could increase towards the time horizon 2075. These findings are in agreement with our results and the results of Hlavčová et al. (2006), who used the same method for estimating changes in the long-term mean annual runoff for the whole Slovakia including its border regions with Hungary, and the seasonal changes for five selected basins in Slovakia. It was concluded that – according to two climate change scenarios – most of the territory of the country would be affected by a decrease in the long-term runoff.

All these hydrological predictions may be regarded as an indirect verification of our results for the region. They showed similar tendencies, which validate our main result, namely that a significant long-term mean annual runoff decrease may be expected for the end of the 21st century in the Carpathian Basin.

CONCLUSIONS

Regional modelling and evaluating the possible impacts of climate change on water resources over different time scales is essential for agriculture, forestry, and water management in Hungary and the Carpathian Basin. For this purpose, a long-term climate-runoff model proposed by Csáki et al. (2014, 2018) was further developed in this paper. We presented a complex validation methodology of the climate-runoff model, which was verified for the Zala River Basin (which is an essential runoff contributing region to Lake Balaton, the largest shallow lake in Central Europe). Furthermore, our aim was also extending the methodology to enable climate change impact assessment. In a case study, we performed hydrological predictions for the 21st century using the proposed model and analyzed the possible climate change impacts in the study area. These results were compared to similar studies in the region in order to underpin the plausibility of our results.

The averaged long-term mean annual evapotranspiration and runoff predictions performed for three periods (2011–2040, 2041–2070, 2071–2100) over the Zala River Basin, using the proposed climate-runoff model and downscaled scenarios from an ensemble of 12 regional climate models. The predictions showed, that by the end of the century due to the increase of the long-term mean annual evapotranspiration rate by 4.4% relative to the reference period (1981–2010) a substantial decrease can be detected in the case of long-term mean annual runoff, which may exceed 40.0% for all sub-catchments. It can be concluded that the decreasing runoff from the catchments may not be enough to balance the increased evaporation rate of Lake Balaton, transforming it into a closed lake without outflow with severe ecological consequences.

The main advantage of the proposed model is its robust nature, requiring few input parameters that in turn, result in the lower potential of errors. It can be applied if temperature and precipitation time series (e.g. from regional climate models) are available. Predictions obtained using the model can assist in long-term planning in different fields (water management, agriculture, forestry, etc.) and help decision-makers in formulating the necessary courses of action.

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