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Changes and variability of evapotranspiration sums in Slovakia in 1951–2021

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Abstract: Significant changes in air temperature and precipitation occurred in Slovakia during the second half of the 20th century and mainly in the first two decades of the 21st century. These changes influenced potential and actual evapotranspiration, soil moisture, and runoff in Slovakia. The article discusses changes and variability of evapotranspiration in the period 1951–2021 calculated by Budyko's method, which was modified by Tomlain for Slovakia, and due to climate change, the preparation of the evapotranspiration scenarios until the year 2100. The climatic indicator of irrigation, which shows the water's necessity to cover maximum evapotranspiration demands, was also evaluated from 1951 to 2021. We performed the model computation for 26 higher-quality stations in Slovakia. These stations are located in different climatic, especially humid conditions. The input data are air temperature and humidity, cloudiness, number of days with snow cover, and precipitation. The results of measurements and model calculations are presented in detail from stations Hurbanovo, Košice-airport, and Oravská Lesná. Changes in the normal of analysed phenomena between the 1951–1980 and 1991–2020 periods are shown in the table form for 20 selected stations because of limited space. The scenarios of potential evapotranspiration change until 2100, prepared by two regional circulation models (RCM) outputs, are presented at the end of the study. The results confirmed the growth of potential evapotranspiration in 1951–2021 and until 2100, while the actual evapotranspiration depends on soil moisture, which is mainly decreasing. The climatic irrigation index indicates the slightly increasing linear trend in Slovakia from 1951 to 2021.

Key words: actual and potential evapotranspiration, Budyko-Tomlain method, climatic irrigation indicator, scenarios of evapotranspiration

1. Introduction

Evapotranspiration (***E***) is 1) the combined processes through which water is transferred to the atmosphere from open water and ice surface, bare soil, and vegetation that make up the earth's surface; 2) the total amount of water transferred from the earth to the atmosphere (also called fly off, water

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loss, total evaporation). Potential evapotranspiration is maximum evapotranspiration at a given meteorological condition and unlimited soil moisture (*Glossary of Meteorology, 2000*). Evapotranspiration is expressed mainly as actual evapotranspiration to separate it from potential evapotranspiration.

Measurement of evapotranspiration, both real and potential, is very difficult and it is carried out in the specialised institutes dealing manly with agriculture research (by lysimeter, evapotranspirometers). The values of evapotranspiration are usually modelled from other meteorological elements, characteristics of soil moisture and physiological characteristics of vegetation. There are several calculation methods, both potential and actual evapotranspiration (*Nistor and Porumb, 2015; Weiß and Menzel, 2008*, etc.).

Determination of potential evapotranspiration by means of calculation is less problematic than actual evaporation. The theoretical aspects that form the physical basis of potential evaporation have been adequately calculated and described. In Slovakia, the complex method was developed (*Tomlain, 1980*) according to the Budyko method (*Budyko et al., 1978*) based on energy and water balance equations, marked as the Budyko-Tomlain method, which is part of the model for the estimation of energy balance equation components (total radiation balance and its components, potential and actual evapotranspiration, sensible heat flux) developed at the Division of Meteorology and Climatology. These monthly evapotranspiration sums are considered standard values corresponding to potential and actual evapotranspiration from the surfaces at meteorological stations (standard grass cover, with a uniform height 0.12 m, full canopy closure, and optimum moisture conditions all year round). The obtained results can only be directly used to assess soil irrigation under standard conditions, in our case, low-cut natural lawn, which is standard earth's surface around the meteorological booth at SHMÚ observation stations. Nevertheless, these are valuable inputs that experts from other sectors (e.g. agriculture, forestry, and water) can use in their models and analyses.

Global climate change is the most discussed problem worldwide (*Pörtner et al., 2023; Chipanshi et al., 2022; Li et al., 2019; Marková and Monoši, 2020*). Many publications present that claim climate change's negative impact on ecosystems and groundwater recharge (*Ponce-Campos et al., 2013; Prăvălie et al., 2014*). Climate change is predicted to increase both drought frequency and duration, and when coupled with substantial warming, it will establish a new hydro-climatological model for many regions (*Pabón-Caicedo et al., 2020; Hänsel et al., 2019*).

Evapotranspiration (***E***) shapes climate variability, trends, and extremes and connects the land with the atmosphere (*Douville et al., 2013; Miralles et al., 2018*). The ***E*** is integral to meteorological, hydrological, and biological processes. Precipitation and air temperature are climatic factors that strongly influence changes in the global hydrological cycle. Evapotranspiration is driven principally by precipitation and solar radiation variability (*Martens et al., 2018*) and is constrained by land surface conditions, such as soil moisture and vegetation (*Ruscica et al., 2022*). Evapotranspiration impacts regional water balance and is a valuable parameter for climate, hydrology, and agriculture studies (*Fendeková et al., 2018; Bochníček et al., 2018; Nistor and Porumb, 2015*).

Actual evaporation represents the amount of water that evaporates from a soil, water or vegetation surface. It takes place in the real environment and is strongly dependent on the amount of water available at a given place and time. Determination of the actual evaporation by means of measurement is extremely difficult if not virtually impossible. It has to be based on fairly accurate estimates or calculations and such computational procedures can only be applied locally. The fundamental theories used to estimate ***E*** are the Monin-Obukhov similarity theory, the Bowen ratio method, and the Penman-Monteith equation. ***E*** estimates can differ substantially between these three approaches because they use different input data (*Wang and Dickinson, 2012*).

Theoretical evaporative demand is often formally quantified as potential evapotranspiration ($\boldsymbol{E_0}$), which is required to calculate actual evapotranspiration and close the water balance for numerous applications ranging from water resources to agriculture to natural hazards to climate change impact analysis. $\boldsymbol{E_0}$ and ***E*** are also defined in the *Glossary of Meteorology (2000).*

There are widely accepted conventions for calculating $\boldsymbol{E_0}$ from commonly available climate variables, including solar radiation, relative humidity, air temperature, and wind (*Vicente-Serrano et al., 2018*). However, there is currently no available global $\boldsymbol{E_0}$ dataset developed by conventional methods (e.g., Penman-Monteith, Priestley-Taylor) with the combined high spatial and temporal resolutions required to input many environmental models and analyses (*Singer et al., 2021*).

2. Data

For the purpose of this study, the model computation was performed for 26 selected stations on the territory of Slovakia (Fig. 1). Their geographic coordinates and altitudes are presented in Table 1. The altitude and topography are strong climate-differentiating factors.

Slovakia is a landlocked country in Central Europe. It is bordered by Poland to the north, Ukraine to the east, Hungary to the south, Austria to the west, and the Czech Republic to the northwest (Fig. 1). The territory of the West Carpathians in Slovakia is divided into the area of Pannonia (Pannonian Lowland) and the foothills to the north, influenced by the Mediterranean climate, and the area of the inner Carpathians, affected by the sub-ocean mountainous climate and by the climate of both the Northern and Baltic Seas. The area to the north is relatively wetter and colder than the southern one, which is drier and warmer.

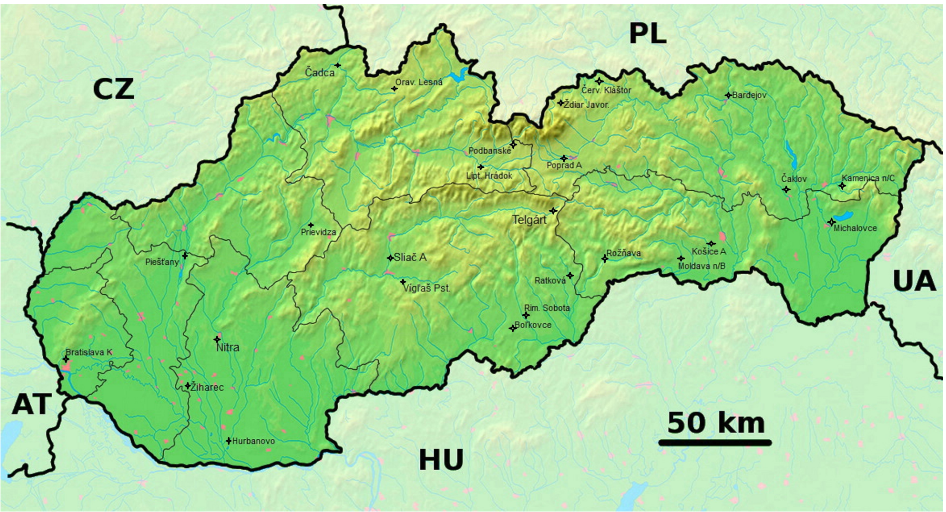

Fig. 1. Map of Slovakia and 26 selected stations for $\boldsymbol{E_0}$ and $\boldsymbol{E}$ calculation.

Table 1 contains the list of all 34 stations used in the previous model calculations by *Hrvoľ et al. (2001)* and the 1961–1990 long-term precipitation means (standard normal). These stations have the most complete observations among about 110 climatological stations having been in operation at the Slovak Hydrometeorological Institute in 1961–1990 and have been used for potential evapotranspiration ($\boldsymbol{E_0}$) and actual evapotranspiration ($\boldsymbol{E}$) calculation for this period.

We found some of these stations have shorter or interrupted observations. Some others have worse observations caused by different reasons, so only 26 stations were selected for processing in 1951–2021 (Table 1, normal letter). In Table 1, the stations (in red) have been excluded from the calculation of $\boldsymbol{E_0}$ and $\boldsymbol{E}$ in 1951–2021 (Bratislava-Airport, Bystrička, Kuchyňa-Nový Dvor, Myjava, Plaveč, Somotor, Štrbské Pleso, and Trstená).

Analysis of evapotranspiration from soil and plant surfaces carried out in 1991 used data from 54 meteorological stations, but some of these are of problematic quality according to additional investigation. These stations have been used at monthly values of $\boldsymbol{E_0}$ and $\boldsymbol{E}$ calculation by *Tomlain (1991)* for the period 1951–1980. We excluded many of these meteorological stations from later analyses because of serious interruption or end of observation in 1951–2021.

The input data for model calculations realized in this study were as follows: air temperature and humidity, cloudiness, number of days with snow cover and precipitation, i.e., meteorological elements regularly measured in the network of meteorological stations. The mentioned elements' time series is considered homogeneous monthly data after preliminary homogeneity testing by the Craddock test (*Craddock, 1979; WMO, 2003*), except for the cloudiness. Since cloudiness plays an essential role in the model calculations, all the cloudiness monthly data have been tested for homogeneity and homogenized using the measured sunshine duration data (*Hrvoľ et al., 2001*). As the first homogenization step, the sunshine duration and cloudiness time series of monthly data have been prepared at the reference stations for cloudiness (Bratislava-Koliba, Piešťany, Sliač, Košice, Kamenica n/Cirochou).

For these reference stations model calculations of monthly cloudiness means have been realized using monthly sunshine duration sums. Model cloudiness time series have been tested for homogeneity with measured ones at the same station by the Craddock test. The measured cloudiness time series needed to be homogenized only insignificantly at the reference stations. In the second step, homogeneity tests continued using the Craddock method and cloudiness time series at the reference stations. The scheme of tests and consequent homogenization looks simplified as follows (the reference station is listed first, then the other stations according to the consecutive procedure of testing and homogenization):

- **Bratislava-Koliba,** Hurbanovo, Nitra, Žihárec,
- **Piešťany,** Poprad, Liptovský Hrádok, Telgárt, Oravská Lesná, Čadca,
- **Sliač-airport,** Vígľaš, Prievidza,
- **Košice-airport,** Moldava n/Bodvou, Rožňava, Rimavská Sobota, Ratková, Boľkovce (Lučenec),
- **Kamenica n/Cirochou,** Michalovce, Bardejov, Čaklov, Červený Kláštor, Ždiar-Javorina, Podbanské.

There needs to be more space to describe the homogenization procedure in more detail. Most monthly cloudiness homogenization corrections were insignificantly low, especially at good stations like Hurbanovo and Poprad.

Table 1. Annual means of precipitation totals [mm] at 34 stations in Slovakia in 1961–1990, (only 26 stations analysed in 1951–2021, normal letter).

Station, altitude [m a.s.l.], location	**P [mm]**	**Station, altitude [m a.s.l.], location**	**P [mm]**
Bardejov, 305, NE	743	Oravská Lesná, 780, NW	1095
Boľkovce (at Lučenec), 214, S	612	Piešťany, 165, W	577
Bratislava-Koliba, 286, SW	647	Plaveč (at Stará Ľubovňa), 488, N	663
Bratislava-Airport, 131, SW	576	Podbanské, 972, N	925
Bystrička (at Martin), 470, C	803	Poprad, 695, N	579
Čadca, 423, NW	926	Prievidza, 260, C	642
Čaklov, 133, E	637	Ratková, 287, S	725
Červený Kláštor, 474, N	748	Rimavská Sobota, 214, S	596
Hurbanovo, 114, SW	523	Rožňava, 289, S	668
Kamenica nad Cirochou, 178, E	724	Sliač-airport, 313, C	702
Košice-airport, 230, SE	622	Somotor, 100, SE	559
Kuchyňa-Nový Dvor, 206, SW	650	Štrbské Pleso, 1360, N	959
Liptovský Hrádok, 640, N	678	Telgárt, 901, C	830
Michalovce, 112, E	606	Trstená, Ústie n/Priehradou, 598, N	798
Moldava nad Bodvou, 210, SE	643	Víglaš-Pstruša, 368, C	606
Myjava, 375, W	668	Ždiar-Javorina, 1020, N	1229
Nitra, 173, SW	540	Žihárec, 111, SW	553

Note: Location in Slovakia: W – west, SW – southwest, NW – northwest, N – north, NE – northeast, E – east, SE – southeast, S south, C – central Slovakia.

The mean precipitation totals have been calculated for the presented purpose only and may slightly differ from those prepared by the Slovak Hydrometeorological Institute as official precipitation normals for Slovakia.

As can be seen in Figure 2, mean areal temperature in Slovakia increased significantly mainly since 1980. The linear trend of annual temperatures was 2.3 °C in 1881–2022, but the polynomial trend reached nearly 3 °C. On the other hand, the annual precipitation totals do not have any significant trend in 1881–2022 (both linear and polynomial). The period 1975–1993 seems relatively dry (low precipitation). All data were measured at the Slovak Hydrometenorological Institute from 1881–2022.

Slovakia has had relatively high-quality air temperature and total precipitation measurements since 1881. The multiple tests showed that monthly averages of air temperature from 3 stations (Hurbanovo, Kosice-airport, and Liptovský Hrádok) and monthly averages of precipitation from 203 stations are sufficient to obtain an image of long-term temperature and precipitation conditions for all of Slovakia (*Fendeková et al., 2018*). They provide a representative climate change image over the past 140 years.

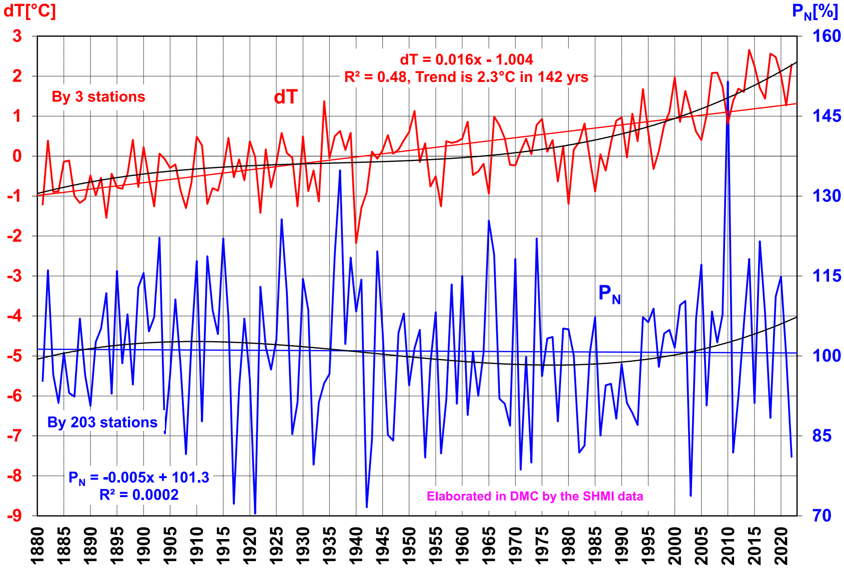

Fig. 2. Deviations of annual mean temperatures (dT) in Slovakia from the 1881–2022 long-term average (red line) and normalized average precipitation totals (PN) in Slovakia (blue line) as a percentage from the 1901–1990 long-term average.

3. Method

Potential and actual evaporation is processed using a mathematical/physical model developed at the Faculty of Mathematics, Physics, and Informatics of the Comenius University in Bratislava (Division of Meteorology and Climatology, DMC). This model (Budyko-Tomlain) comes from a joint solution of the energy and water balance equations of the soil surface (*Budyko et al., 1978*) and the experimentally determined dependence of the evapotranspiration intensity on soil moisture. The evapotranspiration depends only on external meteorological factors, which means it equals the potential evapotranspiration $\boldsymbol{E_0}$ (maximum possible evapotranspiration in the given meteorological conditions at a sufficiently irrigated surface layer of the soil) with sufficient water content in the soil and with snow cover in winter. At soil moisture lower than its critical value, evapotranspiration decreases proportionally with the decrease in soil moisture.

Monthly potential evapotranspiration totals ($\boldsymbol{E_0}$) are given by the equation of water vapour diffusion into the atmosphere:

$$\boldsymbol{E_0} = \rho D\,(q_s - q_2)\,,$$

where ρ is the air density, D – integral diffusion coefficient, q_s – saturated specific humidity at the temperature of evaporating surface and q_2 – specific humidity in meteorological shelter. To determine q_s, it is necessary to know the temperature of the evaporating surface T_w. If the soil surface temperature data still needs to be included, then T_w is easily determined from the surface energy balance equation.

The working formula for calculating $\boldsymbol{E_0}$ takes shape:

$$\boldsymbol{E_0} = 1.68\,(e_s - e_2) \quad \text{for} \;\; t > 0\,^\circ\mathrm{C} \quad \text{and}$$
$$\boldsymbol{E_0} = 1.23\,(e_s - e_2) \quad \text{for} \;\; t \le 0\,^\circ\mathrm{C}\,,$$

when we assume that the external diffusion coefficient $D \approx 0.30$ cm.s^{-1} in months with $t \le 0\,^\circ$C and $D \approx 0.63$ cm.s^{-1} in months with $t > 0\,^\circ$C. Specific humidity q can be expressed as $q = 0.622\,e/p$ (e is water vapour pressure and p air pressure).

The equation for calculating $\boldsymbol{E_0}$ we can break down into:

$$\boldsymbol{E_0} = \rho D\,(q_s - q_2) = \rho D\,(q_s' - q_2) + \rho D\,(q_s - q_s')\,,$$

where $(q_s' - q_2)$ is the saturation deficit in the thermometer screen, the term

$\rho D(q_s - q_s')$ is a mistake we would make if we determined the potential evapotranspiration only from the saturation deficit.

The actual evapotranspiration is supposed to be proportional to the potential evapotranspiration as follows:

$$\boldsymbol{E} = \boldsymbol{E_0}\overline{W}/W_0\,.$$

$\overline{W}$ is the actual soil moisture, and W_0 is the critical humidity. The W_0 usually represents a layer of 100 to 200 mm water with seasonal and regional variations. The storage $\overline{W}$ is specified as the moisture stored in the upper soil layer of one m depth, W_0 is critical value above which the $\boldsymbol{E}$ equals $\boldsymbol{E_0}$. If $\overline{W} \geq W_0$ then $\boldsymbol{E} = \boldsymbol{E_0}$ (then the soil contains enough water) and if $\overline{W} < W_0$ then $\boldsymbol{E} = \boldsymbol{E_0}\overline{W}/W_0$. The W_0 values depend on the plant's developmental stage and the air temperature's annual course. W_0 changes throughout the year. In the initial phase of plant development, when the root system is underdeveloped and concentrated in the uppermost layer of soil, desiccation of the highest soil horizon leads to intensive reduction of evapotranspiration, regardless of soil moisture of the entire 1 m thick surface layer. In this case, the actual evaporation equals the potential at higher humidity values. Similarly, in the autumn W_0 is more significant than during the growing season, when the plants draw water through the root system from greater depths. However, the ratio $\overline{W}/W_0$ varies relatively little for a sufficiently large range of W_0 values. The analysis showed that the differences between the annual evapotranspiration totals determined for the different W_0 values do not exceed 3%. So erroneous W_0 data does not lead to significant errors in determining evapotranspiration.

The critical soil moisture values can be determined from the relationship $\boldsymbol{E} = \boldsymbol{E_0}\overline{W}/W_0$ at given values of $\boldsymbol{E_0}$. The $\boldsymbol{E}$-values are calculated from the water balance equation if we know the runoff, soil moisture, and atmospheric precipitation values.

The average soil moisture $\overline{W} = (W_1 + W_2)/2$ is counted from the water balance equation:

$$P = \boldsymbol{E} + O + W_2 - W_1,$$

by the method of step-by-step approximation. $(W_2 - W_1)$ is the change in soil humidity in the highest lying 1 m thick layer of soil (W_1 is the moisture content of the soil at the beginning and W_2 at the end of the time interval considered). The following parameterization has been applied to the monthly runoff values:

$$O = \frac{\overline{W}}{W_k} P \sqrt{\alpha^2 \left[1 - \left(1 - \frac{\boldsymbol{E_0}}{P}\right)^2\right] + \left(1 - \frac{\boldsymbol{E_0}}{P}\right)^2} \quad \text{for} \ \ P \geq \boldsymbol{E_0} \quad \text{and}$$

$$O = \alpha P \frac{\overline{W}}{W_k} \quad \text{for} \ \ P < \boldsymbol{E_0} \, .$$

W_k is the largest value of the humidity W_0 during the year (the largest water content in the soil, which can be maintained in the highest soil horizon without contact with groundwater). α is a coefficient of proportionality that depends on the intensity of precipitation. If P is the annual precipitation total, the values α are as follows for our conditions:

$\alpha = 0.2$ for $P \leq 760$ mm;
$\alpha = 0.3$ for $760 < P \leq 960$ mm;
$\alpha = 0.4$ for $P > 960$ mm.

The equations for the monthly outflow values have been compiled based on the following assumptions: if the monthly total of the potential evapotranspiration is greater than the monthly precipitation total, then the outflow coefficient is proportional to the soil's moisture. The drain is equal to zero on arid soil and reaches its maximum at $\overline{W}/W_0 = 1$. When $\boldsymbol{E_0} < P$ for monthly values, then the runoff, in addition to the intensity of precipitation, also depends on $(P - \boldsymbol{E_0})$. This means that if $\overline{W}/W_0 = 1$, the drain will be close to the value $(P - \boldsymbol{E_0})$, and the outflow coefficient will converge to $(1 - \boldsymbol{E_0}/P)$. After establishing the relationships for the drain into the water balance equation and adjusting, we get the relationships for soil moisture. The soil moisture is calculated for months with positive air temperatures. The model assumes that soil moisture oscillations during the year depend primarily on precipitation totals and potential evapotranspiration and their distribution during the year.

When determining W_2 for the first spring month with a positive temperature, we add to the total precipitation of this month the total precipitation for previous months with a negative air temperature reduced by the sums of potential evapotranspiration. We check the procedure's correctness for determining soil moisture and evapotranspiration for individual months by the water balance equation for the year: $P = (\boldsymbol{E} + O)$.

The model described above is very well physically substantiated. The input data are temperature and humidity, cloudiness, number of days with snow cover, and precipitation regularly measured in the network of all Slovakia meteorological stations with uninterrupted observation series. This method considers all the essential factors that affect $\boldsymbol{E_0}$. The values determined by this method are close to the real ones. The exactness of the potential evapotranspiration computation estimated by the comparison with the evaporation data from the compensation lysimeter for the season from April to September was about 10% (*Hrvoľ and Gera, 2013; Hrvoľ et al., 2009*). $\boldsymbol{E_0}$ depends on the saturation deficit according to the calculated evaporative surface temperature and measured humidity in the thermometer screen. It means that $\boldsymbol{E_0}$ is reduced compared to other methodologies due to settled precipitation, especially in the winter months. In most cases, December and January have $\boldsymbol{E_0}$ only at 0 mm to 5 mm for the whole month.

A climatic irrigation indicator (climatic indicator of humidification, climatic moisture index) $\boldsymbol{K} = \boldsymbol{E_0} - \boldsymbol{P}$ was used to evaluate irrigation conditions. It represents the relationship between the amount of water which is possible to evaporate from the surface of sufficiently humidified soil and vegetation. $\boldsymbol{E_0}$ is potential evapotranspiration as a function of several meteorological factors in the complex with radiation balance, and $\boldsymbol{P}$ is precipitation total for the same season. The climatic irrigation indicator is a climatological index used for regionalization of the climate in terms of humidification (*Bochníček et al., 2015; Miklós, 2002*). This indicator informs about average humidity conditions in individual months of the year in measurable values – cm. When there is an excess of moisture in the winter months, its values are negative; when there is a lack of moisture in the summer, they are positive.

At the end of the study, the scenarios of potential evapotranspiration $\boldsymbol{E_0}$ by two regional circulation models (RCM) outputs in a version of SRES A1B emission scenario were prepared. The KNMI RCM was obtained from the Dutch Center of Climatic Modelling, and the MPI RCM from Germany. The RCM output downscaling for Slovakia was described by *Gera et al. (2019)*, and different methods of regional climatic scenarios have been presented by *Damborská et al. (2016)* and *Bochníček et al. (2018).*

The RCMs' outputs must be regionally modified using the observed climate from the station's network. Statistical modification of the distribution curves takes place first. The reason is to improve the statistical characteristics of the modelled time series during the control period compared to the observed ones within the same period considered here as a reference. Comparison is done for means and variance. The final goal at the downscaling is to obtain the modified model output in the same format as the measured data. However, some climatic elements, such as evapotranspiration, are unavailable among the RCMs outputs. So, they must be calculated by some analytic physical or semi-experimental methods based on the other measured climatic data. For this purpose, we used daily values of saturation deficits from the RCMs mentioned.

The daily saturation deficit data were calculated from the modified RCM outputs for the daily air temperature averages and relative humidity at ten selected stations, representing different climatic conditions.

4. Results

Tables 2 and 3 present the main characteristics of temperature and precipitation regimen in Slovakia in the period 1951–2020 on the samples of representative meteorological stations (Hurbanovo for southern Slovakia and Oravská Lesná for northern Slovakia). The 30-year moving averages represent 30-year data for 1951–1980, 1961–1990, 1971–2000, 1981–2010 and 1991–2020 periods. The deviation from the 1951–1980 value is presented in the last column. Air temperature averages increased mainly in the last two periods (1981–2010 and 1991–2020) by 0.6 to 1.2 °C in nearly all of Slovakia.

Precipitation totals for 1951–1980 were in Slovakia lower than in 1901–1950 averages by 2.1% annually, by 0.8% in the Apr.–Sept. season and by 3.3% in the Oct.–March season (*National Communications on Climate Change (NCCC), 2001; 2006; 2009; 2014; 2017*). At Hurbanovo, another decrease in precipitation totals was also registered in the 1961–2000 periods, then an increase of 4% annually was registered mainly due to an increase in convective precipitation. At Oravská Lesná, no decrease in precipitation totals occurred up to 2000, then an increase of 9% compared to the 1951–1980 average was registered. Standard deviations of monthly and annual temperature averages slightly increased in the last two 30-year periods at Hurbanovo and the last period 1991–2020 at Oravská Lesná. *Lapin et al. (2016)* presented a serious increase in heat waves and extreme tempera-

Table 2. Mean monthly and annual air temperature for Hurbanovo (114 m a.s.l., SW Slovakia) and Oravská Lesná (780 m a.s.l., NW Slovakia) and mean monthly and annual standard deviations in °C for 30-year periods. The deviation from the 1951–1980 value is presented in the last column.

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Annual	dT
Hurbanovo	Mean monthly and annual temperature in °C													
1951–1980	−1.5	0.7	5.0	10.5	15.3	18.9	20.1	19.4	15.4	10.0	5.0	0.8	10.0	0.00
1961–1990	−1.5	1.0	5.3	10.7	15.7	18.7	20.3	19.5	15.5	10.2	4.7	0.4	10.0	0.06
1971–2000	−0.6	1.3	5.7	10.6	16.0	18.9	20.6	20.1	15.4	10.1	4.4	0.9	10.3	0.32
1981–2010	−0.5	1.1	5.6	11.3	16.5	19.4	21.4	20.6	15.8	10.6	5.0	0.6	10.6	0.66
1991–2020	0.1	1.8	6.1	12.0	16.6	20.3	22.0	21.4	16.1	10.8	5.9	1.0	11.2	1.22
Orav. Lesná	Mean monthly and annual temperature in °C													
1951–1980	−5.5	−4.5	−1.3	3.8	9.1	12.9	14.2	13.4	9.7	5.4	1.0	−3.3	4.6	0.00
1961–1990	−5.6	−4.2	−0.9	4.1	9.6	12.7	14.1	13.4	9.9	5.6	0.7	−3.7	4.6	0.06
1971–2000	−4.6	−3.8	−0.5	4.1	10.0	13.0	14.5	13.8	9.8	5.5	0.3	−3.1	4.9	0.34
1981–2010	−4.7	−3.9	−0.5	4.6	10.5	13.5	15.3	14.4	10.0	5.8	0.8	−3.4	5.2	0.62
1991–2020	−4.1	−3.1	−0.1	5.1	10.6	14.4	15.9	15.2	10.3	6.0	1.8	−3.0	5.7	1.16
Hurbanovo	Standard deviation of mean monthly and annual temperature in °C													
1951–1980	2.3	3.3	2.3	1.6	1.5	1.2	1.2	1.2	1.4	1.6	1.8	2.2	0.65	0.00
1961–1990	2.7	2.8	2.3	1.4	1.4	1.2	1.2	1.1	1.4	1.5	1.9	1.9	0.59	−0.06
1971–2000	2.5	2.7	2.2	1.5	1.5	1.2	1.4	1.5	1.6	1.4	1.9	1.5	0.72	0.07
1981–2010	2.5	2.9	1.9	1.6	1.5	1.5	1.5	1.5	1.4	1.5	2.2	1.8	0.77	0.12
1991–2020	2.2	2.8	1.7	1.6	1.6	1.3	1.3	1.6	1.5	1.5	2.0	2.0	0.76	0.11
Orav. Lesná	Standard deviation of mean monthly and annual temperature in °C													
1951–1980	2.5	3.4	2.4	1.4	1.4	1.3	1.2	1.1	1.4	1.6	1.9	2.4	0.68	0.00
1961–1990	3.0	3.1	2.4	1.5	1.4	1.3	1.2	1.0	1.4	1.5	2.1	2.1	0.63	−0.05
1971–2000	2.7	2.8	2.3	1.5	1.4	1.2	1.4	1.3	1.5	1.6	2.2	1.8	0.67	−0.01
1981–2010	2.8	3.0	2.1	1.6	1.4	1.3	1.4	1.1	1.4	1.6	2.4	2.0	0.67	0.00
1991–2020	2.3	2.8	1.9	1.7	1.5	1.3	1.2	1.2	1.4	1.6	2.1	2.3	0.78	0.10

tures in 2001–2015 compared to 1951–1990. This development probably has not significantly influenced the variance of monthly temperatures. Variance coefficients of precipitation totals increased at Hurbanovo and decreased at Oravská Lesná in the last two 30-year periods. This development also probably did not seriously influence the other climatic characteristics until 2020.

5. Actual and potential evapotranspiration

The results of the processing of the annual sums of potential evapotranspiration for the period 1951–2021 (Figs. 3 and 4) indicate that an increase

Table 3. Mean monthly and annual precipitation totals for Hurbanovo (114 m a.s.l., SW Slovakia) and Oravská Lesná (780 m a.s.l., NW Slovakia) in mm and mean monthly and annual variation coefficient in % for 30-year periods. In the last column, the percentage from 1951–1980 value is presented in %.

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Annual	%
Hurbanovo	Mean monthly and annual precipitation totals in mm, annual value in %													
1951–1980	33	34	29	41	52	69	61	52	41	38	54	42	547	100
1961–1990	34	34	27	39	56	61	51	58	39	32	54	40	523	96
1971–2000	32	27	27	39	57	59	57	53	43	39	51	39	523	96
1981–2010	32	29	32	35	61	62	58	59	47	39	49	43	547	100
1991–2020	34	30	36	32	62	61	69	55	57	47	48	41	570	104
Orav. Lesná	Mean monthly and annual precipitation totals in mm, annual value in %													
1951–1980	75	68	68	73	97	126	142	108	92	76	77	85	1087	100
1961–1990	80	65	63	72	107	123	129	114	91	74	83	95	1095	101
1971–2000	85	66	76	77	98	118	123	110	96	79	77	95	1100	101
1981–2010	95	79	91	70	108	121	131	113	95	76	88	93	1161	107
1991–2020	99	88	91	67	109	118	142	106	100	91	87	86	1184	109
Hurbanovo	Monthly and annual variance coefficient of precipitation in %, change in %													
1951–1980	43	63	58	46	61	53	62	64	63	89	65	53	16.5	0.0
1961–1990	49	66	50	52	63	44	64	60	71	90	66	48	18.1	+1.5
1971–2000	54	72	60	49	64	49	58	60	74	83	56	58	14.3	−2.2
1981–2010	50	69	55	62	70	49	63	56	71	69	50	61	20.4	+3.9
1991–2020	53	82	71	66	69	53	58	59	66	67	55	67	21.2	+4.7
Orav. Lesná	Monthly and annual variance coefficient of precipitation in %, change in %													
1951–1980	67	73	57	30	40	37	43	32	48	62	45	59	15.7	0.0
1961–1990	69	62	50	37	36	32	43	38	50	58	40	63	13.9	−1.8
1971–2000	66	67	73	35	39	33	41	42	49	57	37	55	13.3	−2.4
1981–2010	60	54	64	44	47	28	51	46	55	55	45	54	13.6	−2.1
1991–2020	63	56	63	54	46	34	49	47	49	54	58	44	13.8	−1.9

in potential evapotranspiration ($\boldsymbol{E_0}$) can be seen much more in the south (Hurbanovo) than in the north (Oravská Lesná). This increase is probably caused mainly by global warming impacts (temperature rise) and partly by decreased relative air humidity, especially in the south. Figure 3 shows the linear trend of about 110 mm in 71 years, with a determination coefficient R^2 of around 0.35. In Figure 4, the linear trend is about 110 mm in 71 years with a determination coefficient $R^2 = 0.32$ at Košice and about 55 mm and R^2 round 0.18 at Poprad, O. Lesná and Telgárt.

Tables 4 and 5 demonstrate seasonal sums of potential and actual evapotranspiration for selected meteorological stations and 30-year periods 1951–1980, 1961–1990, and 1991–2020. We present only 20 stations so that they

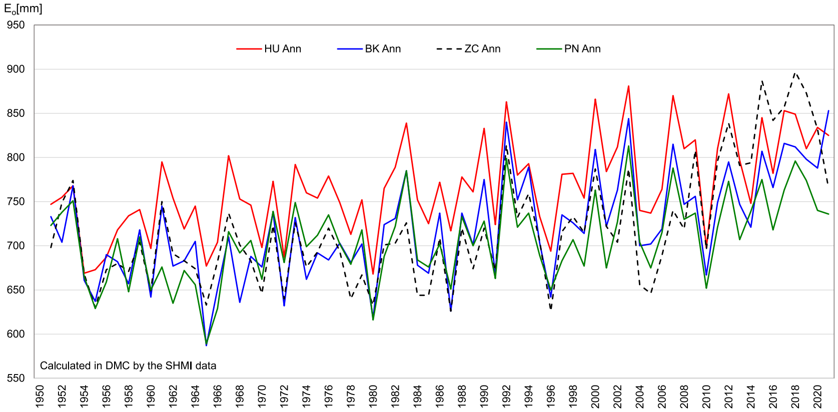

Fig. 3. Annual sums of potential evapotranspiration calculated by Budyko-Tomlain method for stations in SW Slovakia (Hurbanovo (HU), Bratislava-Koliba (BK), Žiharec (ZC), Piešťany (PN), in 1951–2021.

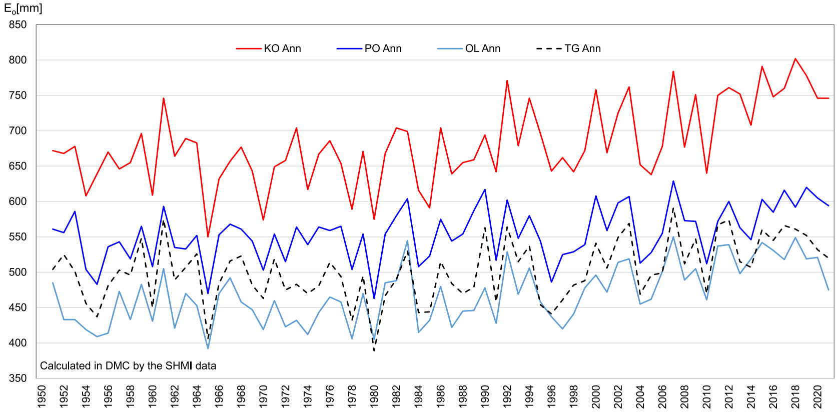

Fig. 4. Annual sums of potential evapotranspiration calculated by Budyko-Tomlain method for stations in SE, N and C Slovakia (Košice (KO), Poprad (PO), Oravská Lesná (OL), Telgárt (TG) in 1951–2021.

characterize the development throughout Slovakia. An increase in $\boldsymbol{E_0}$ in 1991–2020 compared to 1951–1980 is apparent for Slovakia. The increase of potential evapotranspiration in 1991–2020 compared to the 1951–1980 period represented at Hurbanovo 62.6 mm annually; at Oravská Lesná the increase in $\boldsymbol{E_0}$ was 51.6 mm. The maximum $\boldsymbol{E_0}$ occurs in July, but the minimum variation coefficient ($\boldsymbol{C_v}$) is in June (Fig. 5). $\boldsymbol{C_v}$ is the variation

Table 4. Mean seasonal sums of potential evapotranspiration in Slovakia by the Budyko-Tomlain method in 1951–1980, 1961–1990, and 1991–2020 in mm (Ann: Annual, WHY: April – September, Spr.: March – May, Sum: June – August, Aut: September – November, Wint: December – February).

Hurbanovo	Ann	WHY	Spr	Sum	Aut	Wint	Michalovce	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	734	614	223	361	126	24	1951–1980	659	565	202	331	111	14
1961–1990	752	628	230	369	128	25	1961–1990	656	564	202	332	110	13
1991–2020	796	671	245	399	126	26	1991-2020	715	612	222	363	112	17
Bratislava, K.	Ann	WHY	Spr	Sum	Aut	Wint	Košice, Airp.	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	683	574	207	334	121	21	1951–1980	651	554	198	325	112	15
1961–1990	692	581	211	339	122	21	1961–1990	654	557	201	326	112	14
1991–2020	754	635	231	378	119	26	1991–2020	716	610	224	360	115	17
Piešťany	Ann	WHY	Spr	Sum	Aut	Wint	Kamenica, C	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	685	570	210	332	120	22	1951–1980	636	538	194	316	110	16
1961–1990	691	577	214	337	120	21	1961–1990	638	540	198	316	109	15
1991–2020	727	613	223	364	117	23	1991–2020	685	577	214	341	110	20
Žiharec	Ann	WHY	Spr	Sum	Aut	Wint	Rim. Sobota	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	686	582	211	340	118	17	1951–1980	672	580	207	344	109	12
1961–1990	685	582	213	341	115	17	1961–1990	681	586	211	347	111	12
1991–2020	761	642	235	380	122	24	1991–2020	750	638	229	382	120	19
Prievidza	Ann	WHY	Spr	Sum	Aut	Wint	Ratková	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	627	526	190	308	111	19	1951–1980	594	518	183	306	98	7
1961–1990	638	534	195	313	111	18	1961–1990	585	508	182	299	97	7
1991–2020	707	596	218	353	115	21	1991–2020	628	545	199	325	94	10
Sliač, Airp.	Ann	WHY	Spr	Sum	Aut	Wint	Čaklov	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	611	525	188	309	103	11	1951–1980	629	538	194	316	106	12
1961–1990	625	535	192	316	104	12	1961–1990	625	537	195	315	104	11
1991–2020	681	587	213	350	105	14	1991–2020	676	587	211	350	102	13
Vígľaš, Pstr.	Ann	WHY	Spr	Sum	Aut	Wint	Plaveč n/P	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	614	522	188	305	108	13	1951–1980	522	453	157	265	92	7
1961–1990	621	526	192	306	109	14	1961–1990	513	448	159	261	87	6
1991–2020	642	550	203	325	101	13	1991–2020	523	458	165	270	82	6
Lipt. Hrádok	Ann	WHY	Spr	Sum	Aut	Wint	Poprad, Airp.	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	537	462	160	272	97	9	1951–1980	538	464	156	273	101	10
1961–1990	547	471	164	277	97	8	1961–1990	548	472	161	277	101	9
1991-2020	608	530	186	316	97	9	1991-2020	568	492	174	292	92	10
Orav. Lesná	Ann	WHY	Spr	Sum	Aut	Wint	Čer. Kláštor	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	444	400	120	243	79	2	1951–1980	502	434	154	252	89	8
1961–1990	451	406	125	246	78	2	1961–1990	502	434	158	251	87	7
1991–2020	495	452	143	277	73	3	1991–2020	535	464	167	274	85	9
Telgárt	Ann	WHY	Spr	Sum	Aut	Wint	Podbanské	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	487	431	138	257	88	4	1951–1980	444	394	121	235	83	4
1961–1990	487	432	139	257	87	4	1961–1990	448	396	125	236	83	4
1991–2020	521	469	156	281	80	4	1991–2020	486	431	138	260	83	5

Table 5. Mean seasonal sums of actual evapotranspiration in Slovakia by the Budyko-Tomlain method in 1951–1980, 1961–1990, and 1991–2020 in mm (Ann: Annual, WHY: April – September, Spr.: March – May, Sum: June – August, Aut: September – November, Wint: December – February).

Hurbanovo	Ann	WHY	Spr	Sum	Aut	Wint	Michalovce	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	491	416	157	241	80	14	1951–1980	436	372	151	209	65	11
1961–1990	500	423	163	244	80	13	1961–1990	446	382	157	212	67	10
1991–2020	511	425	173	240	82	16	1991–2020	475	399	174	219	69	13
Bratislava, K.	Ann	WHY	Spr	Sum	Aut	Wint	Košice, Airp.	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	471	394	166	218	71	17	1951–1980	469	399	149	232	76	13
1961–1990	460	381	167	205	71	17	1961–1990	467	397	153	228	74	12
1991–2020	489	399	184	212	72	20	1991–2020	482	408	161	238	71	13
Piešťany	Ann	WHY	Spr	Sum	Aut	Wint	Kamenica, C	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	451	373	152	211	71	17	1951–1980	491	416	157	241	80	14
1961–1990	444	366	155	203	70	16	1961–1990	500	423	163	244	80	13
1991–2020	451	371	160	206	68	17	1991–2020	511	425	173	240	82	16
Žiharec	Ann	WHY	Spr	Sum	Aut	Wint	Rim. Sobota	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	432	363	157	199	62	14	1951–1980	449	386	156	219	64	10
1961–1990	420	351	156	188	63	13	1961–1990	442	380	161	213	59	9
1991–2020	462	379	170	206	69	18	1991–2020	476	398	172	223	67	15
Prievidza	Ann	WHY	Spr	Sum	Aut	Wint	Ratková	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	466	389	152	223	76	16	1951–1980	469	411	157	238	68	6
1961–1990	455	378	154	213	73	15	1961–1990	458	400	155	231	66	6
1991–2020	484	401	171	224	72	16	1991–2020	480	415	163	241	67	8
Sliač, Airp.	Ann	WHY	Spr	Sum	Aut	Wint	Čaklov	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	464	398	154	229	71	10	1951–1980	458	393	150	227	71	10
1961–1990	462	393	157	224	71	10	1961–1990	455	392	152	225	69	9
1991–2020	481	409	172	232	66	12	1991–2020	479	413	166	235	68	10
Vígľaš, Pstr.	Ann	WHY	Spr	Sum	Aut	Wint	Plaveč n/P	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	434	368	144	211	68	11	1951–1980	444	389	131	230	77	6
1961–1990	438	371	147	212	67	11	1961–1990	438	384	134	226	73	5
1991–2020	457	390	157	224	66	10	1991–2020	462	406	143	243	69	5
Lipt. Hrádok	Ann	WHY	Spr	Sum	Aut	Wint	Poprad, Airp.	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	448	388	133	231	76	8	1951–1980	430	373	122	224	75	9
1961–1990	448	387	139	227	75	7	1961–1990	428	371	126	221	73	8
1991–2020	479	414	155	242	73	8	1991–2020	451	392	139	234	70	8
Orav. Lesná	Ann	WHY	Spr	Sum	Aut	Wint	Čer. Kláštor	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	424	382	112	235	75	2	1951–1980	447	389	133	230	78	7
1961–1990	431	388	119	237	73	2	1961–1990	453	394	139	230	78	6
1991–2020	459	415	135	252	68	4	1991–2020	483	420	148	251	77	8
Telgárt	Ann	WHY	Spr	Sum	Aut	Wint	Podbanské	Ann	WHY	Spr	Sum	Aut	Wint
1951–1980	443	394	122	240	76	4	1951–1980	422	376	111	229	77	4
1961–1990	442	395	124	240	74	4	1961–1990	426	377	116	229	78	4
1991–2020	464	418	139	253	69	4	1991–2020	452	401	129	244	74	5

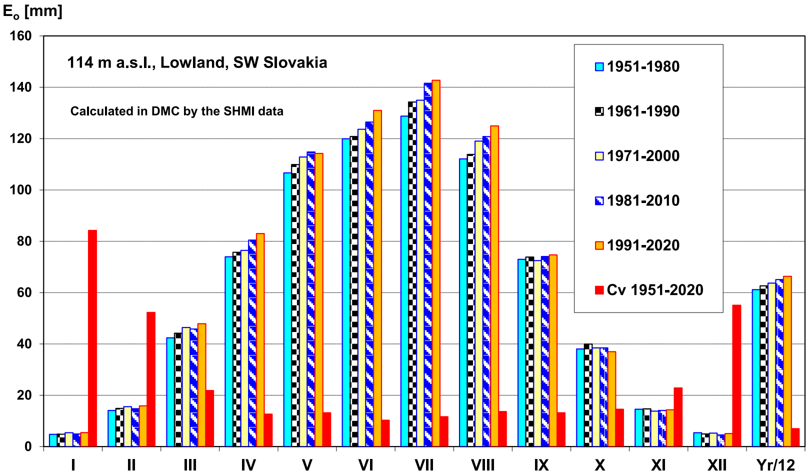

Fig. 5. Mean potential evapotranspiration at Hurbanovo in 30-year periods from 1951 to 2020.

coefficient of monthly and annual sums of $\boldsymbol{E_0}$ for whole 70-year period in %. The minimum $\boldsymbol{E_0}$ is usually in December, January, or February (in the mountains, only about one mm for monthly sums).

The potential evapotranspiration $\boldsymbol{E_0}$ mainly increases in the vegetation period (Apr. – Sep.). Comparable increases were obtained for all lowland stations in Slovakia and lesser increases for sites in northern Slovakia.

In warmer and relatively dry areas of south Slovakia, like the Hurbanovo station, the average monthly sums of potential evapotranspiration ($\boldsymbol{E_0}$) exceed precipitation totals mainly in the March to October season; at annual totals of precipitation, it makes 69.1% of $\boldsymbol{E_0}$ in 1991–2020. In the mountainous areas, like the Oravská Lesná station (780 m a.s.l.), where an excess of moisture during the whole year is observed, precipitation totals represent 239.0% from $\boldsymbol{E_0}$ in 1991–2020. The actual evapotranspiration ($\boldsymbol{E}$) shows only minor deviations from $\boldsymbol{E_0}$ (92.6% in 1991–2020). It represents about 38.8% of annual precipitation totals in 1991–2020 (39.0% in 1951–1980).

The results of the processing of actual evapotranspiration are illustrated in Figs. 6–9 and Table 5. $\boldsymbol{C_v}$ in the graphs is the variation coefficient of monthly and annual sums of $\boldsymbol{E}$ for the whole 70-year period in %. The maximum of actual evapotranspiration ($\boldsymbol{E}$) is usually in May or June in the south of Slovakia and in July in the north. In these months, the $\boldsymbol{C_v}$ of monthly $\boldsymbol{E}$ reaches the minimum in the annual course. The $\boldsymbol{E}$ values depend on the precipitation distribution and trend, so some $\boldsymbol{E}$ values decrease from 1951–80 to 1967–96, and then a slight increase can be recognized in the south. Only insignificant trends in $\boldsymbol{E}$ means have been observed in some regions of Slovakia. However, there is a significant increase in the mountains where potential evapotranspiration ($\boldsymbol{E_0}$) increased, and there is also enough

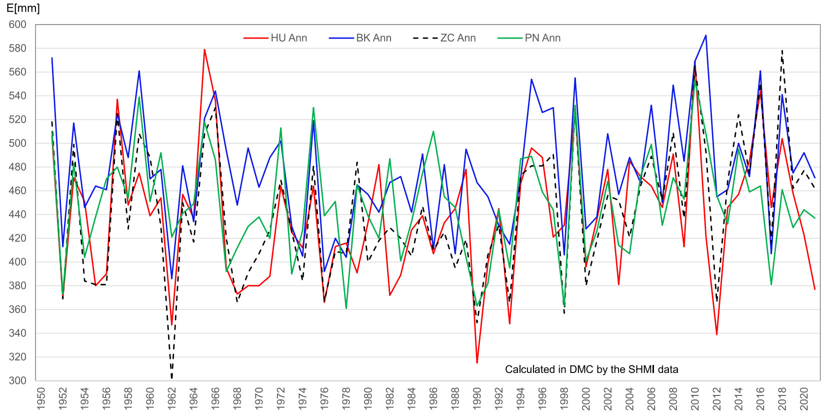

Fig. 6. Annual sums of actual evapotranspiration calculated by Budyko-Tomlain method for stations in SW Slovakia (Hurbanovo (HU), Bratislava-Koliba (BK), Žiharec (ZC), Piešťany (PN) in 1951–2021.

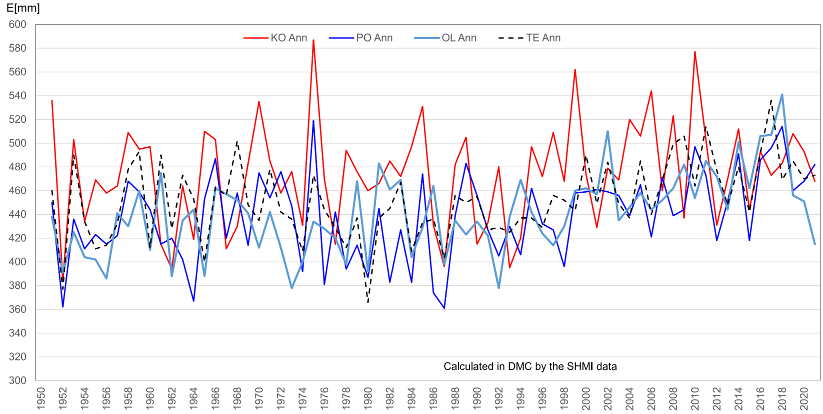

Fig. 7. Annual sums of actual evapotranspiration calculated by Budyko-Tomlain method for stations in SE, N and C Slovakia (Košice (KO), 230 m a.s.l., Poprad (PO), 695 m a.s.l., Oravská Lesná (OL), 780 m a.s.l., Telgárt (TE), 901 m a.s.l.) in 1951–2021.

precipitation to evaporate (Figs. 6–9, Table 5). The important side effect of this process is decreasing runoff, which can be observed there by the SHMI measurements (*Fendeková et al., 2018; Bochníček et al., 2018; Gera et al., 2019*).

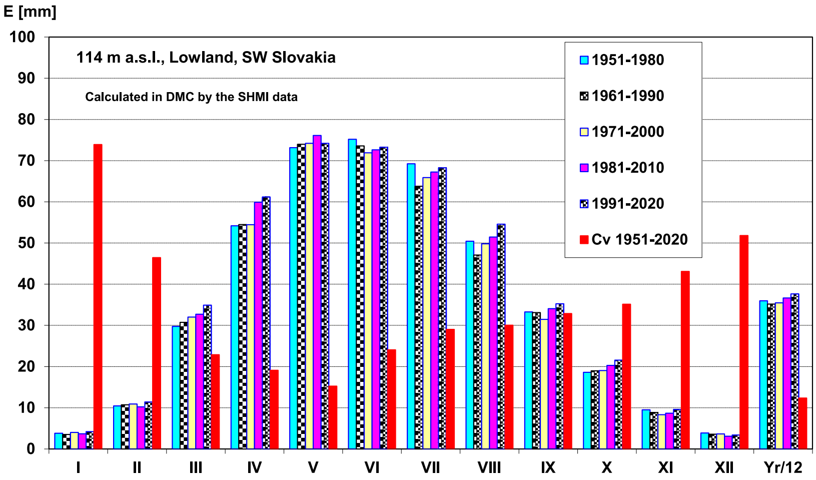

Fig. 8. Mean actual evapotranspiration at Hurbanovo in 30-year periods from 1951 to 2020 by the Budyko-Tomlain method.

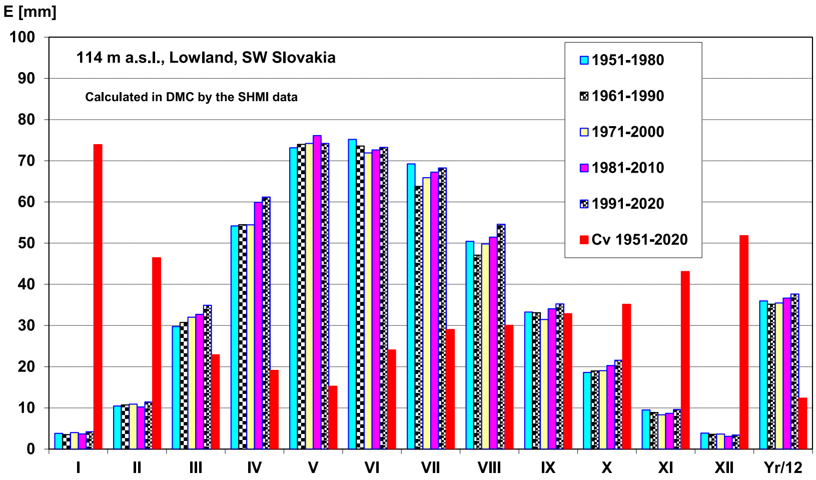

Fig. 9. Annual actual evapotranspiration sums at 26 selected meteorological stations for the 1951–1980, 1961–1990, and 1991–2020 periods (M – mountainous stations).

The development of actual evapotranspiration $\boldsymbol{E}$ (calculations according to a complex method) depends both on the potential evapotranspiration of $\boldsymbol{E_0}$ and on precipitation or soil moisture. In 1951–1980, there was enough precipitation, and the soil moisture was relatively high even in the lowlands; therefore, the $\boldsymbol{E}$ was relatively higher despite the lower $\boldsymbol{E_0}$ than in 1961–1990. In the normal period 1961–1990, precipitation was mostly low, especially after 1974, which reduced soil moisture and limited the size of the $\boldsymbol{E}$ amounts. Since 1994, precipitation has increased slightly, but $\boldsymbol{E_0}$ amounts in the growing season have also increased considerably, contributing to a significant increase in annual amounts of $\boldsymbol{E}$ and a decrease in soil moisture. The linear trend of annual and vegetation period evapotranspiration sums is mostly insignificant; in higher altitudes, it is about 40 mm in 71 years, with a determination coefficient R^2 of about 0.15.

Model testing was performed to evaluate the accuracy of evapotranspiration calculations concerning possible errors in determining the overall radiation balance, integral diffusion coefficient, critical soil moisture, and precipitation measurement. The effect of atmospheric precipitation trapped by vegetation on evapotranspiration totals was also evaluated. The analysis of the calculation of $\boldsymbol{E_0}$ about possible errors of those parameters showed that the error in determining monthly totals $\boldsymbol{E_0}$ for the summer months is 7 to 10% and for the whole year, 4 to 5%. The differences between the average annual evapotranspiration totals determined from the water balance equation (annual precipitation – annual runoff) and evapotranspiration totals determined by applying the proposed model for Slovakia territory are around 6% on average.

6. Climatic irrigation indicator

$\boldsymbol{E_0}$, $\boldsymbol{E}$, and $\boldsymbol{P}$ values have been used in Slovakia (as well as other countries) to analyse irrigation conditions and drought risk (*Bochníček et al., 2015*). In this case, it is a meteorological or climatological drought. The climatic indicator of irrigation $\boldsymbol{K} = \boldsymbol{E_0} - \boldsymbol{P}$, or evapotranspiration deficit $\mathrm{d}E = E_0 - E$, or relative evapotranspiration $E_r = E/E_0$, are good indicators. We used the climatic irrigation indicator $\boldsymbol{K}$ to evaluate the irrigation conditions. It is a climatic characteristic of the country's soil-water balance with an excellent physical justification. This coefficient expresses the relationship between the amount of moisture in a given location in the form of precipitation and the amount of moisture that can evaporate from sufficiently irrigated soil and plants. Negative values of the climatic irrigation indicator occur in regions with sufficient moisture, so the amount of the total precipitation exceeds possible evapotranspiration.

Because of limited space, the calculated $\boldsymbol{K}$ values are presented in Fig. 10 only for meteorological station Košice, Airport (southeastern Slovakia) from 1951 to 2021. This indicator shows the water's necessity to cover maximum evapotranspiration demands. So, it is also possible to utilize precipitation water from the previous months. That is why this indicator is more credible at long-term averages. On the other hand, the results illustrated in Fig. 10 show some increasing trends in irrigation indicators, which is valuable information for users in many branches. The low determination coefficient indicates no statistically significant linear growth at a constant rate in the monitored period. This is also observed at other stations in Slovakia. However, the final conclusions on the $\boldsymbol{K}$ trend will be possible after several decades of climate change continuation (e.g. in 2040). The issue of drought and irrigation conditions has been solved for a long time within the framework of the National Communications on Climate Change from 1995–2017 (*NCCC, 1995, 1997, 2001, 2006, 2009, 2014, 2017*).

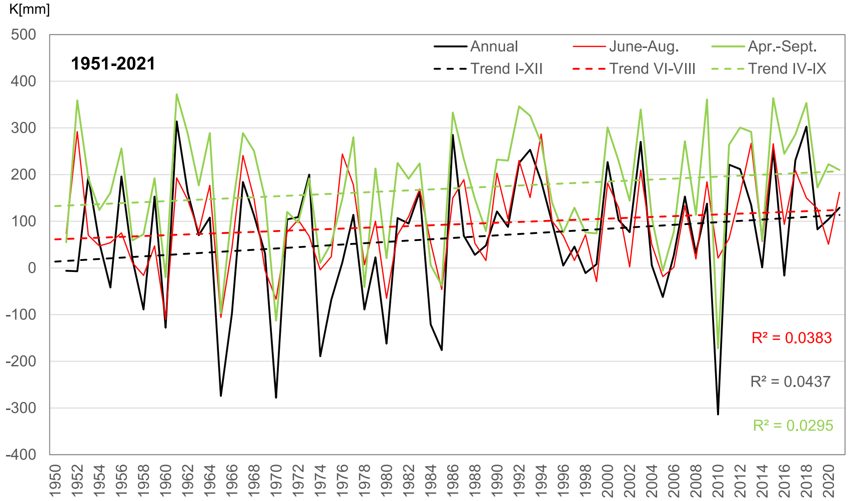

Fig. 10. Irrigation indicator $\boldsymbol{K} = \boldsymbol{E_0} - \boldsymbol{P}$ for Košice Airport in 1951–2021.

7. Evaporation scenarios

At the end of this study, the scenarios of potential evapotranspiration $\boldsymbol{E_0}$ by two regional circulation models (RCM) outputs in a version of the SRES A1B emission scenario were prepared. The process of evapotranspiration scenario design is challenging. The potential evapotranspiration is a complex hydrologic, meteorological, and climatic variable. In addition, the Budyko-Tomlain method needs snow cover and duration of sunshine monthly data, which are not directly available from RCM outputs and must be calculated indirectly by a regression method. That is why this method's calculation of $\boldsymbol{E_0}$ scenarios is more difficult.

So, we applied quite a simple Zubenok method (*Zubenok, 1976*) to calculate the monthly and seasonal evapotranspiration totals. This method uses a saturation deficit in different geobotanic regions and can be easily applied to climate change scenarios of $\boldsymbol{E_0}$. The results of processing $\boldsymbol{E_0}$ for selected stations based on daily saturation deficit data from the RCMs mentioned are demonstrated in Figs. 11 and 12.

The $\boldsymbol{E_0}$ scenarios were treated according to the nomograms presented in the work of *Zubenok (1976).* The Zubenok method uses nomograms based on mean monthly saturation deficit different for each month during the year and for specific geobotanic regions. In the case of Hurbanovo and other lowland locations, we applied the steppe-forest region nomogram. We used nomograms for deciduous or mixed forests for higher or wooded positions. To calculate $\boldsymbol{E_0}$ using nomograms, we needed to determine as reliably as possible the monthly averages of the saturation deficit $D = e^* - e$ (e^* is the water vapour pressure in the state of saturation at a given temperature, and e is the actual water vapour pressure). Since the D values depend on the calculation methodology (e^* and e also change exponentially with the air temperature T), we calculated e^* and e from the model outputs for each day. The monthly averages of D we determined using the arithmetic mean. The values calculated this way are reliable. This method is comfortable for calculating the monthly potential evapotranspiration totals up to 2100. The Zubenok method provides higher monthly sums of $\boldsymbol{E_0}$ than the Budyko-Tomlain method in the cold half-year (CHY) because ground condensation and deposited precipitation are not considered. The utilization of the Zubenok method for $\boldsymbol{E_0}$ calculation is discussed in more detail in *Lapin et al. (2015).*

The potential evaporation sums $\boldsymbol{E_0}$ in mm by MPI and KNMI D scenarios and Zubenok method for chosen stations in Slovakia in the 1951–1990, 2001–2050, and 2051–2100 periods are presented in Fig. 11. 1951–1990 is a base; the 2001–2050 and 2051–2100 periods represent the time frames of 2025 and 2075. For illustration, we selected only ten stations so that they characterize the development throughout Slovakia.

Scenarios of the relative $\boldsymbol{E_0}$ values (in % from 1951–1990) for the time horizons 2001–2050, 2026–2075, and 2051–2100 are illustrated in Fig. 12 (the mentioned periods represent time frames of years 2025, 2050, and 2075). Under the MPI model, which has a higher relative humidity, the increase in $\boldsymbol{E_0}$ in the 21st century is slightly smaller than under the drier KNMI model. Overall, the growth of $\boldsymbol{E_0}$ is less than that of the saturation deficit D. It is related to the nonlinear dependence of $\boldsymbol{E_0}$ on D in nomograms, according to Zubenok. Table 6 shows the expected evolution of D in the 21st century compared to D in 1951–1990.

Since the saturation deficit from the thermometer screen is considered in the calculations (not due to the evaporating soil surface), the monthly amounts of $\boldsymbol{E_0}$ are moderately higher than when using the complex method

Table 6. Averages of saturation deficit D from modified outputs of regional KNMI and MPI models in hPa at Hurbanovo for months, year, warm half year, and periods 1951 to 2100.

	model KNMI				model MPI			
Months/ period	1951–1990	2001–2050	2026–2075	2051–2100	1951–1990	2001–2050	2026–2075	2051–2100
I	0.9	1.0	1.1	1.2	1.0	1.2	1.5	1.6
II	1.3	1.5	1.7	1.7	1.4	1.6	2.1	2.1
III	2.6	2.9	3.2	3.3	2.8	3.2	3.5	3.5
IV	4.7	5.3	5.4	5.6	4.8	5.3	5.2	5.2
V	6.1	6.9	7.3	8.1	6.1	6.2	6.4	6.7
VI	7.2	7.9	8.3	9.7	7.2	7.7	7.7	8.5
VII	8.2	9.1	10.0	12.0	8.3	9.0	9.2	10.3
VIII	7.3	8.0	8.9	9.9	7.7	8.8	9.6	10.8
IX	4.5	5.1	5.6	5.9	4.8	5.6	6.1	6.9
X	2.9	3.2	3.4	3.5	3.0	3.5	3.7	3.8
XI	1.5	1.6	1.7	1.8	1.6	1.9	2.0	2.1
XII	1.0	1.0	1.1	1.2	1.0	1.2	1.4	1.5
Year	4.0	4.5	4.8	5.3	4.1	4.6	4.9	5.3
IV–IX	6.3	7.0	7.6	8.5	6.5	7.1	7.4	8.1

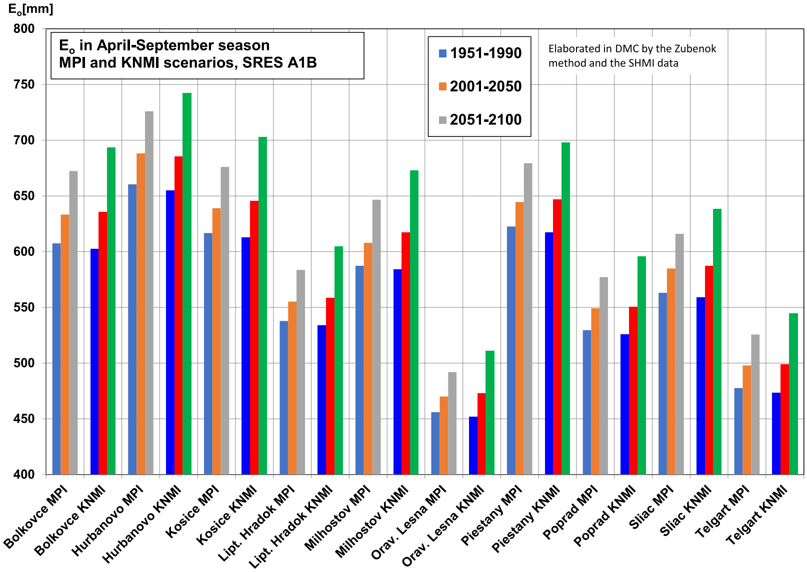

Fig. 11. Scenarios of potential evapotranspiration sums for the Warm half-year (April – September) and ten stations in Slovakia.

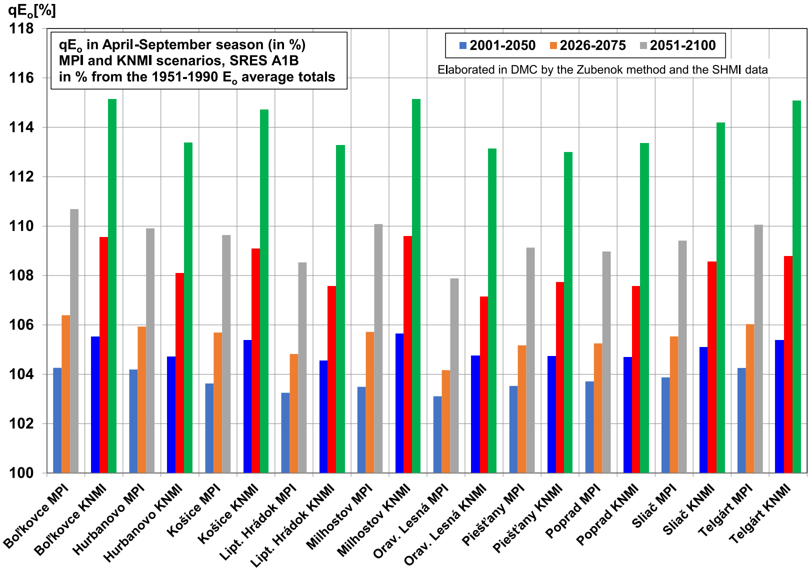

Fig. 12. Scenarios of potential evapotranspiration sums in % of 1951–1990 average for the Warm half-year (April – September) and ten stations in Slovakia.

(primarily in winter). Because the average IPCC SRES A1B emission scenario was applied, the increase of $\boldsymbol{E_0}$ is probably lower than expected. The RCMs use this medium pessimistic scenario (SRES A1B) with global warming by 2.9 °C until 2100 compared to 1961–1990. In terms of temperature, the period 1991–2021 was as warm as expected by the scenario until around 2050. The expected warming until the end of the 21st century is about two times greater than the global warming scenario according to the medium emission scenario A1B. We are following such developments throughout Slovakia.

A significant increase in $\boldsymbol{E_0}$ totals in the WHY (Apr. – Sep.) can be seen on the one hand, and a rise of the interannual variability on the other. A similar development can also be expected for the other lowland sites and the lower localities in northern Slovakia.

8. Conclusion

Evapotranspiration, as a physical process, depends on the heat supply. Therefore the amount of water vapour in the atmosphere depends on the temperature conditions. Previous analyses (*Gera et al., 2019; Bochníček et al., 2018; Damborská et al., 2016*) showed significant changes in some climatological elements in Slovakia in the second half of the 20th century and the start of the 21st century. The changes in air temperature and precipitation in Slovakia, mainly in the first two decades of the 21st century, influence evapotranspiration, which is integral to meteorological, hydrological, and biological processes.

Potential evapotranspiration is an essential climatological and hydrological element that belongs to energetic and hydrological balance elements. The information about spatial and time distribution of potential evapotranspiration is of great importance in theoretical and practical problems of agriculture, forest and water management, or forming and protection of the environment.

In this paper, we focused on the changes and variability of evapotranspiration sums in 1951–2021 and scenarios of potential evapotranspiration up to the time horizon 2100. The measured data at 26 meteorological stations and the modified RCMs outputs were used for this purpose.

The monthly sums of potential and actual evapotranspiration are considered to be evaporation and transpiration from a standard natural grass plot at the meteorological stations. The complex method also enables the calculation of the monthly means of soil moisture (W) in the upper 1 m soil layer. These data can also be applied by the recommended methods to calculate evapotranspiration from different surfaces.

For limited space, only selected results are presented in this paper. The annual sums of potential evapotranspiration calculated by the Budyko-Tomlain method in 1951–2021 indicate that an increase in potential evapotranspiration can be seen much more in the south than in the north of Slovakia. This increase is caused mainly by global warming impacts (temperature rise) and partly by decreased relative humidity, especially in the south. An increase in air temperature and potential evapotranspiration can be partly connected with global warming caused by the atmospheric greenhouse effect rise. Because of complex physical processes connected with water and hydrological balance during the climate change period, the interrelation among temperature, precipitation, relative humidity, snow cover, radiation balance, evapotranspiration, and soil moisture long-term means must be solved more in detail in the following years.

Based on model calculations of potential evapotranspiration, we determined the climatic irrigation index $\boldsymbol{K}$ to analyse irrigation conditions and drought risk in Slovakia from 1951 to 2021. The results show a slightly increasing linear trend in irrigation indicators. Negative values of $\boldsymbol{K}$ occur throughout the year in the mountainous area and the whole of Slovakia during the winter.

The prepared potential evaporation scenarios based on two regional circulation model outputs (KNMI and MPI) in a version of medium SRES A1B emission scenario indicate that an increase in potential evapotranspiration follows the rising air temperature and saturation deficit. Changes in actual evapotranspiration are due to changes in potential evapotranspiration, precipitation, and soil moisture availability. Under the MPI model with a higher relative humidity, the increase in $\boldsymbol{E_0}$ in the 21st century is slightly smaller than under the drier KNMI model.

The evapotranspiration calculated by the Budyko-Tomlain method and prepared scenarios can be successfully used to prepare studies on the impacts of and the vulnerability to climate change in different sectors, including agriculture, hydrology, water resources, and water management.

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