EVALUATION OF THE GROUNDWATER RECHARGE FOR THE DANUBIAN PLAIN (NORTHERN BULGARIA) BASED ON CLIMATIC DATA

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ABSTRACT. Long-term groundwater recharge is a valuable characteristic for the groundwater management. It is subject to changes under pressure of the substantial climate variability, common for South-Eastern Europe. The aim of the study is to evaluate the groundwater recharge for the Danubian Plain (Northern Bulgaria) based on climatic data.

The method used is based on the water balance equation (Miegel et al., 2013) and requires the following climatic data: the average monthly air temperature, precipitation sums and solar radiation. It is assumed that the actual evapotranspiration during the cold period of the year (October-March) is equal to the potential. The potential evapotranspiration is calculated by the Turc radiation equation. The ratio of actual evapotranspiration to potential evapotranspiration for the Danubian Plain is assessed using a simple linear regression equation with one independent variable – the aridity index. This equation is obtained on the basis of the climate and soil data typical for the study area.

The average annual groundwater recharge is assessed for 27 stations from the Danubian Plain. The obtained results are presented both in tables and on maps with contour lines. The maps represent regional distribution of the respective values. The special case of the Northeastern part of the country, where karst rocks are overlain by thin soils is not considered. Both the advantages and the limitations of the method are described. The estimates made for the period 2000-2011 in respect to these for the 20th century show increasing air temperature, potential evapotranspiration and the respective reduction of the groundwater recharge.

The method used is applicable to flat terrain with negligible surface runoff and interflow. It is not appropriate in areas with shallow groundwater table. In general, the method shows good results and can be recommended for wider use within its limitations.

Key words: water budget, groundwater recharge, Danubian Plain, Northern Bulgaria

ОЦЕНКА НА ПОДХРАНВАНЕТО НА ПОДЗЕМНИТЕ ВОДИ В ДУНАВСКАТА РАВНИНА (СЕВЕРНА БЪЛГАРИЯ) ПО КЛИМАТИЧНИ ДАННИ
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РЕЗЮМЕ. Информацията за подхранването на подземните води, характеризиращо техния възобновяем ресурс, е необходима при управление на водните ресурси. Подхранването се променя под влиянието на значителна изменчивост на климата, характерна за Югоизточна Европа. Целта на изследването е да се оцени подхранването на подземните води в Дунавската равнина (Северна България) въз основа на климатични данни.

Използваният метод е основан върху уравнението на воден баланс за равнинни територии (Miegel et al., 2013). Предполага се, че действителната евапотранспирация през студения период на годината (октомври - март) е равна на потенциалната. Методът изисква следните климатични данни: средна месечна температура на въздуха, валежи и слънчева радиация. Потенциалната евапотранспирация е изчислена по радиационното уравнение на Turc. Съотношението между действителната евапотранспирация и потенциалната за условията на Дунавската равнина се оценява по линейно регресионно уравнение в зависимост от индекса на аридност. Това уравнение е получено с използване на климатични и почвени характеристики, характерни за района на изследването.

Оценката на средното многогодишно подхранване на подземните води е извършена за 27 станции в пределите на Дунавската равнина. Получените резултати са представени, както в табличен вид, така и на карти с изолинии. Картите дават представа за регионалните закономерности и не отчитат специфичните условия в Североизточна България, където окарстяващите се скали са припокрити с по-тънки почви. Изброени са предимствата и ограниченията на метода. Резултатите, получени за периода 2000-2011г., показват увеличени стойности на температурата на въздуха и потенциалната евапотранспирация, както и съответното намаляване на подхранването на подземните води, по сравнение с тези за 20-ти век.

Използваният методът е приложим при равнинен терен, с незначителен повърхностен и вътрепочвен отток. Той не е подходящ за условия на плитки подземни води. Общо взето, методът показва добри резултати и може да се препоръча за по-широка употреба.

Ключови думи: воден баланс, подхранване на подземните води, Дунавска равнина, Северна България

Introduction

Long-term groundwater recharge is a valuable characteristic for the groundwater management. Besides its considerable spatial and temporal variability, it is subject to significant climate change proven for South-Eastern Europe.

The aim of the study is to evaluate the groundwater recharge for the Danubian Plain (Northern Bulgaria) based on climatic data for the 20th century.

In addition, an attempt is made to assess possible changes of the groundwater recharge in respect to climate variations, based on data for the period 2000-2011.

Short description of the study area

The Danubian Plain is located in Northern Bulgaria along the Danube River. The climate is temperate with cold winters and hot summers. Seasonality is well expressed. The coldest month is January with negative values of the mean air temperature, and the hottest is July (mean temperature over 20 ºC).

The mean annual precipitation sums decreases from the southern mountain part (more than 1000 mm/a) to the Danube River (about 500-550 mm/a). Maximum precipitation generally occurs in late spring and early summer. The cold half-year is characterized by lower precipitation (about 40-45% from the annual sum).

Fertile Chernozems are the major soil type in the area (Koinov et al., 1998). The soils are mostly deep, medium-to-low permeable. They are developed on the loess sediments that cover the Danubian Plain.

Agricultural land use predominates in the area. The natural vegetation is presented by temperate deciduous forests (mostly broadleaf trees, shrubs, and herbs).

The first regional estimate of the natural groundwater resources of the study area was obtained by V. Spassov (1966, 1969) using the hydrograph separation method. The permeability of the outcropping formations was taken into account.

Methods and data base

Water balance equations

The average groundwater recharge R for flat terrains with negligible surface runoff and interflow is defined by the water balance equation (Wessolek et al., 2011; Miegel et al., 2013):

$$R = P - E_a, \tag{1}$$

where P denotes the yearly mean precipitation and Ea is the actual evapotranspiration, which depends on the site, soil, and crop properties. If the difference between the potential and actual evapotranspiration during the cold half-year is negligible, the last value in Eq. (1) may be substituted by the sum (Wessolek et al., 2011):

$$E_a \approx E_{as} + E_{pw} = E_{as} + E_p - E_{ps}, \tag{2}$$

where Eas is the actual evapotranspiration during the "summer months" (warm period of the year: April-September) and Epw is potential evapotranspiration during the "winter months" (cold period: October-March). From here, the average groundwater recharge according to Miegel et al. (2013) may be defined as follows:

$$R = P - E_p + E_{ps}\left(1 - E_a / E_p\right). \tag{3}$$

The Eq. (3) is an approximate equality. More precisely, the ratio between the actual and potential evapotranspiration should refer to the summer half-year instead of the annual values:

$$R = P - E_p + E_{ps}\left(1 - E_{as} / E_{ps}\right). \tag{4}$$

This last equation is used in this study to evaluate the long-term groundwater recharge in the Danubian Plain.

Assessment of the potential evapotranspiration

Generally, the potential evapotranspiration is represented by the FAO-56 grass reference evapotranspiration ET$_o$ (the Penman-Monteith method, Allen et al., 1989). As this standard method is rather complex and has a high data demand, several alternative methods are often used. Under the humid weather conditions, the Turc (1961) radiation equation appears to be an appropriate alternate method for estimating ET$_o$ (Fisher and Pringle, 2013 as an example).

The Turc radiation method (Turc, 1961) estimates the potential evapotranspiration (mean monthly value, mm/day) based on the average air temperature (T, ºC) and solar radiation (R_s, MJ m^{-2}day^{-1}) using the equation (for relative humidity > 50%):

$$E_p = 0.01333 \cdot \left[(23.9001 \cdot R_s) + 50\right] \cdot \left(\frac{T}{T+15}\right) \tag{5}$$

Assessment of the actual evapotranspiration

The well-known Budyko curve presents the relationship between the E$_a$/P ratio and the aridity index (Faybishenko, 2007):

$$E_a / P = \left\{\phi \tanh\left(1/\phi\right)\left[1 - \exp\left(-\phi\right)\right]\right\}^{0.5}, \tag{6}$$

where the aridity index ϕ is defined as a relation between the potential evapotranspiration and the precipitation sum:

$$\phi = E_p / P. \tag{7}$$

This semi-empirical equation was obtained for numerous catchments with the known values of the mean annual precipitation and total river runoff.

The model of Porporato et al. (2004) is more complicated compared to the Budyko curve (Eq. 6). The partitioning of the rainfall input into evapotranspiration and deep infiltration plus runoff was done based on the theoretical analysis taking into account the water-holding capacity of the soil. The rainfall input was modelled as a Poisson process with a mean rainfall depth per event α. Thus, the model of Porporato et al. has an additional parameter γ:

$$\gamma = PAWC / \alpha, \tag{8}$$

where PAWC denotes the plant available water capacity of a soil profile. This model is expressed by the equation (Porporato et al., 2004):

$$\frac{E_a}{P} = 1 - \left(\phi \cdot \gamma^{\gamma/\phi - 1} \cdot e^{-\gamma}\right) / \left(\Gamma(\gamma/\phi) - \Gamma(\gamma/\phi, \gamma)\right) \quad (9)$$

where $\Gamma(.)$ and $\Gamma(.,.)$ are the Gamma function and Incomplete Gamma function respectively. It was proven that the Budyko equation (6) is a special case of Eq. (8) for $\gamma = 5.5$, i.e. for thin soils (Porporato et al., 2004).

The values of the relation E_a/P in respect to the aridity index by equations (6) and (9) are presented in the first columns of Table 1.

Table 1.
Relation of some climatic values in respect to the aridity index ϕ *based on Eqs (6) and (9)*

ϕ	Budyko	Porporato (γ = 15)		
	E_a/P	E_a/P	E_a/E_p	E_{as}/E_{ps}
1.0	0.694	0.808	0.808	0.782
1.1	0.727	0.852	0.774	0.749
1.2	0.756	0.884	0.737	0.712
1.3	0.782	0.911	0.701	0.678
1.4	0.804	0.931	0.665	0.643

The relation E_a/E_p is as follows:

$$\frac{E_a}{E_p} = \frac{E_a}{P} : \phi , \quad (10)$$

and the respective values are presented in Table 1.

Data base

The data base for the study includes climatic data for meteorologic stations in Northern Bulgaria (Table 2, Fig. 1), namely: the mean annual values of the precipitation sum (period 1931-1985), as well as mean monthly values of the air temperature for the period 1931-1970 (Koleva and Peneva, 1990; Kuychukova, 1983).

An additional period covers 12 years from the new century (2000-2011) in order to compare the obtained results for some stations. The data are from the National Institute of Meteorology and Hydrology.

The data for the solar radiation R_s are from the monthly climatic data for the respective climatic zone identified in Bulgaria and presented in appendix №2 of the Ordinance on heat and energy savings in buildings in Bulgaria (Anonymous, 2005).

The plant available water capacity of a soil profile (PAWC) is set at 150 mm – a typical value for agricultural regions in Eastern Europe with deep roots (Dunne and Willmott, 1996). The mean rainfall depth per event α is about 10 mm. It is defined as a relation between the mean annual precipitation sum and the average number of the precipitation events (>2 mm, to eliminate the interception by vegetation) per year. Similar value was reported for the Ogosta River basin in northwestern part of the study area (Orehova et al., 2012). According to Eq. (8), the value of the additional parameter in the model of Porporato et al. (2004) is $\gamma = 15$.

Table 2.
Input and output data for the study area (20th century)

Station	P, mm	E_p, mm	E_{ps}, mm	ϕ	R, mm	R/P, %
Vidin	581	710.4	615.4	1.22	52.5	9.0
Gramada	594	686.0	598.4	1.15	70.7	11.9
Lom	548	719.1	619.1	1.31	31.1	5.7
Oryahovo	517	734.5	629.0	1.42	11.7	2.3
B. Slatina	583	656.4	570.1	1.13	75.9	13.0
Knezha	579	656.4	570.1	1.13	73.4	12.7
Somovit	507	725.6	624.9	1.43	11.4	2.2
Pleven	578	682.2	580.9	1.18	58.9	10.2
Svishtov	543	730.0	625.3	1.34	24.3	4.5
Byala	595	683.4	580.6	1.15	68.2	11.5
Pavlikeni	611	679.7	576.8	1.11	79.6	13.0
V. Tarnovo*	680	659.8	553.5	0.97	135	19.9
Ruse	585	732.4	627.1	1.25	44.3	7.6
Silistra	501	717.1	612.5	1.43	9.4	1.9
Razgrad	564	658.3	561.1	1.17	60.7	10.8
Dve mogili	588	712.9	614.4	1.21	54.5	9.3
Obr. Chiflik	600	700.8	609.6	1.17	67.7	11.3
Samuil	650	664.0	579.9	1.02	117	18.0
Isperih	587	695.4	599.5	1.18	60.8	10.4
Popovo	593	709.6	604.1	1.20	56.4	9.5
Slavyanovo	593	653.9	558.1	1.10	80.7	13.6
Tzarev brod	600	701.6	598.7	1.17	64.2	10.7
Shumen	597	706.6	602.2	1.18	60.2	10.1
Targovishte	646	709.6	604.1	1.10	88.8	13.7
Krushari	506	697.7	596.7	1.38	17.1	3.4
Kubrat	611	681.0	591.7	1.11	82.6	13.5
Izgrev	604	664.3	577.5	1.10	85.7	14.2

* period 1976-1995 for T, ºC

Results and discussion

At first, the Turc radiation method (Eq. 5) is used to evaluate mean monthly data of the potential evapotranspiration for all stations. Then the mean annual potential evapotranspiration is calculated along with its portion for the "winter months" (cold period of the year: October-March). The aridity index is estimated using Eq. (7) – see Table 2 and Fig. 2.

During the warm half-year, the actual evapotranspiration is restricted by insufficient water availability (especially, in July and August). Therefore, the relation $E_{as}/E_{ps} < E_a/E_p$. Based on previous estimates made by the second author (for the climate and soil characteristics typical for the Danubian Plain) the relation is obtained for the study area:

$$\frac{E_{as}}{E_{ps}} : \frac{E_a}{E_p} \approx 0.967 . \quad (11)$$

For practical applications, a simple linear regression equation may be used (obtained for the data from Table 1):

$$E_{as}/E_{ps} = -0.348 \, \phi + 1.13 . \quad (12)$$

Both equations (11 and 12) are developed based on the climatic and soil characteristics typical for the study area and

would produce similar results. In this paper, the last equation is applied.

To evaluate the long-term groundwater recharge value, Eq. (4) is used. The obtained results are presented in the last columns of Table 2 and in Fig. 3 and 4.
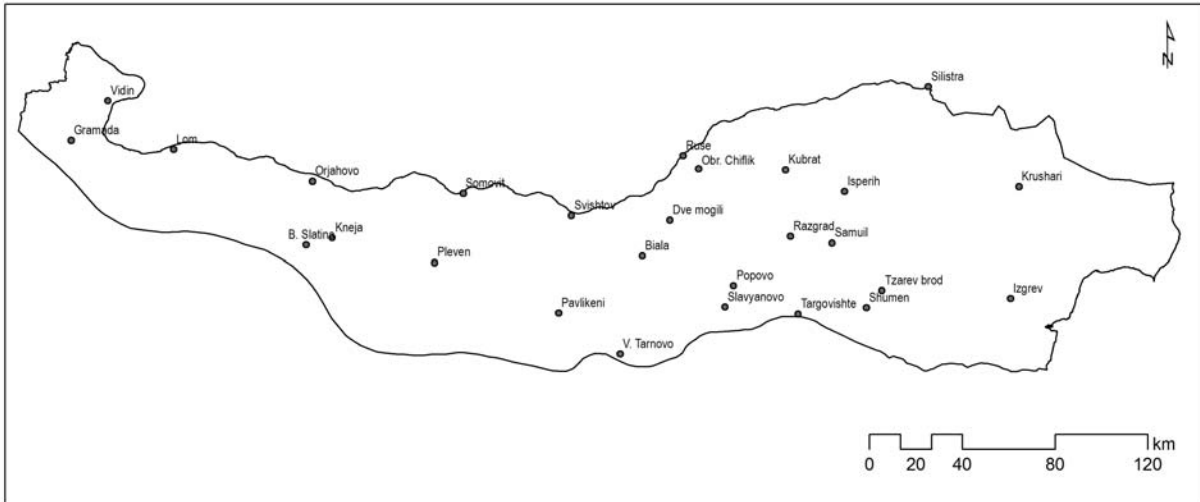
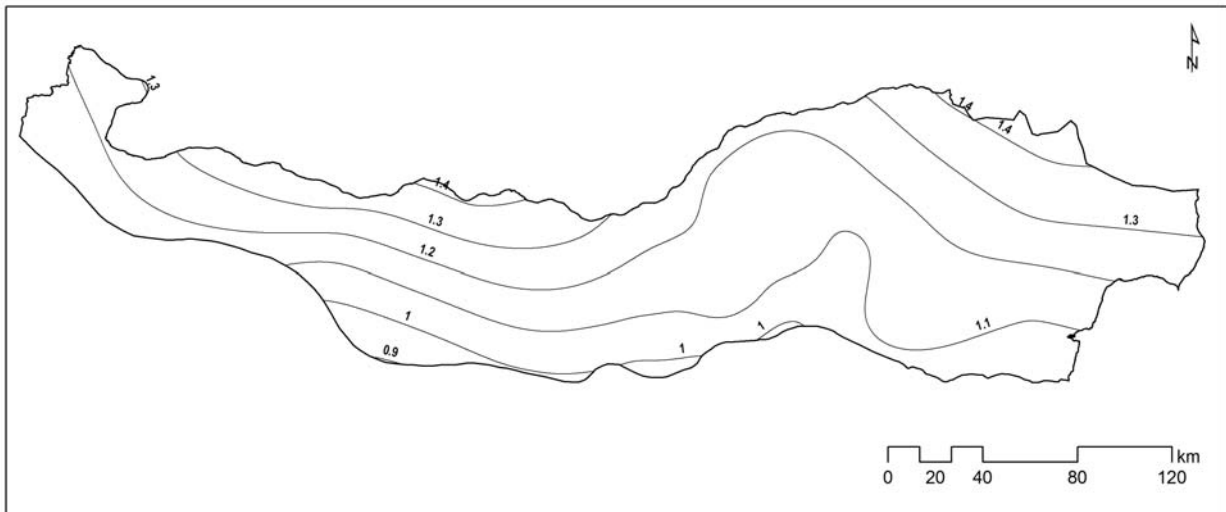

Fig. 1. Location of the meteostations used for the study

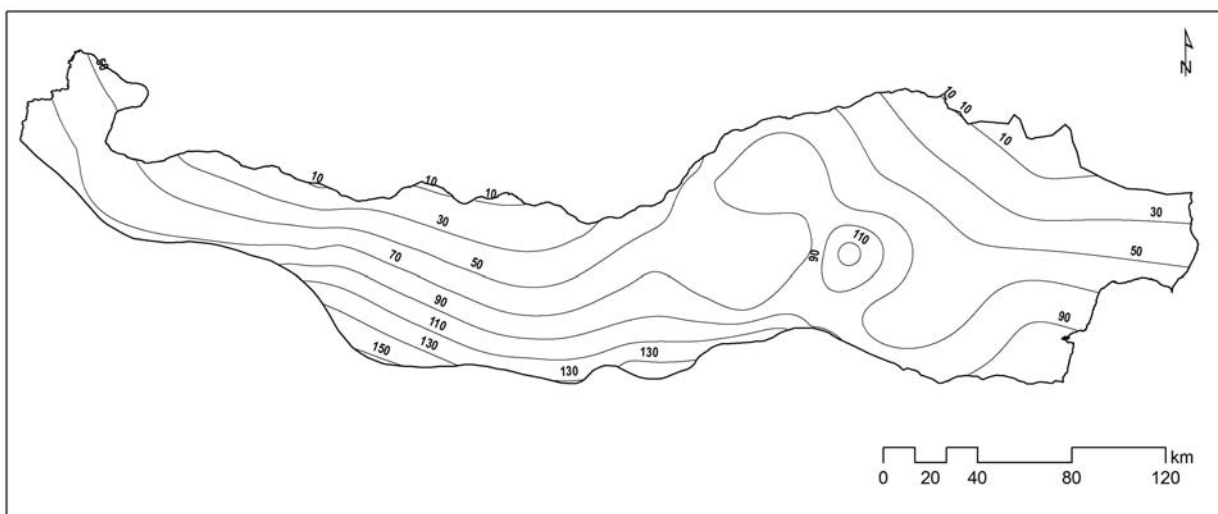*Fig. 2. Isolines of the aridity index ϕ for the study area*

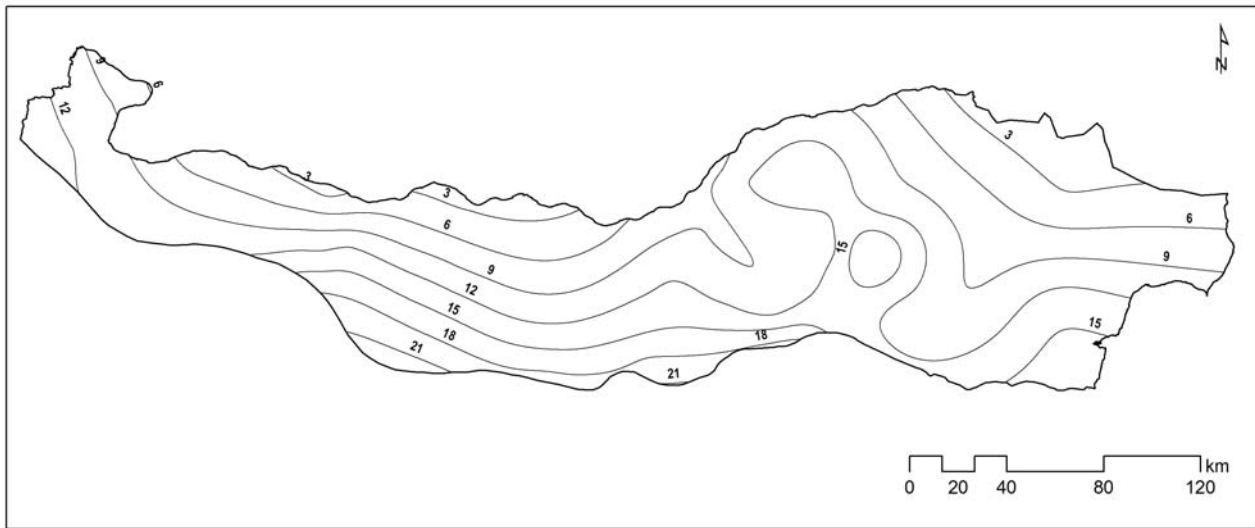*Fig. 3. Isolines of the long-term annual groundwater recharge for the study area (R, mm)*

Fig. 4. Isolines of the long-term relation of the groundwater recharge to precipitation sum (R/P, %).

The evident advantages of the applied method are as follows. It has clear physical background (namely, it presents a multi-annual water balance), with input data from the meteostations located within the study area. Furthermore, it takes into account (from the regression equation) the high PAWC typical for the Danubian Plain.

The presented estimates and figures stress on the regional distribution of the respective values. The special case of the Northeastern part of the country, where karst rocks are overlain by thin soils is not considered. Additional information is needed for the root depth in this area to estimate reduced value of the PAWC.

Compared to the previous estimates of the groundwater water resources by Orehova & Gerginov (2014), using the only input parameter, the aridity index, to evaluate the baseflow Q_b, which focuses on the output from the groundwater system), the present method would give more reliable results. Indeed, the data obtained by both methods are similar only for lower values of the aridity index (see Table 3, where the stations are arranged in order of increasing value of the aridity index).

The discrepancy between the estimates in the lower part of the Table 3 is explained mostly by the influence of the thick soil with high plant available water capacity (typical for the study area) on the formation of the groundwater resources.

The method allows assessing the possible changes of the groundwater recharge in respect to climate variations as well as for different climate change scenarios.

Mean groundwater recharge values for the period 2000-2011 for the two stations show the decrease of the respective values (see Table 4). This period is characterized with enhances values of the air temperature and potential evapotranspiration. The increased values of the mean annual precipitation originate from very wet year 2005 with precipitation sums about 50% above the norm.

Table 3.
Comparison of the recharge values with the previous estimates

Station	ϕ	R, mm	Q_b, mm	Q_b/R
Pavlikeni	1.11	79.6	91.1	1.14
Knezha	1.13	73.4	83.0	1.13
Gramada	1.15	70.7	81.0	1.15
Obr. Chiflik	1.17	67.7	79.5	1.17
Isperih	1.18	60.8	75.2	1.24
Shumen	1.18	60.2	76.6	1.27
Pleven	1.18	58.9	74.7	1.27
Vidin	1.22	52.5	70.6	1.34
Ruse	1.25	44.3	65.5	1.48
Lom	1.31	31.1	57.6	1.85
Svishtov	1.34	24.3	50.1	2.06
Krushari	1.38	17.1	43.6	2.55
Oryahovo	1.42	11.7	41.4	3.54
Somovit	1.43	11.4	39.4	3.46
Silistra	1.43	9.4	38.7	4.12

Table 4.
Comparison of some parameters for the 20th and the beginning of the 21st century

Parameter	Pleven		Krushari	
	20th	21st	20th	21st
P, mm	578.0	598.9	506.0	520.1
T_{av}, ºC	11.6	12.4	10.7	11.6
E_p, mm	682.2	708.1	697.7	734.4
aridity index	1.18	1.18	1.38	1.41
R, mm	58.9	56.2	17.1	10.8
R/P, %	10.2	9.4	3.4	2.1

Conclusion

The long-term groundwater recharge in the Danubian Plain of Bulgaria is estimated based on the climatic data. The approximate equation (3) given by Miegel et al. (2013) is slightly modified to describe the water balance more precisely.

This modified equation (4) is used for calculation of the groundwater recharge.

The ratio E_{as}/E_{ps} (the actual evapotranspiration to potential evapotranspiration for the summer half-year) is assessed using a simple linear regression equation (12) in respect to the aridity index. This equation is obtained on the basis of the climate and soil data typical for the study area and takes into account the enhanced value of the PAWC in the Danubian Plain.

The values of the average annual groundwater recharge are assessed for 27 stations from the Danubian Plain. The results are presented both in table and on maps with contour lines. Comparison of the estimates made for the 20th and beginning of the 21st century revealed increasing air temperature and reduction of the groundwater recharge for the first decade of the period 2000-2011.

The applied approach gives promising estimates of the groundwater recharge based on climatic data.

The method is not valid for mountainous regions where the surface runoff and interflow play important role in the water budget. Also, it is not applicable in areas with shallow groundwater tables. Out of these limitations, the described method may be widely used.

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