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Groundwater recharge and baseflow as products of climate: example of Southeast Bulgaria

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Abstract. The study area is located in Southeast Bulgaria. The main factors affecting climate in Burgas lowland are the proximity to the Black Sea and to mountains. The aim of the study is to quantify the long-term value of the baseflow and other water balance elements. The methods include Turc-Radiation equation, equation relating baseflow coefficient with the aridity index, regression set for Conterminous USA based on climatic parameters, etc. All water balance elements are estimated as reasonable, as compared with available data from previous studies. Therefore, the methods applied are recognized as suitable for the study area. The results show that the baseflow varies from 20 to 70 mm per year, and the baseflow coefficient ranges from 5 to 10 percent in respect to the proximity to the Black Sea coast. Possible impact of the climate change on the groundwater recharge and baseflow is evaluated based on the climate scenario for the period between 2040 and 2070. The expected decrease of baseflow as a result of the increased aridity is up to 50% in comparison to the baseline state.

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Key words: groundwater recharge, baseflow, water balance, aridity indices, climate change.

INTRODUCTION

Global warning registered by the end of the XX century has raised awareness on its impact on the water resources worldwide. The Mediterranean region is one of the most vulnerable areas in this respect. The climate projections (based on the General Circulation Models) for this region indicate progressive warming and reduction of the precipitation input. In particular for the territory of Bulgaria, for the period between 2040 and 2070 in comparison to 1960-1990, the rising of the air temperature with 2.5ºC and about 10% reduction in precipitation amount is anticipated (García-Ruiz et al., 2011). Such shift of the climate would impact all elements of the water balance, including the groundwater recharge.

The issue "climate change and groundwater" has become urgent all over the world (Green et al., 2011) and particularly in Bulgaria (Orehova, Bojilova, 2001; Benderev et al., 2008), as a part of Southeast Europe. Quantification of the renewable groundwater resources is an actual task taking into account the threat of more frequent droughts in future in the Mediterranean region according to climatic models. For water management purposes it is necessary to quantify the groundwater recharge value which is characterized by high spatial and temporal variability.

130 years ago the Russian hydrologist Voeikov (1884) stated: "Rivers are the product of climate". Similarly, one may state that the groundwater recharge and baseflow are climate dependent (without underestimating the role of rocks). Up to now numerous attempts were made to evaluate mean annual recharge based on climatic data such as precipitation sum (e.g., Xu, Beekman, 2003).

The aim of the study is to evaluate and map the groundwater recharge and the baseflow coefficient for the study area in Southeast Bulgaria based on climatic data and aridity indices. As recharge is a part of the water balance of an area, other water budget elements have to be assessed independently as well. In addition, an attempt is made to assess the impact of the possible climate change on the groundwater recharge and baseflow values.

STUDY AREA

The study area (about 3500 km^2) is located in Southeast Bulgaria and encompasses Burgas lowland and the Strandzha Black Sea coast (Fig. 1).

Climatically, the study area belongs to the Continental – Mediterranean climatic area (Velev, 1997). Long and warm summer and a small amount of summer rainfall are typical of this area. Maximal rainfalls occur in November or in June, and the average annual precipitation is in the range 450-550 mm for Burgas lowland and about 650 mm in the Strandzha Black Sea coast (Koleva, Peneva, 1990).

Positive trend in annual temperature and negative trend in annual total precipitation (for the study period 1950-2000) were registered for the study area (Koleva-Lizama, Lizama Rivas, 2004).

The main rivers in Burgas area are Hadzhiyska, Aytoska, Rusokastrenska, Sredetska, Fakiyska, Ropotamo and Veleka. The basic statistical parameters of the monitored catchments in this area are presented by Lizama Rivas, Koleva-Lizama (2005) along with analysis of the long-term variations in precipitation and runoff. For the period 1952-2002 a negative trend was observed for the annual runoff of the rivers within the South Black Sea basin.

According to the tectonic scheme of Bulgaria, the area is a part of the East Srednogorie Unit (Dabovski et al., 2002). The Upper Cretaceous volcano-sedimentary successions are widespread. The study area is a part of the Burgas hydrogeological region located within the Burgas synclinorium. It is built mainly of Upper Cretaceous volcano-sedimentary complex. As a secondary structure, the Upper Eocene depression is superimposed on it (Nedev, 1997). Neogene and Quaternary deposits overlay the Mesozoic and Paleogene rocks. The most abundant in groundwater are alluvial deposits of the numerous rivers as well as the fissured Upper Cretaceous complex, especially where it is affected by tectonic faults. The aquifers are recharged mainly from precipitation, river flow and the Upper Cretaceous aquifer. The groundwater is drained mostly by streams and the Burgasko and Mandrensko lakes (General Master Plans, 2000).

Fig. 1. Location of the study area.

The main soil types in the area are: Pellic Vertisol, Chromic Luvisols and Fluvisoils in riparian zones (Koinov et al., 1998). Agricultural landuse is wide-spread in the area.

METHODOLOGY

The main methodological approach is application of the known methods to evaluate the water budget elements of the study area, with particular attention to the groundwater recharge and baseflow.

The mean annual water balance of an area (for spatial resolution of about 1 km) is as follow (Szilagyi et al., 2003; Lee et al., 2006):

$$P - E = Q_s + Q_b \,, \qquad (1)$$

where P, E, Qs and Qb are mean annual precipitation sum, actual evapotranspiration, surface runoff and baseflow (groundwater contribution to runoff), respectively. For flat areas and highly permeable terrains the surface runoff may be unimportant (Qs = 0). On the contrary, for mountain areas the interflow becomes the third important component of the total runoff (Van Beek, Bierkens, 2008).

On a long-term basis, baseflow represents a lower bound to groundwater recharge within a given water-shed suggesting that the portion of areal evapotrans-piration originating from the groundwater is negligible. Szilagyi et al. (2003, 2005) define “base recharge” **Rb** based on the equations (also Lee et al., 2006):

$$BFI \cdot (P - E) = Q_b = R_b \approx R \,; \; BFI = \frac{Q_b}{Q_b + Q_s} \,, \qquad (2)$$

where BFI - baseflow index, is the ratio of baseflow and total stream runoff.

Wang, Wu (2013) studied the relation between the baseflow coefficient (Qb/P) and the aridity index **Φ** using datasets from the Model Parameter Estimation Experiment (MOPEX) watersheds. They found that the complementary Turc-Pike curve describes well this relation:

$$\frac{Q_b}{P} = 1 - \left[1 + (\Phi)^{-\nu}\right]^{-1/\nu} \,, \qquad (3)$$

where Qb is baseflow, P is mean annual precipitation, the estimated value for the parameter ν is 3.3, and the aridity index is defined as a ratio of the mean annual potential evaporation **Ep** to precipitation:

$$\Phi = E_p / P \,. \qquad (4)$$

The relationship (3) was set in the frames of the International MOPEX project aimed to estimate *a priori* parameters for hydrological models. To define **Ep** is a cumbersome task. The Penman-Monteith method was adopted as the standard method for computation of the so-called reference evapotranspiration (Allen et al., 1998). The only factors affecting it are climatic parameters. For practical use, simpler equations have been proposed. The Turc method also known as the Turc-Radiation equation is largely used for this purpose as it requires only two parameters, namely solar radiation R_s and a mean air temperature **T**. For the relative air humidity RH>50%, it can be expressed as (Shahidian et al., 2012):

$$E_p = \alpha \cdot \left[(23.9001 \cdot \mathrm{R_s}) + 50 \right] \cdot \left(\frac{T}{T+15} \right), \quad (5)$$

where α is 0.01333, and R_s is expressed in MJ m^{-2}day^{-1}. This equation is used for both daily and monthly time scale. According to numerous studies, the Turc equation (5) is the best approximation of the Penman-Monteith method for humid locations. Generally, the Turc method overestimated the reference evapotran-spiration in windless locations and generally under-estimated it in windy locations (Shahidian et al., 2012).

While the index **Φ** defined by the relation (4) includes the potential evapotranspiration $\mathbf{E_p}$, the aridity index by de Martonné is determined directly from the climatic data (de Martonné, 1926):

$$I_{dM} = P/(T+10), \quad (6)$$

where P and T are mean annual precipitation (mm) and air temperature (˚C), respectively. This index is widely used in meteorological and agrometeorological studies.

The actual evapotranspiration depends on both the values of potential evapotranspiration and water availability. Sanford, Selnick (2013) proposed an approach to evaluate actual evapotranspiration (**E**) for the Conterminous USA based on the following climatic values: precipitation sum **P**, mean annual daily temperature **Tm**, mean maximal **Tx,** and mean minimal **Tn** temperature (from the maximal and minimal thermometers):

$$\frac{E}{P} = \frac{\tau \cdot \Delta}{\tau \cdot \Delta + \Pi}; \tau = \frac{(T_m + T_0)^m}{(T_m + T_0)^m + a};$$

$$\Delta = \frac{T_x - T_n}{T_x - T_n + b}; \Pi = \left(\frac{P}{P_0} \right)^n, \quad (7)$$

where **To**, **Po**, **a**, **b**, **m** and **n** are the parameter values for the regression equal to: 13.735; 505.87; 10000; 18.262; 2.4721 and 1.9044, respectively.

The given equations allow calculation of the total water balance of an area according to equation (1).

The aridity index **Φ** could be defined based on the index $\mathbf{I_{dM}}$ using the regression obtained by Paltineanu et al. (2007) for various regions of Romania:

$$1/\Phi = -8 \cdot 10^{-5} \cdot I_{dM}^2 + 0.0302 \cdot I_{dM} - 0.0236. \quad (8)$$

The regression equation is highly significant, with R^2 exceeding 0.99. This equation is valid for the indexes **Φ** and $\mathbf{I_{dM}}$ in the ranges 0.362-2.02 and 14-160, respectively.

DATA SOURCES

The data used include information from eight meteorological stations located in the study area (Table 1). The data cover long lasting periods: mostly 1931-1985 for precipitation (Koleva, Peneva, 1990), and 1931-1970 for air temperature (Kuychukova, 1983). For the period 1931-1970, the temperature values **Tm, Tx, Tn** presented in Table 1 are taken from the Tables 1, 20 and 25 of the volume 3 of the Climatic reference book (Kuychukova, 1983), respectively. The three-decade averages of climatological variables (climate normals for the period 1961-1990) are used for the synoptic station Burgas as well (Global climate normals, 1998).

Table 1
Geographic coordinates of the stations and main climatological parameters

Station	H (m asl)	Latitude	Longitude	T_m (ºC)	T_x (ºC)	T_n (ºC)	P (mm)
Burgas[1]	2	42.50	27.48	12.7	17.1	8.8	540
Burgas[2]	21	42.50	27.48	12.4	17.2	9.1	520
Nesebar[1]	16	42.66	27.74	12.7	16.2	8.8	449
Pomorie[1]	2	42.55	27.65	12.5	16.4	8.1	473
Aytos[1]	90	42.70	27.25	12.2	18.0	6.6	539
Karnobat[1]	194	42.65	26.98	11.4	17.0	5.9	555
Sredets[1]	36	42.33	27.18	12.8	18.4	6.7	587
Sozopol[1]	9	42.42	27.70	13.3	16.6	9.9	494
Tsarevo[1]	17	42.17	27.85	13.1	16.9	9.3	655

H – elevation; P – precipitation; T_m, T_x, T_n – mean annual daily temperature, mean maximal and mean minimal temperature respectively;
[1] - period 1931-1985 for P and 1931-1970 for T_m, T_x and T_n
[2] - period 1961-1990

Table 2
Climatic parameters, indices and water balance elements for stations in the study area

Station	T (ºC)	P (mm)	I_{dM}	E_p (mm)	Φ	Q_b/P (%)	Q_b (mm)	E (mm)	P-E (mm)	Q_s (mm)	$Q_b/(P-E)$ (%)
Burgas [1]	12.7	540	23.8	806.7	1.49	6.9	37.2	457.9	82.1	44.9	45.3
Burgas [2]	12.4	521	23.3	799.5	1.53	6.4	33.3	441.9	79.1	45.8	42.1
Nesebar [1]	12.7	449	19.8	803.2	1.79	4.1	18.2	393.7	55.3	37.1	33.0
Pomorie [1]	12.5	473	21.0	796.2	1.68	4.9	23.1	412.3	60.7	37.6	38.0
Aytos[1]	12.2	539	24.3	791.1	1.47	7.2	39.1	467.7	71.3	32.2	54.8
Karnobat [1]	11.4	555	25.9	762.0	1.37	8.7	48.4	472.1	82.9	34.5	58.4
Sredets[1]	12.8	587	25.8	807.2	1.38	8.7	51.0	501.6	85.4	34.4	59.7
Sozopol [1]	13.3	494	21.2	823.2	1.67	5.0	24.8	421.1	72.9	48.0	34.1
Tsarevo [1]	13.1	655	28.4	804.2	1.23	11.7	76.7	514.5	140.5	63.9	54.6

[1] - period 1931-1985 for P and 1931-1970 for T
[2] - period 1961-1990 for P and T

The data for the solar radiation R_s are from monthly climatic data for the zone №5 (Burgas Province) among the nine climatic zones identified in Bulgaria and presented in appendix №2 of the Ordinance on heat and energy savings in buildings in Bulgaria (Anonymous, 2005). South Bulgaria receives between 4600 and 5000 MJ m^{-2} annually. Based on climatic data, the relative air humidity for all stations is lower than 50% for all months.

RESULTS

The equations presented in the previous section are used to calculate the water balance elements in the study area (Table 2). The values of the mean annual baseflow **Qb** (or base recharge **Rb**) are interpolated, and the respective map is presented in Fig. 2. The second map (Fig. 3) refers to the mean annual baseflow coefficient (Qb/P, %). The highest values of both baseflow and the baseflow coefficient refer to Tsarevo, where the climate is under the influence of the Strandzha Mountain.

A specific task is to evaluate and predict baseflow or recharge for the study area as a result of the future climate change.

Mean annual climate change scenarios projected for the Mediterranean region (the period between 2040 and 2070 in comparison to 1960-1990) by general circulation models anticipate for Southeast Bulgaria an increase in the air temperature with 2.5ºC and 10% decrease in precipitation (García-Ruiz et al., 2011).

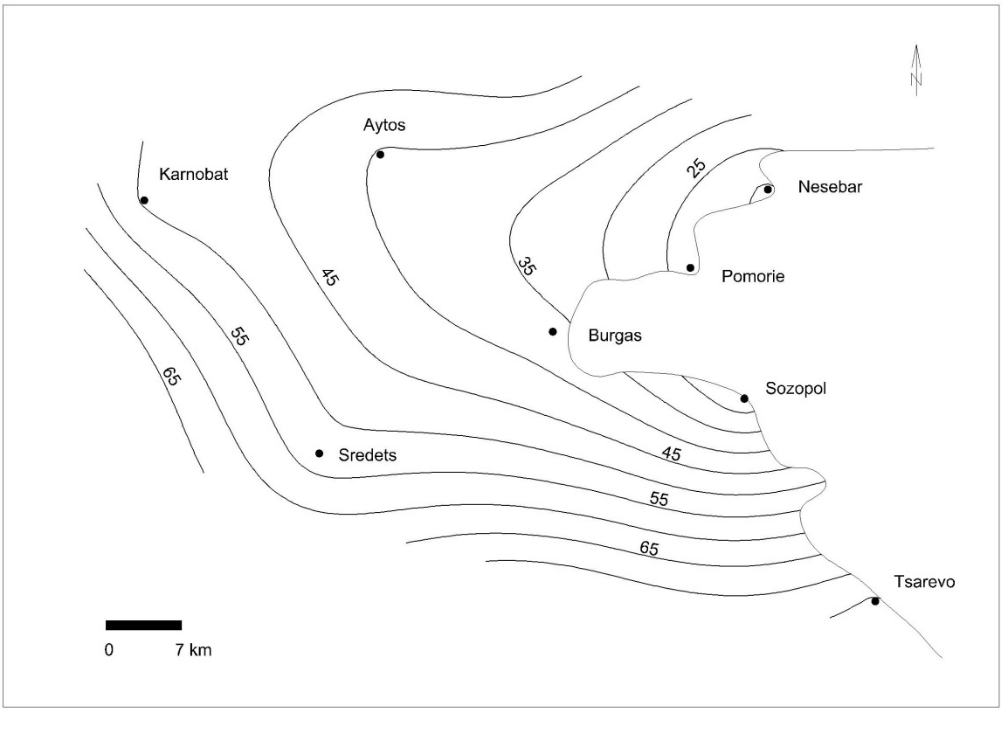

Fig. 2. Isolines of the mean annual baseflow **Qb** in mm (or base recharge **Rb**) for the study area.

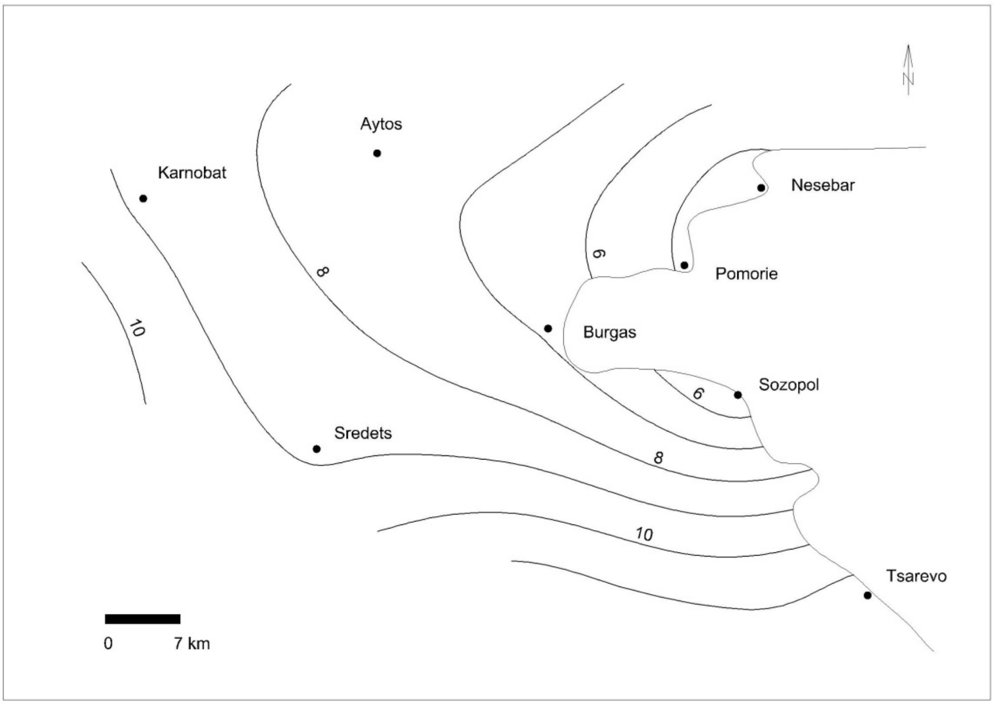

Fig. 3. Isolines of the mean annual baseflow coefficient (in percent, in respect to the mean annual precipitation sum) for the study area.

To assess the impact of climate change on the groundwater resources in the study area, several scenarios for Burgas station are considered: (1) baseline state; (2) increase in mean annual temperature with 2.5ºC and decrease in precipitation sum with 10% according to projections for the period between 2040 and 2070; (3) intermediate scenario (decrease in precipitation sum with 5% and increase in temperature with 1.5ºC.

The equation (3) allows calculation of the future baseflow coefficient (**Qb/P**) based on the aridity index **Φ**. According to the data presented in Table 2, a relation is set between the two indices:

$$1/\Phi = -3 \cdot 10^{-4} \cdot I_{dM}^{2} + 0.0424 \cdot I_{dM} - 0.1859 \ . (9)$$

This regression equation is highly significant, with R^2 exceeding 0.998.

The aridity index **Φ** may be evaluated from $\mathbf{I_{dM}}$ based on the regression (8) as well, which is other possibility. The results of the possible climate change on baseflow are presented in Table 3. There is no substantial difference in the results from using different regressions expressed by equations (8) and (9). The impact from the projected climate change (increase in the temperature with 2.5ºC and decrease in precipitation by 10%) would result in a substantial decline of the baseflow in the study area (over 50%). An intermediate scenario (1.5ºC increase in the temperature and decrease of precipitation by 5%) would reduce the baseflow by one third.

Table 3.
Future climatic parameters, aridity indices and baseflow values for station Burgas

Scenario	dT (ºC)	dP (mm)	T (ºC)	P (mm)	I_{dM}	Φ_1	Q_{b1}/P (%)	Q_{b1} (mm)	Φ_2	Q_{b2}/P (%)	Q_{b2} (mm)
Baseline	0	0	12.7	540	23.8	1.53	6.4	34.7	1.54	6.3	34.2
2040-2070	+2.5	-54	15.2	486	19.3	1.92	3.3	15.9	1.89	3.4	16.7
Intermediate	+1.5	-27	14.2	513	21.2	1.73	4.5	23.1	1.72	4.6	23.4

dT, dP –change in the mean air temperature and precipitation sum in comparison to the Baseline scenario
$_1$ - from regression equation (9) for the study are
$_2$ - from regression equation (8)

DISCUSSION

The values of the water balance elements obtained for the study area are reasonable. The estimates of the potential and actual evapotranspiration are close to the respective values presented in the Agroclimatic Atlas of Bulgaria (Hershkovitch, Stefanov, 1982). Further-more, the baseflow values are in accordance to the previous data for the area.

The estimated local values of the baseflow index (Table 2) are compared with the average values of BFI (for the period 2000-2005) obtained for the watersheds in the South Black Sea region: 38.2% for Fakiyska River at Fakia; 44.6% Fakiyska River at Zidarovo; 37.1% Sredetska River at Prohod (pers. comm. Tanya Vasileva, 2012). Taking into account that all mentioned watersheds include the headwater part where the surface runoff predominates, the obtained relation between the surface runoff and baseflow is reasonable.

The groundwater flow modules for the same period and the same stations are as follows: 1.44, 1.61 and 1.36 $l\ s^{-1}km^{-2}$, and the base recharge values are: 45.3, 50.7 and 42.8 mm/yr, respectively. This data are similar to the presented in Table 2 despite the short period (2000-2005).

In general, all calculated values of the water balance elements presented in Table 2 are in accordance with the previous data, and the applied methods are relevant for the study area.

The results refer to baseflow and the so-called “base recharge” (Szilagyi et al., 2003), which is approximately equal to the total recharge if evapotranspiration from groundwater is low (it is high only in wet zones – mainly riparian and near lakes or marshes).

The obtained results and the respective maps refer to the regional values. They are not applicable for alluvial aquifers in the river valleys where groundwater level is close to the surface, and the relation between surface and groundwater is specific.

The assessed decline in the baseflow as a result of climate change is up to 50% (Table 3). More precise estimates may be obtained if the values of the future monthly air temperatures and relative humidity are known (to assess potential evapotranspiration by Turc-Radiation equation necessary to define the aridity index from Eq. 4). In general, the seasonality of the precipitation input is important for its partitioning between evapotranspiration and runoff, as well as future changes in the land cover.

CONCLUSION

The main factors affecting climate in the study area are the proximity to the Black Sea and to mountains. The same factors are responsible to the value of the aridity indices, baseflow and other water balance elements.

Based on climatic data, both the baseflow and the baseflow coefficient are assessed along with other water balance elements. The applied methods give reasonable results for the study area. The baseflow varies from 20 to 70 mm per year, and the baseflow coefficient ranges from 5 to 10 percent in respect to the proximity to the Black Sea coast. The possible impact of the climate change on the groundwater resources is assessed. The expected decrease of the baseflow is from 30 to 50% for different scenarios as a result of the increased aridity.

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