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EVALUATION OF THE POTENTIAL GROUNDWATER RECHARGE. EXAMPLE OF THE OGOSTA RIVER BASIN, NW BULGARIA

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Abstract

The aim of the study is to evaluate the potential recharge to the groundwater for the chosen study area – the Ogosta River basin in Northwestern (NW) Bulgaria. Various techniques are used for quantifying groundwater recharge. Some of them are based on water budget methods. The Budyko-type curves allow partitioning of the long-term precipitation sum between evapotranspiration and potential recharge. In case of well expressed seasonal variability and thick soils, usual for water-limited environments, this relationship is shifted towards higher evapotranspiration on the account of the reduced recharge, as predicted by theoretical model developed by Porporato. According to this model, this partitioning is governed by two parameters: the aridity index and the relation of the soil available water capacity (AWC) to the average rainfall depth. The long-term potential groundwater recharge, defined as the excess of precipitation over evapotranspiration, may be estimated based on this model. This method was applied for evaluation and mapping of the long-term potential recharge in the Ogosta River basin. The described method is applicable for sub-humid areas, and is especially useful for the purposes of mapping of the renewable water resources.

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Key words: groundwater recharge, water balance, evapotranspiration, Ogosta River basin

Introduction. Sustainable development of the society is based on balanced use of renewable water resources. Quantification of the groundwater recharge is important to ensure the equilibrium between the input of fresh water, its ecological role and abstraction for human needs. Knowledge of the aquifer recharge is essential due to more frequent droughts and enhanced water demand.

Different types of recharge are distinguished – potential, actual and rejected recharge. *Potential recharge* is defined as the excess of precipitation over evapotranspiration [1]. *Actual recharge* may be much less than the potential recharge because of low aquifer storativity. THEIS [2] defined '*rejected recharge*' as the amount of total (or potential) recharge that discharges from an aquifer because it is overfull and cannot accept more water. Evidence of 'rejected recharge' includes high level springs, flooding and water logging of land [3]. Rejected recharge becomes interflow and surface runoff. Therefore, *potential recharge* is the sum of actual recharge and rejected recharge.

In the evaluation and mapping of the groundwater resources in Bulgaria, the method of the hydrograph separation at river gauges was widely used [4, 5]. This method focuses on the groundwater contribution to streams and refers to the output from the groundwater system.

The present study is focused on processes at the land surface which are related to the input to the groundwater system. More specifically, the separation of rainfall between evapotranspiration and potential recharge is investigated. The aim of the study is to evaluate this potential recharge to the groundwater system for the chosen study area – the Ogosta River basin (NW Bulgaria) and to compare the obtained results with the previous estimates of the groundwater recharge and flow.

Study area – brief description. The study area with a total surface area of 4231 km^2 is located in Northwestern Bulgaria (Fig. 1). This is the Ogosta river basin with maximal and minimal altitude 2016 m and 24 m a.s.l. respectively. The climate is temperate with cold winters and hot summers. The air temperature and precipitation values show clear zonality according to the altitude.

The mean annual air temperature in the plain part of the study area is about 11 °C. The average precipitation is below 500 mm for the lower part of the study area, about 700 mm in the fore-mountain and up to 1200 mm in its mountain part. The spatial distribution for the precipitation sums is presented in Fig. 1, based on data for 55-year period [6].

The Ogosta River flows across large varieties of rocks from Precambrian to Quaternary age. Detailed description of the loess cover is given by MINKOV [7], and of the Neogene sediments – by KOJUMDGIEVA and POPOV [8]. Due to the heterogeneous geological structure of the study area, a multi-aquifer system is

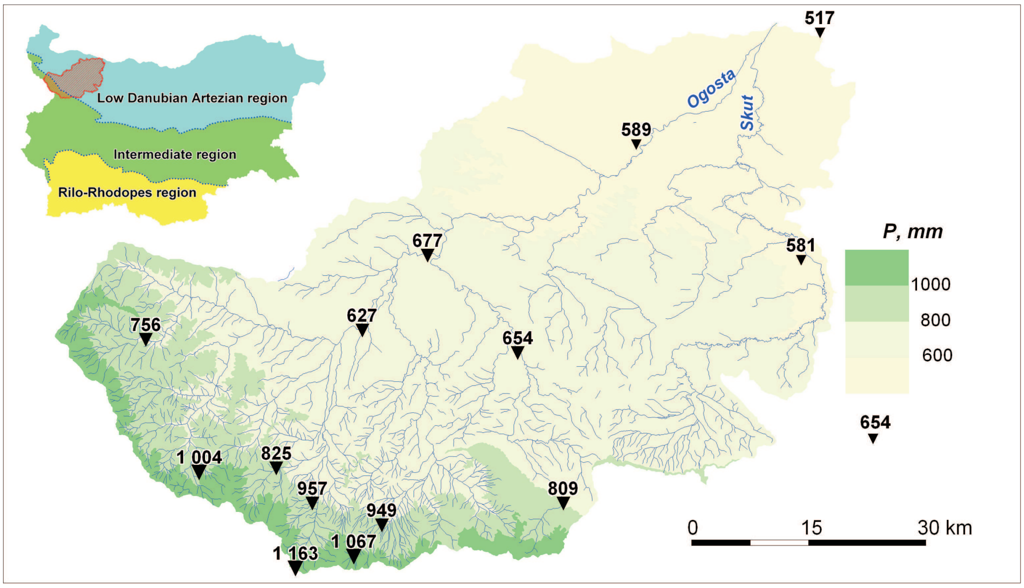

Fig. 1. Spatial distribution of the precipitation sums (mm/a); numbers are values at rainfall stations

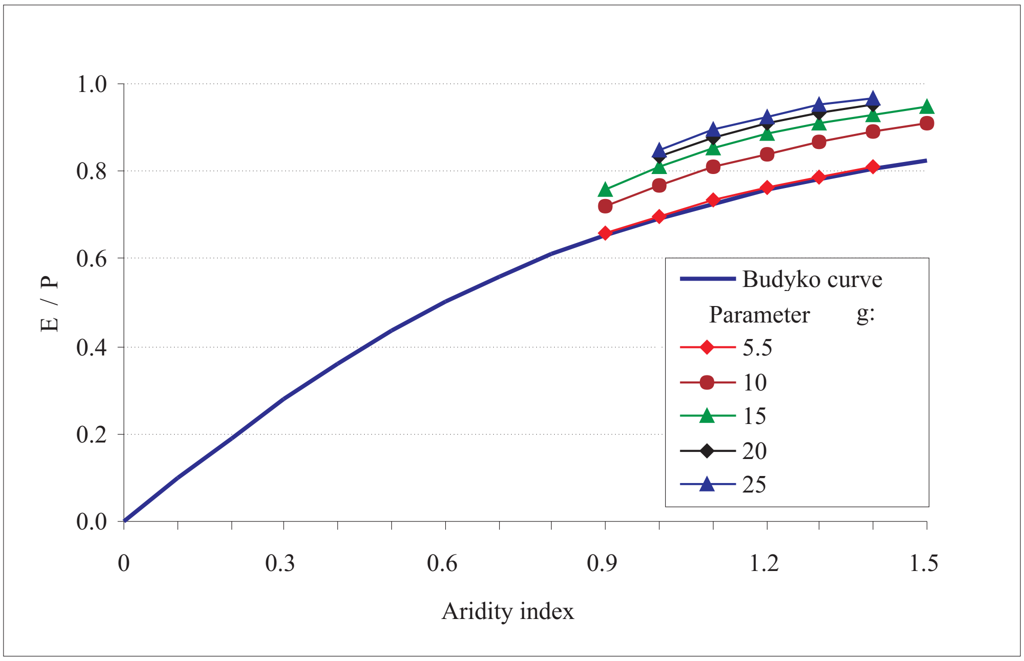

Fig. 2. Ratios E/P as function of the aridity index Φ and the parameter γ according to Eq. 6

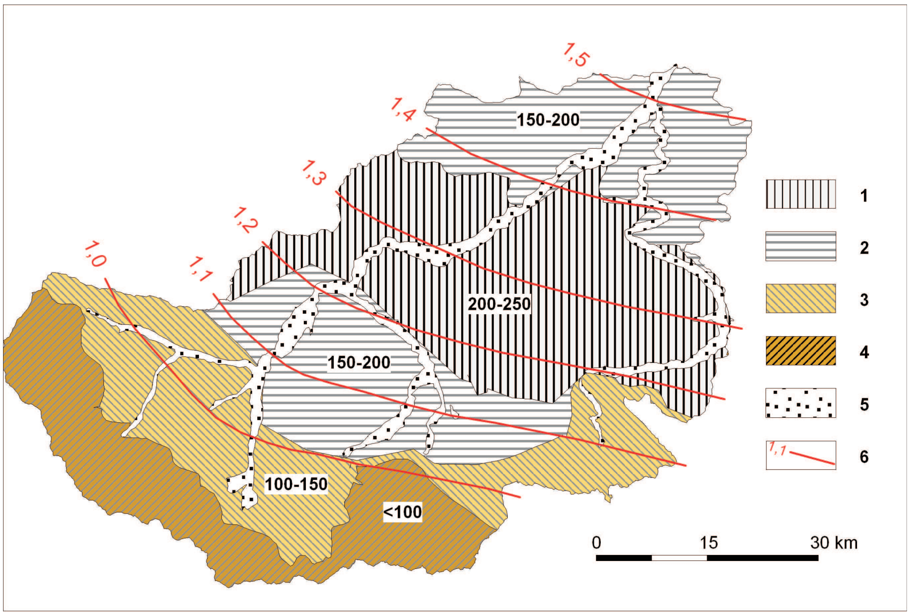

Fig. 3. Map of aridity index and spatial distribution of AWC of the soil (mm): 1) 200–250; 2) 150–200; 3) 100–150; 4) < 100; 5) Fluvisols on alluvial deposits; 6) aridity index

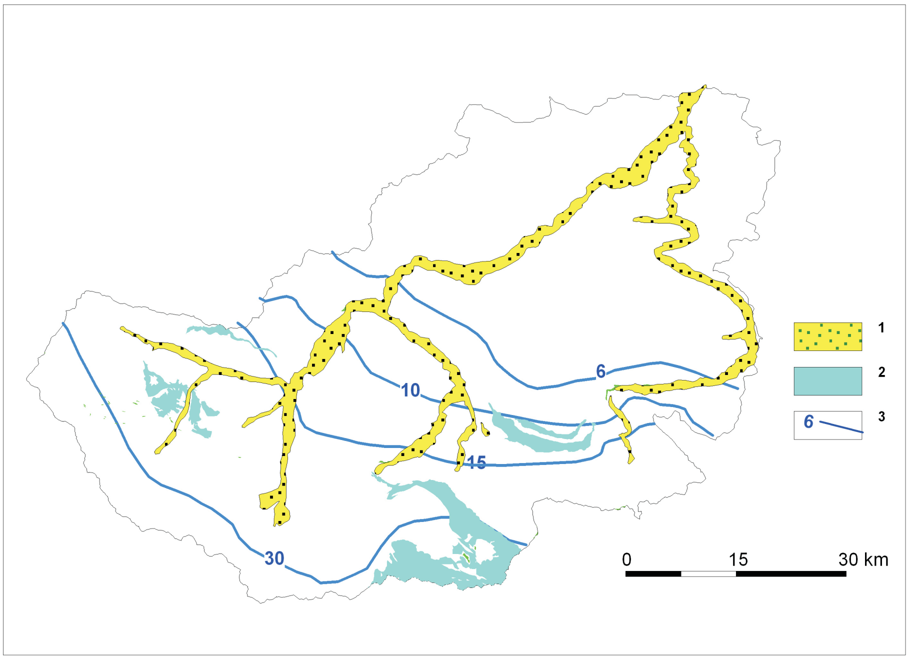

Fig. 4. The potential recharge map for Ogosta River Basin. Mean annual potential recharge as a percentage of precipitation: 1 – Fluvisols on alluvial deposits; 2 – Rendzinas in carbonate terrains; 3 – groundwater recharge/precipitation ratio (%)

formed. The main aquifers are related to carbonate (both Mesozoic and Neogene), alluvial and proluvial formations. Specific features of the Ogosta river basin are outcropping carbonate formations in their upper and middle parts.

In the uppermost mountain part of the study area, carbonate terrains are drained by springs with average discharge of several hundred litres per second. For areas covered by low permeable fissured rocks, dense stream network is typical, with numerous high level springs. The outcropping carbonate formations, proluvial and alluvial deposits, receive the highest groundwater recharge [4, 5]. More data on the geological and hydrogeological settings of the study area are given in the previous paper of the authors [9].

Agricultural activity is widespread in the lower plain part of the study area, whereas mountains are covered by forests. Chernozems are the main bio-climatic soil types for North Bulgaria, genetically related to the loess cover in the Danubian plain. Fluvisols are azonal soils that are developed on the alluvial deposits in the river valleys. The agro-meteorological studies in the region show that the soil moisture in the plain is highly variable throughout the year, and thus it is actively involved into the water balance of the area.

Methods. The water budget of any soil is related to the climate characteristics, which may be expressed through the aridity index. This index refers to the water-supply conditions and energy input which both govern the water budget. The Budyko's water-balance model is expressed by semi-empirical curve [10–12]:

$$E/P = \{\Phi \tanh(1/\Phi)\ [1 - \exp(-\Phi)]\}^{0.5}; \tag{1}$$

$$\Phi = Eo/P, \tag{1a}$$

where E is the long-term evapotranspiration rate, mm/a; P is the precipitation sum, mm/a; Φ is aridity index; Eo is the potential evapotranspiration, mm/a.

This curve allows partitioning of the precipitation between evapotranspiration and potential recharge (Fig. 2). It has two asymptotes – energy-limited for low values of the aridity index, and water-limited – for high values [9]. The Budyko method is applicable for large territories and multi-annual values [10, 11, 13].

Sub-humid and humid climatic regimes are defined based on the range of the aridity index $0.75 \div 2$ and < 0.75 respectively [14]. The potential recharge R generated from the area is as follows:

$$R/P = 1 - E/P. \tag{2}$$

The method described above allows the evaluation of the potential groundwater recharge based on the long-term climatic average data using Eqs (1) and (2).

Using of the Budyko method presumes calculating of the aridity index based on multi-annual values of precipitation and potential evapotranspiration. Recently, the Penman-Monteith method is recommended as a new standard for reference evapotranspiration ETo [15]. The calculation of the ETo is based on numerous meteorological data. Here subsidiary technique is used to evaluate the potential evapotranspiration necessary to define the aridity index Φ, as presented below. It uses other indexes along with relationships between them. One of the first is the aridity index after De Martonné (I_{DM}), which is widely used due to commonly available input data

$$I_{DM} = P/(T + 10), \tag{3}$$

where P and T are the mean annual precipitation sum (mm) and mean annual temperature (°C), respectively. The climatic water deficit (WD) is defined as difference between the annual precipitation sum and the potential evapotranspiration sum (in mm). In this study, the reference evapotranspiration ETo is used

$$WD = P - ETo. \tag{4}$$

Paltineanu et al. [16] showed high correlation between the annual climatic water deficit (Eq. 4) and the aridity index after De Martonné defined by the regression equation

$$WD = 0.0005 \cdot I_{DM}^3 - 0.2247 \cdot I_{DM}^2 + 32.406 \cdot I_{DM} - 915.1. \tag{5}$$

This equation allows an easy calculation of the reference evapotranspiration and the relevant aridity index defined by Eq. (1a). So, ETo is here back-calculated using equation (4) based on equations (3) and (5) .

Generally, the average water balance of the land surface is sensitive to the water-holding capacity of the soil [17]. The theoretical analysis of the partitioning of the rainfall input into evapotranspiration and deep infiltration plus runoff was made by Porporato et al. [18] using a minimalist approach. The soil moisture dynamic was taken into account. The rainfall input was modelled as a Poisson process with frequency λ (day^{-1}) and a mean rainfall depth per event α (mm). The rainfall in excess of the available storage capacity of the soil is lost by runoff, deep percolation or drainage. The available water capacity (AWC) of the soil (w_0, mm) is an important parameter of this eco-hydrological model [12]. This is the maximum amount of plant available water a soil can provide. The theoretical solution of the model is as follows [18]:

$$E/P = 1 - \left(\Phi \cdot \gamma^{\gamma/\Phi - 1} \cdot \exp(-\gamma)\right) / \left(\Gamma(\gamma/\Phi) - \Gamma(\gamma/\Phi, \gamma)\right), \tag{6}$$

$$\gamma = w_0/\alpha, \tag{6a}$$

where γ is a governing parameter, $\Gamma(\cdot)$ and $\Gamma(\cdot,\cdot)$ are the Gamma function and Incomplete Gamma function respectively. The graphical representation of Eq. (6) is presented in Fig. 2.

It has to be noted that for $\gamma = 5.5$ the solution (6) compares very well to Budyko's curve expressed by Eq. (1) [18]. Szilagyi and Jozsa [12] derived the value $\gamma = 9$ for watersheds in USA with low human impact and reliable data on precipitation. For the study area, we obtained data for γ in the range from 5.5 to 25 (Fig. 2).

Equation (6) takes into account the effect of the seasonal variability in soil moisture on the multi-annual water balance. Therefore, it should be preferred for major agricultural areas in contrast to Eq. (1), applicable for areas with thin soils.

Results and discussion. The method described above was applied to the study area – the Ogosta River basin. At first, the spatial distribution both of the aridity index and the available water-holding capacity of soils was defined.

The aridity index after De Martonné (Eq. 4) was calculated based on the values of the mean annual precipitation and mean annual temperature for the climate and rainfall stations in the study area. The relationships (3) and (5) were used for this purpose. The values obtained for the stations were interpolated to receive the spatial distribution of the aridity index Φ (see Fig. 3).

The plant available water-holding capacity of soil (w_0) for Bulgarian soils varies from < 100 mm for thin/shallow soils in mountains up to 250 mm for Chernozems [19]. The spatial distribution of this parameter for the study area is presented in Fig. 3. Within the Danubian Plain, the available water capacity of the topsoil is maximal in its middle part, decreasing towards the Danube River as a result of higher sandy fraction in the topsoil.

The average (above the threshold value of 2 mm) rainfall depth per event α for the plain part of the study area was based on daily data on precipitation for the period 2000–2004, resulting in 10 mm. Given the short range, the average rainfall depth was obtained after division of the mean annual precipitation sum by the mean number of rainy days above the threshold value ≥ 2.0 mm (multiannual values for 55 years [6]). Both methods give values very close to 10 mm.

The groundwater recharge as a ratio from the precipitation sum was evaluated using Eqs (2) and (6). The input parameters are the last parameter which depends on the plant available water capacity of the soil. According to (6a), the value of γ varies from 10 up to 25 for Chernozems.

The potential recharge map (Fig. 4) reveals substantial decrease of the recharge rate towards the Danube River. Within the Danubian Plain, the groundwater recharge is scarce (below 6% from the long-term precipitation sum) due to high values both for the aridity index and the parameter w_0 (and consequently high γ value). Similar low values of the groundwater recharge were obtained for areas below Chernozems within the study area, based on estimations with accounting for soil moisture budget [20].

Areas covered by the azonal soils (both Fluvisols on alluvial deposits and Rendzinas on carbonate terrains) are characterized with specific features of the recharge formation. They are marked in Fig. 4 and are excluded from the regional evaluation of the groundwater recharge. These areas receive the highest recharge and are the most vulnerable to pollution [9]. In general, groundwater recharge in karst areas is a complex process due to the duality of recharge and infiltration, as well as typical allogenic infiltration through swallow holes and sinking streams. The method applied above is not applicable for karst terrains.

Whether potential recharge becomes actual recharge depends on the soil texture and the lithological composition of the geological environment, along with the topographic features and the intensity of the rainfall events. This question is not treated in this paper.

Generally, the spatial distribution of the potential recharge is in agreement both with the map prepared by SPASSOV [4, 5] based on the hydrological method, as well as with newer data. Thus, for the plain part of the Ogosta River basin within the Moesian plate, the groundwater recharge according to V. Spassov varies in the range of 15–30 mm per year, and in the fore-mountain part – 30–50 mm/a. The results obtained by the present study are comparable: < 30 mm/a and 36–52 mm/a respectively.

Some difference between the two approaches is evident in the uppermost part of the river basin. Low productive formations there cannot accept all the potential groundwater recharge, and reject some part of it, generating high level springs and thick network of streams. Thus, the potential groundwater recharge is high, but the actual recharge is low.

Conclusion. The presented method to estimate the potential groundwater recharge is based on the two parameters: the aridity index (Φ) and the parameter γ (relationship of the soil available water capacity AWC to the average rainfall depth per event α). The method reflects the hydro-climatic zonality of the area as the division between evapotranspiration and potential recharge depends on the water-energy balance. Thick soils are usual for water-limited environments, and the plant available water-holding capacity of soil is an important parameter that controls the hydrological regime and balance. Such conditions are usual plains in Bulgaria. The method is not applicable for karst terrains.

The potential groundwater recharge is evaluated for the Ogosta River basin in the NW Bulgaria, and the respective map is prepared. The spatial distribution of the potential recharge is in agreement both with the map prepared by V. Spassov, as well as with newer data. Thus, the present paper puts a theoretical background for the recharge values observed in the Ogosta River basin. The obtained results refer to the long-term values that may be used for estimates of the renewable water resources in sub-humid areas. The prepared maps will be useful for the water management authorities.

The presented method may be used as an alternative approach for evaluation of the groundwater resources in different regions of Bulgaria and abroad.

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