ASSESSMENT OF GROUNDWATER STORAGE IN A KARSTIC AQUIFER

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***Abstract*:** This article outlines a methodology for assessment of groundwater storage in a karstic aquifer. The approach is based on an assumption that a karstic massif contains porosity capable to retain significant quantities of water during the rainy season and to release it during the dry periods. The procedure for evaluation of the groundwater storage depends on the balance equation applied to the complete catchment of the karstic aquifer. All the components are evaluated separately from the available data. Computation can be carried on for different time increments (usually day or month). The groundwater storage capacity is determined from the difference of the storage in the aquifer at the beginning and the end of the considered long-term period containing two or more full cycles. The approach was applied to calculate the storage volume discharged at the Blederija spring in the Miroc Mountain.
Keywords: ground water, karst aquifer, goundwater storage

Introductory remarks

The basic concern of this paper is to define the water balance and volume of groundwater storage. The underlying assumption is that the karstic massif contains cracks and fissures that can temporary retain significant amounts of water, which is to be discharged at later times. The main objective of this paper is to describe a procedure for evaluation of the groundwater storage that represents an important component affecting temporal distribution of the water balance.

Methodology

The equation of hydrologic balance of a closed hydrogeologic system (catchment) represents a basis for the evaluation of the groundwater storage associated with an aquifer. The time increments can be different depending on the available data. The balance is usually calculated for the time increments from one day to one month. The time period for assessment of the water balance should encompass at least two full cycles (a cycle contains a dry and a wet season).

Assuming that the calculation is carried on for one day time increments, the balance equation is:

$$P_j = h_j + E_j + \left(V_j - V_{j-1}\right) = h_j + E_j + \Delta V_j \qquad (1)$$

where the symbols denote:

- h_j - average daily water layer discharging out of the karstic aquifer,
- E_j - daily sums of evapotranspiration from the catchment,
- V_j - volume of water contained within the aquifer at the day j
- ΔV_j - change of the storage within the karstic aquifer during the day j.

Values of variables contained in Equation (1) are determined in the following way: Daily sum of precipitation, P_j, is arithmetic mean of rainfall from all gauging stations within the catchment. Daily layer of runoff is obtained from the total discharge out of the aquifer, Q, according to the equation:

$$h_j = \frac{Q_j \cdot 86400}{F \cdot 10^6} \qquad (2)$$

where

- Q_j - represents average daily discharge out of the karstic spring (m^3/s) during the day j,
- F_j - catchment area of the karstic spring in km^2.

The water balance equation in view of the available data has two unknown quantities E_j and ΔV_j. For that reason a new boundary condition has been introduced. That condition assumes that the "real" evapotranspiration is calculated from the balance equation with known rainfall on the catchment and discharge of the spring assuming that the ground water storage is equal at the beginning and the end of the considered long time period.

First approximation of the daily evapotranspiration E_j^* can be calculated from the monthly sum of the potential evapotranspiration, which can be obtained from the Thornthwaite's model based on the mean monthly air temperature given by the expression:

$$E_j^* = \frac{PET_k}{m_k} \tag{3}$$

$$PET_k = 16 \cdot N_k \cdot \left(\frac{10 \cdot \overline{T}_k}{I} \right)^a \quad \text{(mm)} \tag{4}$$

were the symbols denote

- PET_k - sum of potential monthly evapotranspiration
- N_k - N/12 is monthly corrective factor accounting for actual duration of sunshine
- $\overline{T}_k$ - monthly mean of the air temperature
- m_k - number of days in the k-th month
- I - the annual heat index
- a - function of the heat index

The annual heat index is defined as the sum of monthly values:

$$I = \sum_{k=1}^{12} i_k = \sum_{k=1}^{12} \left(\frac{\overline{T}_k}{5} \right)^{1.514} \tag{5}$$

Polynomial expression for a is given as:

$$a = 6.75 \cdot 10^{-7} \cdot I^3 - 7.71 \cdot 10^{-5} \cdot I^2 + 1.79 \cdot 10^{-2} \cdot I + 0.49 \tag{6}$$

Evaluation of the true - "real" daily evapotranspiration is carried out by an iterative procedure using equation (1) where the following assumptions are made:

- the storage content of the karstic massif at the initial time equals the one at the end of the considered period, namely
  $V_0 \cong V_M$
  where the subscript M denotes the final date of the considered period;
- distribution of the daily amounts of evapotranspiration is nonlinear so that for the rainy days is given by:
  $E_j = E_j^*$
  while for the non-rainy days evapotranspiration is decreasing according to the following model:
  $$E_{(j+\tau)} = \Theta^{\tau} \cdot E_{(j+\tau)}^* \tag{7}$$
  where τ = 1,2,3,...,l

Application

The described methodology was applied to define water balance and to estimate groundwater storage associated with the Blederija Spring in the karstified massif of the Miroc Mountain in Easter Serbia. The effective catchment area of 35.43 km^2, was monitored between September 1997 and October 2000. Rainfall observations over the catchment were taken daily. In addition, the water stage and flow measurements at the Blederija Spring were performed.

The results of flow measurements at the Blederija Spring indicated that significant groundwater storage is formed during the rainy season. This can be feasible only under condition that massif of the Miroc Mountain contains large voids in which water can be temporarily stored.

Quantity of the dynamic reserve, i.e. of the groundwater storage being discharged at the Blederija Spring was evaluated for the period September 1997 – October 2000. The daily observations of rainfall and spring discharge, as well as average monthly air temperatures were used.

First approximation of the daily sums of potential evapotranspiration was obtained using equation (3). The average monthly air-temperatures from meteorological station Negotin were used for the period 1946 – 2000.

Daily amounts of the "real" evapo-transpiration were determined indirectly. The procedure based on equation (1) was used to calculate water balance of the Blederija Aquifer, assuming that the water volumes at the karstic aquifer are equal at the beginning and at the end of the considered time period. The initial condition for this calculation was assumed $V_0 = 0\times10^6$ m^3, and the value of parameter $\Theta = 0.98$.

The results of changes of the groundwater reservoir content associated with the Blederija Aquifer in the period of observation are depicted in Figure 1. From that it can be assessed that the maximum groundwater storage in the period of observation was $V = 16.9\times10^6$ m^3 which is equivalent to an effective water layer over the catchment of 0.87 m.

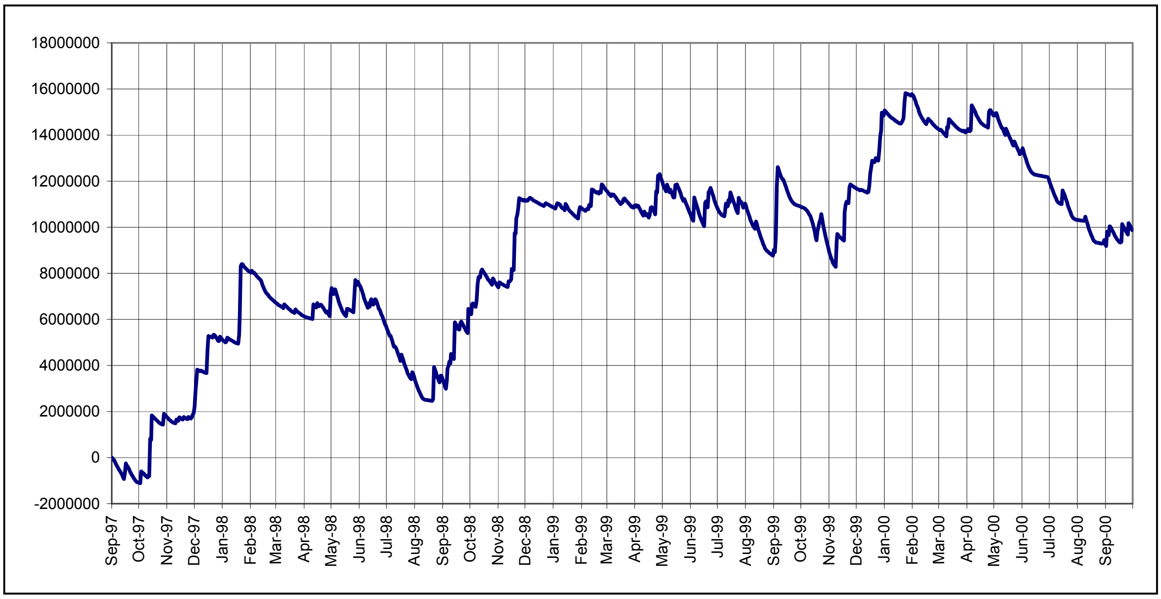
The analyses of the water balance of the karstic aquifer Blederija in the period August 18, 1997 to October 17, 2000 yield the following results:

- Average spring outflow $Q = 0.264$ m^3/s;
- Volume of discharged water $W = 24.256\times10^6$ m^3;
- Effective depth of water h = 720.2 mm;
- Total rainfall in the considered period was P = 2199 mm;
- Evapotranspiration in the same period was E = 1219 mm.

In view of the above in the period of observation it comes out that

$$\Delta h = P - E - h = 2199 - 1219 - 720 = 260\text{mm}$$

This represents water volume used, that forms the groundwater storage, which can be seen from Figure 1.



$$\frac{V_M - V_0}{F} = \frac{10.0\cdot10^6 - 0\cdot10^6}{35.43\cdot10^6} = 0.282\text{m} = 282\text{mm} \cong 260\text{mm}$$

Figure 1. Fluctuation of groundwater storage in the karstic aquifer Blederija during the period of observation September 1997 – October 2000

The water balance of groundwater storage was calculated for the monthly time increment in the long time period 1946 – 2000, which basically contains a full macro cycle

[2]. The VNC model simulated the series of average monthly discharge, while rainfall data series from official meteorological stations were used. Fist approximation of evapotranspiration was estimated by the Thornthwaite's model, which used air temperature data at the m. s. Negotin.

The results of calculation are depicted in Fugue 2. From that figure it can be asserted that the total active groundwater storage in the period 1946 – October 2000 was $V = 65.8\times10^6\ m^3$. This value indicates a large retentional capacity of the karstic aquifer associated wit the Blederija Spring.

The most important characteristics of the Blederija Spring in the long-time period are:

- Average annual discharge – $Q = 0.320\ m^3/s$;
- Average annual rainfall depth – P = 737.7 mm;
- Average annual real evapotranspiration E = 437.6 mm;
- Average annual volume of discharge $W = 10.04\times10^6\ m^3$
- Water depth equivalent to the discharge h = 298.1 mm;
- Average annual unit-area runoff $q = 9.50\ l/s\cdot km^2$;
- Average annual runoff coefficient $\varphi = 0.40$.

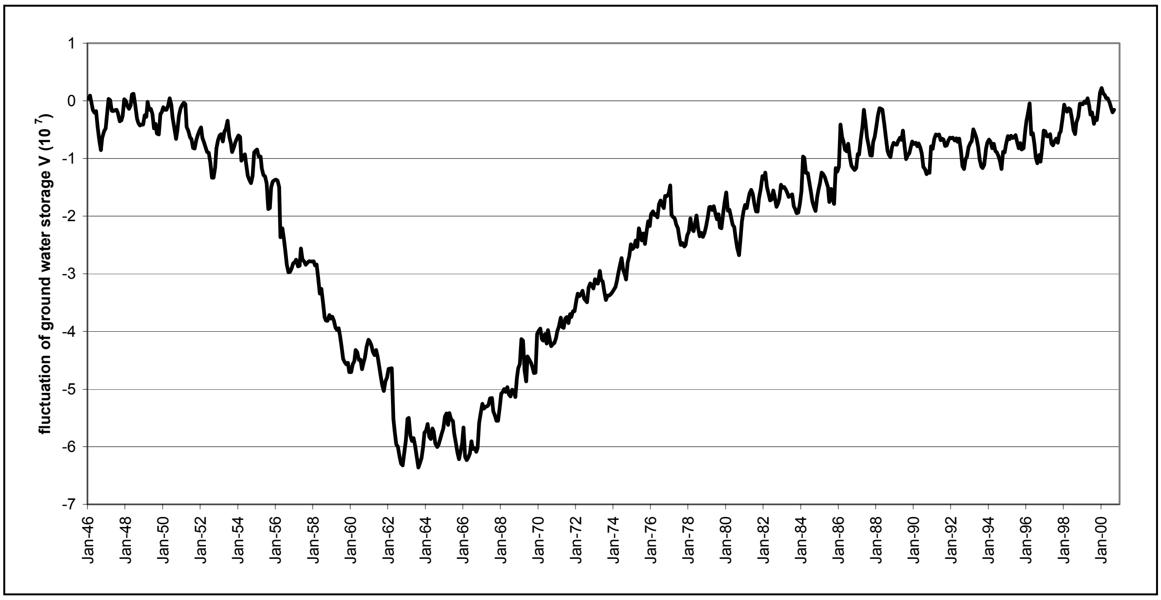


Figure 2. Fluctuation of groundwater storage in the karstic aquifer of the Blederija Spring for the period 1946 – October 2000

Comparison of the water balance in the long-time period yields:

$$\Delta h = P - E - h = 737.7 - 437.6 - 298.1 = 1.6 mm$$

which is negligible.

Conclusion

The outlined procedure allows determination of the groundwater storage in a karstic aquifer both in a short- and long-time period. It actually harmonizes all components of the water balance over a long time: discharge out of the aquifer, precipitation and real evapo-transpiration. Application of the described model for evaluation of the groundwater storage indicated a large retentional capacity of the karstic massif of the Miroc Mountain tied to the Blederija Spring, which can represent important water source for the broad area.

Literature

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