Modelling of Spring Discharge with Low Annual Variability

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In the upper Struma river basin several karstic springs drain elevated massifs of Triassic limestones and dolomites. Low variability of flow during year is the characteristic feature of these springs. The flow regime of spring N 86 at the village of Polska Skakavitza was simulated using a linear response model. The spring is part of the National Hydrogeological Network and its discharge is measured 1-2 times monthly using a current meter. The low variability of the regime is explained by the predominance of small pores in the porous space providing large capacity of the rock massif. The results from application of the model are satisfactory using 10-day precipitation values as well as monthly data. The method can be used for forecasting of spring discharge.

Моделирование дебита карстового источника со слабой изменчивостью режима *Т. Орехова* В верховьях р. Струма несколько карстовых источников дренируют триасовые известняки и доломиты. Источники отличаются слабой изменчивостью режима. Проведено моделирование режима дебита карстового источника № 86 у с.Полска Скакавица на основе линейной модели. Источник входит в Национальную гидрогеологическую сеть, частота измерения его дебита - 1-2 раза в месяц с помощью гидрометрической вертушки. Слабая изменчивость режима карстового источника объясняется преобладанием мелких пор формирующих значительную емкость водоносного горизонта. При моделировании были получены удовлетворительные результаты при использовании как 10-дневных, так и месячных сумм осадков. Метод может быть использован для прогноза дебита источника.

1. Introduction

Models of recharge - discharge transfer for modelling the response of karstic springs are widely used. Such models provide temporal variations of spring discharge and could be used for forecasts. When modelling river flows data are needed on daily basis. It is evident however that for the case of low variability of spring flow simpler models can be used with relatively modest data needs.
Karstic springs are widespread in Bulgaria and provide valuable resources for water supply. Most of them show a large variation of discharge. Karstic springs in the Upper Struma basin have specific appearance. They show low variability of spring flow throughout the year.
The aim of this paper is to describe the discharge of a karstic spring with low variability using rainfall – runoff model and to assess its forecasting applicability.

2. Description of the Study Area

2.1. General Description of the Karstic Springs

The region is situated in western part of the country in the Upper Struma basin, within the Zemenski gorge that divides Zemenska and Konyavska mountains. The relief is highly varied and is characterised as upland. The highest point in the region is the peak Viden in the Konyavska mountain with altitude 1487 m, and the lowest ones are near to the Struma river – about 500 m. The climate is temperate with annual precipitation sum about 600-660 mm.
From geological point of view, the region is a part of the Kraishtidi with wide presence of intensively fractured Mesozoic rocks. From hydrogeological point of view, the most important rocks are Triassic dolomites and limestones that are intensively cracked and karstified (Antonov and Danchev, 1980). Due to block differentiation, they form detached local karstic basins. The recharge of karstic water is mainly due to precipitation, and the recharge is through karsting springs situated in the valley of the Struma river and at the boundary of mountains with Kjustendilska valley. From these springs in the National Hydrogeological Network, located at the National Institute of Meteorology and Hydrology, are included as follows:
-N 460 "Studenetz" at Zemen,
-N 481 at Zemen,

-N 86 at P.Skakavitza,
-N 461 "Shegava" at Razhdavitza,
-N 85 at Konyavo.

The observation of karstic springs from the Hydrogeological Network starts from 1959-1961. All springs are perennial. Time series of spring discharge data were studied. The analysis of the interannual discharge distribution shows that it is difficult to distinguish the seasonal high and low flow periods. This can be attributed to the structure of karstic massifs.

2.2. General Description of the Regime

The hydrogeological stations in the Upper Struma basin have long observation periods. The human impact is minimal. For the chosen springs the measurements are made normally from 12 to 24 times per year, using a current meter. The interannual regime of spring N 86 is presented in Fig.1.

The chronology of annual spring flows is given in Fig.2. The deviations were calculated using annual discharges:

$$\psi = \frac{Q - \overline{Q}}{\sigma_Q} \qquad (1)$$

where $\overline{Q}$, σ_Q are average values and standard deviations respectively for the 1961-90 period. This period was chosen taking into account the recommendation of WMO for defining of normals (WMO, 1984).

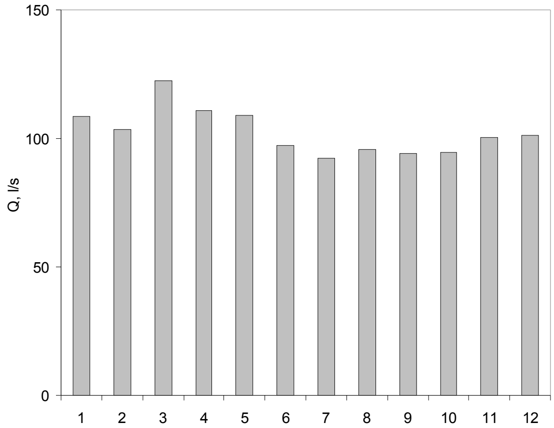

Fig. 1. Interannual regime of spring 86

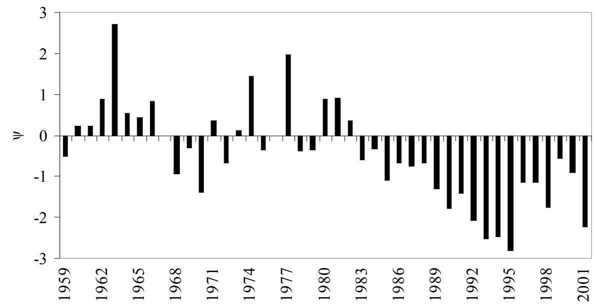

Fig.2. Chronological structure for springs 86

The regime of the springs was influenced by the drought during 1982-94. The decrease of discharge for the spring N 86 was 17-18% for the period 1982-94 and about 25% for the shorter period 1985-94 (Orehova et al., 2000, 2001a, 2001b). Similar results were obtained for other regions of Bulgaria.

Obviously, seasonal fluctuations of the spring discharge in the study region are smoothed, but multiannual variations are evident (see Figs.1 and 2).

It was found that during recessions the largest values of discharge are observed for springs in dolomite rocks due to their higher porosity (Collin et al., 1994). Very low decrease of spring discharge in Mesozoic limestone has been observed as well in western Turkey. "The data show that the discharges of the springs do not change significantly between wet and dry seasons. Variations in monthly precipitation do not have immediate effect on the spring discharges which means that the amount of groundwater flow is related to the cumulative effect of precipitation" (Özler, 1999). Little change in the springs through the year there was assigned to large storage capacity of the limestone. Probably, the carbonate rocks in western Turkey are with similar properties and have an important dolomite component.

Specific properties of the porous space (matrix) for Triassic dolomites of the Cracow-Silesia region are characterised by Motyka et al. (2001). Matrix in dolomites is rich in water store and its part in water transmission cannot be omitted. Thanks to the properties of the porous space, fluctuations of the water table in dolomites show considerably smaller amplitudes compared to observed in limestones. Dolomite matrix significantly decreases progress of the depression cone around drainage centres. The retardation due to diffusion to the matrix is usual (Motyka et al., 2001).

3. Modelling

3.1 Model Description

For modelling the response of karstic springs the most appropriate are models of recharge - discharge transfer.

It was found that recession curves reveal basic features of the karstic massif. According to the classical formula of Maillet the recession curve of karstic spring has exponential form. Later some suggestions present recession curve as a sum of several exponential functions (generally three) (Forkasiewicz and Paloc, 1967; Kullman, 1980; Grasso and Jeannin, 1994; Benderev et al., 1997):

$$Q_s = Q_1 e^{-\alpha_1 t} + Q_2 e^{-\alpha_2 t} + Q_3 e^{-\alpha_3 t} \qquad (2)$$

where $\alpha_1, \alpha_2, \alpha_3$ are recession coefficients. Different models could lead to this kind of recession curve. These models are 3 - cellular but the cells can be arranged by different ways. Two of the models were considered and compared by using Laplace transform (Orehova, 1999). The approach has been used in the previous papers of the author (Orehova, 1995, 1998).

The 3 - cellular linear model presented by Estrela and Sahuquillo (1997) gives good possibilities to simulate the response of the karstic aquifer to the recharge. It gives explicit expression for the discharge.

According to the model, for the uniform recharge rate R_r for each period of time t:

$$Q_{i_{t+\Delta t}} = Q_{i_t} e^{-\alpha_i \Delta t} + b_i R_r \left(1 - e^{-\alpha_i \Delta t}\right) \qquad (3)$$

$$Q_{t+\Delta t} = \sum_{i=1}^{3} Q_{i_{t+\Delta t}} \qquad (4)$$

The parameters b_i refer to the proportions according to which R_r is distributed over the n terms of the summation (Estrela et al., 1997):

$$\sum_{i=1}^{3} b_i = 1 \qquad (5)$$

$$b_1 : b_2 : b_3 = Q_1 : Q_2 : Q_2 \qquad (6)$$

3.2. Case Study

Karstic spring N 86 from the Basic hydrogeological network, situated close to the village of Polska Skakavitza, was chosen for the case study. The assumption is that some constant part of precipitation is going to recharge of the aquifer. As we do not know exactly the value of this part, nor the area of the aquifer drained by the spring, we proceeded with fitting: the initial value of simulated discharge was taken equal to the observed value.

The data from the nearest meteorological station (in Sofia) were used. Precipitation data are monthly sums, as well as 10-day sums. Uniform distribution of the precipitation amount was accepted respectively for 10-day and monthly values. The period from 11th June to 19th December 1987 was chosen due to its succession of wet and dry periods. Then measurements of the discharge were twice in a month.

4. Results and Discussion

The data from the long-lasting summer drought period in 2000 were used to assess parameters of the 3 - cellular model. The values of the parameters are presented in Table 1 in the last row.

The comparison between observed and simulated values is represented in Figs. 3 and 4 for 10-day and monthly precipitation. The fitting is satisfactory. These results encourage wider application of this model. The statistical assessment is better for 10-day data ($R^2 = 0.50$) compared to 30-day data ($R^2 = 0.46$).

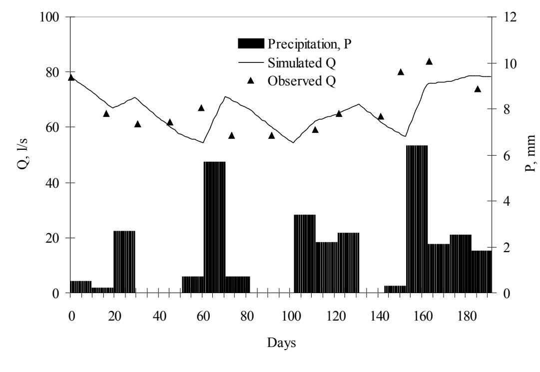

Fig.3. Observed and simulated values of discharge at spring N 86 using 10-day precipitation data

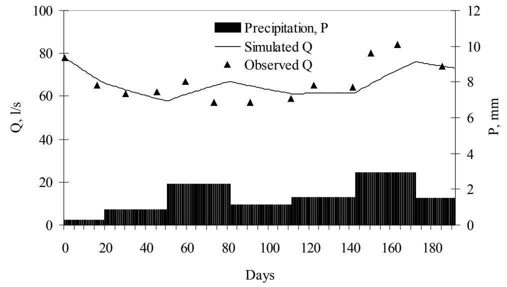

Fig.4. Observed and simulated values of discharge at spring N 86 using monthly precipitation data

Table 1

Parameter values for the 3 - cellular model obtained for different karstic springs

Author, models	α_1, 1/day	α_2, 1/day	α_3, 1/day	b_1	b_2	b_3
Forkas.	0.0032	0.048	0.5	0.13	0.19	0.68
Grasso	0.0022	0.11	1.32	0.08	0.14	0.78
Estrela	0.008	0.043	0.66	0.29	0.32	0.39
Orehova [1999]	0.0396	0.358	1.32	0.25	0.46	0.29
Model	0.002	0.005	0.08	0.7	0.2	0.1

The parameters of the model have been estimated for some karst springs of France, Switzerland, Spain and Bulgaria and are presented for comparison in Table 1.

The parameters α_1 and b_1 refer to the smallest units of the pore space (pores, thin fissures), α_2 and b_2 to the middle ones (fissures), and α_3 and b_3 to the largest fissures and conduits. The values of b_1, b_2 and b_3 refer to the relative part of such units in the porous space. For the case under consideration, very high values of b_1 give idea about very important role of small pores or thin fissures. Such rocks are with low conductivity but have good storage capacity. Obviously, this is common case for carbonate rocks with high dolomite component.

Differences between simulated results and the observed ones are due to unaccounted factors: evaporation, snowmelt, etc. The model does not consider spatial variations of precipitation. Important factors: soil type, vegetation cover, etc. are ignored. Only precipitation data were used.

Considering these factors, the differences between the observational data and the simulated results are not unexpected. The results are deemed satisfactory, considering the objective. The model was chosen because of its minimum data requirements.

The advantage of the method proposed by Estrela et al. is that the explicit expression is given that allows solving direct problem (forecasting of discharge) as well as inverse problem (recharge assessment).

5. Conclusions

The model of linear response (Estrela et al., 1997) was used giving explicit expression for the spring discharge. Modelling has been carried out for the case study of spring N 86 from the Upper Struma basin having low variability of discharge.

Satisfactory results were obtained despite limited input data (monthly and 10-day precipitation sums). For such springs with low variability of discharge such simple model are appropriate. Daily data are not necessary in this case.

The values of parameters reflect important role of the small pores or thin fissures in the porous space of karstic aquifers. The low variability of the regime is explained by the predominance of small pores in the porous space providing large capacity of the rock massif.

The processes of evapotranspiration and snowmelt have not been taken into consideration. The aim of this paper was to study the ability of the model to describe the discharge of the karstic spring as a result of recharge events to the aquifer.

The method proposed by Estrela et al. can be used for different purposes: forecast or recharge assessment, through solving of direct or inverse problem respectively.

6. References

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Received VII.2002