6-15-1905

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Hydrological Sciences Journal

ISSN: 0262-6667 (Print) 2150-3435 (Online) Journal homepage: https://www.tandfonline.com/loi/thsj20

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Abstract By analysing the hydrographs of karst springs it is possible to identify aquifer characteristics and, accordingly, the main features of a karst rock-fissure massif. Consequently, relevant data can be obtained by analysing hydrograph recession curves. This paper presents a detailed analysis and explanation of numerous cases of break points on recession curves via various values of the recession coefficient α in Maillet's (1905) equation. The paper also identifies the relationship between α and a linear reservoir coefficient by employing groundwater hydrograph methods. It is shown that the linear reservoir coefficient changes with time in accordance with changes of the flow conditions in the karst massif.

Les hydrogrammes des sources karstiques en tant qu'indicateurs des aquifères karstiques

Résumé En analysant les hydrogrammes des sources karstiques il est possible d'identifier les caracteristiques d'un massif rocheux. Un grand nombre d'informations est obtenu en analysant la partie tarissement d'un hydrogramme. On a analysé et expliqué en détail de nombreux cas de ruptures de courbes de tarissement exprimées par des valeures différentes du coefficiant de tarissement α d'après la formule de Maillet (1905). En appliquant la méthode de l'hydrogramme des eaux souterraines (groundwater hydrographs) on explique la relation entre le coefficiant de tarissement α et un coefficient du réservoir linéaire. Il est prouvé que le coefficient d'un réservoir linéaire varie dans le temps avec les changements des caractéristiques de l'aquifère et donc avec les conditions d'écoulement dans le massif karstique.

INTRODUCTION

In this paper, the term *karst spring hydrograph* implies primarily the discharge hydrograph (water quantity) appearing at a spring in a karst region where surface flow is almost not possible due to well-developed surface and underground karst landforms. Such a spring is formed due to the high infiltration capacity of the karst relief and the well-developed underground communication of the fissures and conduit system. Although this paper deals only with karst spring discharge hydrographs, similar conclusions, perhaps even more numerous and reliable, could be reached after performing an analysis of spring hydrographs of other phenomena and/or by using natural and artificial tracers such as water temperature, suspended particles, chemical content of water, microorganisms present in water, flow velocity, dissolved ions, tritium, transportation

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of flood pulse, etc.

Since in the case analysed the water is transported exclusively underground through the karst, it is necessary to describe the main characteristics relevant to the phenomenon and to process modelling. Karstification, i.e. the density, frequency and number of all types and dimensions of karst fissures, is greatest at the ground surface and decreases with the depth of a karst massif. According to experimental investigations in Dinaric karst, Milanović (1981) suggested the following law for a karstification index, ϵ, which decreases with depth H measured from the surface:

$$\epsilon = a\exp(-bH) \tag{1}$$

where a and b are empirical parameters which have to be determined for a given region. Identical conclusions, expressed in a different form, have been confirmed by investigations carried out in Switzerland and France (Burger & Pasquier, 1984) and in Russia (Babushkina *et al.*, 1984).

The capacity of karst for water retention is not great. Numerous analyses carried out in many regions of the world (Bonacci, 1987) showed that the effective porosity, n_e, amounts to 0.1 to 1% on average. The occurrence of large caves and transportation conduits changes this characteristic locally; thus, apparently, a karst massif has a high storage capacity. A clear proof of low storage capacity of a karst massif, however, is the sudden raising and lowering of underground water levels. Using the Cetina catchment as an example (Dinaric karst, Croatia), Bonacci (1987) states an average rate of increase in groundwater levels greater than 2 m h^{-1}, and an average decrease in groundwater levels greater than 0.25 m h^{-1}. Those data illustrate another specific feature of a karst massif, i.e. its great transportation capacity. Physical and chemical processes in limestones, dolomites and other soluble rocks which form karst, accompanied by tectonic movements, have formed well-linked fissure systems in karst massifs with dimensions varying from micrometres to several metres. Water circulates rapidly through such systems and thus makes their water storage capacity seemingly great. Storage in superficial deposits overlying limestones and in the subcutaneous zone, as Williams (1983) and Ford & Williams (1989) note, can play an important role in sustaining baseflow recession.

Due to the stated characteristics of karst, there are two types of flow (Atkinson, 1977; Gunn, 1986). Slow flow, i.e. the so-called diffuse flow, occurs through karst fissures of small dimensions, generally in the laminar regime. Turbulent fast flow, or conduit flow, occurs in larger fissures, through irregular karst conduits, with dimensions varying from 10 mm to one metre or more. Depending upon the development of the fissure system, the outflow hydrographs of some karst springs are presented schematically in Fig. 1. The data given in that Figure served as a basis for the development of the main idea presented in this paper, viz. the possibility of precisely identifying the characteristics of the karst aquifer from which an outflow occurs by the analysis of

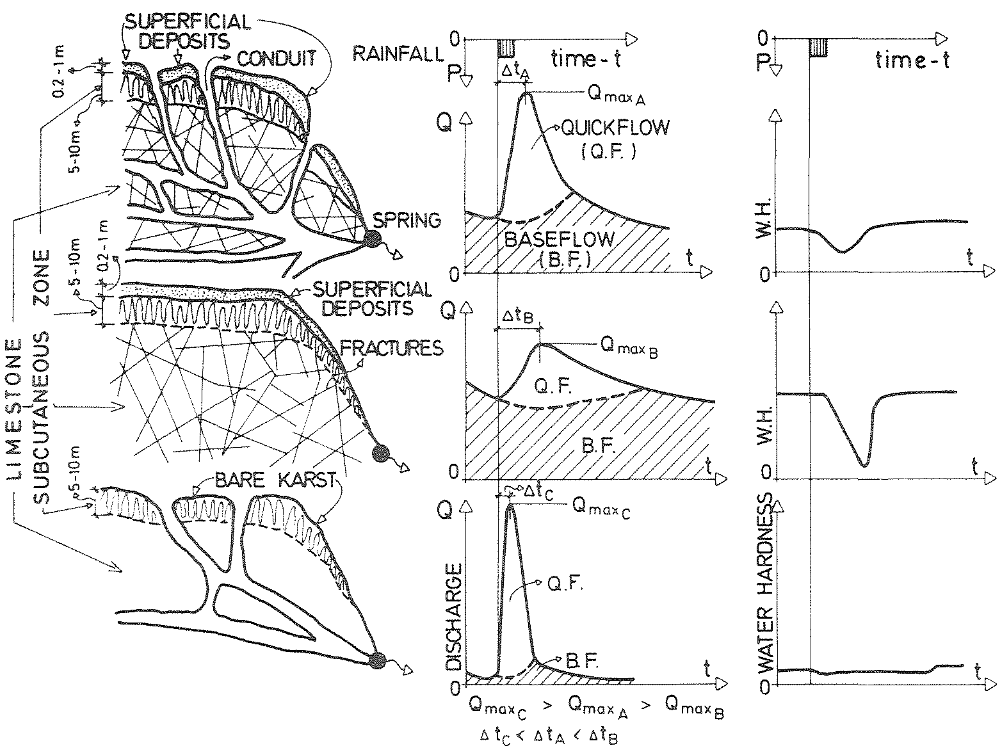

Fig. 1 Various forms of discharge hydrograph: Q and water hardness (WH) for; (a) combined; (b) diffuse; and (c) conduit type karst springs, as a reaction to the same rainfall (P).

karst spring hydrographs. The idea is not completely new since it has been used more or less successfully by various authors (Bonacci & Jelin, 1988; Mudry, 1990; Newson, 1973; Atkinson, 1977; Hess & White, 1988; Ford & Williams, 1989). The novelty herein is that it is possible to identify, both generally and for each particular case, the karst underground storage and transportation system by performing an analysis of karst spring hydrographs.

It should be emphasized that, in many situations, the identification of a karst underground system using spring hydrographs has not been possible primarily due to insufficient data or to their unsatisfactory accuracy. In order to define a discharge hydrograph accurately, it is necessary to have a precise water level hydrograph and an accurate stage-discharge curve. The second condition is often difficult to satisfy. Consequently, it may be difficult to identify a karst underground system accurately.

ANALYSIS OF THE RECESSION CURVE

Maillet (1905) introduced an analytical expression into hydrotechnical theory and practice for defining a hydrograph recession curve in a long-lasting dry

period (with no precipitation):

$$Q_t = Q_0 \exp(-\alpha t) \quad (2)$$

where Q_t is the discharge at time t, Q_0 is the discharge at the start of the recession, and α is a recession coefficient which depends upon the geological and morphological structure of the catchment analysed.

Although Maillet (1905) developed equation (2) from catchments with aquifers consisting of granulated media, it has been very widely used for karst media, i.e. non-homogeneous and anisotropic media with fissures. Numerous authors have used equation (2) to describe the discharge hydrograph of a karst aquifer and identify its transportation and storage characteristics (Castany, 1967; Schöeller, 1967; Atkinson, 1977; Korkmaz, 1990; Karanjac & Altug, 1980; Drogue, 1972; Bonacci, 1987; Bonacci & Jelin, 1988; and Soulios, 1991). Ford & Williams (1989) have provided a detailed review of the application of recession curves to karst aquifers.

Schöeller (1967) defined the recession coefficient, α, for both laminar and turbulent regimes assuming one-dimensional flow through a homogeneous medium of constant porosity. Subsequently, equation (3), which refers exclusively to the laminar flow regime, was presented:

$$\alpha = a\frac{kH}{n_e L^2} = a\frac{TB}{n_e LA} \quad (3)$$

where: k is the Darcy hydraulic conductivity; H is the depth of the aquifer; n_e is effective porosity; L is aquifer length; $T = kH$ is the aquifer transmissivity; A is the area of the active storage part of the aquifer ($A = BL$); B is the aquifer breadth; and a is a constant which characterizes the dynamic and spatial characteristics of the aquifer. Clearly, the parameters mentioned determine the characteristics of the water outflow from a karst aquifer. Equation (2) is used exclusively during a hydrograph recession period, while equation (3), for the recession coefficient, is valid for the laminar regime. The forms of recession hydrographs are very complex and different since the parameters presented in equation (3) vary in time and space. Nevertheless, it is possible to systematize and classify parts of the calculations for a karst spring hydrograph and to connect them with aquifer characteristics. From the hydrogeological standpoint, such an attempt was made by Soulios (1991).

Castany (1967), Larras (1972) and many others have established a connection between the outflow discharge of karst springs, Q, during a recession period, and the height of the groundwater level, H, of a karst aquifer, i.e. of the underground karst reservoir. This connection has been described using the following expression:

$$Q = \lambda H^n \quad (4)$$

where λ is a coefficient which characterizes the conductivity of the underground aquifer and which influences the type of the connection and decides

whether it is linear ($n = 1$) or nonlinear ($n > 1$). Although it is generally recognised that hydrological processes are nonlinear (Amorocho, 1964), linear concepts, due to their simplicity and practical applicability, have become common in hydrological practice, including the linear analysis of hydrological processes in karst. It has been shown that the linear concept applies satisfactorily within certain constraints on the physical environment. When the constraints change, the value of the coefficient λ also changes, but the linear concept is nevertheless valid for certain conditions.

By introducing equation (4), with $n = 1$, into the continuity equation it is possible to derive the following relationship between the recession coefficient, α, the area of active aquifer, A, and the coefficient λ (Castany, 1967):

$$\alpha = \lambda / A \qquad (5)$$

According to equation (5), while taking into consideration the assumptions previously mentioned, it appears that break points on the recession curves can result from the following factors:

(a) a change in the micro-regime flow throughout the karst aquifer (primarily changes in the fissure system which generally changes according to equation (1); and

(b) sudden changes in the active surface area of the aquifer and/or karst spring catchment. Avdagić (1987), Bonacci (1987) & Bonacci and Jelin (1988) presented some practical examples of break points on the recession curves of the springs in the Dinaric karst primarily caused by a sudden change in the catchment area. Soulios's (1991) investigations in the karst in Greece confirmed the influence exerted by sudden changes in the catchment area and/or karst springs aquifer after sudden changes in characteristics of the recession curves (Militsa and Mikro Vuono Springs).

Applying the principles of linear reservoir behaviour based on the following equation:

$$V = jQ \qquad (6)$$

where V is the reservoir volume, Q is the discharge from the reservoir and j is the linear reservoir coefficient (expressed in time units), it is possible (de Zeeuw, 1983) to establish the following connection between the recession coefficient, α, and the coefficient j:

$$\alpha = 1/j \qquad (7)$$

In hydrological practice it is customary to represent the recession curves graphically with a semi-logarithmic plot, so that discharge, Q, is plotted on the logarithmic ordinate and time, t, is plotted on the normal abscissa. A relationship such as equation (2) will then appear as a straight line. It is possible, only in rare situations, to obtain a recession hydrograph with only one straight line, i.e. defined with only one recession coefficient, α. More frequently, it is possible to achieve satisfactory agreement over the whole plot only by using

two or three lines, sometimes using four or more lines. Every break point on the line is caused by a change in a characteristic of an underground and/or surface karst reservoir. A common situation, appearing very frequently in practice, is represented in Fig. 2. The break points on the recession curve presented on a semi-logarithmic plot result from the decrease in the catchment area (in this case, of the underground hydrogeological catchment area), and also from the decrease in the effective porosity of the karst massif according to equation (1). The last section of the recession curve (the third portion in Fig. 2) actually represents the master depletion curve. The importance of this latter section of the recession curve is significant and its function is to define and predict the behaviour of the remaining groundwater reserves during drought periods. McCuen (1989) and Wilson (1983) present relatively simple procedures for the definition of this curve. According to the author's own experience, it should be stressed that the definition of the master depletion curve is a very complex and relatively inaccurate procedure where estimations by individual researchers play an important role. This can be partly explained by the inevitable inaccuracy occurring when measuring low water levels.

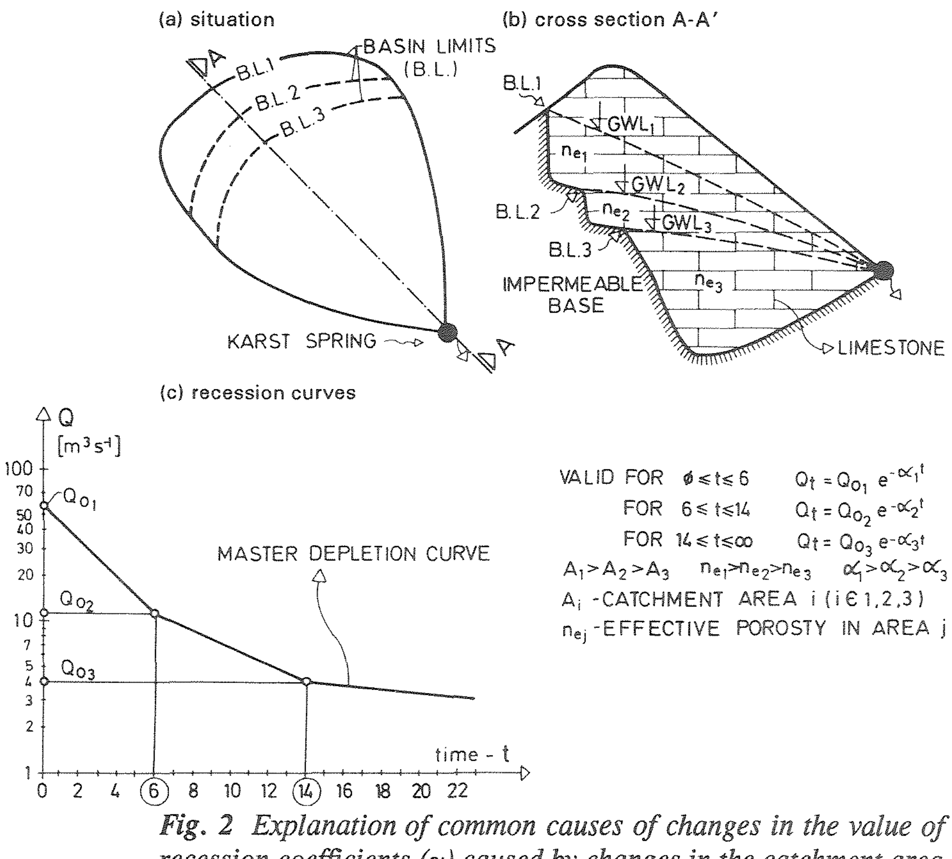

***Fig. 2** Explanation of common causes of changes in the value of recession coefficients (α) caused by changes in the catchment area (A) and effective porosity (n_e).*

Figure 3 presents unusual situations for the recession curve and the changes in recession coefficients. The main difference between Figs 2 and 3 is that ($\alpha_2 > \alpha_1$) in the latter, i.e. the recession coefficient α increases with time. The reasons for this can be numerous; Fig. 3 shows three main reasons which can explain nearly all other cases. Figure 3(b) gives a schematic presentation of a catchment which consists partly of limestone and partly of schists. The outflow through limestone is much quicker than through the schists, which causes a lag in the water inflow (in the period $t_i - t_j$) from the schists, and thus a change (increase) in the slope of the recession curve in the Mikro Vuono spring in Greece (Soulios, 1991). Figure 3(c) gives a schematic representation of a temporarily flooded cave in a karst region. The bottom of the main evacuation opening of the cave is at height *H*. As long as the groundwater level is below that height the emptying occurs very slowly or not at all. A sudden lowering of the groundwater level leads to water outflow from the flooded cave. Understandably, this is not particular to caves; it can occur in a wider karst area with locally more effective porosity.

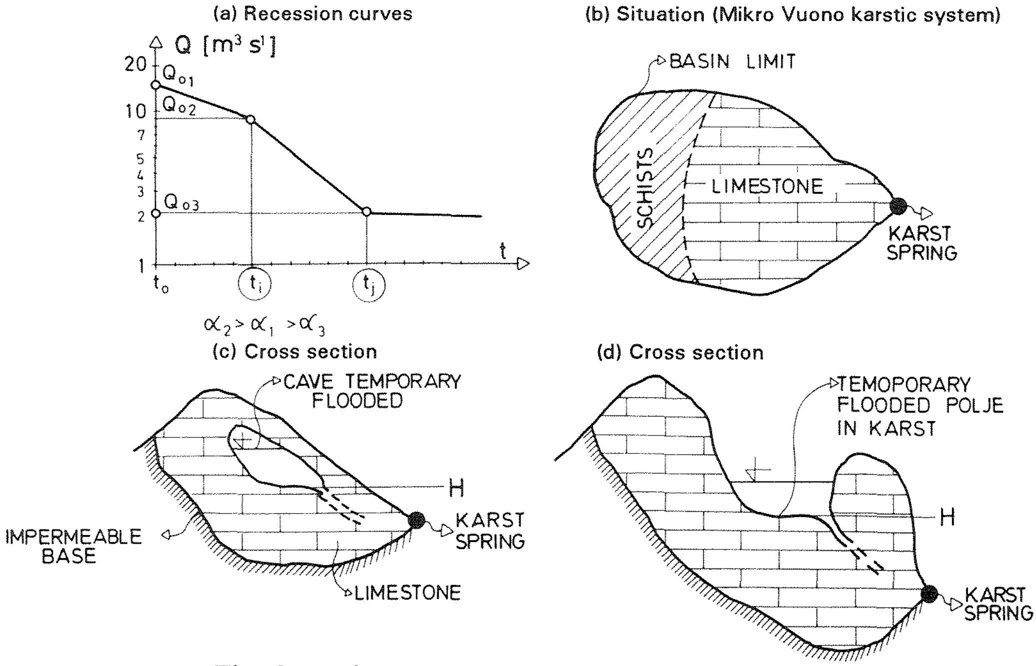

Fig. 3 Explanation of other causes for changes in the value of recession coefficients (α).

Mangin (1975) noticed this phenomenon and called it a "trop-plein" type of karst springs. An identical situation is presented in Fig. 3(d). In this case there is a temporarily flooded polje in the karst instead of an underground reservoir in the cave. The roles of the cave and the polje are identical. The

problem of the spring capacity, dependent upon the water level in the flooded polje and upon the groundwater levels, was explained by Bonacci (1987) (Chapter 5.2. pp. 109-115). An example from hydrological practice for the case presented in Fig. 3(d) is illustrated by the recession of the hydrograph for the Buna karst spring (Avdagić, 1987) plotted with a normal discharge scale (Fig. 4(a)). Figure 4(b), with a logarithmic discharge scale, shows there are as many as four sections in the recession curve with individual recession coefficients, α. The increase in α_2 with respect to α_1 was caused by the beginning of sudden emptying (t = 8 days) of the, until then flooded, Nevesinjsko polje which is situated in the spring catchment. The master depletion curve was formed after the flooded polje was emptied (t = 19 days).

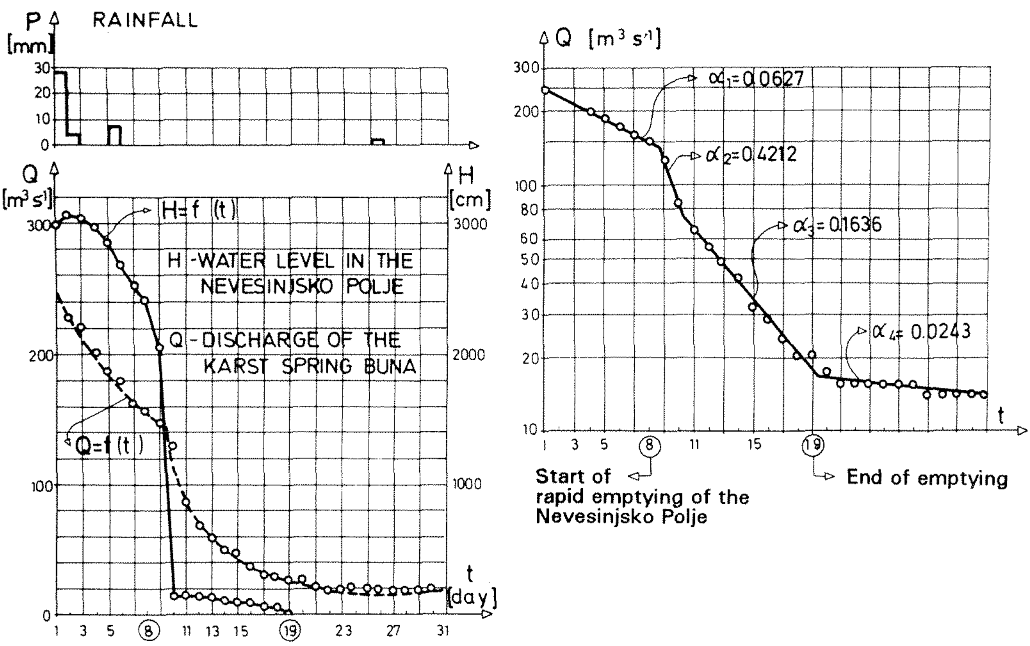

Fig. 4 Example of break-points in the recession curve of the Buna karst spring caused by flooding of Nevesinjsko Polje (Dinaric karst, Bosnia and Herzegovina) (Avdagić, 1987).

GROUNDWATER HYDROGRAPHS

The analysis of groundwater hydrographs (de Zeeuw, 1983) was developed for the outflows from granulated aquifers and was not intended for application in fissured karst aquifers which are generally very inhomogeneous. The first attempts to apply a simple theoretical solution for karst regions were made by Bonacci (1987). The possibility of applying groundwater hydrographs in karst to the analysis of karst springs is based primarily on the fact that there is practically no surface outflow in karst regions and that the entire discharge

comes from underground karst aquifers. The theory is based on non-stationary groundwater flow and on changes in the volume of the aquifer which control the water flow out of the springs.

The following system of equations proved sufficiently accurate for practical application, in conditions of karst outflow:

$$\begin{aligned} Q_{1T} &= f_1[1-\exp(-T/j)] \\ Q_{iT} &= f_i[1-\exp(-T/j)] + Q_{(i-1)T}\exp(-T/j) \end{aligned} \tag{8}$$

where: Q_{iT} is the discharge at time iT; T is the time increment of the calculation (one day or part of a day); j is the reservoir coefficient in equation (7); and f_i is the groundwater recharge expressed by the following equation:

$$f_i = P_i - ET_i - SM_{i-1} \tag{9}$$

where P_i is precipitation in the catchment, ET_i is evapotranspiration from the catchment, and SM_i is moisture deficit in the catchment area (all in mm at time instant iT). For calculation one should know the discharge Q_0 and soil moisture SM_0 at the beginning of the first day.

Figure 5 and Table 1 give a graphical and numerical representation of the actual and simulated hydrographs (applying equations (8) and (9)) for the Crnojevića Spring in the Dinaric karst. Notably, there is excellent agreement between the measured and simulated values. The most important factor in obtaining the agreement was the selection of the values of the coefficient of the linear reservoir, j, for the several intervals. A decrease in the spring

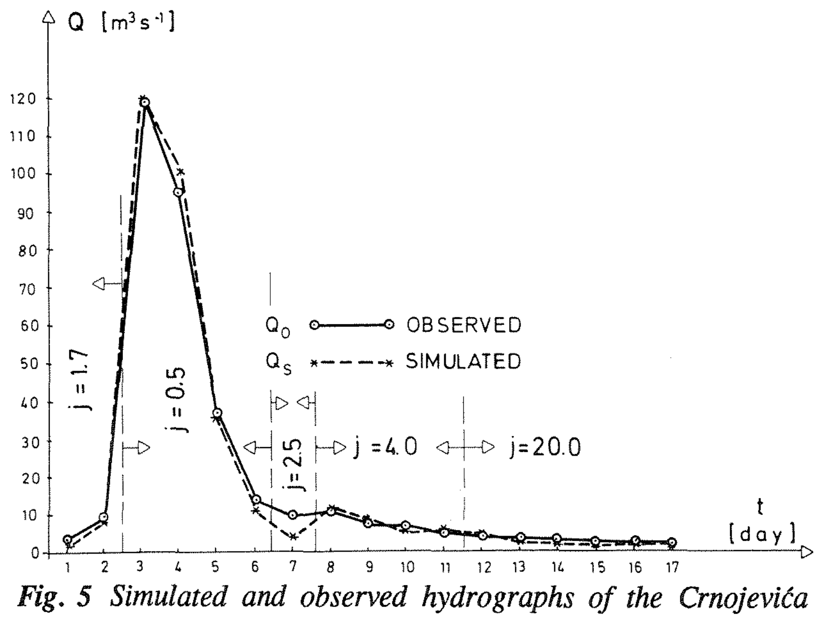

Fig. 5 Simulated and observed hydrographs of the Crnojevića spring.

Table 1 Observed (Q_o) and simulated (Q_s) hydrographs for the Crnojevića spring

t [day]	Q_o [m^3s^{-1}]	Q_s [m^3s^{-1}]	j [day]
1	3.2	2.5	1.7
2	9.3	9.4	1.7
3	119.0	120.7	0.5
4	94.7	100.5	0.5
5	36.8	36.5	0.5
6	13.6	10.5	0.5
7	9.6	3.2	2.5
8	10.6	11.2	4.0
9	7.7	8.6	4.0
10	6.0	6.7	4.0
11	5.0	5.2	4.0
12	4.2	4.0	20.0
13	3.6	3.2	20.0
14	3.2	2.5	20.0
15	3.0	2.3	20.0
16	2.8	2.2	20.0
17	2.6	2.1	20.0

discharge leads to an increase in the value of j. After establishing the connection between this statement and the characteristics of the recession curve, particularly the recession coefficient, α, it is possible to estimate, using equation (7), the value of the linear reservoir coefficient, j, which is introduced into the calculation. In the case of the Crnojevića Spring, the recession curve consisted of four parts. For discharges between 3.4 and 10 $m^3 s^{-1}$, $\alpha = 0.33$, which corresponds to a reservoir coefficient of $j = 3$ days. For discharges from 0.02 to 3.4 $m^3 s^{-1}$, $\alpha = 0.07$, which corresponds to $j = 14.3$ days. Evidently a satisfactory agreement has been achieved between theory and its practical application. Since measurements were consistently inaccurate it is not possible to expect absolute agreement. However, the results are encouraging and point out the possibility of further more detailed analyses and calculations. These analyses require very accurate and reliable measurement data for all hydrological and climatological parameters to be introduced into the computation, i.e., all the essential elements for a hydrological budget for a catchment. All researchers who study hydrological problems are aware of the fact that this is still the greatest difficulty in testing the practical applicability and value of each theoretical finding. At present, the main problem is neither the applied theory nor adequate software but obtaining reliable site data.

CONCLUSIONS

According to the analysis presented of karst spring hydrographs it was possible to identify some characteristics of the karst aquifer. The primary role in the identification process is played by the hydrograph and especially the values of

the recession coeficient, α, from Maillet's (1905) equation (2). It has been shown that α expresses both the storage and transportation characteristics of the aquifer. The procedure of representing the recession of a hydrograph in semi-logarithmic form can be a useful accessory in the analysis. It would be wrong, however, to believe that this procedure has a direct physical foundation. The process of flow in karst is very dynamic and non-stationary, but it can be divided into segments, using certain formal procedures, in which it is at least quasi-stationary. This fact should be borne in mind when considering the presentation of the hydrograph recession curve of karst springs on a semi-logarithmic scale. The same applies to the treatment of the water outflow at karst springs according to the concept of a linear reservoir. In this case, one can also refer only to quasi-linearity, valid in a certain segment of space, and thus accordingly for a certain discharge range. Presently, it is quite clear that generally there exists one continuous aquifer in a karst region and that spring discharges are directly related to groundwater levels. Consequently, it is easy to explain the transportation and storage characteristics of a karst aquifer by the analysis of karst springs hydrographs. The application of a simplified system of equations for defining the hydrograph controlled only by the groundwater recharge (equations (8) and (9)) confirms the connection between spring discharges and the characteristics of an aquifer as a reservoir. The concept of a linear reservoir with one value of the linear reservoir coefficient, j, is valid within a certain segment of discharge and segment. Outside this segment, the flow can be approximately described with a new value of the coefficient, j, again as the outflow from a linear reservoir. The analyses presented above have confirmed the relationship between the recession coefficient, α, and the linear reservoir coefficient, j, according to equation (7).

Consequently, the analysis of hydrograph recession curves has been assigned another important role. However, it is impossible to expect absolute agreement, primarily due to the fact that the accuracy of the measurement data does not guarantee a precise and reliable definition either of discharges or, even less, of other required hydrological and climatological parameters. In a karst terrain there is an additional problem, viz. that the initial catchment area can never be reliably defined. Another important problem in these analyses is the selection of the time increment of the calculations. The measurement methods often restrict the treatment to a time unit of one day. This unit can be too long; there is a need for reliable data obtained with units of one, two, three hours, up to six hours. Thus, further research efforts should be oriented in this direction.

This paper has shown that the underground flow in karst can be analysed and explained by taking into account the assumptions of one-dimensional flow in a homogeneous medium of constant porosity by applying the concept of the linear reservoir. However, this will not be possible in some particularly complex situations. Experience has shown that the procedures analysed yield results which are not sufficiently satisfactory in analysing the outflow through conduits in prevalently turbulent springs (case (c), Fig. 1).

REFERENCES

Amorocho, J. (1964) Nonlinear hydrologic analysis. In: *Advances in Hydroscience*, vol. 9, Academic Press, New York, USA.

Atkinson, T. C. (1977) Diffuse flow and conduit flow in limestone terrain in Mendip Hills, Somerset (Great Britain). *J. Hydrol.* **35**, 93-100.

Avdagić, I. (1987) Oticanje u kraškim hidrološkim sistemima (Modelling of runoff from karstic catchments). Ph Sc Thesis, Sarajevo Univ., Sarajevo, Yugoslavia.

Babushkina, V. D., Lebedyanskaya, Z. P. & Plotnikov, I. I. (1984) The distinctive features of predicting total water discharge from deep-level mines in fissure and karst rocks. In: *Hydrogeology of Karstic Terrains*, vol. 1. (ed. A. Burger & L. Dubertret), 229-232, UNESCO, Paris, France.

Bonacci, O. (1987) *Karst Hydrology*. Springer Verlag, Herdelberg, Germany.

Bonacci, O. & Jelin, J. (1988) Identification of a karst hydrological system in the Dinaric karst (Yogoslavia). *Hydrol. Sci. J.* **33**(5), 483-497.

Burger, A. & Pasquier, F. (1984). Prospection et captage d'eau par forages dans la vallée de la Brevine (Jura Suisse). In: *Hydrogeology of Karstic Terrains*, vol. 1. (ed. A. Burger & L. Dubertret), 145-149. UNESCO, Paris, France.

Castany, G. (1967) *Traité Pratique des Eaux Souterraines*. Dunod, Paris, France.

Drogue, C. (1972) Analyse statistique des hydrogrammes de décrues des sources karstiques. *J. Hydrol.* **16**, 49-68.

Ford, D. & Williams, P. W. (1989) *Karst Geomorphology and Hydrology*. Unwin Hyman, Winchester, Massachusetts, USA.

Gunn, J. (1986) A conceptual model for conduit flow dominated karst aquifers. In: *Karst Water Resources*, ed. G Günay & A. I. Johnson, Proc. Ankara Symp., July 1985, 587-596. IAHS Publ. no. 161.

Hess, J. W. & White, W. B. (1988) Storm response of the karstic carbonate aquifer of south central Kentucky. *J. Hydrol.* **99**, 235-252.

Karanjac, J. & Altug, A. (1980) Karstic spring recession hydrograph and water temperature analysis: Oymapinar Dam Project, Turkey. *J. Hydrol.* **45**, 203-217.

Korkmaz, N. (1990) The estimation of groundwater recharge from spring hydrographs. *Hydrol. Sci. J.* **35**(2), 209-217.

Larras, J. (1972) *Prévision et Prédétermination des Etiages et des Crues*. Eyroles, Paris, France.

Maillet, E. (1905) *Essais d'Hydraulique Souterraine et Fluviale*. Herman, Paris, France.

Mangin, A. (1975) Contribution a l'étude hydrodynamique des aquiferes karstiques. *Ann. Speleol.* **26**(2), 283-339.

McCuen, R. (1989) *Hydrologic Analysis and Design*. Prentice-Hall, Englewood Cliffs, New Jersey, USA.

Milanović, P. (1981) *Karst Hydrogeology*. Water Resources Publications, Littleton, Colorado, USA.

Mudry, J. (1990) Les courbes flux chimique débit et le fonctionnement des aquifères karstiques. *J. Hydrol.* **120**, 283-303.

Newson, M. (1973) The hydrology of limestone caves. *Cave Sci. J. Brit. Speleol. Assoc.* **50**, 1-12.

Schöeller, H. (1967) Hydrodynamique dans le karst (écoulement et emmagasinement). *Proc. Dubrovnik Symp. Hydrology of Fractured Rocks*, vol. 1, 3-20.

Soulios, G. (1991) Contribution à l'étude des courbes de récession des sources karstiques: Exemples du pays Hellenique. *J. Hydrol.* **127**, 29-42.

Williams, P. W. (1983) The role of the subcutaneous zone in karst hydrology. *J. Hydrol.* **61**, 45-67.

Wilson, E. M. (1983) *Engineering Hydrology*. Macmillan Publ., London, UK.

de Zeeuw, J. W. (1983) Hydrograph analysis for areas with mainly groundwater runoff. In: *Drainage Principles and Applications*. Publ. no 16(II), ILRI, Wageningen, The Netherlands.

Received 11 February 1992; accepted 26 September 1992