ASSESSING DEGREE OF KARSTIFICATION: A NEW METHOD OF CLASSIFYING KARST AQUIFERS

Khaled A. Rashed

Associate Professor, Department of Civil Engineering, Tripoli University, Libya.
E. mailk65rashed@yahoo.co.uk

ABSTRACT

Karst aquifers are often classified as highly heterogeneous systems. Such systems are very complex to assess and model due to the presence of discontinuous porosity, large spatial variability of hydraulic parameters and the difficulties encountered in establishing the fundamental spatial properties of the system. In fact, karst aquifers have been studied and classified into groups based on several methods such as chemograph analysis (monitoring water quality variations at springs), linear systems analysis (kernel functions and time moment analysis), heterogeneity ratio, recession hydrograph analysis and flashiness of an aquifer. All these methods have been reviewed, with emphasis on the fourth and fifth approaches because they are based on hydrograph analysis. The problem with these two methods is the fact that they do not take in account the duration time between the starting of the rising limb and the peak discharge and the duration time between rising limb and the returning to the baseflow condition. On these reasoning it may be argued that taking in consideration the whole hydrograph components (rising limb, peak and recession limb) could be used as bases to introduce a new parameter called Degree of karstification index (D_k) Which then can be used as a measure of the karstifiaction of karst aquifers. Several sets of hydrograph data obtained from different springs have been analysed to determine values of (D_k). The results have yielded values ranging from less than 10 where the aquifer is considered to be Darcian to more than 60 where the aquifer is assumed to be highly karstified. Application of such classification method may help to provide a basis for deciding whether to use Equivalent porous medium, fracture or conduit based models to simulate karst aquifers.

1 BACKGROUND

This brief background will mention all possible ways of classifying karst aquifers such as chemograph analysis (monitoring water quality variations at springs), linear systems analysis (kernel functions and time moment analysis), heterogeneity ratio, recession hydrograph analysis and flashiness of an aquifer. Although the second and third approaches are not part of hydrograph analysis, they will be used for comparison purposes. The fourth and fifth approaches are based on hydrograph analysis.

1.1 Chemograph analysis

Shuster and White (1971) proposed a method for classifying karst aquifers as either diffuse (Darcian) or conduit type aquifers based on spring chemistry. In diffuse aquifers, springs are usually small and controlled by stratigraphic and structural features. Also spring chemistry does not vary seasonally or after storm events because recharge is completely mixed with pre-existing water in the aquifer, so the spring flow show very little variation in chemistry over time. In conduit type aquifers, the specific conductivity of spring flow is highly variable, seasonally and after large storm events, reflecting the fact that little mixing takes place within the aquifer.

1.2 Linear systems analysis

Kernel functions derived from spring storm responses represent the residence time distribution of rapid groundwater recharge in the conduit networks. The shape of the kernel function can be analysed using statistical time moment analysis. The method of moments is widely used in time series analysis. It has been used to study karst aquifer systems. Dreiss (1989) applied the method of moments to different kernel functions and a tracer test to calculate the statistical properties of the travel or residence time distribution of the aquifer. The calculated moments are useful means of describing the system in terms of the mean travel time and the degree of spreading and mixing within the aquifer. For instance, kernels for well-developed karst aquifers normally have a relatively low coefficient of variation (α_2) because very large quantities of water are transmitted very rapidly in conduit networks, therefore, little mixing or spreading will take place during the transport. Whereas, the coefficient of variation should be larger for springs in less mature karstic areas.

1.3 Heterogeneity ratio (H_R)

Recently, Karami (2002) in his research at Newcastle University introduced a new method that allows the objective definition of the degree of heterogeneity of karst aquifers by re-evaluation of ordinary constant rate pumping test data. The method yields a parameter termed the heterogeneity ratio (H_R), which reflects the variations in successive transmissivity values detected by the outwardly expanding cone of depression as the duration of the pumping test increases. Karami in his study analysed several sets of test-pumping data from different carboniferous limestone sites in the UK to determine (H_R). The results have yielded values ranging from 0% where the limestone is hydraulically homogeneous to about 14% where the limestone is heterogeneous. However, karst aquifers are highly heterogeneous in character, therefore, any quantitative data obtained from selected points in the system using pumping test data tend to represent the immediate surroundings of that point and can rarely be extrapolated to evaluate the system as a whole (Padilla et al, 1994).

1.4 Recession hydrograph analysis

The shape of the outflow hydrograph of a spring is a unique reflection of the response of an aquifer to recharge. Ford and Williams (1989) have given broad reviews of this subject. The analyses of spring hydrographs offer considerable potential insight into the structure and hydraulics of karst drainage systems. After

analysing recession curves from Ompla spring in Yugoslavia, Milanovic (1981) concluded that the aquifer is characterised by three types of porosity, represented by three recession coefficients of successive orders of magnitude. He interpreted these three coefficients as follow; (1) The highest recession coefficient is a reflection of rapid outflow via conduits; (2) The intermediate recession coefficient is interpreted as characterising the outflow from well integrated karstified fissures and (3) The smallest recession coefficient is thought to be a response to the drainage of water from matrix.
Despite the fact that recession curve analysis techniques provide very useful information on the storage and structural characteristics of the aquifer system sustaining the spring, they might not give a clear distinction or classification about whether the aquifer is fully or partially karstified since these methods only consider the recession limb of the hydrograph and do not take in consideration the rising limb of the hydrograph, which is a very important part of the spring hydrograph.

1.5 Flashiness of an aquifer (Q_f)

Some researchers used another parameter called flashiness of an aquifer Q_f that can be defined as the ratio of the maximum discharge (peak flow) to the minimum discharge (baseflow). Based on aquifer flashiness values, Delleur (1999) grouped spring hydrographs into three types of aquifers; Type-I (fast response), Type-II (mixed response), and Type-III (slow response). Fast response aquifers have Q_f in the range of 70 - 100, Mixed response aquifers in the range of 5 - 10 and slow response aquifers in the range of 1 - 2. The problem with this parameter is the fact that it does not take in account the duration time between the starting of the rising limb and the peak discharge and the duration time between the peak discharge and the returning to the baseflow condition.

On these reasoning mentioned above it may be argued that taking in consideration the whole hydrograph components (rising and recession limbs) including the time when the rising starts, the time when the peak occurs and the time when the hydrograph returns to its baseflow condition can be used as bases to introduce a new method to evaluate karst aquifer systems. It is the principal goal of this paper to propose such a method. Which then will be used as a measure of the karstifiaction of karst aquifers.

2 CALCULATING DEGREE OF KARSTIFICATION (D_k)

As was stated in the preceding section, degree of karstification index is a value calculated from analysing a spring hydrograph taking in account the whole hydrograph components illustrated in figure 1. Before calculating the degree of karstification, it is necessary to separate baseflow component from quickflow component. Baseflow is an important genetic component of a spring hydrograph, which comes from groundwater and/or shallow subsurface storage. Through most of the dry season of the year, the spring discharge is composed entirely of baseflow.

During a wet season, discharge is made up of baseflow and quickflow. The latter represents the direct catchment response to rainfall events. Baseflow may be characterised by its hydrograph, which is derived from the total spring hydrograph by various baseflow separation techniques. A variety of event-based separation methods are available, which focus on separating baseflow from a flood hydrograph and are eventually aimed at the estimation of the surface runoff or quickflow component of a flood. The descriptions of such methods may be found in many classical hydrology textbooks and are not examined in this paper. In this study, a common separation technique, as described by Shaw, 1994, which is simply to draw a line between the start of the rising limb (point A) to point C on the falling limb where the recession is assumed to become exponential, and is fixed uniquely on the semi-logarithmic scale (figure 1). After baseflow separation is complete, the dimensionless degree of karstification (D_k) can be calculated using the following equation:

$$D_k = \frac{Q_{msx}}{Q_{\min}} \frac{t_{event}}{t_{peak}} \qquad (1)$$

Where $t_{event} = t_C - t_A$ & $t_{peak} = t_B - t_A$

$Q_{\max}$ = Maximum discharge at point (B)

$Q_{\min}$ = Minimum discharge at point (A)

t_A = Time when the rising limb starts

t_B = Time when the maximum discharge is recorded and t_C is the time when the spring flow returns to the baseflow condition

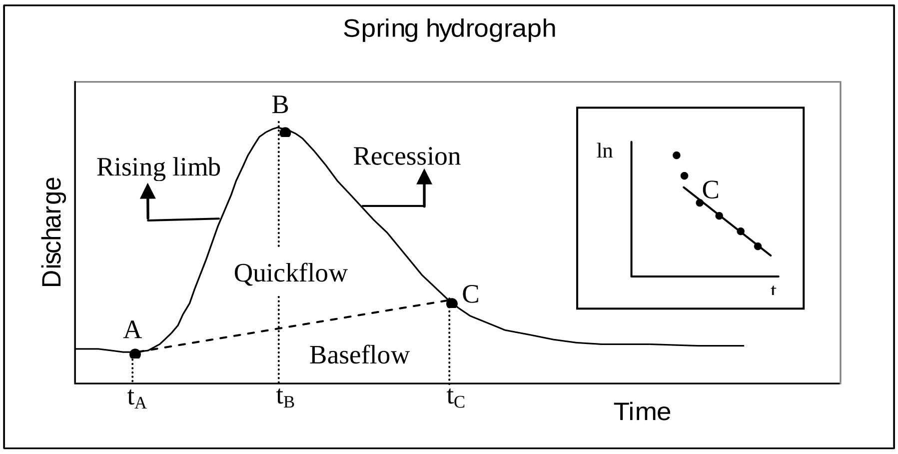

Figure 1: Components of a spring hydrograph during a storm and separation of baseflow component.

3 APPLICATIONS TO SPRING HYDROGRAPHS

Equation 1 will be applied to different hydrographs produced from different well-known spring sites. These sites are Nanos catchment in Slovenia, Zlatna catchment in Bulgaria, GRAN catchment in Wales, Crnojevica catchment in Yugoslavia and Maramec catchment in the USA. The chosen hydrographs are based on the following criteria:

(1) Each hydrograph must be preceded by some time with little or no rainfall to ensure that the hydrograph has got a clear baseflow condition before the rising limb starts.
(2) The chosen hydrograph should have got a clear return to baseflow condition after the end of the storm, so baseflow separation can be done easily.
(3) Each hydrograph should represent different flow conditions, such as high, medium or low flow conditions.

3.1 Application to Nanos catchment

Four hydrographs have been chosen, based upon the above conditions, to calculate the degree of karstification (D_k) from each one. The results obtained, using equation 1, reveal that the values of degree of karstification range between 22 and 47 (table 1).

Table 1: Degree of karstification (D_k) for Nanos catchment.

Site	Nanos			
Hydrographs	1	2	3	4
Q_{max} (m^3/s)	13.1	27.4	40.7	54.6
Q_{min} (m^3/s)	1.79	2.32	2.54	2.68
t_A (days)	80	398	1190	2341
t_B (days)	82	400	1192	2344
t_C (days)	86	402	1195	2348
D_k	22	24	40	47

3.2 Application to Zlatna catchment

Three hydrographs have been chosen from this catchment. The calculated degree of karstification (D_k) values, as presented in table 2, is in the range between 12 and 20. These values are relatively lower than the values calculated for Nanos catchment.

Table 2: Degree of karstification (D_k) for Zlatna catchment.

Site	Zlatna		
Hydrographs	1	2	3
Q_{max} (m^3/s)	11.106	9.264	17.680
Q_{min} (m^3/s)	1.759	2.980	3.670
t_A (days)	209	242	323
t_B (days)	211	247	327
t_C (days)	213	261	340
D_k	13	12	20

3.3 Application to GRAN catchment

From this catchment, equation 1 has been applied to two hydrographs and the values of degree of karstification (D_k) are in the range between 12 and 17 (table 3).

Table 3: Degree of karstification (D_k) for GRAN catchment

Site	GRAN	
Hydrographs	1	2
Q_{max} (m^3/s)	0.109	0.073
Q_{min} (m^3/s)	0.012	0.016
t_A (min)	12870	870885
t_B (min)	15960	871200
t_C (ins)	18630	871680
D_k	17	12

3.4 Application to Crnojevica catchment

Only one hydrograph has been used to calculate degree of karstification for the catchment. The calculated D_k , as presented in table 4, was found equals to 93. This is a very high value compared to the previous catchments.

Table 4: Degree of karstification (D_k) for Crnojevica catchment.

Site	Crnojevica
Hydrographs	1
Q_{max} (m^3/s)	119
Q_{min} (m^3/s)	3.2
t_A (days)	1
t_B (days)	3
t_C (days)	6
D_k	93

3.5 Application to Maramec catchment

Only one hydrograph has been analysed using equation 1 to calculate the degree of karstification (D_k) for this aquifer. It has been found, as tabulated in table 5, that D_k is equal to 55.

Table 5: Degree of karstification (D_k) for Maramec catchment.

Site	Maramec
Hydrographs	1
Q_{max} (m^3/s)	4.375
Q_{min} (m^3/s)	0.20
t_A (days)	310
t_B (days)	314
t_C (days)	320
D_k	55

4. CLASSIFICATION OF KARST AQUIFERS BY USING DEGREE OF KARSTIFICATION

In order to do comparison between the highest resultant degree of karstification values (D_k) for different sites and the flashiness of aquifer values (Q_f) for the same sites, calculations of the flashiness of an aquifer for each catchment have been determined and the results are presented in table 6. According to flashiness of aquifer classifications, Nanos, Crnojevica and Maramec catchments fall between fast to intermediate response aquifers, while Zlatna and GRAN catchments can be classified as intermediate response aquifers. These classifications are more general since there is a huge gap between the intermediate response aquifers (Q_f =5 to 10) and fast response aquifers (Q_f =70 to 100). For example, Crnojevica catchment, which is a highly karstified area as reported by Bonacci (1993), could be classified, using flashiness of an aquifer, as intermediate to fast aquifer response. Another example, Nanos and maramec catchments could also be classified, according to flashiness method, as intermediate to fast aquifers. In fact, Nanos catchment has been analysed using linear systems analysis (Rashed, 2002) and Maramec catchment was analysed by Dreiss (1989) using linear systems analysis method. The results of both analyses show that the coefficient of variation (α_2) for Nanos catchment ranging from 0.69 to 0.97 and for Maramec catchment ranging from 0.68 to 0.77. The variance or coefficients of variation for both aquifers are quite in fair agreement and relatively small, reflecting the fact that little mixing takes place within the aquifers. As a result, both aquifers can be classified under one category. Consequently, Dreiss (1989) classified Maramec aquifer as a conduit-type karst aquifer. Also Nanos aquifer can be classified as a conduit-type karst aquifer. Therefore, there is a need to much more precise classifications. Based on the above comparison, it may be argued that degree of karstification can be used to classify karst aquifers. Table 7 shows a proposed karst aquifer classification based on degree of karstification values. The classification classes of the studied sites according to this classification are tabulated in table 8.

Table 6: Comparison between degree of karstification values and flashiness of aquifer values for five different sites.

Site	Nanos	Zlatna	GRAN	Crnojevica	Maramec
D_k	47	20	17	93	55
Q_f	16	5	9	37	22

Table 7: Proposed karst aquifer classification based on degree of karstification.

Degree of karstification (D_k)	Classification
Less than 10	Darcian aquifer
10 – 20	Partially karstified aquifer
20 – 60	Karstified aquifer
More than 60	Highly karstified aquifer

Table 8: Aquifer (catchments) classifications based upon degree of karstification values.

Site	D_k	Classification category
Nanos	22-47	Karstified aquifer
Zlatna	12-20	Partially karstified aquifer
GRAN	12-17	Partially karstified aquifer
Crnojevica	93	Highly karstified aquifer
Maramec	55	karstified aquifer

5. CONCLUSION

The degree of karstification of karst aquifers has been evaluated using spring hydrograph data obtained from different karst sites. A simple, practical method has been introduced to assess and evaluate karst aquifers using spring discharges. Based on the calculated degree of karstification values for five sites, karst aquifers have been classified into four groups: Darcian or diffuse, partially karstified, karstified and highly karstified aquifers. Application of such classification method has the potential to remove some of the confusion regarding site characterisation. It may also help to provide a basis for deciding whether to use Equivalent porous medium, fracture or conduit based models to simulate karst aquifer systems.

ACKNOWLEDGEMENTS

We are grateful to Simon Neale, Environment Agency, for his contribution to the preparation of this paper by providing some discharge data. The work would not have been possible without the scholarship awarded to the first author by the Libyan Ministry of High Education.

REFERENCES

[1] Atkinson, T. C. (1977). Diffuse flow and conduit flow in limestone terrain in the Mendip hills, Somerset (GB). J. Hydrol., 35, 93-110.

[2] Bonacci, O. (1995). Groundwater behaviour in karst: example of the Ombla spring (Croatia). J. Hydrol., 165, 113-134.

[3] Bonacci, O. (1993). Karst springs hydrographs as indicators of karst aquifers. Hydrol. Sci. J., 38(1-2), 51-62.

[

[4] Dreiss, S. J. (1989). Regional scale transport in a karst aquifer: 2. Linear systems and time moment analysis. Water Resour. Res., 25(1), 126-134.

[5] Dreiss, S. J. (1982). Linear kernels for karst aquifers. Water Resour. Res., 18(4), 865-876.

[6] Ford, D. C. and Williams, P. W. (1989). Karst Geomorphology and Hydrology. UK: Chapman & Hall.

[7] Karami, G. H. and Younger, P. L. (2002). Assessing karst aquifer heterogeneity using test-pumping data. Conference on what's new in Groundwater, London, The Geological Society.

[8] Milanovic, P. (1981). Karst hydrogeology. Water Resources Publications, Littleton, Colorado, USA.

[9] Padilla, A. and Pulido-Bosch, A. (1995). Study of hydrographs of karstic aquifers by means of correlation and cross-spectral analysis. J. Hydrol., 168, 73-89.

[10] Padilla, A., Pulido-Bosch, A and Mangin, A. (1994). Relative importance of baseflow and quickflow from hydrographs of karst spring. Groundwater, 32(2), 267-277.

[11] Ryan, M. and Meiman, J. (1996). An examination of short-term variations in water quality at a karst spring in Kentucky. Groundwater, 34(1), 23-30.

[12] Samani, Nozar (2001). Response of karst aquifers to rainfall and evaporation, Maharlu basin, Iran. Journal of cave and karst studies, 63(1), 33-40.

[13] Shaw, E. M. (1994). Hydrology in practice. UK. Chapman & Hall.

[14] Shuster, E. T. and White, W. B. (1971). Seasonal fluctuations in the chemistry of limestone springs: A possible means for characterising Carbonate aquifers. J. Hydrol., 14, 93-128.

[15] Tallaken, L. M. (1995). A review of baseflow recession analysis. J. Hydrol., 165, 349-370

[16] White, W. B. (1999). Groundwater Flow in Karstic Aquifers. In: The Handbook of Groundwater Engineering [J. W. Delleur, Ed.], Chapter 18, CRC Press.