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GEOCHEMISTRY OF SPRINGS IN TEMPERATE CARBONATE AQUIFERS: RECHARGE TYPE EXPLAINS MOST OF THE VARIATION

by

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Abstract

The variation in hardness of springs in carbonate aquifers has been used in the past to explain two different variables: the recharge type to an aquifer (allogenic or autogenic), and the type of flow within the aquifer (conduit or diffuse). Statistical analysis of hardness data from 39 springs in six countries with temperate climates demonstrates that more than 75% of hardness variation is explained by recharge type. No evidence was found to support the hypothesis that hardness variation is an indicator of flow conditions within an aquifer.

1) Introduction

Carbonate aquifers are often drained by prominent springs. Springs offer the advantage over wells that they provide an integrated sample of discharge from the aquifer. A large number of case studies have been made on the discharge and hydrochemistry of springs; many of these are summarised by Milanović (1981), White (1988), and Ford and Williams (1989). However, it has not been a straightforward task to interpret variations of physical or chemical parameters at springs. These studies have often inferred flow processes within an aquifer from spring behaviour, but there has been little testing of the hypotheses proposed.

This paper will compare conflicting hypotheses on the cause of variation in spring chemistry, and provide evidence supporting one hypothesis, that geochemical variation of spring waters is related to type of recharge. The variation in spring hardness in temperate climates only will be discussed. In Alpine climates there are strong seasonal contrasts in spring chemistry, so the intensity of the snowmelt regime is an important factor in determining spring chemistry.

2) Hypotheses to explain spring chemical variability

Springs in limestone and dolomite terranes have a wide range of chemical responses to precipitation events. Some springs respond within hours with variations of >20% in major ions. However, in the same area, nearby springs may show very little response in chemistry (Shuster and White, 1971). Two hypotheses have been proposed to account for these contrasts.

The first hypothesis was proposed by Jakucs (1959). He suggested that recharge mode strongly influenced spring response. This relationship was quantified by Newson (1971), who studied nine springs in the British Isles. He found a linear correlation between the proportion of sinking stream (allogenic) recharge to a spring catchment and the spring's coefficient of variation of hardness (CVH).

The second hypothesis was proposed by Shuster and White (1971), who found strong contrasts in spring CVH. High variation springs were largely fed by allogenic recharge, and low variation springs were fed by autogenic recharge. They suggested that the CVH measured at the spring could be used to indicate whether the aquifer and its spring was fed by conduit flow or diffuse flow. Diffuse flow in this sense was suggested to be essentially Darcian in form.

These conflicting hypotheses of Jakucs (1959) and Newson (1971) on the one hand, and Shuster and White (1971) on the other hand have not been resolved in the last twenty years. Is CVH an indicator just of the recharge mechanism to the aquifer (allogenic/conduit feeder or autogenic/diffuse feeder), or does CVH indicate the type of flow within the aquifer?

The differentiation is important because the mean velocities of the two flow types, one in conduits, the other in pores and narrow fissures, vary by more than four orders of magnitude (Kiraly, 1975; Sauter, 1992). Conduits often have diameters >1m, so there is low resistance to flow, resulting in high velocities. The mean flow velocity in conduits, as indicated by a large numbers of tracer tests, is about 2×10^{-2} m s^{-1} (Gèze, 1958; Milanović, 1981). By contrast, flow through pores and narrow fissures, as indicated by a large number of well tests, has a mean velocity of about 10^{-6} m s^{-1} (Freeze and Cherry, 1979, p29; Worthington, 1991).

Although many of the publications cited herein discuss hardness and perhaps its CVH, the most practical parameter to monitor at a spring or well is electrical conductivity (also called specific conductivity, or just conductivity). This is because it easier to measure than hardness, and can be monitored continuously (e.g. Bakalowicz, 1979; Hess and White, 1988). Conductivity is directly proportional to hardness, and highly correlated with it. Therefore conductivity can be used as a surrogate parameter for hardness at springs. The coefficient of variability of conductivity (CVC) is the most practical statistic for characterizing the water quality of springs.

3) Correlation between recharge type and spring chemistry

It is simplest to test the hypothesis that spring CVH is a function of recharge type, because CVH depends on data that can be collected on the surface. Data for 39 springs were taken from the literature (Table 1). For each spring, the catchment is sufficiently well delineated so that the proportions of allogenic and autogenic recharge can be determined from topographic and geologic maps. The number of total hardness determinations for individual springs ranged from 12 to 508 samples.

The correlation between CVH and recharge type is shown in Figure 1, and shows that CVH is principally a function of recharge type. The relationship is even clearer when individual areas are considered (Table 1).

For the five individual areas shown in Table 1, the poorest correlation is for Central Kentucky. It is somewhat difficult to define allogenic recharge in this region because there are actually two types of allogenic recharge. One type is from sinking streams which flow off the Sinkhole Plain from the south, and the other type is from the sandstone caprock which overlies much of the area. Recharge from the caprock occurs both as seeps and small sinking streams, and as downward leakage eventually into the aquifer (Hess and White, 1989, p.46). The respective areas for the two types of recharge were subjected to a multiple linear regression and the results shown in Table 2.

Table 1 **Linear regression statistics for relationship between CVH and percentage of allogenic recharge**

Area	Intercept	Coefficient	r^2	Number of springs	Source
Mendip Hills, England	0.41	0.51	0.95	9	Newson (1971), Atkinson (1977b)
Pennsylvania, USA	3.2	0.27	0.81	13	Shuster and White (1971)
Gower Peninsula, Wales	12.2	0.22	0.85	4	Ede (1972)
Central Kentucky, USA	5.4	0.23	0.53	5	Hess and White (1989), Quinlan and Ewers (1989)
Yorkshire, England	5.2	0.23	0.88	3	Ternan (1972), Pitty (1974)
All data	3.8	0.28	0.77	39	above, plus Pitty (1968), Williams and Dowling (1979)

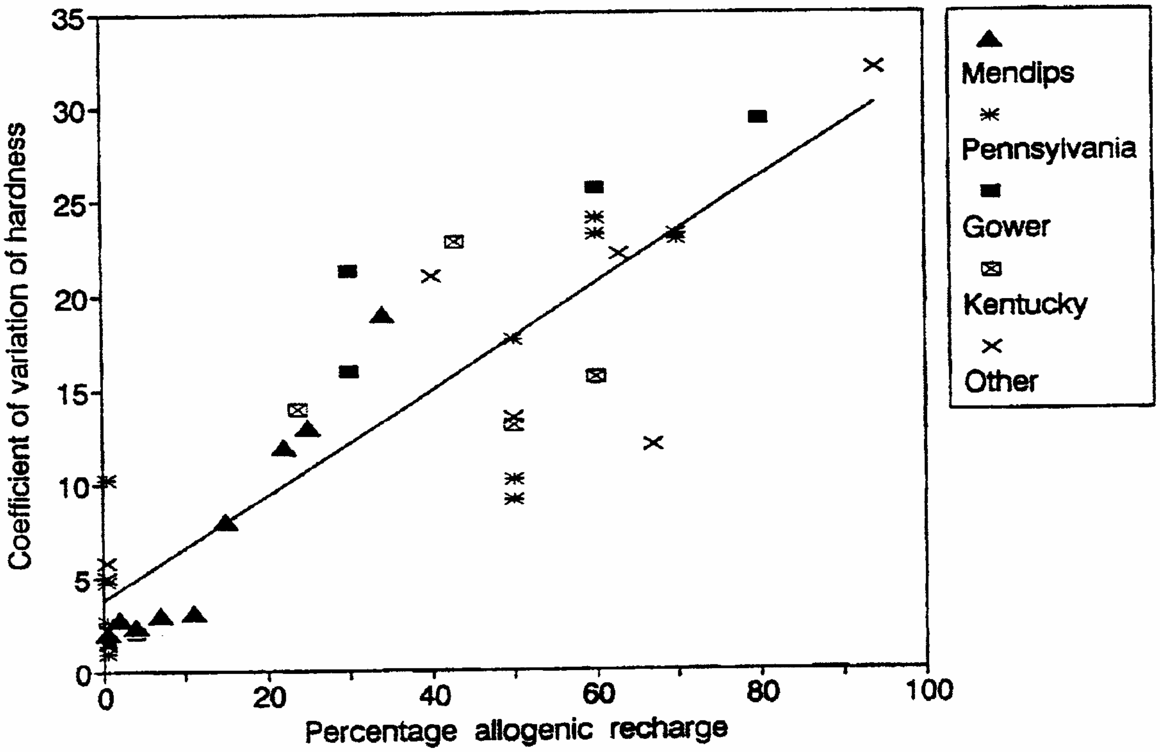

Figure 1 **Relationship between CVH and recharge type for 39 temperate springs. Data sources are given in Table 1.**

Table 2 Multiple Linear Regression of CVH Data from Kentucky.

Catchment	Sinking stream catchment	Caprock catchment	CVH
Owl Cave	28%	16%	22.8%
Pike Spring	0	59	15.6
Echo Spring	0	48	13.1
Waterworks Spring	4	0	2
Graham Spring	23.8	0	14

Multiple regression yields:

$$\mathrm{CVH} = 0.66\,S + 0.29\,C - 0.93 \qquad (r^2=0.994)$$

where S is the sinking stream percentage and C is the caprock percentage of the catchment. The high coefficient of determination suggests that the two allogenic recharge types have contrasting effects on spring CVH, with sinking stream recharge having more than twice the variation caused by caprock recharge. Thus, after taking account of the two distinct types of allogenic recharge in Kentucky, at least 80% of the variation in CVH for each area listed in Table 1 is accounted for by recharge type.

4) Characteristics of allogenic and autogenic recharge

The linear relationship between CVH and percentage allogenic recharge suggests that a two-component mixing model may adequately explain the variation in CVH. The low-variation end-member is autogenic recharge. This water is relatively constant in hardness and discharge, so that springs fed by autogenic recharge commonly have CVH values <5%. The high-variation end-member is allogenic recharge. There are three ways in which allogenic recharge can cause a high variation in spring CVH.

The simplest cause of CVH variation is where a spring is fed by a single sinking stream with high CVH. For instance, 63% of the catchment for the spring of Clapham Beck Head, England (CVH 22%) is provided by the sinking stream of Fell Beck (CVH 28%; based on data from Pitty, 1974).

The second cause is where a spring is fed by several sinking streams with different hardnesses. For instance, in the Mendip Hills, England, Drew (1970b) found that five sinking streams feed St. Dunstan's Well springs. The CVH of individual streams varies from 14 to 26%, but the mean hardness of these streams varies from 58 to 121 mg l^{-1}. Thus a storm event that affected only a small area could produce very different recharge to the aquifer depending on which subcatchment it affected. Consequently, St Dunstan's has a CVH of 19%, which is higher than expected for a spring with only 34% allogenic recharge (Figure 1).

The third cause of variation is due to the contrasting mix of low-hardness allogenic water and high-hardness autogenic water. Drew (1970a) demonstrated that these two components can contribute widely varying percentages to spring discharge. At three springs in the Mendip Hills, England, Drew measured allogenic contributions to total springflow to be 5-26%, 9-39%, and 24-50%, respectively, over the course of one year. For a further two springs in the Mendip Hills, Newson (1972) showed that the variation of the autogenic and allogenic components accounted for 62-74% of the variation in spring hardness.

5) Conduit flow in autogenic catchments

The simplest method of testing whether low CVH is due to percolation recharge to an aquifer or diffuse flow through the aquifer is to perform tracer tests. In the former case there could be rapid flow (>0.001 m s^{-1}) along most of the flow route. In the latter case, flow velocities <<0.001 m s^{-1} would be expected. Tracer tests for three of the springs shown in Figure 1 have been made.

Atkinson (1977b) studied the two springs of Wookey Hole and Cheddar Spring in the Mendip Hills, England. He observed that the low CVH (2.4% and 2.8%, respectively) would suggest these were diffuse-flow springs in the classification of Shuster and White (1971). The recharge for the two springs is almost completely by percolation water, but a detailed study of the hydrogeology indicated that 60-80% of the flow was in conduits (Atkinson, 1977a). This flow mechanism was supported by tracer tests revealing velocities up to 0.074 m s^{-1} to Cheddar Spring, and up to 0.089 m s^{-1} to Wookey Hole (Stanton and Smart, 1981). Furthermore, scuba divers have penetrated several hundred metres of flooded conduits at each spring (Farr, 1991).

The third spring in Figure 1 to which tracer tests have been made is Waterworks Spring, Kentucky. More than 95% of the recharge to the spring catchment is by percolation water. The low CVH (2%) and low turbidity suggested that this might be a diffuse flow spring (Quinlan and Ewers, 1989). However, a tracer test revealed rapid flow >0.004 m s^{-1}, thus indicating the presence of well-developed conduits.

On a global scale, many of the most significant explored caves are found in autogenic catchments. For instance, nine of the ten deepest caves and five of the ten longest caves in carbonates in the world have no allogenic recharge (Courbon et al., 1986). Thus there can be no doubt that carbonate aquifers recharged only by percolation may have both low CVH and well-developed conduits. These examples indicate that low CVH does not signify diffuse-flow within the aquifer, in the form suggested by Shuster and White (1971).

6) Conclusion

CVH and CVC are excellent indicators in temperate catchments of whether the recharge is autogenic (percolation recharge) or allogenic (sinking stream recharge). Typically, springs with allogenic recharge have high CVH because they discharge varying proportions of percolation and sinking stream recharge. At baseflow stage, there is a high proportion of high-hardness percolation recharge. At flood stage, there is a high proportion of low-hardness sinking stream recharge.

There has been confusion in the literature over the terms diffuse flow and conduit flow, which have been applied in three ways: recharge to an aquifer, flow within an aquifer, and types of springs (Shuster and White, 1971; Quinlan and Ewers, 1989). Also, rather than some carbonate aquifers being characterized by rapid flow in conduits, and others by slow, diffuse flow, the evidence indicates that all subaerially-exposed carbonate aquifers have both rapid-flow and slow-flow components. The rapid-flow component occurs in solutionally-enlarged fissures and conduits, and the slow-flow component is through pores and narrow fissures. The hydrogeology of these carbonate aquifers can only be adequately understood by using complementary techniques (such as well tests and tracer tests) that characterize both the slow-flow and the rapid-flow components. Spring CVH is not an indicator of flow type, but it is an excellent indicator of whether aquifer recharge is from percolation or from sinking streams.

References

ATKINSON T.C. (1977a) - Diffuse and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain). *J. Hydrol.*, 35, p. 93-110.

ATKINSON T.C. (1977b) - Carbon dioxide in the atmosphere of the unsaturated zone: an important control of groundwater hardness in limestones. *J. Hydrol.*, 35, p. 111-123.

BAKALOWICZ M. (1979) - Contribution de la géochimie des eaux à la connaissance de l'aquifère karstique et de la karstification. *Thèse doct. sci. nat., Univ. Curie*, Paris, 269p.

COURBON P., et CHABERT C. (1986) - Atlas des grandes cavités mondiales. *Union Internat. de Spéléologie et Fédération Francaise de Spéléologie*, Paris, 255p.

DREW D.P. (1970a) - The significance of percolation water in limestone catchments. *Ground Water*, 8(5), p. 8-11.

DREW D.P. (1970b) - Limestone solution within the East Mendip area. *Trans. Cave Research Group of G.B.*, 12, p. 259-270.

EDE D.P. (1972) - Limestone drainage systems. *J. Hydrol.*, 27, p. 297-318.

FARR M. (1991) - The darkness beckons: the history and development of cave diving. *Diadem*, London, 280p.

FORD D.C., and WILLIAMS P. (1989) - Karst geomorphology and hydrology. *Unwin Hyman*, London, 601p.

FREEZE R.A., and CHERRY J.A. (1979) - Groundwater. *Prentice Hall*, Englewood Cliffs, N.J., 604p.

GÈZE B. (1958) - Sur quelques caractères fondamentaux des circulations karstiques. *Annales de spéléologie*, 13, p. 5-22.

HESS J.W. and WHITE W.B. (1988) - Storm response of the karstic carbonate aquifer of Southcentral Kentucky. *J. Hydrol.*, 99, p. 235-252.

HESS J.W. and WHITE W.B. (1989) - Chemical hydrology. *In: Karst hydrology: concepts from the Mammoth Cave area, (Eds: W.B. White and E.L. White), Van Nostrand Reinhold*, New York, p. 145-174.

JAKUCS L. (1959) - Neue Methoden der Höhlenforschung in Ungarn und ihre Ergebnisse. *Die Höhle*, 10(4), p. 88-98.

KIRALY L. (1975) - Rapport sur l'état actuel des connaissances dans le domaine des charactères physiques des roches karstiques. *In: Hydrogeology of karstic terrains, (eds. A. Burger and L. Dubertret). Internat. Union Geol. Sci., Series B, 3*, p. 53-67.

MILANOVIC P.T. (1981) - Karst hydrogeology. *Water Resources Publications*, Littleton, Colorado.

NEWSON M.D. (1971) - A model of subterranean limestone erosion in the British Isles based on hydrology. *Trans. Inst. British Geographers*, 54, p. 55-69.

NEWSON M.D. (1972) - Comment on "Seasonal fluctuations in the chemistry of limestone springs" by E.T Shuster and W.B. White. *J. Hydrol.*, 16, p. 49-51.

PITTY A.F. (1968) - Calcium carbonate content of karst water in relation to flow-through time. *Nature*, 217, p. 939-940.

PITTY A.F. (1974) - Karst water studies in and around Ingleborough Cavern. *In: The limestone and caves of north-west England, Ed. A.C. Waltham. David and Charles*, Newton Abbot, p. 127-139.

QUINLAN J.F. and EWERS R.O. (1989) - Subsurface drainage in the Mammoth Cave area. *In: Karst hydrology: concepts from the Mammoth Cave area, (Eds: W.B. White and E.L. White), Van Nostrand Reinhold*, New York, p. 65-103.

SAUTER M. (1992) - Assessment of hydraulic conductivity in a karst aquifer at a local and regional scale. *In: 3rd Conference on Hydrology, Ecology, Monitoring, and Management of Ground Water in Karst Terranes, Nashville, Tenn. (Eds. J.F. Quinlan and A. Stanley). National Ground Water Association*, Dublin, Ohio, p. 39-57.

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.

STANTON W.I. and SMART P.L. (1981) - Repeated dye traces of underground streams in the Mendip Hills, Somerset. *Proc. Univ. Bristol Speleological Soc.*, 16, p. 47-58.

TERNAN J. L. (1972) - Comments on the use of a calcium hardness variability index in the study of carbonate aquifers: with reference to the Central Pennines, England. *J. Hydrol.*, 16, p. 317-321.

WHITE W.B. (1988) - Geomorphology and hydrology of karst terrains. *Oxford Univ. Press*, 464p.

WILLIAMS, P.W., and DOWLING R.K., 1979. Solution of marble in the karst of the Pikikiruna Range, northwest Nelson, New Zealand. *Earth Surf. Processes*, 4, 15-36.

WORTHINGTON S.R.H. (1991) - Karst hydrogeology of the Canadian Rocky Mountains. *Unpubl. PhD thesis, McMaster Univ.*, Hamilton, Ontario, 380p.