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A comprehensive strategy for understanding flow in carbonate aquifer

Stephen R.H. Worthington

55 Mayfair Avenue, Dundas, Ontario, Canada, L9H 3K9. E-mail: worth@interlynx.net

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Abstract

Studies of carbonate aquifers usually either concentrate on sampling the channel flow (e.g. sink to spring tracer testing, spring monitoring) or on sampling the non-channel flow (e.g. borehole measurements). A comprehensive approach is advocated here, integrating both sources of information, as well as measuring the porosity and permeability of the unfractured rock. Representative sampling can be achieved by treating carbonates as triple porosity aquifers, with one-, two-, and three-dimensional porosity elements. The division of carbonate aquifers into "karstic" or "non-karstic" types is unwarranted.

Keywords: karst aquifers, porosity and permeability of carbonate rocks

Introduction

In the past three decades carbonate aquifers have usually been considered in one of three ways. The simplest and most commonly-used approach has been to assume that fractures may be locally important, but that fracture density is great enough that the aquifer can be treated as an equivalent porous medium, and modelled using a package such as MODFLOW. A second approach has been to recognize that fractures may be laterally continuous for considerable distances, and that these are much more conductive than the matrix of the rock. In this case a double porosity (or double permeability) model is used for the aquifer. In both these cases it is assumed that boreholes facilitate representative sampling of the aquifer. A third approach has been to recognize the existence of a high-permeability network of conduits within the aquifer, and to concentrate on studying the conduits. Techniques include tracer testing from dolines or sinking streams to springs and monitoring of spring discharge or hydrochemical parameters. This approach is most commonly used where there are abundant surficial karst landforms.

The use of *a priori* assumptions on the behaviour of carbonate aquifers tends to result in studies that only partially characterize an aquifer. Studies of spring flow or tracer testing from sinkholes to springs succeed in characterizing channel flow in the aquifer, but little is learnt about non-channel flow. Conversely, studies using wells as sampling and monitoring points may characterize fracture and matrix flow, but often give little or no indication of the rapid solute transport that is occurring in the channel network located between the wells. A full understanding of flow in carbonate aquifers can only be gained by studying all the flow components in the aquifer.

The conceptual model described below incorporates the techniques used for monitoring wells and those used for monitoring springs to gain a more holistic understanding of carbonate aquifers.

1. A conceptual model for carbonate aquifers

One way of studying carbonate aquifers that may prove useful is to consider aquifers in terms of the three fundamental geometric elements that can exist within it. These are shown in Fig. 1, and are:

- one-dimensional, or linear elements. These are often referred to as *channels*. In carbonate aquifers large channels in which there is turbulent flow are commonly termed *conduits*, and if they are accessible by people they are *caves*.
- two-dimensional, or planar elements, such as bedding planes, joints and faults
- the three-dimensional matrix

Carbonate aquifers can be considered as triple porosity aquifers since they contain these three porosity elements. Analysis of an aquifer in terms of three porosity elements results in a better understanding of flow and storage than if the aquifer is treated as having only two porosity components. Furthermore, there have been two different ways in which two porosity components in carbonate aquifers have been studied; a double porosity aquifer is not the same as a conduit and diffuse flow aquifer (Table 1). Analysis as a triple porosity aquifer can avoid potential confusion, and lead to more accurate insights on aquifer behaviour.

2. Formation, size and distribution of channels

Fracture planes commonly have variable apertures, and most of the flow is concentrated along the more open portions of fractures, which are called channels. For instance, in granites in Great Britain and in Sweden, it has been found that such channels may occupy 5-20% of a given fracture plane (Tsang, 1993). However, in carbonate rocks some channels may be greatly enlarged by solution processes. This is due to two factors:

a) the non-linear nature of carbonate dissolution; as thermodynamic equilibrium is approached the solution rate decreases by several orders of magnitude (Plummer and Wigley, 1976). This results in carbonate groundwater being slightly under-saturated with respect to calcium (or magnesium) carbonate at most sites where there is notable flow.

b) the positive feedback relationship between dissolution rate and discharge which permits larger channels to grow at the expense of smaller ones (Ford and Williams, 1989, p. 249 et seq.).

The two factors combine to create broadly dendritic networks of channels. In unconfined carbonate aquifers in moist climates, channeling

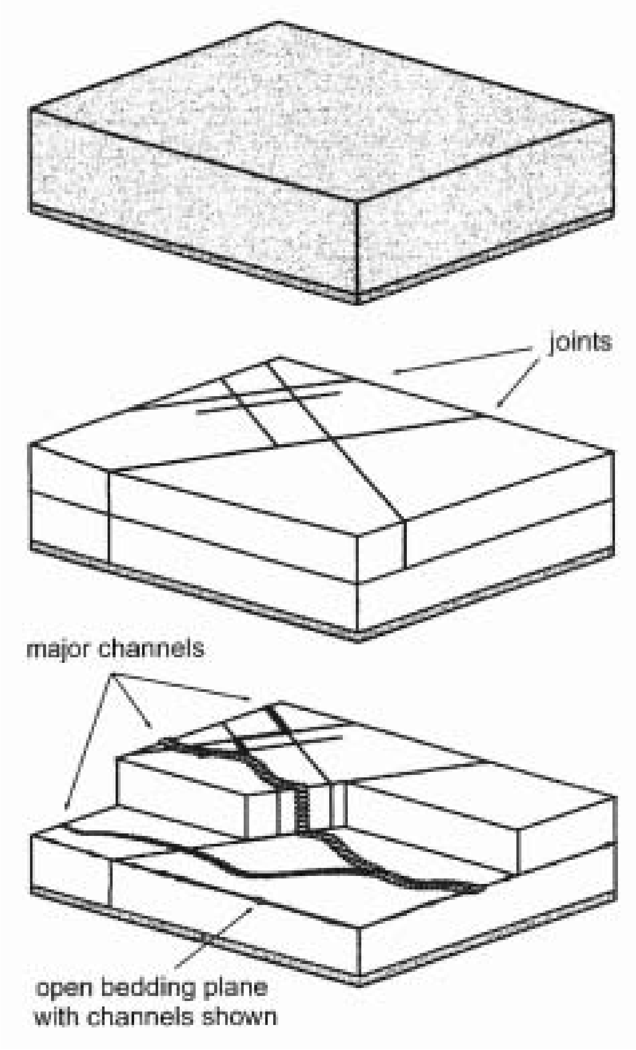

Fig. 1. Model for a single porosity aquifer with matrix flow (top), a double porosity aquifer with matrix and fracture flow (center), and a triple porosity aquifer with matrix, fracture and channel flow (bottom).

TABLE 1

Comparison of classification schemes for porosity elements in carbonate aquifers

Element geometry	Flow regime	Karst spring studies	Double porosity	Triple porosity
3D	laminar	diffuse	matrix	matrix
2D	laminar	diffuse	fracture	fracture
1D	laminar	diffuse	not included	channel
1D	turbulent	conduit	not included	channel (conduit)

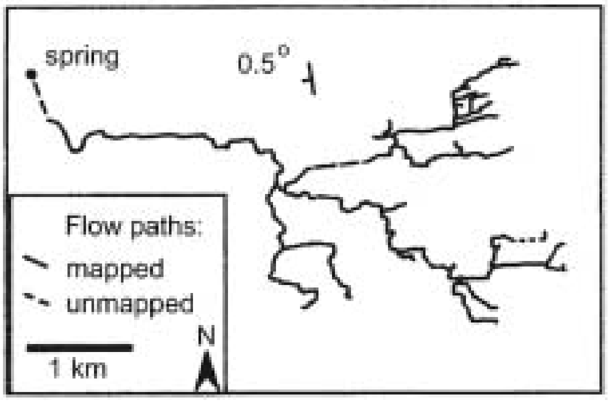

Fig. 2. Convergent flow paths draining to a spring, as mapped in Blue Spring Cave, Indiana (after Palmer, 1969)

should always develop. An example of a dendritic channel network is shown in Fig. 2. Twenty-three small tributaries converge in this well-mapped cave to form a flow path which discharges to the surface at a spring. The channels shown in Fig. 2 are all accessible to people, and are all >0.3m in diameter.

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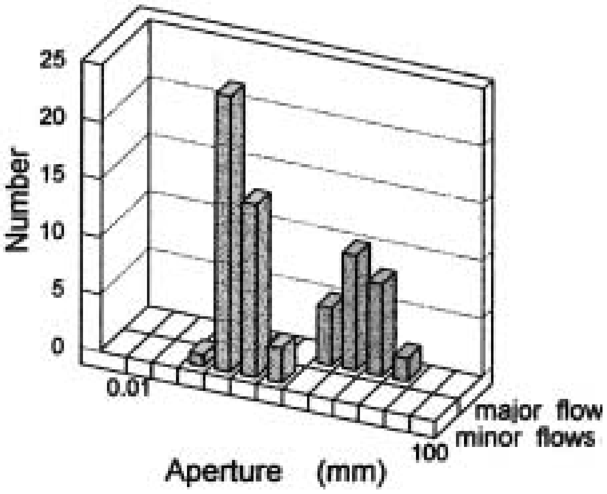

Fig. 3. Calculated apertures of minor flows into four New Zealand caves and major flows into GB Cave, England (calculated from measurements by Gunn (1978) and Friederich and Smart (1982)

There are also smaller channels than cave passages. These channels are sometimes encountered in boreholes (Waters and Banks, 1997), but are better visible in quarry walls, outcrops and in cave passages. Fig. 3 shows the calculated apertures of two sets of small channels. The "minor flows" are from measurements at 44 drip points from stalactites into four New Zealand caves (Gunn, 1978), and the "major flows" are from the 25 largest flows into GB Cave, England (Friederich and Smart, 1982). Apertures were calculated using the Hagen-Poiseuille equation and the maximum recorded discharge at each flow point, assuming a hydraulic gradient of unity and a circular channel shape. The calculated apertures are only estimates, as channel roughness and surface tension effects are ignored, and the measured flow may be much less than the channels are capable of delivering. However, the calculated values are likely to be fairly accurate since discharge varies with the fourth power of pipe diameter. Natural gradient tracer tests were carried out from the surface to the input points in GB Cave, which were on average 60 m below the surface. Tracer arrival times varied from less than one day to several weeks, giving velocities mostly in the range 10-100 m/day (Friederich and Smart, 1981). These velocities are between the 1700 m/day average velocity for sink to spring tracer tests (Worthington et al., 1999a) and calculated velocities of a meter per day or less results derived from equivalent porous medium analysis.

Dolines are input points to channels. The channel at the base of a doline is an efficient drain point which promotes centripetal drainage and facilitates the enlargement of the doline. The channels draining dolines are likely to be at least some millimeters in diameter, and are often found to be much larger. Such channels not only must be able to carry the discharge from the depression, but also the suspended load of insoluble material resulting from the erosion of the bedrock within the doline. Furthermore, the channels must be part of a continuous channel network with its outlet at a spring; if this were not the case then the doline-draining channels would becomes choked with insoluble material, and doline formation would be halted at an early stage.

3. Sampling and monitoring the three porosity components

(i) Channels: Springs in carbonate strata represent the output points for channel networks, and provide a sampling point that integrates the groundwater flow from what is often a considerable area e.g. 10-1000 km^2. They are thus ideal for sampling off-site migration from contaminant sites. Tracer testing from dolines or sinking streams to springs is common, and serves to establish flow direction and velocity. If both spring discharge and the hydraulic gradients in the aquifer are known, then an "equivalent hydraulic conductivity" for the aquifer can be calculated (Worthington and Ford, 1999a). This is an average value across the cross-section of the catchment draining to a spring, and ignores turbulent flow, which may be important. The use of an equivalent hydraulic conductivity facilitates comparisons of channel flow with matrix and fracture flow.

Boreholes are of limited use in studying channeling. Table 2 gives data on channeling in a number of well-studied carbonate aquifers where extensive caves have been found. From this data set a borehole would have a probability of only 0.0037 - 0.075 of intercepting one of these mapped cave passages. In volumetric terms the caves only occupy between 0.004% and 0.48% of the bedrock in which they are located. Thus it would be fallacious to assume that an absence of major bit drops in drilling a number of wells at a study site signified an absence of channeling.

(ii) Fractures: The permeability of horizontal or sub-horizontal fractures (usually bedding planes) is routinely determined from hydraulic testing (e.g. packer, slug or pump tests) in vertical boreholes. Fracture aperture can be determined by the cubic law from narrow-interval packer testing. The permeability of vertical or sub-vertical fractures is usually estimated rather than measured. For instance, in horizontally-bedded strata it is often assumed that vertical permeability is ten or 100 times less than horizontal permeability.

(iii) The matrix: The matrix is the solid, unfractured rock. Samples may be collected from boreholes, quarry walls or natural outcrops for testing porosity and permeability. Alternatively, *in situ* packer testing in unfractured sections of boreholes will give values of matrix permeability (Price et al., 1982).

TABLE 2

Cave porosity and areal coverage for some well-mapped caves

Cave	Volume of rock length x width x height m (1)	Volume of cave x 10^6 m^3 (2)	Length of cave km (2)	Cave porosity % (3)	Areal coverage of cave % (4)
Ogof Agen Allwedd - Ogof Daren Cilau, Wales	6200 x 1900 x 50	0.9	75	0.15	1.7
Blue Spring Cave, Indiana	5100 x 2600 x 45	0.5	32	0.08	1.1
Kingsdale Cave System, England	2600 x 1500 x 100	0.17	20	0.04	1.8
Nohoch Nah Chich, Mexico	5500 x 1900 x 80	4	39	0.48	6.5
Mammoth Cave, KY, USA	11000 x 9000 x 90	8	550	0.09	1.4
Castleguard Cave, Canada	6500 x 1200 x 400	0.12	20	0.004	0.51
Friars Hole System, WV, USA	6000 x 2000 x 80	2.7	70	0.28	2.5
McFail’s Cave, New York	3500 x 2300 x 90	0.12	11	0.016	0.37
Skull Cave, New York	1300 x 940 x 60	0.046	6	0.064	1.2
Caves in Southern Gunung Api, Malaysia	7000 x 2500 x 400	30	110	0.43	7.5

(1) This represents the minimum rectangular block of rock that can contain the 3-D array of mapped passages in each cave.

(2) These refer to the explored and mapped cave passages. Increases in these values are likely as the caves are more completely explored.

(3) Cave porosity is defined as the volume of mapped cave divided by the minimum rectangular block of rock that can contain the cave.

(4) The areal coverage is the plan area of the cave divided by the minimum rectangular area which can contain the cave, and this represents the probability of a borehole intersecting the cave.

3.1. The extent of channel networks

Dolines represent the upgradient ends of channels, and it is possible to gain a better understanding of channel distribution by using doline distribution to construct a model of the channel network. For instance, Fig. 4a shows the north-east portion of Blue Spring Cave, Indiana (Fig. 2), with the doline watersheds shown. A simple map of channeling could be constructed by linking the low points in each of the 38 dolines with either the eight major inputs into this section of the cave or into other major channels (Fig. 4b). Such a procedure obviously simplifies the geometry of the major channels and ignores smaller channels (e.g. channels feeding drip points at stalactites), but it does represent an important fraction of flow in the aquifer.

The above procedure is a starting point to modeling channeling in a polygonal terrain such as at Blue Spring Cave, where the whole surface is occupied by contiguous dolines. However, many surfaces above carbonate aquifers have dolines that are widely spaced. These can be linked in the same fashion as at Blue Spring Cave to give a channel network draining to a spring, but this network will be a great simplification of the true channel network. Furthermore, some carbonate aquifers have no dolines overlying them, such as where the aquifer is overlain by non-carbonates or by glacial sediments. Prominent examples are the most extensive cave in Canada (Castleguard Cave) and the most extensive cave in the USA (Mammoth Cave); the majority of both caves underlie surfaces where dolines are absent, so the channel network in these aquifers cannot be inferred from the surface landforms. However, in both cases channel networks have been demonstrated from tracer testing (Smart, 1988; Quinlan and Ray, 1981) as well as from cave exploration.

Where there are no dolines or sinking streams above a carbonate aquifer then it is most difficult to estimate the extent of channeling. If there are no faults or high-permeability facies at a spring to explain the concentration of aquifer discharge at one point then the best explanation is that the spring is the outlet for a channel network, and this is likely to extend throughout the spring's catchment. Some carbonate aquifers discharge into thick alluvium, lakes, or the sea, so that location of springs may be extremely difficult, and the characterization of channeling will be extremely difficult.

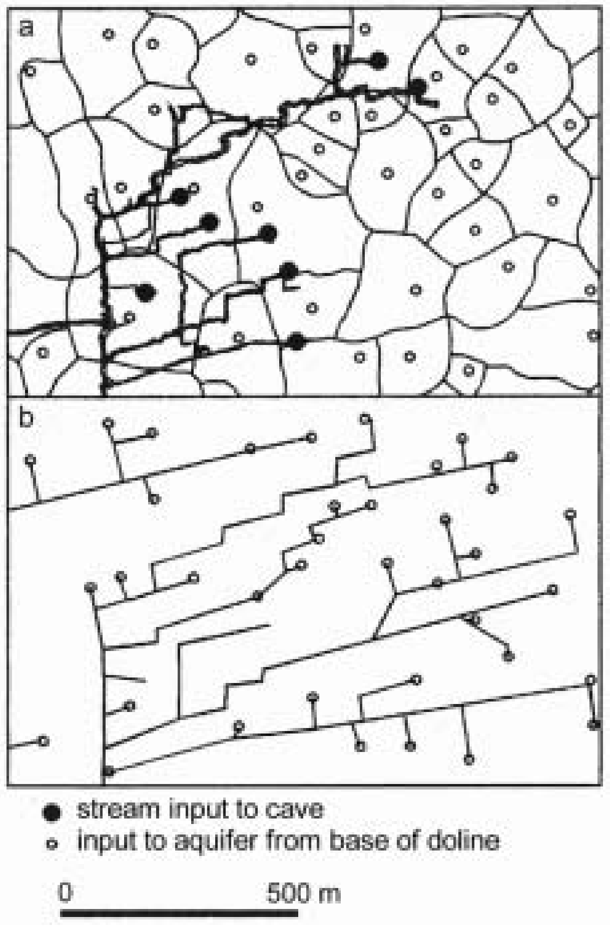

Fig. 4. Channeling in the north-east section of Blue Spring Cave, Indiana , showing (top) doline watersheds and underlying cave passages (after Palmer, 1969) (bottom) a dendritic network of the major channels

3.2. Sampling boreholes for channeling

Boreholes are not ideal for investigating channeling because of the low probability of intercepting channels, as explained above. However, there are some aquifer testing and monitoring techniques that can give an indication that there may be channels close to the borehole. The following list of the techniques for inferring channeling is based on the discussion in Worthington and Ford (1995):

a) Well-to-well or well-to-spring tracer tests. Tracer tests from sinking streams or dolines to springs were established in the 1870s as an excellent method of determining channel velocities and connections. Well tests are much more problematic as wells may be poorly connected to channels. It is likely that longer distance traces (e.g. > 100 m) are more likely to show evidence of channeling than shorter distance traces, as the widely-spaced channels are more likely to be encountered along a longer tracer path.

b) Combination of core, packer, slug and pump tests. Kiraly (1975) first suggested there is a scaling effect in carbonate aquifers, with larger scale tests encountering more permeable fractures and channels.

c) Variable rate pumping tests. Hickey (1984) showed that the pumping rate should be proportional to the drawdown in observation wells if Darcy's Law is valid within the cone of depression. If there are major channels within the cone of depression, and if these are well-connected to the pumping well then there should be a non-linear pumping rate/ drawdown response.

d) Matrix and fracture packer test to calculate fracture extent. Price (1994) described a method for estimating the extent of interconnected fractures intersected by wells by using steady-state packer testing.

e) Symmetry of cones of depression at pumping wells. The cone of depression at a pumping well is symmetrical in a homogeneous porous medium. However, the cone of depression is likely to be irregular if there is extensive channeling nearby.

f) Continuous water level monitoring. Interconnected channel networks transmit water quickly, so a prompt water level response following rainfall can be expected in boreholes which are well-connected to the channel network.

g) Frequent water quality monitoring. Precipitation which rapidly infiltrates along channel networks commonly has a much lower solute concentration than long-residence matrix water. Thus variation in solute concentration at a well should be an indicator of connectivity to major channel networks. Frequent sampling (e.g. at least daily) is necessary to detect the rapid response following rainfall. Continuous measurement of electrical conductivity is ideal.

h) Troughs in the water table. The combination of high permeability in channels and tributary flow to channels means that there are lower heads in channels than in the surrounding aquifer. Quinlan and Ray (1981) showed that such water table troughs correspond with flow in channels and that they terminate in a downstream direction at springs.

i) Decreasing hydraulic gradients in the downflow direction. The water table map of the Central Kentucky karst, which is based on measurements in 1500 wells, the results from 500 dye traces, and the mapping of 700 km of cave passage (Quinlan and Ray, 1981) shows that there are decreasing hydraulic gradients in the downflow direction along water table troughs. This contrasts with flow in a porous medium, where increasing gradient are needed in a downflow direction to drive the increasing discharge.

j) Use of environmental isotopes to characterize age distribution of water in the aquifer. In a porous medium there will be increasing age with depth in recharge areas. Where channels provide rapid recharge to the subsurface then younger water in channels will underlie older water in overlying fractures and the matrix.

The problem with all of these tests is that they cannot unequivocally demonstrate the presence of channeling. For instance, major fractures opened by tectonic forces could give many of the above results. However, the evidence from caves, from tracer testing, and from the kinetics of dissolution suggest that channeling is ubiquitous in unconfined carbonate aquifers. Thus the first assumption in a carbonate aquifer should be that a well-developed channel network is likely to be present.

4. Examples of triple porosity analysis of carbonate aquifers

Worthington et al. (2000) examined matrix, fracture and channel flow in four carbonate aquifers. The four aquifers are:

a) a Silurian dolostone aquifer in a glaciated area, where there have been a large number of studies at a PCB spill site (Smithville, Ontario).

b) the Mississippian aquifer at the world's most extensive known cave (Mammoth Cave, Kentucky).

c) the most important aquifer in Britain (the Cretaceous Chalk).

d) a tropical Cenozoic limestone aquifer (Nohoch Nah Chich, Yucatan, Mexico). In recent years scuba divers have mapped more than 60 km of submerged channels in this cave.

Porosity and permeability results from these four aquifers are given in Tables 3 and 4, respectively. In all four cases more than 90% of the aquifer storage is in the matrix and more than 90% of the flow is in channels (Table 5), with fractures playing an intermediate role. Thus there are considerable similarities between the four aquifers. However, only the aquifer at Mammoth Cave has been traditionally treated as a karst aquifer; a majority of studies of the other three aquifers have treated them as double porosity aquifers or equivalent porous media.

TABLE 3

Matrix, fracture and channel porosity in four carbonate aquifers

Area	Porosity (%)		
	Matrix	Fracture	Channel
Smithville, Ontario	6.6	0.02	0.003
Mammoth Cave, Kentucky	2.4	0.03	0.06
Chalk, England	30	0.01	0.02
Nohoch Nah Chich, Mexico	17	0.1	0.5

TABLE 4

Matrix, fracture and channel permeability in four carbonate aquifers

Area	Hydraulic conductivity (m s^{-1})		
	Matrix	**Fracture**	**Channel**
Smithville, Ontario	1×10^{-10}	1×10^{-5}	3×10^{-4}
Mammoth Cave, Kentucky	2×10^{-11}	1×10^{-5}	3×10^{-3}
Chalk, England	1×10^{-8}	4×10^{-6}	6×10^{-5}
Nohoch Nah Chich, Yucatan, Mexico	7×10^{-5}	1×10^{-3}	4×10^{-1}

TABLE 5

Principal flow and storage components in four carbonate aquifers

Area	Fraction of storage in the matrix, %	Fraction of flow in channels, %
Smithville, Ontario	99.7	97
Mammoth Cave, Kentucky	96.4	99.7
Chalk, England	99.9	94
Nohoch Nah Chich, Yucatan, Mexico	96.6	99.7

5. Discussion and conclusions

It has often been considered that there is a range in carbonate aquifers between "karstic" and non-karstic" end members. For instance, Atkinson & Smart (1981) classify the English Chalk as being close to the “non-karstic fissured aquifer” end of the spectrum, while the Carboniferous Limestone in England (in which most of the well-known caves are found) is classified as being closer to the “karstic” end of the spectrum. Worthington et al. (2000) compared inflow data to adits in the two aquifers. Both had irregularly spaced inputs, and in both cases there were water-yielding fissures with discharges up to several hundred liters per second. Most of the permeability in both adits is attributable to widely spaced inputs. Consequently, dissolution in both aquifers has resulted in channel networks which contribute minimally to enhancing aquifer porosity, but have greatly enhanced aquifer permeability. Therefore these aquifers have marked similarities in terms of hydraulic functioning.

One reason why these two limestone aquifers have been viewed differently is the presence of surficial karst features and of known caves in the Carboniferous Limestone, and their scarcity in the Chalk. The presence or absence of the surficial features has led to assumptions about aquifer behaviour. A second reason is the lack of comprehensive sampling and monitoring in either aquifer in most studies. Few wells have been drilled in the Carboniferous Limestone, and most aquifer studies have used springs. Conversely, most aquifer studies in the Chalk have used wells, and the many springs that exist have been ignored in most hydrogeological studies. Consequently, there is widespread knowledge of channel flow in the Carboniferous Limestone, and of fracture and matrix flow in the Chalk.

The similarity between the matrix, fracture and channel flow and storage proportions in the four contrasting carbonate aquifers documented in Tables 3, 4 and 5 suggests there is likely to be a similarity between all unconfined carbonate aquifers. This can be explained by fracturing and then dissolution resulting in low-porosity, high-permeability channel networks. Differences cited in the literature are often largely attributable to sampling differences. This problem can be diminished by considering carbonate aquifers as triple porosity aquifers. Data collection and analysis of the three components of matrix, fracture and channel flow can give an overall understanding of how a carbonate aquifer functions.

Acknowledgments

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