Identification of a hydrodynamic threshold in karst rocks from the Biscayne Aquifer, south Florida, USA

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Abstract

A hydrodynamic threshold between Darcian and non-Darcian flow conditions was found to occur in cubes of Key Largo Limestone from Florida, USA (one cube measuring 0.2 m on each side, the other 0.3 m) at an effective porosity of 33% and a hydraulic conductivity of 10 m/day. Below these values, flow was laminar and could be described as Darcian. Above these values, hydraulic conductivity increased greatly and flow was non-laminar. Reynolds numbers (Re) for these experiments ranged from <0.1 to 7. Non-laminar flow conditions observed in the hydraulic conductivity tests were observed at Re close to 1. Hydraulic conductivity was measured on all three axes in a permeameter designed specifically for samples of these sizes. Positive identification of vertical and horizontal axes as well as 100 percent recovery for each sample was achieved. Total porosity was determined by a drying and weighing method, while effective porosity was determined by a submersion method. Bulk density, total porosity and effective porosity of the Key Largo Limestone cubes averaged 1.5 g/cm^3, 40% and 30%, respectively. Two regions of anisotropy were observed, one close to the ground surface, where vertical flow dominated, and the other associated with a dense-laminar layer, below which horizontal flow dominated.

Key Words: Karst, hydraulic properties, porosity, Reynolds number, USA

Introduction

Due to their heterogeneity, karst aquifers can vary greatly in their hydrologic properties as a function of scale (Kiraly 1975 [as cited in Ford and Williams 1989] Rovey 1994, Rovey and Cherkauer 1995, Whitaker and Smart 2000), rock type (Pulido-Bosch et al. 2004, Motyka et al. 1998) and type of porosity (Zuber and Motyka, 1994). For instance, hydraulic conductivity of one aquifer has been determined to increase by as much as six orders of magnitude with increases in the volume of rock tested (Ewers 2006, White 2006). Small-scale tests are usually performed on rock cores with diameters less than 0.1 m, resulting in average hydraulic conductivity values of less than 1 m/day. Hydraulic conductivity testing of karst aquifers in wells or boreholes with typical lengths of 1 to 10s of meters produces hydraulic conductivity values in the range of 1 to 100 m/day (Rovey 1994, Schulze-Makuch and Cherkauer 1998). Higher hydraulic conductivity values of greater than 100 m/day are often determined in karst aquifers from pumping tests conducted at the 100 to 1000s meter scale. These higher values are most likely obtained from rock that contain fractures which provide high connectivity to the system but are often missed by testing at smaller size intervals (Rovey 1994). The scaling effect in hydraulic conductivity has been observed on rocks collected at a variety of sites under diverse fluid flow regimes (Schad and Teutsch 1994) and proven to be dependent on the scale, and independent of the method of testing (Schulze-Makuch and Cherkauer 1998).

The anisotropy and heterogeneous nature of karst aquifers is due to three types of water flow; 1) matrix flow; 2) fracture flow; and 3) conduit flow (Motyka 1998, Worthington et al. 2000). Matrix flow moves through intergranular (primary) pores, macrofissures and microcaverns (Motyka 1998) and is often characterized by Darcian flow. Fracture flow occurs in apertures of 50 to 500 μm, but may be enlarged by dissolution up to 1 cm (White 2002).

Conduit flow occurs in enlarged fractures or solution openings with a minimum size of 1 cm, and is often turbulent, with non-Darcian behavior occurring when the conduit aperture exceeds 1 cm (White 2002). Additional types of porosity described in karst include touching-vug porosity, which is common in young eugenic karst such as the Pleistocene limestone of the Biscayne Aquifer, south Florida, USA (Cunningham et al. 2006), and the filling of voids by secondary material as is common in fully karstified carbonate aquifers (Motyka 1998).

An open question in karst hydrology is an understanding of the hydraulic properties of conduit porosity in the size range of 0.01 to 0.5 m (White 2002), which represents the scale between the typical rock core size and the well or borehole test. Conduits in this size range are suspected to result in flow that is in the transition between laminar and turbulent conditions under typical hydraulic gradients between 0.1 and 0.001 (White 1988). Under laminar flow conditions Darcy's law is considered valid. Under fully turbulent conditions, Darcy's law is no longer valid and the applicability of a hydraulic conductivity value is in question. Jeannin (2001) recommends that the Louis model be used to adequately estimate head losses in karst conduits with effective hydraulic conductivities between 1 and 10 m/s. White (2006) suggests that the Darcy-Weisbach equation is more applicable in describing conduit flow, as it can be applied to flow regimes ranging from laminar to turbulent.

At which point flow becomes non-laminar and turbulent is often determined by the Reynolds number. White (2002) proposes that the onset of turbulent flow occurs as Reynolds numbers approach 500. However, a lower Reynolds number of 5 is often cited as the upper limit for Darcian flow conditions (Fetter 2001).

The limestone used in this investigation, Key Largo Limestone, is a coralline limestone of Pleistocene age (Hoffmeister and Multer 1968). The Key Largo Limestone is a member of the

Biscayne Aquifer, a highly transmissive, karst aquifer. The occurrence of the Key Largo Limestone is limited to a thin strip along the eastern edge of Miami along the Florida Keys (Randazzo and Halley 1997). The Key Largo Limestone is exposed at the ground surface in the upper keys, from Soldier Key to Bahia Honda (Fig. 1). In the lower Keys, including Big Pine Key and Key West, the Ley Largo Limestone is overlain by the oolitic facies of the Miami Limestone. The thickness of the Key Largo Limestone varies, but is at least 60 m (Randazzo and Halley 1997). It is not used extensively for water supply purposes, because the fresh water lens under the Florida Keys is ephemeral and not adequate to support its population (Parker et al. 1955). However, concern for the transport of wastewater from numerous septic tanks and deep well injection sites in the Florida Keys to the surrounding surface waters has led to several hydraulic investigations (Shinn et al. 1994, Dillon et al. 1999, Paul et al. 2000, Dillon et al. 2003). The objective of this research was to investigate the hydraulic properties of karst in a previously untested size range. In this investigation, porosity, hydraulic conductivity and anisotropy was determined on Key Largo Limestone cubes with the dimensions of 0.2 m or 0.3 m on each side. The applicability of Darcy's Law on limestone cubes in this size range was also tested.

Materials and Methods

Limestone Cubes

A single large block of Key Largo Limestone, measuring approximately 1.5 m by 1.5 m at the land surface and approximately 3 m deep, was extracted from Key Largo, Florida (Fig. 1). The extracted block was cut to produce seven cubes 0.2 m on each side and six cubes 0.3 m on each side. Cubes were labeled before being removed from the cutting carts to preserve vertical and horizontal axis orientation as well as the position of each cube in relation to the land surface (Fig. 2). Seven cubes of 0.2 m on each side were cut from one column of the large block, and labeled 1 through 7, with 1 being the block closest to the ground surface. The column used to produce the 0.3 m cubes was long enough to produce only five cubes. A sixth 0.3 m cube was cut from the bottom of the adjacent column, and was from the same depth as cube 5. Vertical axes in each cube were labeled as v, while the horizontal axes were labeled as h1 and h2.

Porosity

Prior to the determination of porosity, the limestone cubes were dried at 110º C for 5 days for the 0.2 m cubes and for 7 days for the 0.3 m cubes. Bulk density (P_b) was calculated by dividing the weight of each dry cube, in grams, by its volume, in cm^3. Total porosity (n) was calculated using the equation:

$$n=1-[P_b/P_s]; \qquad (1)$$

where, P_s referred to the density of calcite (2.71 g/cm^3). The total porosity calculated by equation 1 is an estimate since it assumes that the limestone in the Biscayne Aquifer is composed entirely of calcite.

Effective porosity was calculated in a chamber made of 0.635 cm thick Plexiglass. The chamber had a square base of 0.35 m on each side and a height of 0.60 m (Fig. 3). These measurements allowed the largest limestone cube, 0.3 m on each side, to fit within the chamber without overflow. A drain valve was installed 0.34 m above the base of the chamber. This height guaranteed that all cubes would be completely submersed during testing. A cover sealed with 0.635 cm thick auto gasket material allowed a vacuum to be drawn on the chamber. Vacuum pressure within the chamber was regulated in a 0.635 cm thick Plexiglas cylinder partially filled with water (Fig. 3). A hollow rod within the chamber extended 0.06 m below the surface of the water and was open to the atmosphere. Two hoses were connected to the top of the chamber, above the water; one went to a vacuum line and the other went to the chamber containing the limestone cube. Vacuum pressure was regulated to insure a constant flow of bubbles into the chamber, thus ensuring vacuum pressure did not exceeded 0.06 m of water. The change in pressure (Δp) caused by the 0.06 m of vacuum was determined to be 600 kg/ms from the equation:

$$\Delta p = \Delta h \rho g; \qquad (2)$$

Where, Δh was the change in head, ρ was the density of water (1000 kg/m^3), and g was the acceleration due to gravity (9.8 m/s^2). This value was used in the Laplace equation:

$$r = 2\gamma/\Delta p; \qquad (3)$$

where, r referred to the radius of the pore to be evacuated, and γ referred to the surface tension of water ($7.24\text{x}10^{-2}$ Joules/m^2). In this case r was determined to be 0.02 cm. Multiplying the radius by 2 gave a diameter of 0.04 cm for the maximum size of a pore that was evacuated by vacuum. Pores up to and including this diameter should have been flooded.

Testing began by setting the water level to the height of the drain. The drain was then closed and the limestone cube immersed. The cover was sealed in place and the chamber was vacuumed for 4 hours. When the vacuuming time was completed the vacuum was released and the drain valve was opened while the limestone cube remained submerged. Water exiting the drain was measured until the water level again equaled the height of the drain. The volume collected represented the volume displaced by the limestone cube and the lifting strap. The volume displaced by the lifting strap was subtracted from the total volume displaced, leaving only the volume displaced by the limestone cube. Effective porosity (n_e) was calculated using the formula:

$$n_e=[v_e-v_d]/v_e; \quad (4)$$

where v_e referred to the volume expected to be displaced and v_d referred to the actual volume displaced. The 0.2 m cubes were expected to displace 0.008 m^3, and the 0.3 m cubes were expected to displace 0.027 m^3 of water if the cubes were solid with zero porosity. The water temperature used in these experiments was 23.5°C. This gives the water a density of 997.5 kg/m^3, a slightly different value from 1000 kg/m^3used in the equation 2. The error introduced by using this value is less than 1 percent.

Hydraulic Conductivity

Hydraulic conductivity was determined using a Plexiglas permeameter assembled around the three mutually perpendicular axes of each cube (Fig. 4). Plastic was wrapped around 4 faces of each cube in preparation for testing, thus leaving one axis of the cube available for water flow. The faces of the cube wrapped in plastic were then wrapped in a sheet of 0.635 cm closed cell neoprene rubber. This rubber sheet was covered with 0.635 cm aluminum plates. Pressure was applied to the aluminum plates using nylon straps tightened with a ratcheting mechanism. This assembly prevented preferential flow around the cube instead of through the cube. Integrity of the assembly was checked after testing by confirming the imprint of the cube in the rubber sheet, confirming that the rubber sheet was dry, and inspecting the plastic wrap for holes. Input and output panels of the box were aligned with the face of the cube and tightened into position with threaded rods. Seams were filled with 100% silicone and allowed to dry for 12 hours. When the silicone had cured, the permeameter was flooded with water and vacuumed until the cube was saturated. The apparatus was allowed to stand flooded for 12 hours and vacuumed again to assure saturation of the cube. A static head difference between the input and output level of approximately 0.2 m for 0.2 m cubes and 0.3 m for 0.3 m cubes was established and water was allowed to flow through the cube for 1 hour or until equilibrium was established.

Sampling was conducted by collecting volumes of water discharged at timed intervals from various static heads at the outflow side of the permeameter. Seven trials were conducted at each static head difference and then averaged to give a discharge value for each head level. Head differences ranging from 0.025 m to 0.2 m, in increments of 0.025 m, were used for the 0.2 m cubes. Head differences ranging from 0.05 m to 0.3 m, in increments of 0.05 m, were used for the 0.3 m cubes.

Data were plotted as discharge (Q) in m^3/day versus the product of A(dh/dl) in m^2, where *A* referred to area of the face of the cube perpendicular to flow, dh referred to the difference in head between the outflow side and inflow side of the permeameter, dl referred to the length of the cube. A linear regression line passing through the origin was fit through the data points and its 95% confidence interval was calculated using Sigma Plot. The slope of the linear regression line was considered as the hydraulic conductivity of the axis being tested.

Tests using high hydraulic heads were run on the vertical axis of 0.2 m cube #7 to test for non-Darcian flow conditions. Static head levels ranging from 0.025 m to 0.2 m were first used in these tests. Tests were then conducted using a 0.4 m static head, twice the length of the cube, and a 0.6 m static heads three times the length of the cube. Hydraulic conductivity values obtained from the two sets of tests were compared for differences. The difference was found to be less than 1 percent. This test was conducted on only one cube because of the excessive strain the high head level exerted on the test equipment.

To test for non-laminar or turbulent flow conditions, Reynolds numbers (*Re*) were calculated using the equation:

$$Re=\rho vd/\mu; \qquad (5)$$

where, ρ referred to fluid density (997.5 kg/m^3), v referred to specific discharge (m/s) as determined by dividing the discharge measured from the apparatus (m^3/s) by the length of the cube (either 0.2 m or 0.3 m), d referred to pore diameter in m, and μ referred to absolute (or dynamic) viscosity of water (9.25 x 10^{-4} Pa≅s at 23.5 ^{o}C). Reynolds numbers were calculated for a pore diameter of 0.01 m. This value was chosen since it was suggested by White (2002) as the critical diameter above which non-Darcian flow conditions occurred in karst, and because pore sizes of this diameter were commonly observed on the sides of the cubes (Fig. 2).

Results

Porosity

Bulk density values of the cubes ranged from 1.2 g/cm^3 to 1.9 g/cm^3 with a mean of 1.5 g/cm^3 (Table 1). Total porosity values for the cubes ranged from 0.30 to 0.54 with a mean of 0.45 (Table 1). Effective porosity values were lower than the total porosity values and ranged from 0.16 to 0.38 with a mean of 0.3 (Table 1).

Hydraulic Conductivity

The hydraulic conductivities obtained on each axis for the 0.2 m cubes ranged from 0.48 m/day to 38 m/day (Table 2). The geometric mean of the hydraulic conductivity of the 0.2 m cubes was 4.5 m/day. For the 0.3 m cubes, hydraulic conductivity values ranged from 0.23 m/day to 67 m/day with a geometric mean of 2.2 m/day (Table 3). Data points from two-thirds of the tests fell within the 95% confidence interval about the linear regression line (Fig. 5a-c). Approximately one third of the plots showed a slight curvature of the data points relative to the best-fit straight line, with some of the data points falling outside of the 95% confidence intervals (Fig. 6a-c). These results suggest a deviation from Darcian flow conditions during these tests, and the hydraulic conductivity values obtained from the best-fit linear regression of the data for these tests most likely underestimates the true hydraulic conductivity.

The highest Reynolds numbers obtained for each of the permeameter tests on the 0.2 m cubes ranged from 0.06 to 4.47 (Table 2). For the 0.3 m cubes, Reynolds numbers varied from 0.03 to 7.43 (Table 3). Plots with observed non-linearity of the data points relative to the linear regression lines had Reynolds numbers ranging from 0.77 to 7.43, with most having Reynolds numbers close to 1 or higher.

There was no detectable change in the slope of the best-fit lines for the cube tested with and without the high head conditions (Fig. 7a-b). The resulting hydraulic conductivity value for both situations was 10 m/day. The best-fit lines had R^2 values of 0.99 and 1.0 for the data without and with the high heads, respectively. In addition, all of the data points for these tests fell within the 95 % confidence intervals around the best-fit line. The highest Reynolds number for this test was 3.83 when determined for a pore diameter of 0.01 m.

There was a significant increase in the geometric mean of the hydraulic conductivity (K_G) of cubes with effective porosities greater than 33% (Fig. 8). Cubes with average effective porosity values less than 33% had geometric mean values for hydraulic conductivity of less than 6 m/day (Fig. 8). Above 33% effective porosity, small increases in effective porosity caused large increases in hydraulic conductivity with values ranging from 6.7 m day to over 30 m/day.

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Anisotropy

Plotting hydraulic conductivity ellipses facilitated a comparison between axes. Axes of each ellipse were the square root of the hydraulic conductivity (m/day) of the vertical axis and the average of the horizontal axes (Fig. 9-10). Circles would be formed if the values of the vertical and horizontal axes were equal. If an ellipse is formed there is anisotropy between the axes. The more elliptical the shape, the more anisotropy exists (Freeze and Cherry 1979). The larger axis of the ellipse shows the axis of preferred flow. In the 0.2 m cubes, blocks 1, 3, and 5 show anisotropy in which vertical hydraulic conductivity is favored over horizontal conductivity (Fig. 9). Cubes 2 and 6 show virtually no anisotropy. Cubes 4 and 7 show anisotropy with horizontal hydraulic conductivity being favored over vertical hydraulic conductivity (Fig. 9).

In the 0.3 m cubes, blocks 1 and 2 demonstrated anisotropy with the vertical axis preferred (Fig. 10). Cubes 3 and 4 show little anisotropy. Cubes 5 and 6 show large anisotropy with the horizontal axis being favored over the vertical. In general hydraulic conductivity increased with depth in the 0.3 m cubes (Table 3) corresponding with an increase in total and effective porosity (Table 1).

Discussion

Porosity

The total porosity values of 30 to 54% obtained in this investigation for the Key Largo Limestone are within the range of values reported by others from rock cores, well logs and used in modeling studies. Porosity obtained on rock core of Key Largo Limestone ranged from 20% to above 45% when determined by water displacement (Shinn et al. 1994). Using well logs of south Florida Pliestocene limestones, Schmoker and Halley (1982) reported porosities of 40 to 55%. A porosity value of 50% was used in two recent modeling studies of groundwater flow through Key Largo Limestone (Dillon et al. 1999, 2003).

Effective porosity is more commonly used in groundwater modeling as opposed to total porosity since it more accurately estimates the porosity available for fluid flow. The effective porosity values obtained in this investigation (16 to 38%) are expectedly lower than the total porosity values (30 to 54%), but slightly higher than effective porosity values obtained from rock cores of the Key Largo Limestone (Shinn et al. 1994). Time must be considered when determining the difference between total and effective porosity. Over a short time period less of the total porosity will be utilized as effective porosity than over a long time period. This is because time is required for flow to penetrate deeper into the matrix material and contact pore space that is not readily accessible to flow. Lacking sufficient time these pore spaces within the matrix are not accessed and therefore do not contribute to effective porosity. In the present study, effective porosity was estimated on the cubes after flooding and vacuuming for 4 hours. The effective porosity value determined would therefore correspond to an event lasting hours and possible days, but caution should be used when applying the effective porosity values to events lasting longer.

The results of this research demonstrate an interesting relationship between effective porosity and the geometric mean of the hydraulic conductivity (K_G), with K_G increasing from 6.7 m/day (a value close to 7) to over 30 m/day, almost a 3 fold increase, at effective porosity values of 33% and greater (Figure 9). The 33% effective porosity value may represent a minimum level of connectivity between vugs that allows for rapid fluid flow. Both the effective porosity value of 33 % and the K_G value of 7 m/day may represent a critical hydrodynamic threshold for macroscopic flow as described in percolation theory (Moreno and Tsang 1994, Shah and Yortsos 1996). Increasing the porosity through dissolution of the limestone matrix allows the vugs to be interconnected, so that a critical macroscopic threshold is exceeded allowing for enhanced fluid flow. Using geographical information system (GIS) analysis of porosity from borehole images of the Biscayne Aquifer, Manda and Gross (2006) identified limestone with porosities between 25 and 50% to be riddled with large macropores. These large marcopores are characteristic of the "touching-vug' porosity identified by Cunningham et al. (2006) as solution-enlarged molds of fossils, burrows or roots, and are easily observed in the rock slab depicted in Figure 2.

Darcian versus non-Darcian Flow

The results of this research suggest that Darcian flow conditions prevailed in most of the permeameter tests (Tables 2-3; Fig. 5). Reynolds numbers for the tests showing a linear relationship between discharge and the hydraulic gradient were typically less than 1, also indicative of laminar flow conditions. One third of the tests showed a slight curvature of the data points relative to linear regression line (Tables 2-3; Fig. 6), suggesting that non-Darcian flow conditions occurred in these tests. The non-linear conditions tended to occur with K values of 7 m/day or greater and with Reynolds numbers close to or greater than 1 (Tables 2-3). These results combined with the relationship observed between effective porosity and the geometric mean of the hydraulic conductivities (K_G) of each stone (Fig. 8) imply that a K value near 7 m/day (7 x 10^{-5} m/s) may represent a limit between Darcian and non-Darcian flow conditions in the Key Largo Limestone.

The observed linear relationship between discharge and hydraulic head under the conditions of the high hydraulic head test are anomalous to the other test results in two respects. First, the resultant K value of 10 m/day was greater than the critical value of 7 m/day observed in the other tests. Secondly, the resultant Reynolds number was greater than 1 suggesting that non-Darcian conditions should have been observed. The results of the high head test can be explained in context with the other tests by several means. First, the Reynolds number was calculated using a pore diameter of 0.01 m. There may be a lack of interconnected pores in 0.01m size in the vertical flow direction of this cube (0.2 m cube #7). A smaller pore diameter of 0.005 m for this test would have produced Reynolds numbers less than 1. This explanation is supported by the anisotropy analysis for this cube that showed a preference for higher K in the horizontal direction (Fig. 9). Secondly, the K values for all of tests were calculated assuming a linear relationship between discharge and hydraulic gradient. For those tests in which non-Darcian flow conditions were observed, the resultant K values would be an under-estimation of the true hydraulic conductivity. Non-linear conditions were observed for K values as low as 7 m/day, but K values greater than 10 m/day maybe more representative of the actual conditions. For this reason, a K value slightly greater than 10 m/day may be more representative of the hydrodynamic threshold for macroscopic flow in karst, or at least for the Key Largo Limestone.

The range in K values (0.23 m/day to 67 m/day) obtained for the 0.2 and 0.3 m cubes is significantly smaller than values of 1000 to 38,400 m/d reported for the Key Largo Limestone by others (Wightman 1990, Vacher et al. 1992, Halley et al. 1997, Langevin et al. 1998, Dillon et al. 1999). These other studies estimated K for the Key Largo Limestone based upon field tracer tests at a scale of 3 to 10 m (Dillon et al. 1999), and on modeling studies of Big Pine Key at a scale of 2 to 10 km (Wightman 1990, Vacher et al. 1992, Langevin et al. 1998). As has been demonstrated by many studies, hydraulic conductivity typically increases with scale of measurement, therefore, the K values obtained for the 0.2 and 0.3 m cubes are expected to be lower than K values obtained at larger scales.

The flow conditions most likely observed in the cubes were linear to non-linear, but not turbulent, since Reynolds numbers did not exceed 10. White (2002) suggests that under typical hydraulic gradients for karst aquifers, the onset of turbulent flow and the resulting loss of Darcian behavior occurs at higher Reynolds numbers near 500, and that this hydrodynamic threshold is often associated with apertures of 1 cm in diameter. The results indicate that a transition from laminar to non-Darcian conditions occurs at Reynolds numbers of 1 for apertures of 1 cm in diameter.

Non-linear conditions are typically observed in karst aquifers (Bakalowicz 2005). The heterogeneity of karst aquifers often results in a type of dual flow where both Darcian and non-Darcian flow occur in the same area. Due to the anisotropic and heterogeneous nature of a karst aquifer it may be necessary to imagine flow as passing mostly through an interconnected conduit system imbedded within a less porous (or fissured) matrix (Ford and Williams 1989). Heterogeneity of hydraulic conductivity can be visualized as a hydraulic conductivity field of high permeability within an unknown channel network imbedded in a low permeability limestone volume (Kiraly 2003). The intent in developing an aquifer model is to create a virtual setting that will behave like an actual aquifer. This allows different management strategies of the aquifer and their consequences to be tested in a virtual setting. Undesirable consequences predicted by the model can be avoided in reality, thus maximum usage of the aquifer can be maintained. Karst aquifers are challenging to model because there is significant variability in the physical aquifer (Anderson and Woessner 1992). Such variability affects how the system gains, stores, transmits and discharges water through the system. The concept of dual flow explains how non-linear flow conditions are possible in a karst aquifer. In dual flow water passes both through the limestone matrix and through conduits situated within the matrix (Shuster and White 1971). Flow through the matrix is slow and behaves in a Darcian-way, flow through the conduits has the potential to behave in a non-Darcian way. The results of this research clearly indicate that both Darcian and non-Darcian flow occurs within the Key Largo Limestone. The use of double porosity models that include both matrix and conduit (or fracture) flow have been developed for karst aquifers (Jeannin 2001, Małoszewski et al. 2002). Consideration must be given to the interplay of both types of flow possible in a virtual karst aquifer to make the model approximate reality.

Anisotropy

When hydraulic conductivity is the same regardless of direction of measurement the aquifer is isotropic, but if hydraulic conductivity varies with the direction of measurement the aquifer is anisotropic (Ford and Williams 1989). Should anisotropy exist, groundwater will be conducted better in one direction than in another (Kiraly 2003). In this study, two general areas of anisotropy were identified in the Key Largo Limestone. One was near the land surface, while the other was in proximity to a dense laminated layer at depth. Hydraulic conductivity in cubes positioned near the land surface was lower in comparison to hydraulic conductivity in cubes positioned at deeper depths. Vertical hydraulic conductivity was enhanced in relation to horizontal hydraulic conductivity within the uppermost cubes, most likely as a result of plant root penetration. This occurred in both the 0.2 and 0.3 m cubes. Proximity to a dense laminated layer that transversed cubes 4 and 6 on Figure 2, caused large changes in hydraulic conductivity. Vertical hydraulic conductivity through the layer was greatly reduced. The density and tight structure of the layer itself probably caused the reduction. Areas below the layer were noticeably more porous and had high horizontal hydraulic conductivity. The exception to this is 0.2 m cube # 6, which is above the dense laminated layer, but has increased hydraulic conductivity. The overall result of the anisotropy caused by the dense laminated layer was to reduce vertical infiltration of water from the surface through the layer but allowing rapid horizontal mobility once the layer was penetrated. The effect of this feature on contaminant transport would be to reduce infiltration across the feature, but once passed, transport would be extremely fast with the groundwater flow.

The sedimentology of the Key Largo Limestone cubes was discussed in detail by K. Cunningham of the United States Geological Survey (personal communication, 2005). The Key Largo Limestone cubes tested were highly granular and lacked the presence of corals that are common to the Key Largo Limestone. The lack of laminations that would be caused in a high-energy depositional environment indicates the material was originally deposited in a lagoon-type setting. This depositional setting would be comparable to modern day Florida Bay located on the north side of the Florida Keys (Fig. 1). The Key Largo Limestone material was extensively burrowed. Dissolution of these burrows has increased the porosity. The dense laminated layer contained in the large block from which the cubes were cut (Fig. 2) may have been caused by scouring or the result of by-product material from burrowing activities. The feature is noticeably denser than the surrounding block material, contains little organic material, and has only sparse reworked root features. Cunningham et al. (2006) described the occurrence of porosity and permeability in the Miami Limestone and Fort Thompson Formations of the Biscayne Aquifer as related to depositional cycles which are often punctuated by a laminated calcrete layer, and similar results were found in the Key Largo Limestone. The limestone block used in this study, was extracted from an area of Key Largo that is about 6 m above sea level. Although the block was extracted in the present-day vadose zone, the high horizontal hydraulic conductivity at depth, particularly below the dense laminated layer, suggest that the water table may have been shallower in the recent past.

Conclusions

The results of this research found that a critical hydrodynamic threshold for Key Largo Limestone occurs at an effective porosity value of 33%, a K_G value greater than 10 m/day, and Reynolds number of less than 1 for a pore diameter of 1 cm. The results of this research may provide hydrologic modelers that combine both linear and non-linear flow equations with a basis for chosen K values. However, studies of other karst limestones, conducted at a similar scale of 0.2 to 0.3m would be needed to assess the universal nature of these critical values to karst aquifers.

Anisotropy occurred in two generalized regions. First near the ground surface and second in proximity to a dense laminated layer. Cubes closest to the ground surface showed higher vertical K in comparison to horizontal K within the same cube and higher K in all axes in comparison to the cube immediately below them. This is probably caused by weathering and root penetrating the limestone near the ground surface. The dense laminated layer impeded water flow, thereby significantly reducing vertical K. Horizontal K was enhanced below the layer.

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Figure 8. Graph showing relationship between effective porosity and the geometric mean of the hydraulic conductivity (K_G) for the 0.2 m and 0.3 m cubes. Dashed vertical line indicates effective porosity value (0.33) at which large changes in hydraulic conductivity were observed.

Figure 9. Ellipse diagram showing anisotropy between vertical axis and horizontal axes of 0.2 m Key Largo Limestone cubes.

Figure 10. Ellipse diagram showing anisotropy between vertical axis and horizontal axes of 0.3 m Key Largo Limestone cubes.

Table 1. Bulk density, total porosity, and effective porosity of the 0.2 m and 0.3 m Key Largo Limestone cubes.

0.2 m cube #	**weight (g)**	**bulk density (g/cm^3)**	**total porosity**	**effective porosity**
1	11566	1.45	0.47	0.32
2	15138	1.89	0.30	0.16
3	14061	1.76	0.35	0.20
4	12077	1.51	0.44	0.29
5	11736	1.47	0.46	0.30
6	10999	1.38	0.49	0.34
7	11566	1.45	0.47	0.33
average		**1.56**	**0.43**	**0.28**
0.3 m cube #				
1	43545	1.61	0.40	0.27
2	44271	1.64	0.39	0.25
3	38147	1.41	0.48	0.32
4	37989	1.41	0.48	0.32
5	33453	1.24	0.54	0.38
6	36174	1.34	0.51	0.33
average		**1.44**	**0.47**	**0.31**

Table 2. Hydraulic conductivity (K) determined by the slope of a linear regression line generated by *Q* (m^3/day) versus the product of A(dh/dl) in m^2; the R^2 of the linear regression line, the Reynold's number (Re) determined for the discharge at the highest head (0.2 m) and a pore diameter of 0.01 m, and the geometric mean of the hydraulic conductivity (K_G) of the 0.2 m Key Largo Limestone cubes.

0.2 Cube #	**Axis**	**K (m/day)**	**R^2**	**Re**	**K_G (m/day)**
	v	8.2*	0.73	0.95	
1	h1	7.3	0.98	0.89	
	h2	2.6	0.78	0.31	5.4
	v	0.79	0.98	0.10	
2	h1	0.93	0.95	0.12	
	h2	0.48	0.80	0.06	0.7
	v	2.4	0.99	0.29	
3	h1	1.7	0.93	0.20	
	h2	0.79	0.77	0.12	1.5
	v	2.0	0.99	0.26	
4	h1	3.7	0.99	0.47	
	h2	4.1	0.95	0.48	3.1
	v	8.3*	0.91	0.96	
5	h1	4.9	0.99	0.60	
	h2	3.2	0.99	0.41	5.1
	v	33*	0.94	3.87	
6	h1	38*	0.89	4.47	
	h2	27*	0.96	3.27	32.4
	v	10	0.99	1.29	
7	h1	19*	0.94	2.31	
	h2	13*	0.96	1.59	13.5
Mean		**9.2**			**4.5**
S. D.		**11.0**			**11.2**

*denotes non-linearity in the data when compared to the best-fit linear regression line through all of the data points. v=vertical axis; h1=horizontal 1 axis 1; h2= horizontal 2 axis; K=hydraulic conductivity; R^2= linear regression correlation coefficient, Re=Reynolds number; K_G=geometric mean of hydraulic conductivity; S.D.=standard deviation.

Table 3. Hydraulic conductivity (K) and determined by the slope of a linear regression line generated by Q (m^3/day) versus the product of A(dh/dl) in m^2; the R^2 of the linear regression line, the Reynold's number (Re) determined for the discharge at the highest head (0.3 m) and a pore diameter of 0.01 m and the geometric mean of the hydraulic conductivity (K_G) of the 0.3 m Key Largo Limestone cubes.

0.3 cube #	**axis**	**K (m/day)**	**R^2**	**Re**	**K_G (m/day)**
	v	2.5	0.99	0.31	
1	h1	0.74	0.97	0.10	1.0
	h2	0.48	0.99	0.06	
	v	0.72	0.91	0.10	
2	h1	0.23	0.99	0.03	0.4
	h2	0.28	0.99	0.04	
	v	0.66	0.99	0.09	
3	h1	1.3	0.99	0.18	0.7
	h2	0.46	0.98	0.06	
	v	2.0	0.99	0.26	
4	h1	2.8	0.99	0.35	2.2
	h2	1.8	0.99	0.25	
	v	7.1*	0.83	0.77	
5	h1	67*	0.83	7.37	31.5
	h2	66*	0.78	7.43	
	v	0.81	0.99	0.10	
6	h1	22*	0.95	2.59	6.7
	h2	17*	0.87	2.06	
Mean		**10**			**2.2**
S.D.		**21**			**12.2**

*denotes non-linearity in the data when compared to the best-fit linear regression line through all of the data points. v=vertical axis; h1=horizontal 1 axis 1; h2= horizontal 2 axis; K=hydraulic conductivity; R^2=linear regression correlation coefficient, Re=Reynolds number; K_G=geometric mean of hydraulic conductivity; S.D.=standard deviation.

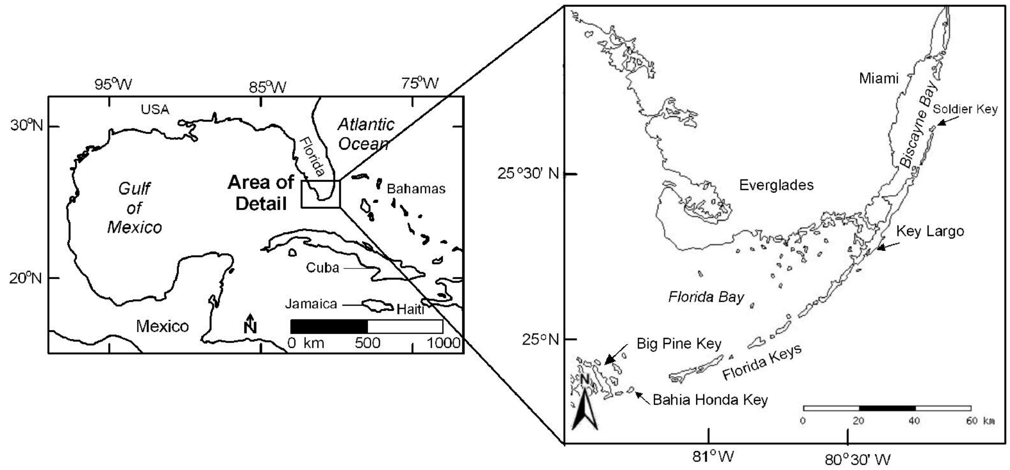

Figure 1
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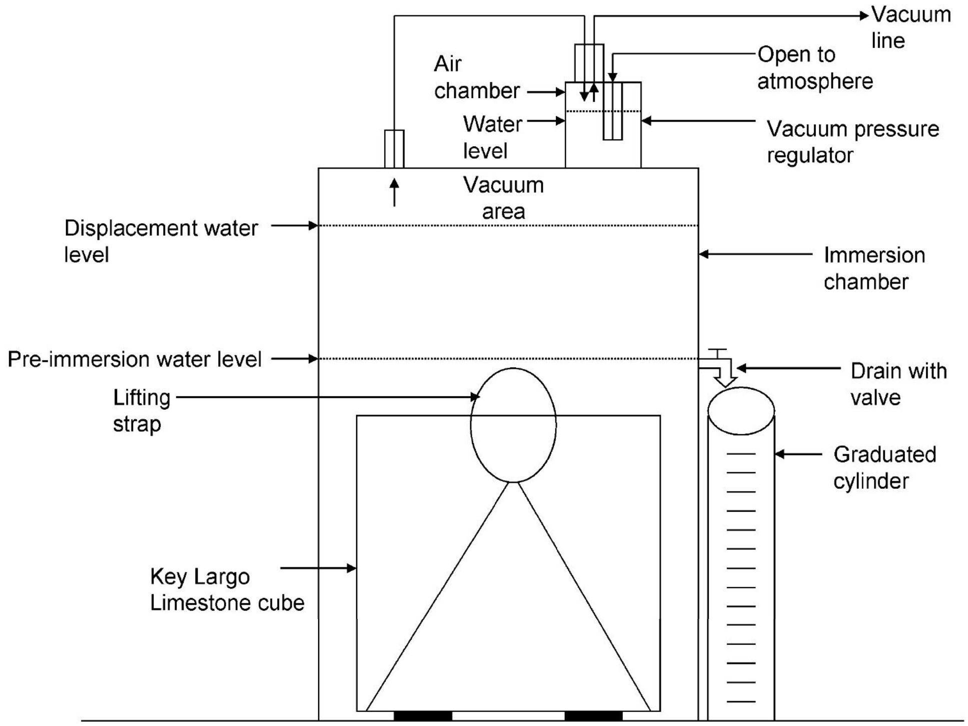

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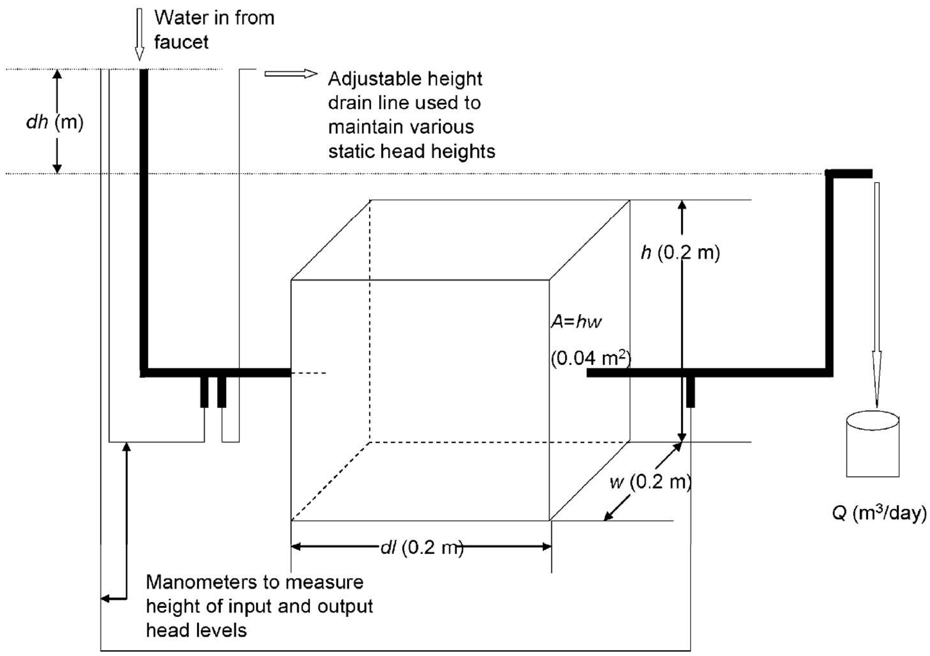

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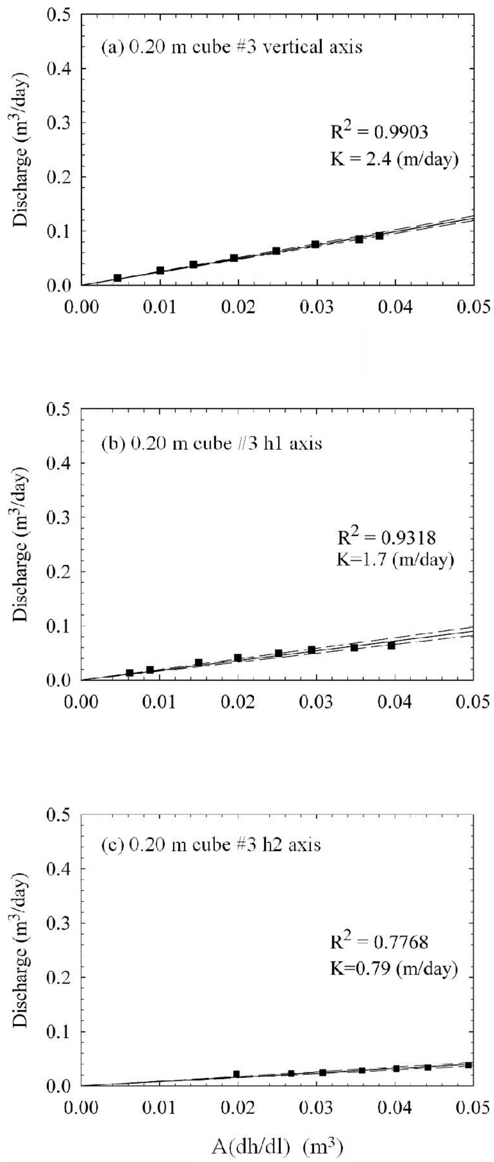

Figure 5
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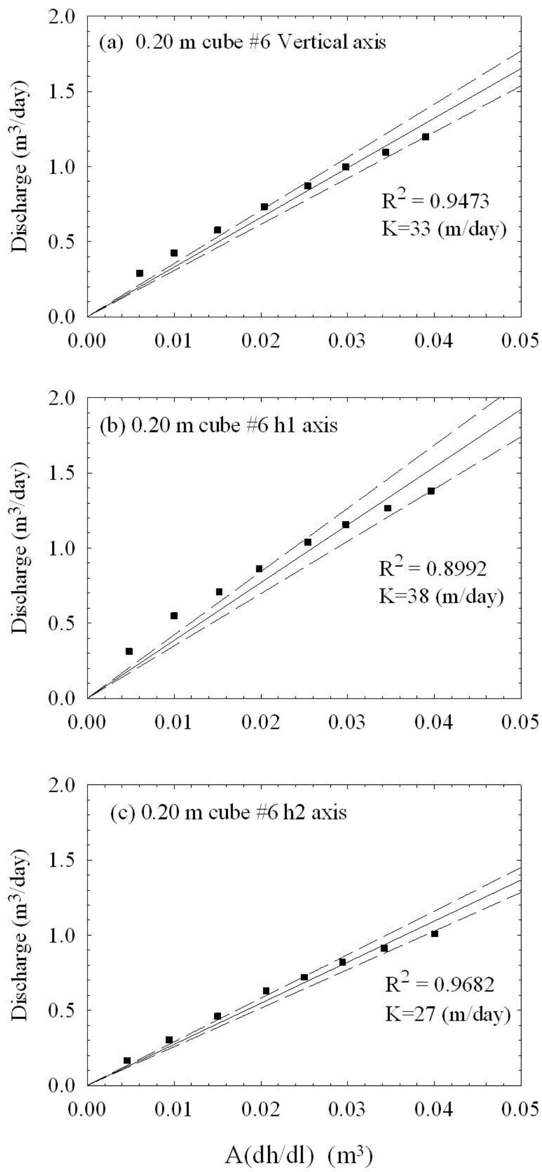

Figure 6
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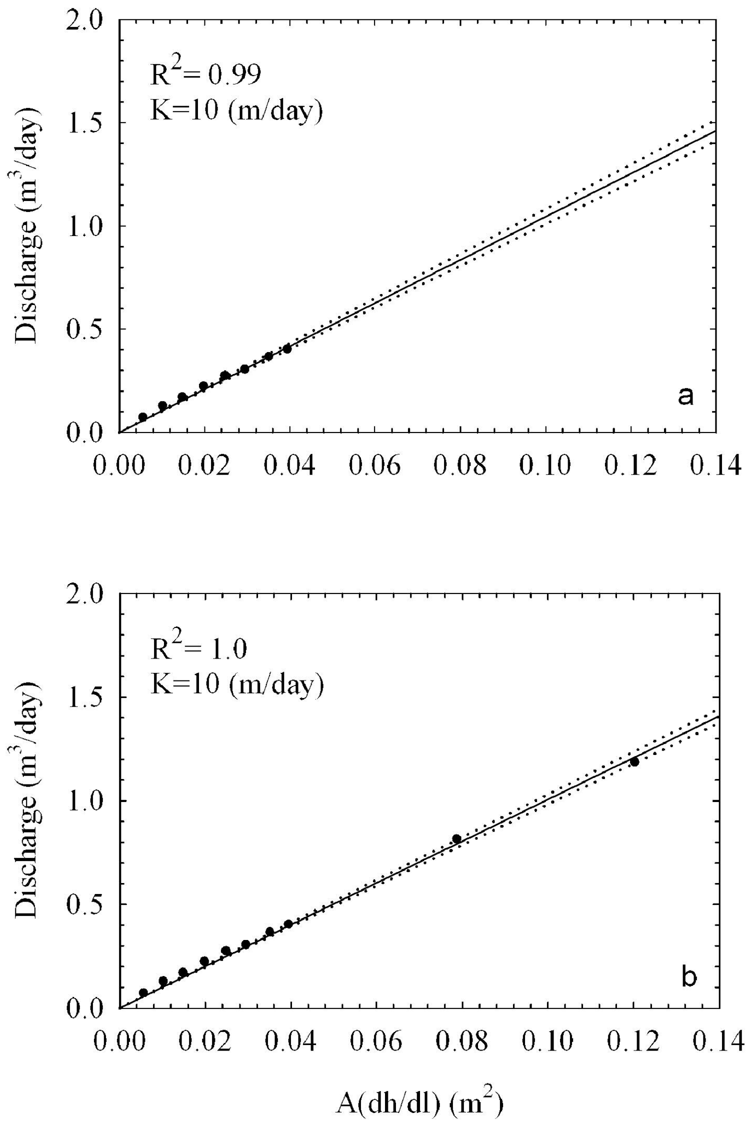

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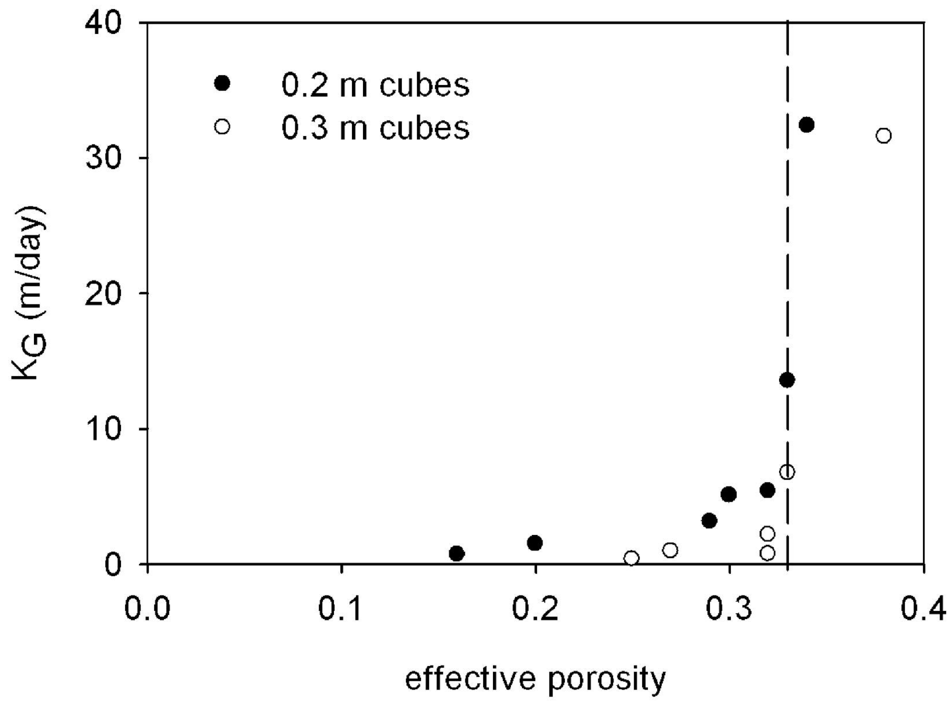

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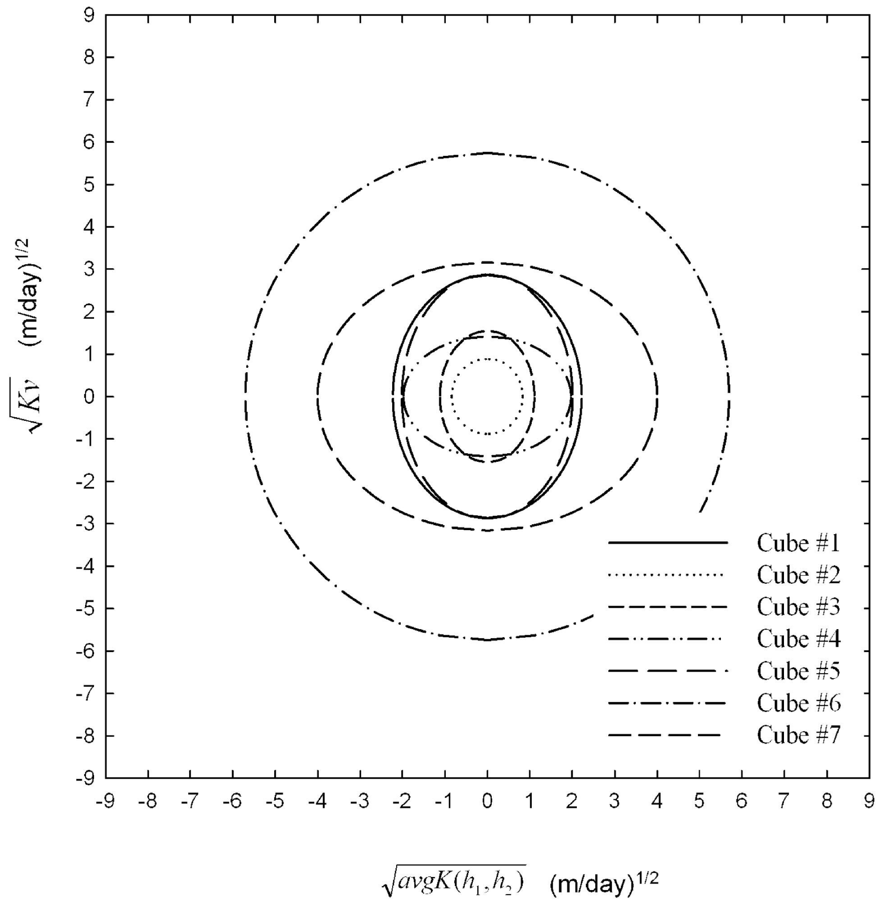

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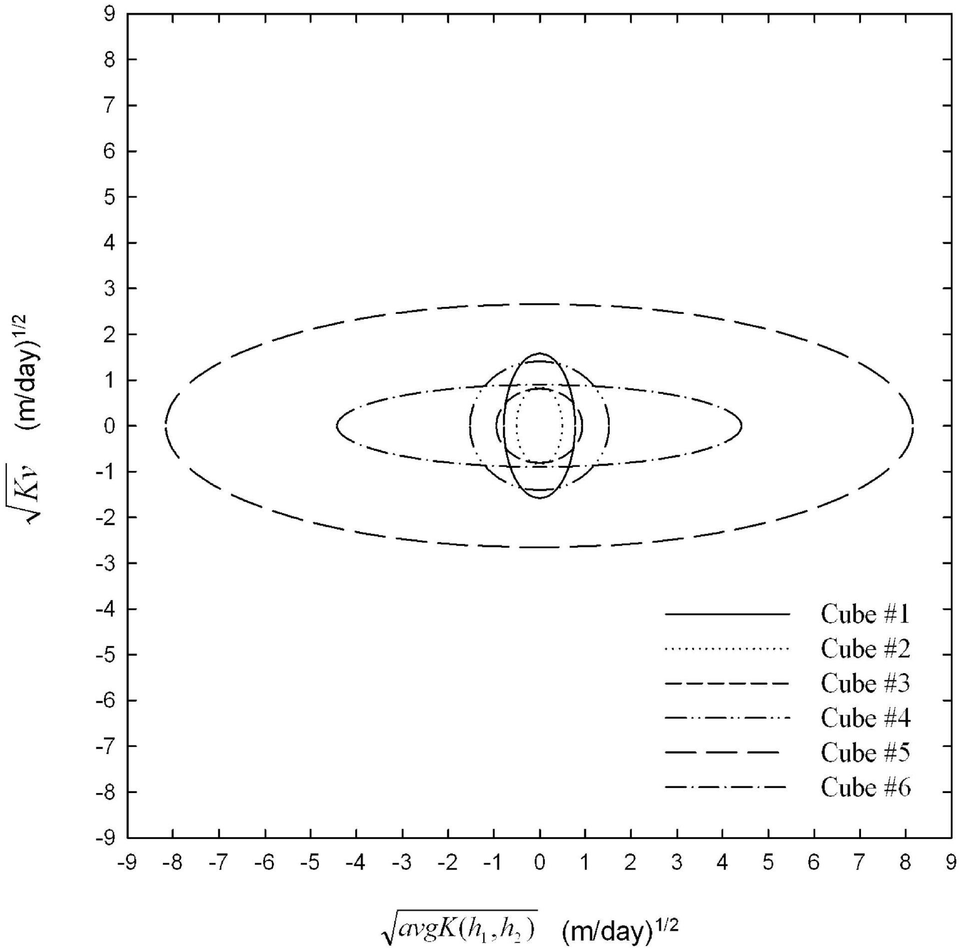

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HJ-2006-0486

Abstract

A hydrodynamic threshold between Darcian and non-Darcian flow conditions was found to occur in cubes of Key Largo Limestone from Florida, USA (one cube measuring 0.2 m on each side, the other 0.3 m), at an effective porosity of 33% and a hydraulic conductivity of 10 m/day. Below these values, flow was laminar and could be described as Darcian. Above these values, hydraulic conductivity increased greatly and flow was non-laminar. Reynolds numbers (Re) for these experiments ranged from <0.1 to 7. Non-laminar flow conditions observed in the hydraulic conductivity tests were observed at Re close to 1. Hydraulic conductivity was measured on all three axes in a permeameter designed specifically for samples of these sizes. Positive identification of vertical and horizontal axes as well as 100 percent recovery for each sample was achieved. Total porosity was determined by a drying and weighing method, while effective porosity was determined by a submersion method. Bulk density, total porosity and effective porosity of the Key Largo Limestone cubes averaged 1.5 g/cm^3, 40% and 30%, respectively. Two regions of anisotropy were observed, one close to the ground surface, where vertical flow dominated, and the other associated with a dense-laminar layer, below which horizontal flow dominated.