Hydrogeologic investigation of groundwater velocity for matrix and conduit in a karst aquifer

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STUDY RATIONALE

The concentration of nitrate has been steadily increasing over the past 30 years in the majority of springs in Florida. In order to protect and manage spring water from pollutants, it is essential to understand the movement pattern of groundwater in the complex flow system of karst aquifer composed of conduit flow and matrix flow. The study area is the karstified Floridan aquifer in the springshed of Silver Springs, in north-central Florida, USA. Silver Springs is one of Florida's first magnitude springs and among the largest springs worldwide. Specific management questions to be addressed included: which flow pattern has the greatest effect on spring discharge? How much water flows through conduits? How much conduit area occupies the entire springshed?

Groundwater flow in karst aquifers

Karst aquifers exhibit strong heterogeneity of porosity, where most of the rock matrix has low values (5 – 15%), interlaced with high-porosity interconnected fractures, faults, and conduits developed from dissolution. These heterogeneous distributions of porosity and permeability control groundwater flow paths, with groundwater velocities that may vary by many orders of magnitude in karst aquifers with among slow seepage from the rock matrix, mixed flow from fractures, and rapid turbulent flow in conduits. Therefore, much importance has been placed on the investigation of conduit flow paths and rates in karst aquifers.

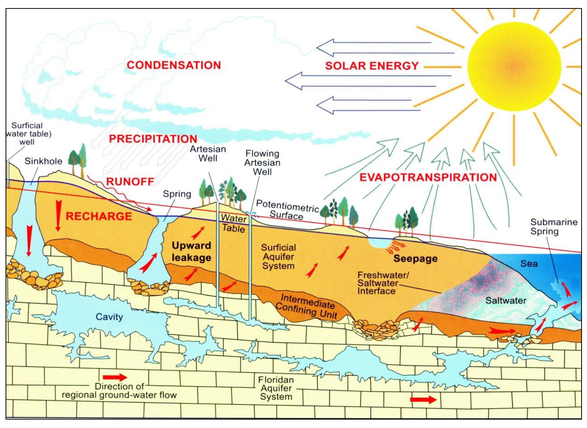

Fig. 1. Schematic illustration of a karst aquifer

OBJECTIVES

The primary objectives of this work are to

1) **determine the relative proportions of matrix and conduit flow to the total spring discharge in the springshed**
2) **estimate relative area proportions of conduits connected to the spring outlet in the springshed**
3) **provide evidence of the conduit contribution using measured head profile with distance from the spring**

METHODS AND MATERIALS

Study site description

Silver Springs, located in Ocala, Florida (Fig. 2a) has an annual average discharge of 20 m^3/s, which originates as recharge to the mostly unconfined 30-60 m thick Upper Floridan Aquifer (UFA) within an approximately 2300 km^2 springshed. Mean annual precipitation, based on data from 1897-2014 from station USC00086414 in Ocala, Florida, is P = 1.34 m/yr. Mean annual evapotranspiration has been estimated as E = 1.01 m/yr, approximately 75% of precipitation.

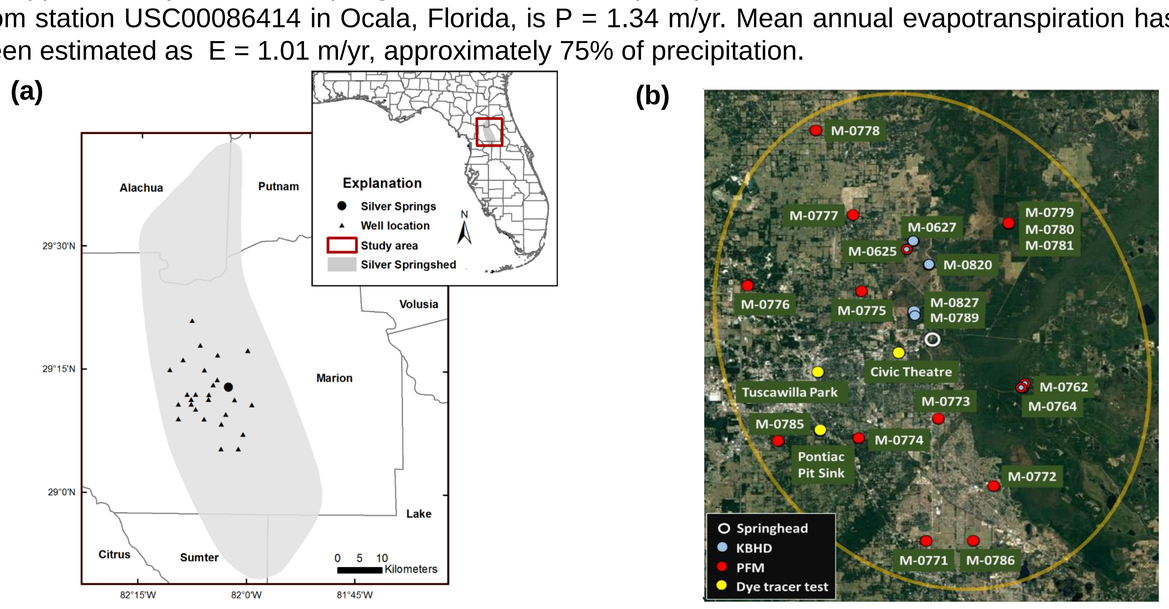

Fig. 2. (a) Regional map showing the location of the study area, Silver Springs, Ocala, Florida. Shaded area indicates the Silver Springs springshed. (b) Map of well locations, where PFMs, BHD, and dye tracer tests were conducted, about two ellipse radius measures, 20 km and 14 km from Silver Springs.

Passive flux meter

Passive flux meters (PFMs) are self-contained permeable units that fit snugly in the interior of wells to measure time-averaged water flux q with depth in a flow field in a porous medium. The interior composition in the PFM consists of granular active carbon as a permeable sorbent that has been pre-loaded with alcohol tracers prior to down-well deployment. When the PFM is exposed to groundwater flow, the alcohol tracers are eluted from the sorbent matrix at rates proportional to groundwater flow through the PFM. Since the magnitude of groundwater flow is unknown in the actual application, multiple alcohols, which have different elution rates, are used. In this study, methanol (R = 5), ethanol (R = 27), isoprophy alcohol (R = 120), and tert-butyl alcohol (R = 295) were used as resident alcohol tracers. PFMs were deployed for approximately two months at three depths in 16 wells within two ellipse radius measures, 20 km and 14 km radius of the spring outlet (Fig. 2b).

Borehole dilution

Borehole dilution is a common well monitoring technique used to estimate groundwater flux. The method relies on isolation of a section of the borehole using inflatable packers, followed by the injection and recirculation of a tracer pulse within the zone between the packers. In this study, the borehole dilution tests using KBHD were conducted in 7 wells to measure groundwater fluxes specifically in fractured and conduit systems (Fig. 2b). These wells were chosen based on visual evidence of fractures (21 targeting depths) identified in down-borehole video and from core logs. Potassium chloride of 200 mg/L and rhodamine WT of 100 μg/L were used as tracers.

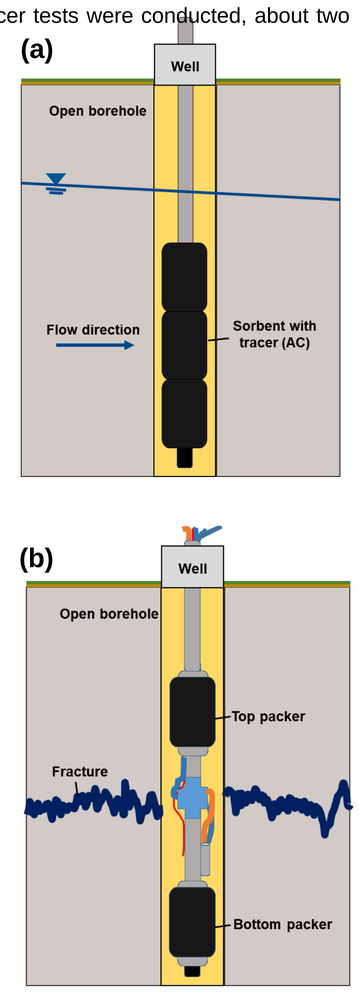

Fig. 3. Schematic illustration of (a) passive flux meter and (b) borehole dilution

Dye tracer tests

Five tracer tests were conducted in the Silver Springs springshed, introducing four different dyes (Fluorescein, Eosine, Rhomdamin, and Sulforhodamine B) at five different locations and monitoring from 8 to 304 days at a series of down-gradient wells at distances from 2.4 to 27 km. Median travel times for dye detections were used to reflect a multiple porous domain consisting of both conduit and matrix. Mean groundwater velocities were determined by dividing a straight-line distance from each introduction location to detection stations such as municipal supply wells and spring vents by median tracer travel time. Three of the five introduction locations were located within 14 km-radius of the study area boundary from the spring (Fig. 2b), and we obtained groundwater velocity data from 12 associated detection stations.

Estimate groundwater flux

The total discharge is the product of the average Darcy flux, q_{avg}, in the aquifer and the aquifer cross-sectional area, Across, for an elliptical cylinder in the aquifer at two ellipse radius measures, r_a and r_b. Therefore, average Darcy flux, q_{avg}, in the UFA may be expressed

$$q_{avg} = \frac{Q_R}{A_{C,T}} = \frac{(P-ET)\pi(r_L r_S - r_a r_b)}{CB} \quad (1)$$

The total discharge may be expressed by the sum of both matrix and non-matrix flows by mass conservation, such that

$$q_{avg} A_{C,T} = q_m A_{C,m} + q_{nm} A_{C,nm} \quad (2)$$

where $A_{C,m}$, and $A_{C,nm}$ are the aquifer cross-sectional areas of the matrix and non-matrix and q_m and q_{nm} are the average measured Darcy flux in the matrix and non-matrix.

The non-matrix fraction of the total area may be expressed

$$\frac{A_{C,nm}}{A_{C,T}} = \frac{q_{avg} - q_m}{q_{nm} - q_m} \quad (3)$$

RESULTS AND CONCLUSIONS

Groundwater flux measurements

A total of 81 groundwater flux values measured from PFMs, BHD, and dye tracer tests within a 14 km radius of Silver Springs are shown in Fig. 4. The mean measured water fluxes using **PFMs (n = 48) was 0.06 ± 0.02 m/day**, indicative of slow flow through the rock matrix (< 1 m/day). Measured fluxes from BHDs (n = 21), which specifically targeted depths of the aquifer that were suggestive of fractures and conduits, were more than 50 times greater than those measured with PFMs, varying from 0.1 to 36.4 m/day with **mean 3.1 ± 8.1 m/day**. For tracer tests (n = 12), the **average flux was 79.9 ± 91.0 m/day** ranging from 8.4 m/day to 316.8 m/day.

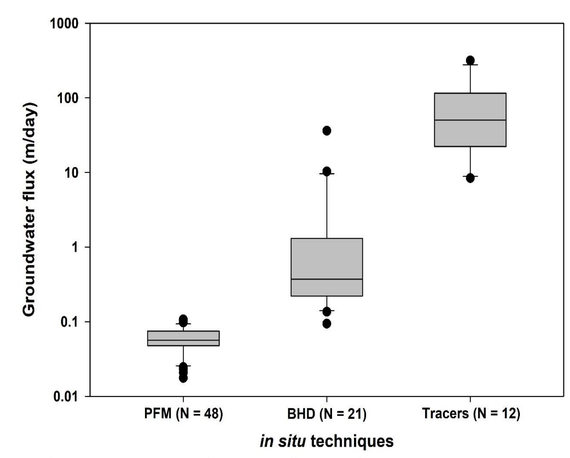

Fig. 4. Measured water fluxes from PFMs, BHD, and tracer tests conducted within 14 km radius of Silver Springs. The black solid line across the box indicates the mean and median values for the data set.

Single domain scenario

The average water flux, q_{avg}, and discharge, Q_R, in the UFA calculated using Eq. (1) with B = 50 m are shown in Fig. 5 as a function of upgradient springshed area, $A_S/A_{S,T}$. Both q_{avg} and Q_R decreased with $A_S/A_{S,T}$ but Q_R decreased gradually while q_{avg} decreased exponentially. The PFM-based in situ measured water fluxes (average: 0.06 m/day) within approximately 0.27 of $A_S/A_{S,T}$ were much lower than the simulated water fluxes (0.2 m/day). These low fluxes are likely representative of the rock matrix. The computed value of q_{avg} at $A_S/A_{S,T}$ = 0.0004 (1 km^2) near the spring was about 8 m/day, but this reduces to less than 1 m/day at $A_S/A_{S,T}$ = 0.03 (60 km^2).

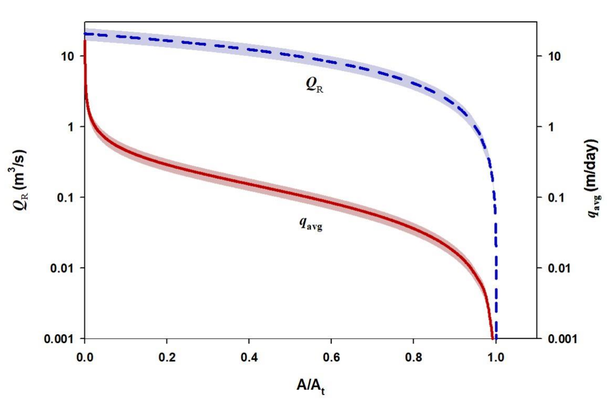

Fig. 5. Calculated average water flux, q_{avg}, and discharge, Q_R, along with the springshad area (Scenario 1). Shaded areas show the results of sensitivity analysis (±20% of P-ET m/day).

Dual domain scenario

Note that q_m = 0.06 m/day and q_{nm} = 30.1 m/day based on the measured fluxes from the PFMs, BHD, and tracer tests. These values were used in Eqs. (2) and (3) to determine the non-matrix fraction of the total flow, Q_{nm}/Q_T, and total cross-sectional area, $A_{C,nm}/A_{C,T}$ (Fig. 6). These results show the estimated non-matrix flow and cross-section area fractions throughout the springshed area, to a maximum $A_S/A_{S,T}$ = 0.7 (1600 km^2). At $A_S/A_{S,T}$ = 0.1 (150 km^2), the non-matrix zones deliver nearly 90% of the flow through the UFA but account for only 2% of the aquifer cross-sectional area. At $A_S/A_{S,T}$ = 0.5, the non-matrix area accounts for 0.2% of the total, while approximately 50% of the flow is carried by non-matrix. This result indicates that a proportion of matrix area is approximately 500 times larger than that of the non-matrix area at the $A_S/A_{S,T}$ = 0.5 boundary.

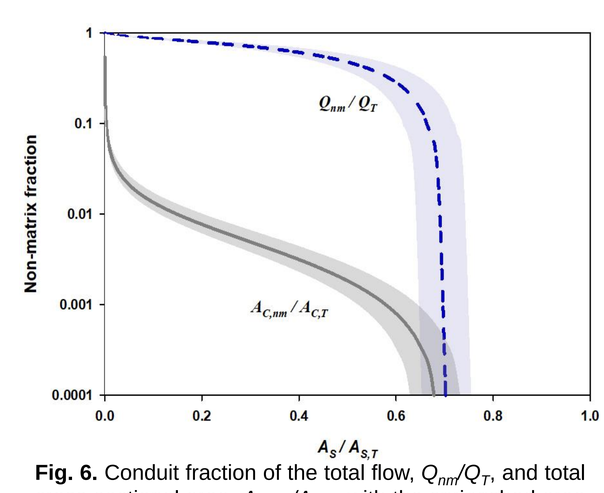

Fig. 6. Conduit fraction of the total flow, Q_{nm}/Q_T, and total cross-sectional area, $A_{C,nm}/A_{C,T}$, with the springshad area from Silver Springs based on mean matrix and non-matrix fluxes q_m = 0.06 m/day and q_{nm} = 30 m/day (Scenario 2). Shaded areas show the results of sensitivity analysis (±20% q_m and q_{nm} m/day).

ENVIRONMENTAL IMPLICATION

This modeling approach might be applied to water quality problems in many of the artesian springs. For example, contaminant mass balance in springshed would consider transport of contaminant loads separately for both matrix and conduit flowpaths. If there are difference in water quality between matrix and conduit sections, mass balance can be calculated between spring and flowpath discharge ($Q_{ss}\ C_{ss} = Q_m\ C_m + Q_{nm}\ C_{nm}$). Also, this approach can be extended to environmentally significant springshed studies related to age distribution and travel time distribution.