Characterization of water and nitrate transport through a dual porosity karstic aquifer and discharge in Silver Springs

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Boy, what ever you is
and where ever you is,
don’t be what you ain’t,
because when you is
what you ain’t, you isn’t.

- Uncle Remus

Contents

Introduction

Silver Springs, Florida, discharges an average of 20 m^3/s making this system the largest inland spring in in the state. In addition to its hydrological relevance, this system has great ecological, cultural and touristic significance. Scientific interest in the system emerged in the early 1900s with flow monitoring by the USGS and over time Silver Springs has become a rich source of hydrological data. The system has also been subject to continuous ecological and hydrological research: pioneering studies in springs ecology were conducted at Silver Springs by H.T. Odum in the 1950s and later by his mentee R. Knight in the 1970s (Odum, 1957; Knight 1980; Odum,1971). These studies monitored pollutant concentrations and inventoried biodiversity. The proposal and partial construction of the Florida Barge Canal also prompted regional hydrological research that allowed deeper understanding of the Floridan Aquifer in general and the Silver Springs system specifically (Knochenmus, 1967; Faulkner, 1973).

The delineation of the contributing areas to the Silver Springshed started when the effects of the Florida Barge Canal were being investigated (Knochenmus,1967; Faulkner, 1973; Tibbals, 1975). Further studies (Sepulveda, 2002; Knowles et al, 2002; Motz and Dogan, 2002) produced varying estimates of the springshed area. The current accepted springshed boundaries are those proposed by Bradner and Knowles (1999), and later adopted by Phelps (2004). This estimate covers an area of 3107 km2 (1200 mi^2); however it has to be noted that this area will change depending on potentiometric elevation conditions.

The springshed is considered to have no surface drainage, all water is internally drained (Phelps, 2004), either directly into closed depressions or by seepage into the unconfined limestone of the Upper Floridan aquifer (UFA, Phelps, 2004). This springshed is part of the UFA, which has a thickness of about 100 m in the region (Sepulveda, 2002). Porosity has been estimated to range from 15 to 40 percent (Phelps, 2004). Because of the significant porosity of the limestone, flow in the Upper Floridan aquifer occurs in both the rock matrix and in fractures or conduit systems.

Ocala Limestone and Avon Park Formation are the geologic constituents of the UFA, 55% of the springshed area is unconfined, while the remaining 45% of the area the UFA and the surficial aquifer (SA) are segregated by the Hawthorne Formation.

Like other karstic aquifers the UFA has been characterized as a system with dual porosity. Phelps (2004) noted that unlike older limestone, where all the flow occurs in the conduits, the UFA's significant porosity of the limestone, flow in the Upper Floridan aquifer occurs in both rock matrix and conduit.

The earliest estimates of land use within the springshed are from 1949, at which time 74% of the springshed comprised natural ecosystems (wetlands, forests, dry prairies and brush land), agriculture and pastures together accounted for less than 20% of the land use and the urbanized fraction accounted for less than 10% (Munch et al., 2006). Since that time, significant urbanization has occurred while forested and vegetative areas continued to decline. By 2005 natural land cover (open water, wetland and forested) reached parity with urban areas, which covered 37% of the land (Munch, 2006).

As a result of expansion of agriculture and urbanization, together with the natural aquifer vulnerability of the area (Arthur, 2005), Silver Springs has been subject to changes in water quality. Increased fertilizer applications and septic tank discharges within the springshed (Phelps, 2004; FDEP, 2000) are responsible for increased nitrate concentrations measured at the spring outlet. Nitrate concentrations have been steadily increasing since the mid-1950s, from 0.05 mg/L to current values ~1.3 mg/L. Furthermore, starting in the 1960s, annual precipitation in the area started a declining trend, with a corresponding, but lagged, trajectory for discharge from Silver Springs.

Conceptual Framework

Silver Springshed can be conceptualized as an internally drained basin with no overland runoff. So river discharge can be can be defined by the following equation

$$Q = P - ET$$

Since the only point of discharge in the basin is Silver Springs, we can draw concentric arcs around the boil, which gives us horizontal surfaces over which we can calculate areal recharge values, and vertical boundaries through which we can calculate horizontal fluxes. Once we know the cumulative recharge within each arc we can calculate the amount of groundwater arriving to each arc horizontal flux boundary. In other words, how much water travels through each plane. This can be calculated if we assume that the only difference between Q_{SS} and Q_{arc} (flow traveling through each vertical arc flux boundary) is only recharge within each arc.

$$Q_{arch} = Q_{SS} - Recharge$$

For this exercise the following assumptions will be made: Silver Springshed has an area of 2000 km2, an average precipitation rate of 1.3 m/year (50 in/year) and an ET of roughly 1.0 m/year (38 in/year), no change in storage is assumed.

The overland area between successive arcs at r1 and r2 is

$$A_{1,2} = \pi(r_2^2 - r_1^2)$$

The vertical flux surface of each arc is compute assuming an average effective depth of the UFA, h.

$$A_{Arch} = 2\pi rh \tag{1}$$

As each arc increases in diameter the amount of horizontal groundwater flux arriving to its boundaries is smaller due to a decreasing contributing area. In order to account for this, cumulative recharge over the area within each arc of interest is subtracted from Q_{SS} (discharge from Silver Springs)

The average Darcy flux through each plane is

$$q_{avg} = Qss/A_{arch}$$

Once we know how much water could be transported by matrix flow, $Q_{M\,max}$, we are able to know the deficit in Q. This deficit in flow by the matrix will be the portion of flow that we will attribute to the conduit.

$$Q_C = 1 - \left({}^{Q_{M\,max}}/_{Q_{arch}}\right)$$

Background

Dye Trace Studies

Tracer studies and background fluorescence of groundwater in the Ocala, Florida, Area

During 1965 and 1966 the USGS conducted a dye trace study to investigate the possible ramifications that the construction of the Cross-Florida Barge Canal would have had in Silver Springs (Knochenmus ,1967). Fluorescein was introduced (the amount of fluorescein injected was not described) in the Ocala Caverns and detected 2.1 km (1.3 miles) away in Wolf Sink. Two days after injection no fluorescein was detected, the dye was detected on day 9 after injection at 20 ppb in Wolf Sink. By day 23, all the fluorescein had passed through the sink and fluorescence was back to background level.

Despite lacking data from the 2nd to the 9th day of observation, they believed that the peak of the pulse took place over this period. This period was recreated by interpolating the BTC between the concetrations of the 2nd and the 9th day.

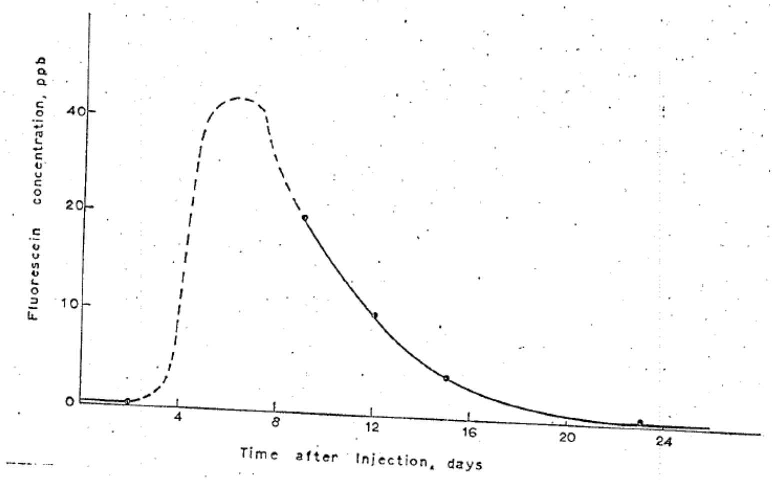


Figure 3. Concentration-time curve of Wolf Sink with injection of 20 pounds of fluorescein in Ocala Caverns, December 8, 1965.

Figure 1 Break through curve from Knochenmus (1968) dye trace sutdy

The BTC was built using measured and extrapolated data, the background and recesion were measured (solid line) while the period when the peak of the pulse was believed to occur (3rd to 6th day) was recreated through interpolation of measured data.

If this interpolation was representative of actual conditions the peak would have arrived to the Wolf Sink in the 6th day, this would mean the water velocity was 350 m/day (0.8 ft/min). Since there was a hole in the data during a critical period (2nd to 9th day) the pulse could have arrived on any day during this period which means that water could have reached the sink as early as the 3rd day and as late as the 9th day. This would translate in a maximum water velocity of 704 m/day (1.6 ft/sec) and a minimum of 220 m/day (0.5 ft/minute).

Silver Springs nutrient pathway characterization project

Karst Environmental Services conducted a dye trace study to identify dominant groundwater pathways and travel times between specific locations and Silver Springs(McGurk et al, 2012)Four different dyes were injected at four identified as points of recharge for the UFA. Sampling locations consisted of municipal supply wells and 24 spring vents in Silver Springs. Dye injection took place in April and October (see table below) 2010.

						Detection Sites		
Group	Date	Injection point	Site Type	Dye	Distance to SSG (km)	Springs	River Station	Well
1	23-Apr-10	Heagy Burry Sink (Orange Lake)	Sinkhole	Fluorescein	27			4
		Tuscawilla Park Stormwater DW	Drainage Well	Eosine	8.2	1		
		Ocala Civic Theatre DRA	Sinkhole	Rhodamine WT	2.4	20	1	
2	05-Oct-10	Pontiac Pit Sink	Drainage sinkhole	Sulforhodamine B	10.1			3

Table 1 Results from KES and Knochenmus dye trace studies

Water velocities were estimated by dividing the distance (Euclidean) between injection and detection point by the number of days that took for the dye to first arrive to the monitoring point. The chart below shows water velocity versus the traveled distance. Notice that this scatterplot includes data from Knochenmus (1967) study. The largest velocity found by KES was for water injected at the Heagy Burry Sink and detected at the Redick Elementary Institution well 9 days later, which translates to 710 m/day.

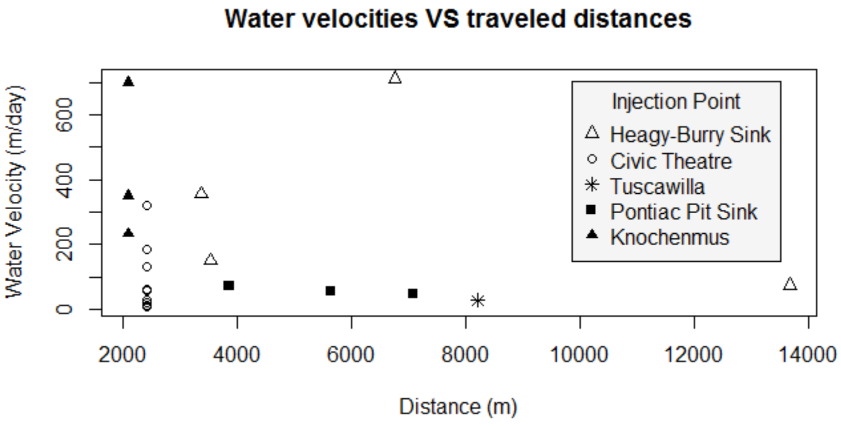


Figure 2 Dye trace studies results, water velocity and traveled distance

The arithmetic average of these velocities is 180 m/day, with a range of 710 m/day for Heagy Burry Sink-Redick Elementary, and 8.4 m/day for Ocala Civic Center to Christmas Tree vent in Silver Springs.

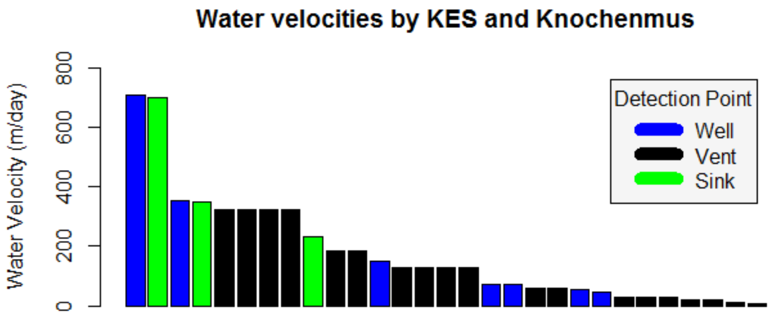


Figure 3 Histogram of dye trace studies

Note: It is my understanding that in order to have seepage velocity we need to use the equation below to account for porosity, however this is confusing to me because we are assuming that there are open channels and fractures, like the ones in the dye studies, that allow for fast water movement, so I don't see how we can apply a porosity value to a particle of water that is moving through an open hole.

$$v_x = \frac{q}{n_e A}$$

$$v_x = average\ linear\ velocity\ (L/T)$$

$$n_e = effective\ porosity$$

Passive Flux Meters

While grab water samples provide a 'snapshot' of the water conditions at the moment when the sample was collected, passive flux meters (PFMs) provides measurements of water and solute fluxes accumulated through a deployment period (Hatfield et al. 2004). The PFM is a self-contained permeable unit that fits snugly in the interior of wells where it will be exposed to groundwater flux. The permeable media in the PFM have contrasting functions, granular activated carbon GAC is preloaded with several alcohols that possess different retardation coefficient, Rd ,which determines the ease with which they will be eluted from the media. The displacement of alcohols by water flowing through the PFM is proportional to groundwater flux, q (cm/day). Concomitantly nutrients contained in groundwater flowing through ion exchange resin will be sorbed to the media. The Darcy flux in the aquifer can be found with using the following equation

$$q = [1.67 r\theta R_d (1 - M_R)/t]$$

$$M_R \text{ is the tracer's remaining mass}, r \text{ is the radius of the well}$$
$$\theta \text{ is the water content in the GAC, and } t \text{ is residence time}$$
$$R_d \text{is the retardation factor of each alcohol}$$
$$q \text{ is the specific discharge through the aquifer } (m/day)$$

The contaminant mass retained on the sorbing porous matrix can be used to estimate solute flux intercepted by the meter (Annable et al.,2005).This mass (J_c) can be calculated:

$$J_c = \frac{M_c}{2rLt\alpha}$$
$$M_c \text{ is the mass of sorbed contaminant}, L \text{ tested aquifer length}$$

$$\text{while } \alpha \text{ is the convergence or divergence factor}$$

PFM’s allow to monitor aquifer conditions on specific locations, unlike water samples that are collected over a larger borehole interval. The ease to locate PFM at specific depths allows for well profiling. Additionally having time averaged measurements can provide with water and solute data for a range of time rather than a single instance.

Borehole dilution test

Borehole dilution is a common well monitoring technique used to estimate groundwater Darcy flux. The method relies on isolation of a region of the borehole using inflatable packers, followed by the injection and recirculation of a tracer pulse in the zone between the packers. Aquifer velocity can be inferred from the dilution of the injected tracer, which is attributed to advective losses (Pitrak et al. 2007).

This method is subject to considerable constraints in open-rock boreholes, as the sharp edges characteristic of conduit/cavernous regions greatly increase the risk of rupturing the rubber packers commonly used to isolate sections of the borehole. Moreover, the test generates Darcy fluxes averaged over the section of the aquifer being tested so the effect of small fractures and high flux zones can be dampened by areas with smaller fluxes.

The governing equation for the borehole dilution tests is

$$V_T = \frac{dC}{dt} - QC$$

where V_T is the total mixing volume (this includes the tested borehole interval and the tubing volume less the volume occupied by any solid obstruction or structural elements inside the test borehole interval) [L3]; Q is groundwater flow through the mixing volume [L3/T]; C is solute concentration, represented here by a proxy of electrical conductivity [-]; and t is time [T]. The groundwater flow is defined as

$$Q = \alpha q 2rl$$

where a is the open borehole flow convergence factor [2]; and q is specific discharge, [L/T]. Solving the governing equation and making appropriates substitutions we obtain

$$q = -\frac{V_{total}}{4rlt} Ln\left(\frac{C}{C_0}\right)$$

Experimental data is plotted Ln(C/C_0) versus t (minutes), with q determined from the slope

$$q = -\frac{V_{total} * 1440 * slope}{4rl}$$

Additionally, the karstic nature of the UFA makes placement and retrieval of testing equipment much more intricate. Thus, a modified karstic borehole device (KBHD) was designed and constructed to aid in the deployment and retrieval of borehole dilution instruments in karstic environments.

Methods

Passive flux meters

PFM’s were installed in 16 wells throughout the Silver Springshed between August of 2014 and November 2015. Most PFM deployments took place in well located in the vicinity of the City of Ocala as this region is where the largest concentration of nitrate generators are located (Phelps, 2004) and also is where the aquifer is the most vulnerable to contamination. All wells are located within a 27 km distance from the Silver Springs boil, the maximum depth of deployment was 110 ft below ground surface.

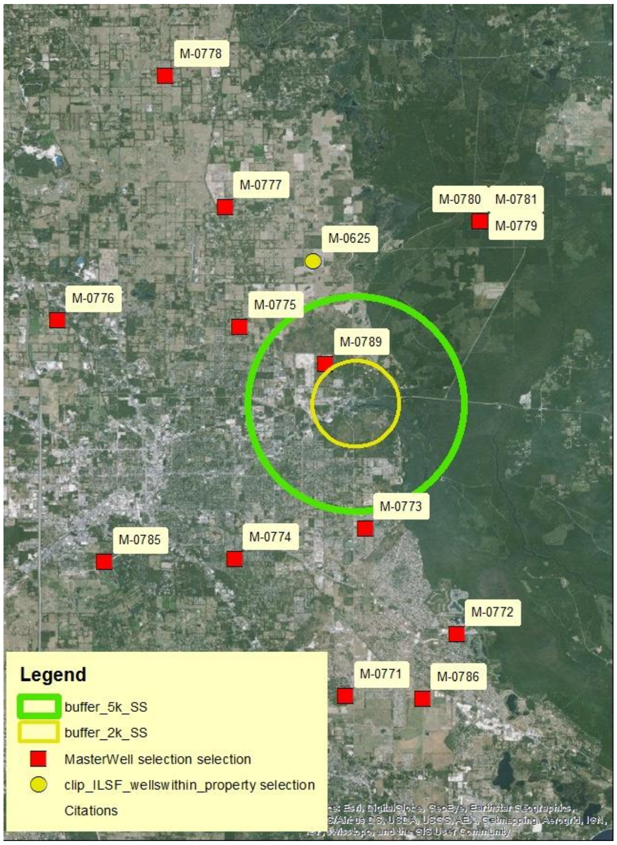


Figure 4 Map of wells where PFM's were installed

Borehole dilution test

BHD test has been performed in 4 wells, all of these wells are within a 5km distance north from the Silver Springs main boil. A total of 19 BHD tests have been performed, the number of tests on each well ranged from 2 in M625 to 9 in M0789. We have tested five conduits, the rest of tests have been performed in matrix sections of the well.

Well M-0789

Borehole dilution was performed on well M789 May9-May27. The first five tests were in matrix region of the well, KCl was used as the only tracer to do this test. The sixth depth is conduit region of the borehole, this test was performed using KCl and Rhodamine, the test was run in triplicate to ensure that the test was run consistently.

Test Number	Depth (ft bls)	KCl q(cm/day)	Rhodamine q (cm/day)
1	69-79	16.0	
2	79-89	28.4	
3	89-99	2.6	
4	99-109	1.0	
5	107-117	1.2	
6-1	120-130	1030.2	775.0
6-2	120-130	869.5	1014.3
6-3	120-130	885.8	1040.2

Table 2 Darcy fluxes for well M0789

Well M-0820

This well is located in the Silver Springs Forest Conservation area. BHD test was performed on August 10-18, at four different depths. Video logs indicated that these intervals would most likely have matrix properties and our test confirmed so. This well was tested on the entirety of its borehole, 20 ft, via 4 tests of 5ft each.

		KCl		Rhodamine	
Test Number	Depth (ft)	Slope	q (cm/day)	Slope	q (cm/day)
1	103-98	-0.0061	40.1	-0.0081	53.3
2	98-93	-0.00584	38.4	-0.0088	57.9
3	93-88	-0.00342	22.5	-0.0053	34.9
4	88-83	-0.00165	10.8	-0.0035	23.0

Table 3 Darcy fluxes for well M0820

Sprayfield well

This well was tested on July 19, based on video logs we decided to only do four 5ft intervals. The matrix intervals were 90-85 and 85-80 ft below ground surface. While the latter two tests 77-72 and 67-62 were performed in conduit sections of the borehole.

Test Number	Depth (ft)	Predominant Porosity	Slope	q (cm/day)
1	90-85	Matrix	-0.00611	40.2
2	85-80	Matrix	-0.01024	67.3
3	77-72	Conduit	-0.02944	193.6
4	67-62	Conduit	-0.04911	323.0

Table 4 Darcy fluxes for Sprayfield well

Well M-0625

This well is located in Indian Lake State Forest and has a total depth of 193ft below ground surface, there are two regions that have been identified, via video log, as areas with conduit flux. Both of those areas were tested, the test was cut short as the original plan was to test two depth with matrix flux, however the top packer of the KBHD got punctured by the borehole.

Well Number	Test Number	Test_Well _depths	Predominant Porosity	Slope	q (cm/day)
M0625	Test_1	111-117ft	Conduit	-0.4005	3636.8
M0625	Test_2	111-117ft	Conduit	-0.3952	3588.7

Table 5 Darcy fluxes for well M6025

Water sampling of matrix and conduit regions of borehole

After performing BHD in matrix and conduit sections of wells, we proceeded to sample background NO3 concentrations from these areas using a SUNA (Submersible Ultraviolet Nitrate Analyzer, Satlantic) device. We used the KBHD device to isolate sections, once the packers were inflated we purged 5 borehole volumes and then connected the SUNA to the water purge line and collected data for half hour. This procedure was done through wells M789 (5 depths) and Sprayfield well (4 depths).

Results and Discussion

Dye trace studies

The distribution of water velocities measured by by KES in 2010 and Knochenmus (1967) in the Silver Springshed, are plotted below. The majority of travel times are below 400 m/day, while each one of these studies saw an outlier with water velocities above 700 m/day.

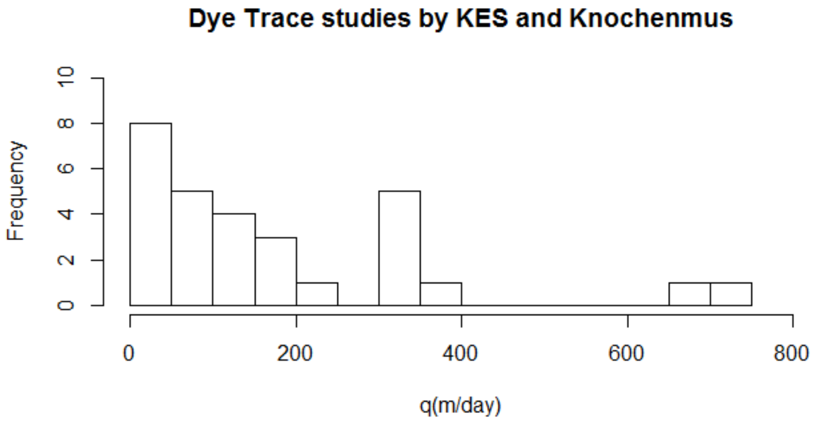


Figure 5 Water velocities from KES and Knochenmus study

Passive flux meters

Passive flux meters have been deployed in 16 wells in the UFA throughout the Silver Springshed. PFMs deployed in this project had three layers of GAC, thus the variability in q on the chart below, some wells had more than one PFM installed in them which contributed to larger ranges of q. Regardless of the distance between Silver Springs (top x axis) and each well, q did not exceed 10 cm/day in any of the tested wells.

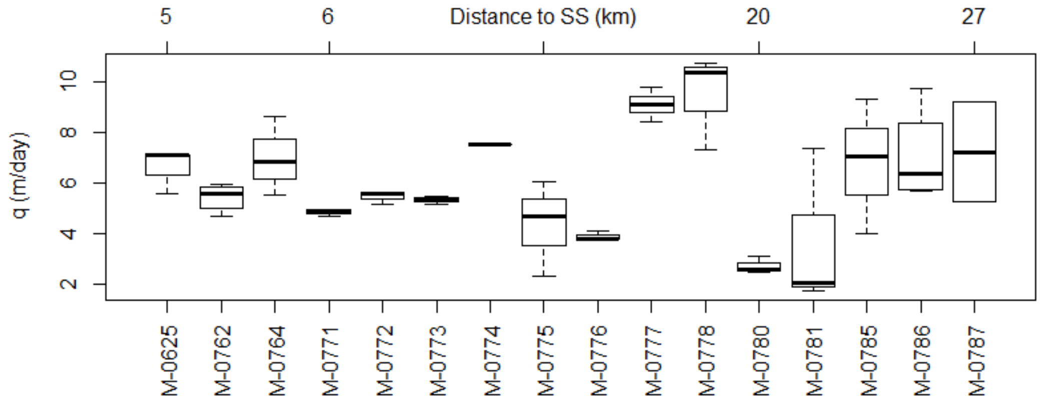


Figure 6 Darcy fluxes from well within Silver Springshed

The PFMs detected NO3 in only four out of 16 wells, however data from SJRWMD have shown discrepancies with PFM derived NO3 concentrations, see table below with NO3-N derived from PFM's, water samping performed by UF and water samples from SJRWMD.

Well	Section of PFM	Average of Darcy Velocity (cm/day)	Average of NO3 (mg/L) as N
M-0625	4B625	5.575	4.943
	4M625	7.103	2.573
	4T625	7.094	0.000
M-0762	M-762 B	5.217	0.000
	M-762 M	5.202	0.000
	M-762 T	5.808	0.000
	SJR-Water Sample		0.009
M-0764	M-764 B	8.654	0.000
	M-764 M	6.833	0.000
	M-764 T	5.514	0.000
	SJR-Water Sample		0.009
M-0771	771B	4.952	18.242
	771M	4.913	15.985
	771T	4.677	0.000
	SJR-Water Sample		9.320
	UF-water sample		8.965
M-0772	772B	5.609	0.000
	772M	5.189	0.005
	772T	5.662	0.000
	SJR-Water Sample		0.365
	UF-water sample		0.333
M-0773	773B	5.479	0.000
	773M	5.386	0.000
	773T	5.188	0.005
	SJR-Water Sample		1.709
	UF-water sample		1.602
M-0774	4B774	7.525	0.000
	4M774	7.558	0.000
	4T774	7.549	0.000
	SJR-Water Sample		2.344
M-0775	M-775B	2.312	0.000
	M-775M	4.711	0.013
	M-775T	6.040	0.000
	SJR-Water Sample		0.273
M-0776	4B776	3.793	0.000
	4M776	4.093	0.000
	4T776	3.759	0.005
	SJR-Water Sample		13.853
M-0777	M-777B	9.779	0.000
	M-777M	9.122	0.000
	M-777T	8.446	0.000
	SJR-Water Sample		0.107
M-0778	778B	10.398	0.011
	778M	10.737	0.002
	778T	7.313	0.000
	SJR-Water Sample		0.365
	UF-water sample		0.239
M-0779	SJR-Water Sample		0.009
M-0780	4B780	2.572	0.000
	4M780	2.463	0.000
	4T780	3.140	0.000
	SJR-Water Sample		0.004
M-0781	4B781	7.365	0.000
	4M781	1.761	0.000
	4T781	2.082	0.000
	SJR-Water Sample		0.001
M-0785	785B	4.019	0.000
	785M	7.043	0.291
	785T	9.300	0.000
	SJR-Water Sample		0.874
	UF-water sample		0.744
M-0786	4B786	5.711	0.000
	4M786	5.778	0.000
	4T786	6.989	0.000
	4T787	9.750	18.844
M-0787	4B787	9.202	20.601
	4M787	5.254	47.949

Table 6 Darcy flux and nitrate from several sources for tested wells

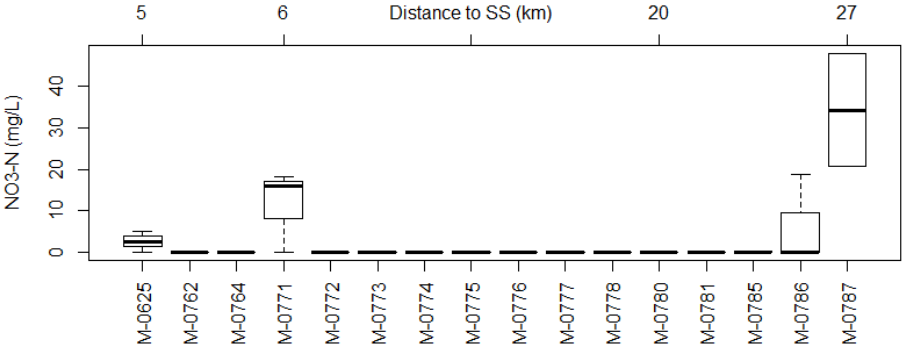
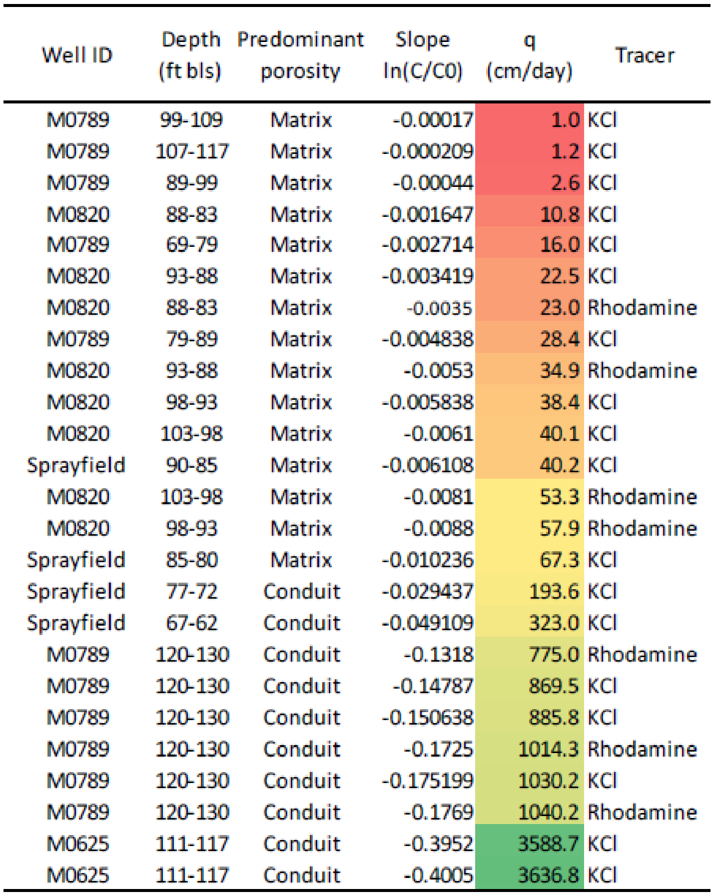


Figure 7 PFM derived nitrate concentrations for tested wells

Borehole dilution tests

Borehole dilution tests were performed in four wells within a 5km radius from Silver Springs between May and October 2016. Every test was performed at several depths in each well, consequently the large variety of q values derived from the test. BHD tests were performed in both matrix and conduit zones, identified from fractures visible in borehole videos, within each well with the exception of M820 which did not have any fractures or indications of high flux zones.

For this analysis we considered q > 1 m/day conduit flux while q below this rate was considered matrix flux. Based on this bimodal analysis we have found four locations characterized as conduit flux.



Well ID	Depth (ft bls)	Predominant porosity	Slope ln(C/C0)	q (cm/day)	Tracer
M0789	99-109	Matrix	-0.00017	1.0	KCl
M0789	107-117	Matrix	-0.000209	1.2	KCl
M0789	89-99	Matrix	-0.00044	2.6	KCl
M0820	88-83	Matrix	-0.001647	10.8	KCl
M0789	69-79	Matrix	-0.002714	16.0	KCl
M0820	93-88	Matrix	-0.003419	22.5	KCl
M0820	88-83	Matrix	-0.0035	23.0	Rhodamine
M0789	79-89	Matrix	-0.004838	28.4	KCl
M0820	93-88	Matrix	-0.0053	34.9	Rhodamine
M0820	98-93	Matrix	-0.005838	38.4	KCl
M0820	103-98	Matrix	-0.0061	40.1	KCl
Sprayfield	90-85	Matrix	-0.006108	40.2	KCl
M0820	103-98	Matrix	-0.0081	53.3	Rhodamine
M0820	98-93	Matrix	-0.0088	57.9	Rhodamine
Sprayfield	85-80	Matrix	-0.010236	67.3	KCl
Sprayfield	77-72	Conduit	-0.029437	193.6	KCl
Sprayfield	67-62	Conduit	-0.049109	323.0	KCl
M0789	120-130	Conduit	-0.1318	775.0	Rhodamine
M0789	120-130	Conduit	-0.14787	869.5	KCl
M0789	120-130	Conduit	-0.150638	885.8	KCl
M0789	120-130	Conduit	-0.1725	1014.3	Rhodamine
M0789	120-130	Conduit	-0.175199	1030.2	KCl
M0789	120-130	Conduit	-0.1769	1040.2	Rhodamine
M0625	111-117	Conduit	-0.3952	3588.7	KCl
M0625	111-117	Conduit	-0.4005	3636.8	KCl

Table 7 Summary of Darcy fluxes from BHD tests

The BHD technique enables measuring q over the spectrum between PFM's and dye trace studies as PFM's can reliable measure very slow flux and dye trace studies have been used to measure high water velocities (>100 m/day), BHD can effectively measure q below 30 m/day.For instance the lowest q measured with the BHD 1 cm/day, well within the detectable range for PFM. The highest q measured through BHD was 35 m/day, which is also well within the low end results find through dye trace studies in the area.

A histogram of all the performed tests seem to have a travel time distribution of the gamma type.

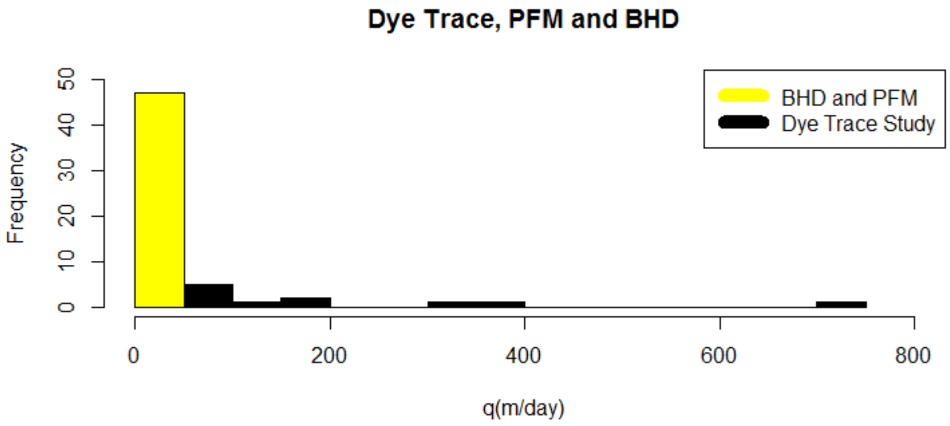


Figure 8Water velocities and fluxes from tested wells

Nitrate concentrations from isolated sections of conduit and matrix

Water quality for isolated sections of the aquifer seems to not show a stark difference in the NO3 concentrations in conduits vs matrix. The regions between 62-67 ft and 72-77 ft in the Sprayfield well and in the 119 to 129 ft range in well M789 do not behave in a consistent way with respect to their matrix counterparts within each well. For instance, NO3 in the conduit sections of the Sprayfield well are larger than matrix, while the opposite case holds truth for well M789. It is interesting to notice that these two wells are at a 200 meter distance from each other, yet the Sprayfield well has a NO3 concentration 4 times higher than M789.

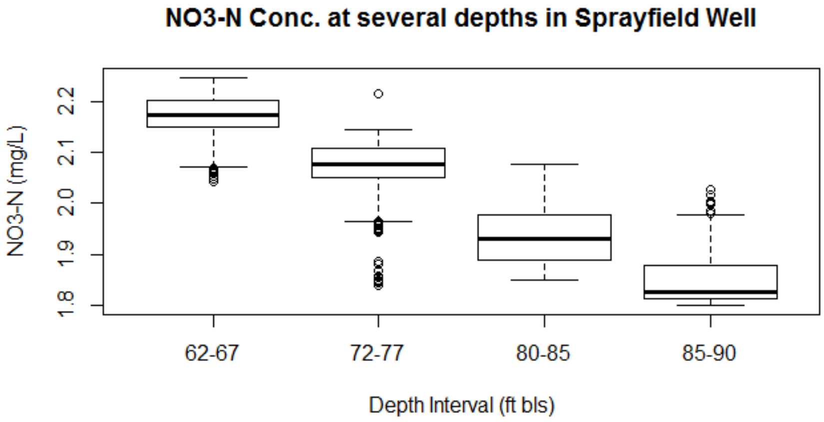


Figure 9 Nitrate concentrations in Sprayfield Well

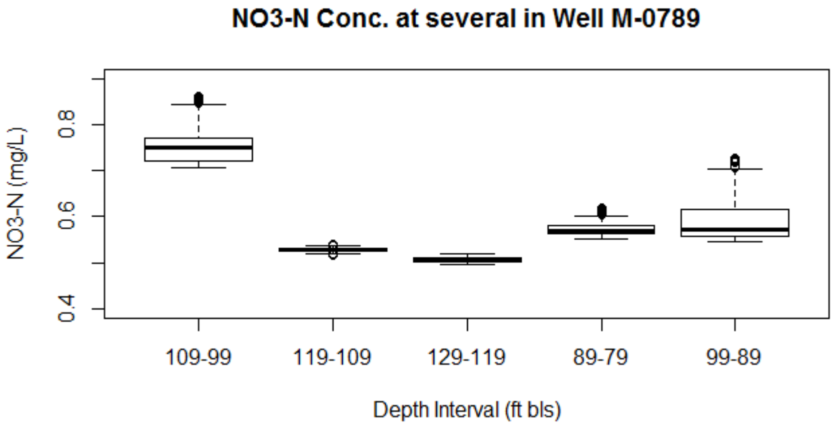


Figure 10 Nitrate concentrations in well M0789

Water and nutrient mass discharge from Silver Springs

Data from the dye trace studies were reviewed along with water flux measurements made with PFM's and BHD tests throughout the Silver Springshed. All of these tests resulted on a range of water velocities that ranged from 0.01 m/day to 700 m/day.

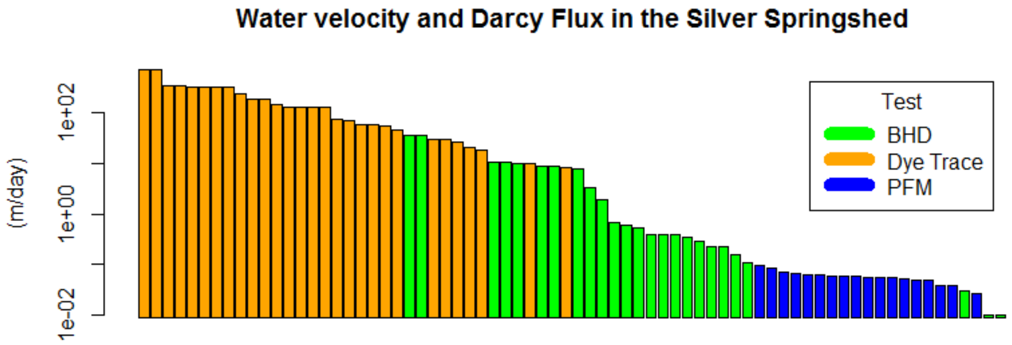


Figure 11 Summary of all measured water velocities and fluxes through the Silver Springshed

References

Annable, M.D., Hatfield, K., Cho, J., Klammler, H., Parker, B.L., Cherry, J.A., Rao, P.S.C., 2005. Field-scale evaluation of the passive flux meter for simultaneous measurement of groundwater and contaminant fluxes. Environ. Sci. Technol. 39 (18), 7194–7201

Bradner, L.A., and Knowles, Leel, Jr., 1999, Pontentiometric surface of the Upper Floridan aquifer in the St. Johns River Water Management District and vicinity, May 1999: U.S. Geological Survey Open-File Report 99-608, 1 map sheet.

Drost,W., Klotz, D., Koch, A., Moser, H., Neumaier, F., Rauert,W., 1968. Point dilution methods of investigating ground water flow by means of radioisotopes. Water Resour. Res., 4 (1), 125–146.

Faulkner, G. L., 1973, Geohydrology of the Cross-Florida Barge Canal Area, with Special Reference to the Ocala Vicinity, Water-Resource Investigations Report 1-73, Tallahassee, Fl: U. S. Geological Survey.

Florida Springs Task Force. 2000. Florida's springs – strategies for protection and restoration. Prepared for Florida Department of Environmental Protection and the citizens of the state of Florida.

Hatfield, K.; Annable, M. D.; Cho, J.; Rao, P. S. C.; Klammler, H. A direct method for measuring water and contaminant fluxes in porous media. J. Contam. Hydrol. 2004, 75, 155-181.

Hicks, Richard, Debra Harrington, Gary Maddox, 2009, Documentation to Support Listing of Nutrient Impaired Springs and Spring Runs. Tallahassee Fl: Florida Department of Environmental Protection

Knight, R. L. 1980. Energy basis of control in aquatic ecosystems. Ph.D. dissertation, University of Florida, Gainesville, FL.

Knochenmus, D.W., 1967, Tracer studies and background fluorescence of ground water in the Ocala, Florida, area: U.S. Geological Survey Open-File Report 67004, 35 p.

Knowles, Leel, 1996, Estimation of evapotranspiration in the Rainbow Springs and Silver Springs basins in northcentral Florida: U.S. Geological Survey Water- Resources Investigations Report 96-4024, 37 p.

McGurk, B.E., J.B. Davis, J.A. Stokes, D.J. Toth, W. Colona, and P. Butt. 2011. Silver Springs Nutrient Pathway Characterization Project. Prepared for Florida Department of Environmental Protection, Tallahassee, FL

Motz, L.H. and A. Dogan. 2002. Regional steady-state groundwater flow model with an active water table. Annual Water Resources Conference, American Water Resources Association, Philadelphia, PA.

Munch, D.A., Toth, D.J., Huang, Ching-tzu, Davis, J.B., Fortich, C.M., Osburn, W.L., Philips, E.J., Allen, M.S., and Knight, R.L., 2006, Fifty-Year Retrospective Study of the Ecology of Silver Springs, Florida. A report prepared for Florida Department of Environmental Protection, Special Publication SJ2007-SP4. Palatka Fl: St Johns River Water Management District.

Odum, H. T. 1957a. Trophic structure and productivity of Silver Springs, Florida. Ecological Monographs 27:55-112.

Odum, H.T. 1971. Environment, Power, and Society. New York: Whiley-Interscience.

Phelps, G. G. 1994. Hydrogeology, Water Quality, and Potential for Contamination of the Upper Floridan Aquifer in the Silver Springs Ground-Water Basin, Central Marion County, Florida: Water-Resources Investigations Report 92-4159. Tallahassee, Fl: U. S. Geological Survey.

Pitrak, M., Mares, S. & Kobr, M. (2007) A simple borehole dilution technique in measuring horizontal ground water flow. Ground Water, 45, 89-92

Sepúlveda, Nicasio, 2002, Simulation of ground-water flow in the intermediate and Floridan aquifer systems in peninsular Florida: U.S. Geological Survey Water- Resources Investigations Report 02-4009, 130 p.

Tibbals, C.H., 1975, Aquifer tests in the Summit reach of the proposed Cross-Florida Barge Canal near Ocala, Florida: U.S. Geological Survey Water-Resources Investigations 28-75, 42 p.