Land use changes and groundwater quality in Florida

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Abstract

Land use changes around 26 karstic cave–spring systems in Florida were evaluated using geographic information system. Located in the unconfined or semiconfined zones of the Floridan aquifer, some of the cave–spring systems are directly connected to the surficial land use processes by sinking streams, whereas others receiving diffuse recharge are still vulnerable to contamination due to a thin sandy cover overlying the aquifer. Comparison of nitrate-producing land use practices between 2004 and 2013–2014 shows increasing risks of groundwater contamination in the Floridan aquifer. Proliferation of septic systems and wastewater treatment sites due to growing residential areas, increased use of fertilizers for farming and landscaping stand out as major causes of nitrate overload in the both surface and groundwater.

Keywords Nitrate · Karst · Floridan aquifer · GIS · Groundwater contamination

Introduction

As the largest liquid freshwater reservoir of our planet, groundwater has been under stress in terms of both quantity and quality. Overpumping to meet the demands of the rapidly growing population in urban areas, coupled with frequent droughts in many parts of the world, has put a substantial stress on groundwater reservoirs. Unsustainable exploitation of aquifers resulted in groundwater mining and seawater intrusion in coastal aquifers. Moreover, groundwater quality has been profoundly impaired not only by point contamination sources such as industrial or municipal waste repositories, but also by nonpoint contamination events such as widespread application of fertilizers and a wide range of chemicals for increased agricultural production (Ki et al. 2015; Wongsabit et al. 2015; Kihumbal et al. 2016; Elisante and Muzuka 2017).

Groundwater contamination becomes much more severe and difficult to deal with in karst aquifers due to their unique groundwater storage and flow characteristics. First, karst aquifers are directly connected to surficial process via dolines, swallets, and disappearing streams. Second, most groundwater flow takes place in enlarged cavities and

conduits with no natural filtration and attenuation of the pollutants. Third, groundwater flow occurs in a dual-porosity medium, i.e., both in matrix and conduit porosity, with drastically different groundwater flow path lengths and residence times. Fourth, contamination plumes may travel much faster than conventional aquifers (COST Action 2004).

In addition to these features of vulnerability, groundwater flow and contaminant transport modeling in karst aquifers require unique approaches. Their anisotropic and heterogeneous structures do not allow them to be adequately characterized by conventional Darcian groundwater flow models (Hartmann et al. 2014).

These unique properties of karst aquifers and the their subsequent vulnerability to groundwater contamination caused by land use practices have been widely addressed in scientific literature (e.g., Lan et al. 2015; Guo et al. 2006; Hasenmuller et al. 2006; Jiang and Yan 2010). A typical case of rapid groundwater flow in a karst aquifer and contamination in municipal wells is reported by Worthington et al. (2002). They discuss the widespread distribution of pathogens due to rapid groundwater flow without attenuation or filtering within the enlarged conduits of the aquifer. In a similar case, Quinlan (1983) discusses rapid and extensive distribution of contamination within the karstic aquifer of the Sinkhole Plain in Kentucky. In addition to a great deal of research on karst groundwater contamination, many studies focused on groundwater protection and management of karst aquifers (Boyer and Pasquarell 1999; Plagnes and

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Bakalowicz 2001; Boyer 2005; Jimenez-Madrid et al. 2012; Eftimi and Zojer 2015; Vallejos et al. 2015).

As one of the major karst aquifers in the world, the Floridan aquifer has been under substantial stress that threatens to impair the groundwater quality and quantity mainly due the population growth from about two millions in 1940s to more than 21 millions (<http://worldpopulationreview.com/states/florida-population/>). An increasingly common cause of surface and groundwater quality impairment in Florida has been the documented steady increase of nitrate over the past several decades (Jones et al. 1996; Champion and DeWitt 2000; Hornsby et al. 2004). Copeland et al. (2011) show 19-fold increase in nitrate concentrations in 13 selected first-magnitude springs between the 1970s and 2000. A plant nutrient along with phosphorus, carbon, potassium, and iron, nitrate is essential for a healthy ecosystem. However, anthropogenic nutrient overload results in excessive growth of algae, and consequently in eutrophication, a growing problem in Florida's surface and spring waters (Edwards et al. 2006; Hefernon et al. 2010; Fulton et al. 2015; Lapointe et al. 2015).

Many studies have attempted to identify the sources and the land use practices that cause nutrient overload in Florida's springs and lakes. In general, most of them state that common sources of nitrate include fertilizers and organic waste that originate from areas of livestock, septic tanks, and wastewater treatment plants. For example, in their study on the nonpoint source pollution in Lower St. Marks–Wakulla River Watershed in Florida, Chelette et al. (2002) cite on-site disposal systems such as septic tanks and cesspits, livestock and commercial fertilizers to explain a threefold increase in total nitrate discharged from the Wakulla springs in the last 25 years. In a later study of the Wakulla Springs area, Eller and Katz (2014) report that septic tanks contribute more nitrogen to groundwater, comprising 51% of the total nitrogen loads. They cite farm fertilizer as the leading source of nitrogen in areas where the Floridan aquifer is confined. Similarly, in their study on the nitrate concentration within the Suwannee River Water Management District, Upchurch et al. (2007) cite two major sources of nitrogen: (1) application of fertilizers to cropland, i.e., land use practices such as row crops, pastures, and groves, and turf such as lawns and golf courses, and (2) animal wastes, including wastes from feedlots, septic tanks, wastewater treatment, and other sources.

Notwithstanding the preponderance of studies on Florida's water quality, mostly reporting an alarmingly increasing trend of nutrient overload due to certain land use practices, there has not been much attempt to determine the land use changes over time. Overall, a statewide urbanization due to population growth can be readily observed, but there is

not much information about the extent of nutrient-loading land use changes around cave–spring systems. In this study, land use changes around major cave–spring systems between 2004 and 2013–2014 are examined as potential causes of nutrient overload in the Floridan aquifer groundwater.

Study area and hydrogeologic setting

The study area covers 26 cave–spring systems in Florida (Fig. 1). These systems represent well-developed sink-hole–cave–spring continuum within the karstic Floridan aquifer.

The Florida carbonate platform is composed of a thick sequence of variably permeable limestone and dolostone, deposited in a stable passive continental margin through most of the Paleogene. Extensively karstified carbonates with high primary porosity give rise to the Floridan aquifer, a prolific aquifer that enjoys abundant recharge from the subtropical rainfall pattern of the area. In much of Florida and Georgia, the Floridan aquifer is confined by a varying thickness of siliciclastic material (Miller 1986). Generally, the confinement provides hydrologic decoupling of the aquifer from surficial contamination sources. Groundwater recharge in the confined area occurs through collapse and subsidence dolines that act as karstic windows to the aquifer by breaching the confining layer.

Impermeable siliciclastic sediments that comprise the confining unit deposits have been entirely or partially eroded along the Suwannee River, resulting in unconfined conditions where the aquifer is directly impacted by surficial process (Miller 1997; Williams and Kuniansky 2016) (Fig. 2). Here, recharge to the Floridan aquifer takes place either by diffuse recharge through a thin sand layer or by point recharge where allogenic streams encounter the carbonate rocks (Upchurch and Lawrence 1984). Unlike many other karst aquifers, the Floridan aquifer has significant primary (matrix/intergranular) and the secondary (conduit) porosities. This dual porosity brings about two different groundwater flow regimes: Darcian flow within the intergranular medium and turbulent and non-Darcian flow within the dissolutional conduits.

Data and methods

This study is based on geographic information system (GIS) analyses of the spatial data. GIS has been widely applied to groundwater contamination studies to determine potential

Fig. 1 Cave/spring locations

Fig. 2 Cave/spring locations and the Floridan aquifer confinement

zones of vulnerability to surficial contamination (Stark et al. 1999; Davis et al. 2002; Capri et al. 2009; Sener and Davraz 2013; Jasrotia and Kumar 2014; Edet 2014; Tokatli 2014; Barroso et al. 2015; Bozdog 2015), or to create interactive karst databases (see Gao and Zhou (2008) for a review of GIS applications to karst). Regarding the land use impact on groundwater quality, Khan et al. (2011, 2017) discuss two case studies of GIS application to calculate groundwater quality index and to prepare a map of groundwater sustainability in terms of water quality.

In Florida, GIS has been widely used especially by the State's Water Management Districts and the Florida Geological Survey. Among many publications and maps, a comprehensive GIS model developed by Arthur et al. (2005) can be named as a significant contribution to the assessment of the aquifer's vulnerability to contamination.

The method applied in this study involves a series of GIS operations to determine land use changes within 10 km of selected cave–spring systems between 2004 and 2013–2014

using ESRI's ArcGIS 10.2. The data used in this study are as follows:

Caves: The centerlines of cave–springs systems, located within the unconfined or semiconfined zones of the Floridan aquifer, were digitized by the author. An example of these data (Wakulla Cave/Spring System) is shown in Fig. 3. The data are in polyline and in point shapefile format.

Land use: 2004 and 2013/2014 Land Use data were obtained from Suwannee River and Northwest Florida Water Management Districts. They are created by the Florida Department of Environmental Protection's Bureau of Watershed Restoration, on Digital Ortho Quarter Quad Aerial Imagery program using color infrared and true color photography. They are in polygon format.

DEP cleanup sites: They are created by Florida Department of Environmental Protection (DEP) in point shapefile format.

The GIS analysis performed in this study consists of buffer and clip operations. In order to observe land use

Fig. 3 Wakulla cave passage centerline

Fig. 4 Land use within 10 km of Madison Blue cave passage centerline (2004)

changes around the cave systems, land use layers of 2004 and 2013–2014 were clipped by 10-km buffers around cave passages, and percentages of selected categories were compared (see Figs. 4 and 5 for land use clipped around Madison Blue cave/spring system). GIS was also used to determine the areal percentages of septic systems around the caves and to find the number of hazardous waste sites that are closest to each cave.

Results and discussion

As discussed above, elevated nitrate concentrations in Florida's springs and streams have been widely reported in scientific literature. In this study, available historic nitrate data obtained from the Suwannee River Water Managements District are presented in Fig. 6. Data are available for only

Fig. 5 Land use within 10 km of Madison Blue cave passage centerline (2013/14)

nine of the cave/spring systems selected for this study. There are increasing trends for all but Falmouth and Little River springs between early 1990s and 2013. Total nitrate concentrations are generally below 2.5 mg/l except for Convict springs with higher than 10 mg/l values repeatedly detected after late 2009.

A review of all the potentially nutrient-loading land use practices (Table 1) shows increasing trends for 14 cave–spring systems (Bonnet, Cathedral-Falmouth, Convict,

Devil's Ear, Green, Hart, Little River, Luraville, Madison Blue, Morgan, Peacock, Rock Bluff, Suwanacoochee, and Telford) (Table 2, Fig. 7).

Individual analysis of these land use practices reveals similar trends. Residential areas increase around all but two caves (Table 3, Fig. 8). Especially around Ginnie springs, there has been substantial amount of development. The cluster of Telford, Convict, Little River, and Blue Hole stands

Fig. 6 Total nitrate concentration changes in time for selected springs

Table 1 Land use categories

Land use code and description
1110: MDC—low density, fixed single-family units
1120: MDC—low density, mobile home units
1130: MDC—low density, mixed units (fixed and mobile home units)
1190: MDC—low density under construction
1210: Medium density, fixed single-family units
1220: Medium density, mobile home units
1230: Medium density, mixed units
1310: High density, fixed single-family units (> 6 DU/acre)
1320: High density, mobile home units
1330: High density, multiple dwelling units, low rise (three stories or less)
1350: high density, mixed units (fixed and mobile home)
1400: Commercial and services
1423: Junk Yards
1510: Food processing
1550: Other light industrial
1660: Holding ponds
1850: ODC—parks and zoos
2110: Improved pastures
2120: Unimproved pastures
2130: Woodland pastures
2140: Row crops
2150: Field crops
2153: Hay fields
2310: ODC—cattle feeding operations
2320: ODC—poultry feeding operations
2400: Nurseries and vineyards
2410: Tree nurseries
2430: Ornamentals
2500: RU—specialty farms
2510: ODC—horse farms
2520: MDC—dairies
3100: Range land, herbaceous (dry prairie)
3300: Mixed rangeland
8110: Airports
8140: Roads and highways
8320: Electrical power transmission lines
8340: MDC—sewage treatment

out with the largest increase in residential areas, whereas pasture lands have grown especially around Devil's Ear (6.6%), Peacock (4.3%), and Bonnet (4%) between 2004 and 2013–2014.

In Florida, application of inorganic fertilizers to agricultural lands such as row and field crops, and hay provide the most substantial input to groundwater (Harrington

Table 2 Total areal changes in potentially nutrient-loading land use categories

Cave	2004	2013–2014	Difference
Alachua	58.7	50.0	−8.7
Blue Hole	47.4	47.1	−0.3
Blue Jackson	44.3	40.5	−3.8
Bonnet	41.5	47.5	6.0
Cathedral-Falmouth	37.5	40.6	3.1
Convict	40.1	49.1	9.0
Devil's Ear	28.9	39.2	10.3
Ginnie	38.2	37.6	−0.6
Green	31.8	36.8	5.0
Hart	47.3	48.7	1.4
Indian	25.2	24.1	−1.1
Leon	20.1	19.9	−0.2
Little River	35.0	37.5	2.5
Luraville	38.4	44.3	5.9
Madison Blue	37.8	42.3	4.5
Manatee	24.3	22.7	−1.6
McBride	24.8	24.8	0.0
Morgan	31.9	37.1	5.2
Peacock	42.7	48.0	5.3
Rock Bluff	35.5	36.8	1.3
Sally	26.6	26.5	−0.1
Shepard	16.2	15.6	−0.6
Suwanacoochee	31.1	37.5	6.4
Telford	37.7	43.9	6.2
Vortex	23.9	22.0	−1.9
Wakulla	25.7	25.0	−0.7

et al. 2010). This study shows that agricultural lands have increased significantly around Suwanacoochee (6.7%) and Rock Bluff (4.4%) (Table 3). Moreover, 18 of the 26 caves show increasing rangeland areas within their 10-km buffers. Bonnet, Green, Peacock, Luraville, and Telford springs are among the largest increases in rangeland percentages.

Overall, Cathedral-Falmouth, Devil's Ear, Madison Blue, and Suwanacoochee show increased areal coverage in all of the four nutrient-loading land use categories: residential, pasture, rangeland, and agriculture (crop).

Other important potential nitrogen load sources such as golf courses, poultry and cattle feeding operations, and wastewater treatment plants are also compared. Table 4 lists the number of these sources around each cave. The numbers, instead of areal percentages, of the sources are listed as they do not cover substantial areas, but contribute significantly to the overall nitrogen load. It is alarming to note that the number of sewage treatment plants has increased dramatically

Fig. 7 Nitrate-producing land use changes around caves/springs (1: Wakulla, 2: Vortex, 3: Telford, 4: Suwanacoochee, 5: Shepard; 6: Sally's Ward, 7: Rock Bluff; 8: Peacock, 9: Morgan, 10: McBride, 11: Manatee, 12: Madison Blue, 13: Luraville, 14: Little River, 15: Leon;

16: Indian, 17: Hart; 18: Green, 19: Ginnie, 20: Devil's Ear, 21: Convict, 22: Cathedral-Falmouth, 23: Bonnet, 24: Blue Jackson, 25: Blue Hole; 26: Alachua)

within only 10 km of all but two caves. These domestic wastewater plants account for significant nitrate loads to groundwater (Chelette et al. 2002; Harrington et al. 2010).

Especially where the Floridan aquifer is unconfined or semiconfined, septic tanks, with their lower attenuation factors than other sources, provide potentially more nitrogen input to the Floridan aquifer. Due to the increased development around the cave–spring systems, the number and density of septic systems have also multiplied, significantly degrading the groundwater quality. The percentage of areas with septic systems around the caves calculated in this study are alarming (Table 5 and Fig. 9).

In addition to potentially harmful land use practices, spatial distribution of point contamination sources such as hazardous waste sites should be considered in assessing vulnerability of cave–spring systems to environmental stress.

This was attempted by a spatial join operation performed in GIS, revealing the number of closest Department of Environmental Protection (DEP) cleanup sites closest to each cave (Table 6 and Fig. 10). Leon cave system with an astonishing number of 206 cleanup sites stands out as the most vulnerable cave system in the study area.

Not only the type of contamination source and the contaminant characteristics, but also the recharge type and the groundwater flow prove to be critical for the Floridan aquifer groundwater quality. Many river and stream sites with significant declining nitrate trends are located where the Floridan aquifer is confined, whereas springs, located on the unconfined area around middle and lower Suwannee River, show increasing nitrate trends (Upchurch et al. 2007). This can be explained by the lack of efficient attenuation of nitrates as recharge occurs through a thin sandy soil cover

Table 3 Areal changes in selected land use categories

Cave	Res. 2004	Res. 2013–2014	Diff.	Pasture 2004	Pasture 2013–2014	Diff.	Crops 2004	Crops 2013–2014	Diff.	Range 2004	Range 2013–2014	Diff
Alachua	14.2	14.9	0.7	21.9	16.5	-5.4	12	13	1.0	1.8	2.1	0.3
Blue Hole	9.4	17.2	7.8	19.6	12.5	-7.1	7.3	6.3	-1.0	6.6	9.1	2.5
Blue Jackson	7.9	8.2	0.3	13.0	9.1	-3.9	19.5	17.0	-2.5	1.0	2.9	1.9
Bonnet	5.3	6.1	0.8	11.8	15.8	4.0	21.6	19.2	-2.4	0.5	4.6	4.1
Cathedral-Falmouth	5.9	6.0	0.1	11.7	11.8	0.1	13.5	15.2	1.7	2.8	5.0	2.2
Convict	5	11.0	6.0	12.1	13.6	1.5	18.8	18.7	-0.1	1.1	4.1	3.0
Devil's Ear	8.9	12.9	4.0	7.4	14.0	6.6	3.9	5.4	1.5	4.0	5.1	1.1
Ginnie	1.1	12.0	11	23.7	13.1	-10.6	4.2	5.9	1.7	8.1	5.4	-2.7
Green	4	4.6	0.6	10.5	11.4	0.9	14.7	14.7	0	0.7	4.7	4.0
Hart	14.3	17.3	3.0	14.5	13.0	-1.5	13.5	13.2	-0.3	2.6	3.1	0.5
Indian	17.4	18.4	1.0	2.7	2.1	-0.6	1.2	0.6	-0.6	2.6	1.5	-1.1
Leon	12.7	13.3	0.6	1.7	1.4	-0.3	0.9	0.4	-0.5	2.1	1.4	-0.7
Little River	3.7	7.3	3.6	16.3	12.1	-4.2	10.4	12.2	1.8	2.1	4.1	2.0
Luraville	5.1	5.8	0.7	11.4	15.2	3.8	18.5	16.8	-1.7	0.7	4.6	3.9
Madison Blue	3.3	3.8	0.5	10.1	10.8	0.7	20.1	21.8	1.7	2.9	4.3	1.4
Manatee	5.3	5.9	0.6	8.4	7.7	-0.72	6.1	5.0	-1.1	0.7	3.1	2.4
McBride	15.6	17.5	1.9	2.4	1.9	-0.5	1.5	0.7	-0.8	3.5	2.2	-1.3
Morgan	3.1	3.9	0.8	6.7	7.7	1.0	12.8	18.9	6.1	4.2	4.1	-0.1
Peacock	5.2	6.0	0.8	11.7	16.0	4.3	22.8	19.7	-3.1	0.5	4.5	4.0
Rock Bluf	4.7	6.6	1.9	17.3	12.3	-5.0	8.3	12.7	4.4	3.4	3.6	0.2
Sally's Ward	18.5	19.5	1.0	2.3	2.4	0.1	1.6	0.7	-0.9	2.8	1.7	-1.1
Shepherd	9.5	10.1	0.6	2.2	1.6	-0.6	1.7	0.9	-0.8	3.0	1.2	-1.8
Suwanacoochee	3.4	4.2	0.8	8.2	8.6	0.4	10.5	17.2	6.7	3.9	4.8	0.9
Telford	2.3	5.6	3.3	11.7	15.1	3.4	17.5	16.3	-1.2	0.8	4.5	3.7
Vortex	3.8	3.7	-0.1	8.6	6.5	-2.1	7.89	7.1	-0.79	2.4	2.9	0.5
Wakulla	16.3	17.0	0.7	3.1	2.4	-0.7	1.71	0.9	-0.81	2.8	2.4	-0.4

Fig. 8 Residential land use changes around caves/springs

material, concentrating into the epikarstic solution pipes before reaching the Floridan aquifer. On the other hand, contamination may also be critical and rapidly progressing when allogenic streams disappear within the swallets formed along the boundary between unconfined and confined areas.

Dual porosity and associated flow regimes in the Floridan aquifer are revealed by studies on the isotopic age of groundwater and by those that involve dye tracing experiments. Based on the groundwater age information, Katz et al. (2014) state that elevated nitrate concentration will persist in groundwater for decades even after substantial decreases in fertilizer *N*-input. As such, immediate improvements in

water quality are not expected, which is typical of Darcian flow conditions that occur within the intergranular (matrix) porosity of the Floridan aquifer. On the other hand, having performed a series of fluorescent dye tracing experiments, Kincaid et al. (2012) report much higher conduit flow velocities (677 to 971 ft/day) between the City of Tallahassee's wastewater spray field and Wakulla Springs.

In karst aquifers, groundwater quality is also affected by the hydraulic balance between the groundwater table and surface runoff, controlling the rate and extent of surface runoff recharge. Karst features may operate as springs or swallets depending on the hydraulic balance. As explained

Table 4 Number of selected land use categories

Name	Golf courses		Poultry feeding		Cattle feeding		Sewage treatment	
	2013	2013–2014	2013	2013–2014	2013	2013–2014	2013	2013–2014
Alachua	3	3	1	0	1	0	4	6
Blue Hole	1	1	2	3	1	0	0	2
Blue Jackson	2	2	0	0	1	3	2	3
Bonnet	0	0	40	35	16	4	2	3
Cathedral-Falmouth	0	0	43	28	2	1	2	6
Convict	0	0	35	32	19	9	2	3
Devil's Ear	0	0	2	1	0	0	0	6
Ginnie	0	0	2	1	0	0	0	3
Green	0	0	38	30	14	3	2	5
Hart	0	0	0	0	0	1	0	5
Indian	0	0	0	0	0	0	0	2
Leon	0	0	0	0	0	0	7	5
Little River	0	0	12	16	17	3	1	4
Luraville	0	0	45	39	15	4	2	3
Madison Blue	0	0	27	10	1	0	0	0
Manatee	1	1	1	0	4	4	1	2
McBride	0	0	25	11	2	1	3	5
Morgan	0	0	25	11	2	1	3	5
Peacock	0	0	46	38	14	4	2	3
Rock Bluff	0	0	5	2	1	1	0	0
Sally	0	0	0	0	0	0	3	4
Shepard	1	2	0	0	0	0	2	4
Suwanacoochee	0	0	20	11	1	1	3	5
Telford	0	0	37	35	16	4	2	3
Vortex	0	0	29	7	2	1	0	4
Wakulla	1	2	0	0	0	0	3	5

by Hensley and Cohen (2017), these episodic flow reversals play an important role in regulating the ecosystem state in Florida.

Protective measures have been taken to reduce particularly the agricultural nitrate input by promoting best management practices (BMP). Adopted by many commercial farms, the effectiveness of BMPs is still a topic of discussion (Currrens 2002; Prasad and Hochmuth 2016).

Conclusions

The assessment of land use changes around selected cave–spring systems confirms the existence of anthropogenic impact on the widely reported elevated nitrate concentrations in spring and surface waters of Florida. The water quality of the Floridan aquifer is under severe risk of impairment due to the substantial proliferation of nitrogen-producing land use practices around selected cave/spring

Table 5 Percentages of septic systems

Name	Septic area (%)
Alachua	40.3
Blue Hole	36.3
Blue Jackson	28.5
Bonnet	30.4
Cathedral-Falmouth	27.0
Convict	27.3
Devil's Ear	35.8
Ginnie	34.8
Green	29.7
Hart	34.8
Indian	32.6
Leon	27.8
Little River	24.4
Luraville	30.5
Madison Blue	25.6
Manatee	19.3
McBride	31.4
Morgan	21.0
Peacock	30.0
Rock Bluff	32.6
Sally	34.5
Shepard	19.1
Suwanacoochee	22.8
Telford	30.1
Vortex	26.5
Wakulla	32.1

Table 6 Cave/spring systems and the number of closest DEP cleanup sites

Cave	Number of DEP sites
Alachua	67
Blue Hole	43
Blue Jackson	0
Bonnet	0
Cathedral-Falmouth	32
Convict	1
Devil's Ear	9
Ginnie	0
Green	0
Hart	9
Indian	0
Leon	209
Little River	3
Luraville	1
Madison Blue	24
Manatee	7
McBride	24
Morgan	2
Peacock	0
Rock Bluff	1
Sally	0
Shepard	13
Suwanacoochee	0
Telford	1
Vortex	0
Wakulla	10

system, and significant number of hazardous waste sites in the area. This problem requires improvement on on-site disposal system technologies, continued long-term monitoring of stream and spring flow and quality, and, despite its varying degrees of success, implementation of BMPs, with particular emphasis on nitrogen-fixing agricultural practices.

This study also shows the importance of spatial databases on karst features that are compatible to GIS analyses.

In karst areas, not only common spatial data layers such as hydrology and land use/land cover, but also detailed inventories of karstic features such as caves and depressions are critical in environmental assessments and modeling studies.

Fig. 9 Percentage of septic systems around caves/springs

Fig. 10 DEP cleanup sites

Compliance with ethical standards

Conflict of interest The author declares that there is no conflict of interest.

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References

- Arthur JD, Baker AE, Clichon JR, Wood AR, Rudin A. (2005) Florida Aquifer Vulnerability Assessment (FAVA): contamination potential of Florida's principal aquifer systems, A report submitted to the Division of Water Resource Management, Florida Department of Environmental Protection, Florida Geological Survey, p 148
- Barroso MF, Ramalhosa MJ, Olhero A, Antao MC, Pina MF, Guimaraes L, Teixeira J, Afonso MJ, Delerue-Matos C, Chamine HI (2015) Assessment of groundwater contamination in an agricultural peri-urban area (NW Portugal): an integrated approach. *Environ Earth Sci* 73:2881–2894
- Boyer DG (2005) Water quality improvement program effectiveness for carbonate aquifers in grazed land watersheds. *J Am Water Resour Assoc* 41(2):291–300
- Boyer DG, Pasquarell GC (1999) Agricultural land use impacts on bacterial water quality in a karst groundwater aquifer. *J Am Water Resour Assoc* 36(2):291–300
- Bozdag A (2015) Combining AHP with GIS for assessment of irrigation water quality in Cumra irrigation district (Konya), Central Anatolia, Turkey. *Environ Earth Sci* 73:8217–8236
- Capri E, Civita M, Corniello A, Cusimano G, De Maio M, Ducci D, Fait G, Fiorucci A, Hauser S, Pisciotta A, Pranzini G, Trevisan M, Huertas AD, Ferrari F, Frullini R, Nisi B, Offi M, Vaselli O, Vasallo M (2009) Assessment of nitrate contamination risk: the Italian experience. *J Geochem Explor* 102:71–86
- Champion KM, DeWitt DJ (2000) Origin of nitrate in groundwater discharging from Crystal Springs, Pasco County, Florida: Brooksville. Southwest Florida Water Management District Report, p 191
- Chelette A, Pratt TR, Katz BG (2002) Nitrate loading as an indicator of nonpoint source pollution in the Lower St. Marks-Wakulla Rivers watershed. Northwest Florida Water Management District, Water Resources Special Report 02-1. p 138
- Copeland R, Doran NA, White AJ, Upchurch, SB (2011) Regional and statewide trends in Florida's spring and well groundwater quality (1991–2003). Florida Geological Survey, Bulletin No. 69 (Revised), p 393
- COST Action 620 (2004) Vulnerability and risk mapping for the protection of carbonate (karst) aquifers, Final Report (COST Action 620), Report EUR 20912, Directorate-General Science, Research and Development, European Commission, Office for Official Publications of the European Communities, Luxembourg, p 297
- Currens JC (2002) Changes in groundwater quality in a conduit-flow-dominated karst aquifer following BMP implementation. *Environ Geol* 42:525–531

- Davis AD, Long AJ, Wireman M (2002) KARSTIC: a sensitivity method for carbonate aquifers in karst terrain. *Environ Geol* 42:65–72
- Edet A (2014) An aquifer vulnerability assessment of the Benin Formation aquifer, Calabar, southeastern Nigeria, using DRASTIC and GIS approach. *Environ Earth Sci* 71:1747–1765
- Edwards TM, Miller HD, Guillette Jr. LJ (2006) Water quality influences reproduction in female mosquitofish (*Gambusia holbrooki*) from eight Florida springs. *Environ Health Perspect* 114 (suppl 1):69–75
- Eftimi R, Zojer H (2015) Human impacts on karst aquifers of Albania. *Environ Earth Sci* 74:57–70
- Elisante E, Muzuka ANN (2017) Occurrence of nitrate in Tanzanian groundwater aquifers: a review. *Appl Water Sci* 7:71–87
- Eller KT, Katz BG (2014) Nitrogen source inventory and loading estimates for the Wakulla spring BMAP contributing area. Florida Department of Environmental Protection, Tallahassee, p 56
- Fulton RS III, Godwin WF, Schaus MH (2014) Water quality changes following nutrient loading reduction and biomanipulation in a large shallow subtropical lake, Lake Griffin, Florida, USA. *Hydrobiologia* 753:243–263
- Gao Y, Zhou W (2008) Advances and challenges of GIS and DBMS applications in karst. *Environ Geol* 54:901–904
- Guo F, Jiang G, Yuan D (2006) Major ions in typical subterranean rivers and their anthropogenic impacts in southwest karst areas, China. *Environ Geol* 53:533–541
- Harrington D, Maddox G, Hicks PG (2010) Florida springs initiative monitoring network and recognized sources of nitrate. Florida Department of Environmental Protection, Division of Environmental Assessment and Restoration, Bureau of Watershed Restoration, Groundwater Protection Section, p 102
- Hartmann A, Goldscheider N, Wagener T, Lange J, Weiler M (2014) Karst water resources in a changing world: review of hydrological modelling approaches. *Rev Geophys* 52:218–242
- Hasenmuller NR, Buehler MA, Krothe NC, Comer JB, Branam TD, Ennis MV, Smith RT, Zamani DD, Hahn L, Rybarczyk JP, Harmon RS, Wicks CM (2006) Water-quality characteristics and contaminants in the rural karst-dominated Spring Mill Lake watershed, southern Indiana. Perspectives on karst geomorphology, hydrology, and geochemistry. The Geological Society of America Special Paper, Boulder, pp 153–167
- Heffernon TM, Liebowitz DM, Frazer TK, Evans JM, Matthew JC (2010) Algal blooms and the nitrogen-enrichment hypothesis in Florida springs: evidence, alternatives, and adaptive management. *Ecol Appl* 20(3):816–829
- Hensley RT, Cohen MJ (2017) Flow rehearsals as a driver of ecosystem transition in Florida's springs. *Freshw Sci* 36(1):14
- Hornsby D, Ceryak R, Zwanka W (2004) Groundwater quality & biological annual report, Suwannee River Water Management District, Live Oak, Florida, WR-04/05-05, p 48
- Jasrotia AS, Kumar A (2014) Groundwater quality mapping based on the geographical information system (GIS) of Jammu District, Jammu and Kashmir India. *J Spat Hydrol* 12(1):1–21
- Jiang Y, Yan J (2010) Effects of land use on hydrochemistry and contamination of Karst groundwater from Nandong underground river system, China. *Water Air Soil Pollut* 210:123–141
- Jimenez-Madrid A, Carrasco-Cantos F, Martinez-Navarrete C (2012) Protection of groundwater intended for human consumption: a proposed methodology for defining safeguard zones. *Environ Earth Sci* 65:2391–2406
- Jones GW, Upchurch SB, Champion KM (1996) Origin of nitrate in groundwater discharging from rainbow springs, Marion County, Florida: Brooksville, Southwest Florida Water Management District Report, p 155
- Katz BG, Berndt MP, Crandall CA (2014) Factors affecting the movement and persistence of nitrate and pesticides in the surficial and upper Floridan aquifers in two agricultural areas in the southeastern United States. *Environ Earth Sci* 71:2779–2795
- Khan HH, Khan A, Ahmed S, Perrin J (2011) GIS-based impact assessment of land-use changes on groundwater quality: study from a rapidly urbanizing region of South India. *Environ Earth Sci* 63:1289–1302
- Khan A, Khan HH, Umar R (2017) Impact of land-use on groundwater quality: GIS-based study from an alluvial aquifer in the Western Ganges basin. *Appl Water Sci* 7:4593–4603
- Ki M, Koh D, Yoon H, Kim H (2015) Temporal variability of nitrate concentration in groundwater affected by intensive agricultural activities in a rural area of Hongseong, South Korea. *Environ Earth Sci* 74:6147–6161
- Kihumbal AM, Longo JN, Vanclooster M (2016) Modelling nitrate pollution pressure using a multivariate statistical approach: the case of Kinshasa groundwater body, Democratic Republic of Congo. *Hydrogeol J* 24:425–437
- Kincaid T, Davies G, Werner C, DeHan R (2012) Demonstrating interconnection between a wastewater application facility and a first magnitude spring in a karstic watershed: tracer study of the Tallahassee, Florida Treated Effluent Spray Field, 2006–2007. Florida Geological Survey Report of Investigation No. 111, p 192
- Lan F, Qin X, Jiang Z, Meng R, Mo R, Yang S, Wang W, An S (2015) Influences of land use/land cover on hydrogeochemical indexes of Karst groundwater in the Dagouhe Basin, Southwest China. *CSAWAC* 43(5):621–786
- Lapointe BE, Herren LW, Deportoli DD, Vogel RA (2015) Evidence of sewage-driven eutrophication and harmful algal blooms in Florida's Indian River Lagoon
- Miller JA (1986) Hydrogeologic framework of the Floridan aquifer system in Florida and parts of Georgia, Alabama, and South Carolina. U. S. Geological Survey Professional Paper no. 1403-B, p 91
- Miller JA (1997) Hydrogeology of Florida. In: Randazzo AF, Smith DS (eds) The geology of Florida. University Press of Florida, Gainesville, pp 57–68
- Plagnes V, Bakalowicz M (2001) The protection of karst water resources: the example of the Larzac karst plateau (south of France). *Environ Geol* 40(3):349–358
- Prasad R, Hochmuth JG (2016) Environmental nitrogen losses from commercial crop production systems in the Suwannee River Basin of Florida. *PLoS ONE* 11(12):e017558. <https://doi.org/10.1371/journal.pone.0167588>
- Quinlan JF (1983) Groundwater pollution by sewage, creamery waste heavy metals in the Horse Cave area. Kentucky. In: Dougherty PH (ed) Environmental Karst. Geology and Speleology Publications, Cincinnati, p 52
- Stark SL, Nuckols JR, Rada J (1999) Using GIS to investigate septic system sites and nitrate pollution potential. *J Environ Health* 61(8):15–20
- Sener E, Davraz A (2013) Assessment of groundwater vulnerability based on a modified DRASTIC model, GIS and an analytic hierarchy process (AHP) method: the case of Egirdir Lake basin (Isparta, Turkey). *Hydrogeol J* 21:701–714
- Tokatli C (2014) Drinking water quality of a rice land in Turkey by statistical and GIS perspectives. *Pol J Environ Stud* 23(6):2247–2258
- Upchurch SB, Lawrence FW (1984) Impact of ground-water chemistry on sinkhole development along a retreating scarp. In: Beck BF (ed) Sinkholes: their geology, engineering & environmental impact. A.A. Balkema, Rotterdam, pp 23–28
- Upchurch SB, Chen J, Cain CR (2007) Trends of nitrate concentrations in waters of the Suwannee River Water Management District, 2007. SDII Global Corporation Project Number: 3017076, p.36
- Vallejos A, Andreu JM, Sola F, Pulid-Bosch A (2015) The anthropogenic impacts on Mediterranean karst aquifers: cases of some Spanish aquifers. *Environ Earth Sci* 74:185–189

- Williams LJ, Kuniandy EL (2016). Revised hydrogeologic framework of the Floridan aquifer system in Florida and parts of Georgia, Alabama, and South Carolina. In: USGS professional paper 1807 Version 1.1, p 140
- Wongsabti J, Teartisup P, Kerdsee P, Thatnpoohasiam P, Wroakhunpiset S (2015) Contamination of nitrate in groundwater and its potential human health: a case study of lower Mae Klong river basin, Thailand. *Environ Sci Pollut Res* 22:11504–11512
- Worthington SRH, Smart CC, Ruland WW (2002) Assessment of groundwater velocities to the municipal wells at Walkerton. In: Stolle D, Piggot AR, CrowderJJ (eds) *Proceedings of the 55th Canadian geotechnical and 3rd joint IAH-CNC and CGS groundwater specialty conferences*, Niagara Falls, Ontario, October 20–23, 2002, Southern Ontario section of the Canadian geotechnical society, pp 1081–1086

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