

Characterizing groundwater flow in a faulted karst system using optical brighteners from septic systems as tracers

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Abstract This study used optical brighteners (OB) released from septic systems to show that groundwater flow direction is largely controlled by the structural framework in a faulted karst groundwater system. Effective protection of groundwater resources requires that groundwater systems are adequately characterized and source water protection areas (SWPA) are developed for drinking water wells. Karst aquifers are among the most sensitive to contamination due to high recharge rates, and among the most difficult aquifers to characterize due to heterogeneity, and anisotropy. Because septic systems may be used to treat wastewater within SWPAs for karst aquifers there is a need to characterize these groundwater systems using tracers. The objective of this study was to characterize groundwater flow in a faulted portion of the Edwards aquifer in Bexar County, Texas using OB that are released as incidental tracers from septic systems. This study included measurement of water levels, sampling of groundwater and surface water, analysis for OB, and spatial analysis in a GIS. Results show that OB intensities were highest to the southwest of the septic area, a direction that is sub-parallel to the fault and fracture orientation and nearly perpendicular to the hydraulic gradient. This indi-

cates that movement of OB, solutes, or non-aqueous liquids/solids in a faulted karst system can be largely controlled by fault/fracture orientation and structural relay ramps.

Keywords GIS · Hydrogeology · Edwards aquifer

Introduction

The growth of agriculturally based and industrially based economies have been strongly affected by the availability and quality of water resources. Most economies rely on water resources for their development, and long-term prosperity is linked to the society's ability to develop, utilize, and protect their water resources (Department of Water Affairs and Forestry and Water Research Commission 1996). Parts of the gulf coast of Texas are highly likely to be faced with major water supply crises by the year 2025, while several other areas (e.g., San Antonio, TX and Austin, TX) are likely to have moderate to substantial water supply crises (US Bureau of Reclamation 2003). These urban centers rely on groundwater as the primary source of drinking water, while approximately 42% of the US population (Hutson et al. 2004) uses groundwater for drinking water supply.

Quantity of water available is often the emphasis of water resources studies (e.g., US Bureau of Reclamation 2003); however, the quality of water is of equal importance and has led to development of source water protection areas (SWPAs), and regulated activities within critical areas for recharge of regional aquifers. When siting wells for water supply or developing SWPAs for existing wells it is necessary to define groundwater flow direction and to quantify groundwater velocity. In homogeneous, isotropic,

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porous media (e.g., uniform sandstone) groundwater flow direction is perpendicular to the hydraulic gradient. Defining flow directions in heterogeneous and anisotropic media may be more challenging and require the use of groundwater tracers.

A groundwater tracer is a naturally occurring or introduced substance that travels with groundwater and can be detected at levels that differ from natural background levels. An ideal groundwater tracer is: non-toxic, inexpensive, easy to detect, non-reactive, conservative, and does not alter the natural direction of groundwater flow (Davis et al. 1980). Groundwater tracers can be generally categorized as suspended solids, dissolved solids, liquids, gases, or isotopes (Holmbeck-Pelham et al. 2000). Bromide, rhodamine, eosine, uranine, neon gas, potassium iodide, and deuterium are the most commonly used tracers (Davis et al. 1980; Holmbeck-Pelham et al. 2000; Sankaran et al. 2005; Smart and Karunaratne 2002).

In a karst region, groundwater and surface water typically constitute a single dynamic system as a result of numerous solution channels that facilitate the exchange of water between the surface and subsurface (Schindel et al. 1997). Unconfined karst aquifers may be recharged by precipitation and surface water infiltration via sinkholes, caves, or solution enlarged fractures and faults with little or no reduction of pollutants from the land surface. Based on mapping completed by Veni (1999, 2002) approximately 25% of the land surface in the US overlies karst; therefore, a large percentage of aquifers in the US are classified as karst and may require the use of groundwater tracers to characterize groundwater flow direction and velocity.

Dye tracers are commonly used to characterize groundwater flow direction and velocity in karst aquifers. Fluorescent dyes (e.g., rhodamine, uranine, etc.) are used because they are conservative (i.e., resistant to adsorption and degradation), non-toxic, and detectable at low concentrations (Mull et al. 1988). Dye tracer studies are usually completed in karst aquifers by injecting a dye into a karst feature (e.g., cave), flushing the dye with a large volume of water, sampling water from wells and surface water features in the vicinity of the injection point, and analyzing the samples for fluorescence by the dyes.

Some engineered systems are designed to leach wastewater (i.e., effluent) into the shallow subsurface and allow for biodegradation to reduce potential contaminants to acceptable levels before the effluent recharges an underlying aquifer. Decentralized wastewater systems (i.e., septic systems) serve approximately 25% of households in the U.S. (USEPA 2003) and contribute about 3.78 million ML/year of wastewater to the shallow subsurface (Frost et al. 2002). Effluent from septic systems contains several non-toxic chemicals (e.g., chloride, optical brighteners) that have the same characteristics as an ideal tracer, but the

concentration, timing, and exact location of septic effluent releases may be unknown.

Optical brighteners (OB) are a type of fluorescent dye added to most laundry detergents. Because the average person in North America and Europe uses about 23 kg of household detergents each year (Stumm 1985), OB are a measurable component of wastewater. When present on a substrate, OB absorb invisible ultraviolet light, which increases the energy state of the electrons in the molecule. The absorbed energy is then released from the OB as visible light, which makes the substrate appear brighter to the human eye. Because OB are used in common household detergents and not easily biodegraded (Mull et al. 1988) they can be released from septic tanks, mainly those that are malfunctioning, at an average concentration of 40 mg/l (Alhajjar et al. 1990) and transported through the vadose zone to the groundwater system. Hence, OB may be detectable in the groundwater and used to assess the migration of septic tank effluent. OB act similarly to conservative fluorescent dyes and are often analyzed as part of larger sampling efforts to assess water quality, and used to identify impacts of septic systems or leaky sewer pipes.

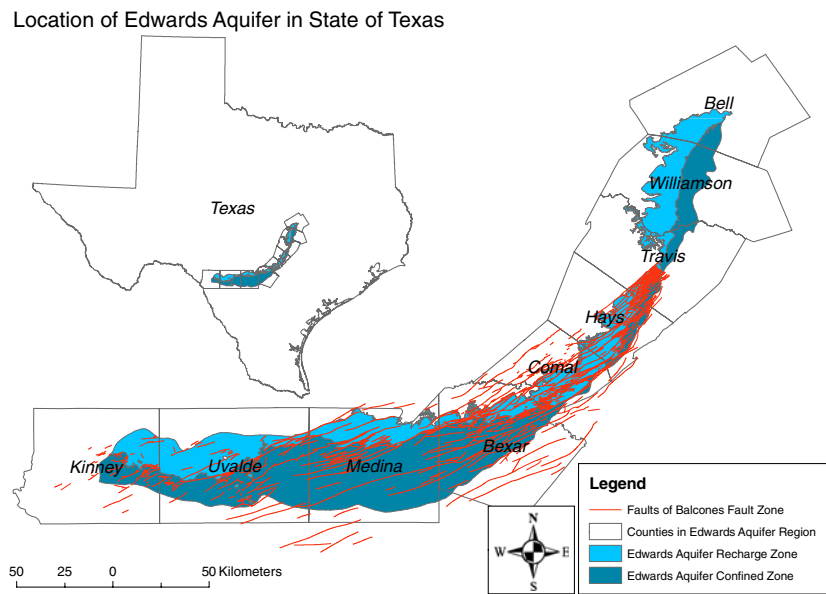
Objectives

Numerous karst aquifers have been characterized using controlled injections of dye tracers; however, few studies have evaluated the potential use of OB as incidental tracers. This study uses detectable levels of OB as tracers to characterize groundwater flow in a faulted karst aquifer, because they are incidentally part of septic tank effluent that is released in the shallow subsurface. The major objectives of this research are threefold: evaluate the presence or absence of OB in surface water and groundwater in a karst aquifer recharge area that contains septic systems; evaluate the relationship between OB detections and hydraulic gradient in a faulted karst aquifer; and relate groundwater flow direction, implied from OB detections, to local faulting and fracturing.

Regional hydrogeologic setting

The Edwards aquifer is one of the most permeable and productive karst aquifers in North America, and a primary water source for many communities in the south-central part of the state of Texas including the City of San Antonio (Sharp and Banner 1997). Matrix porosity of the Edwards aquifer units ranges from 5 to 15%, while transmissivity has been measured as high as 400,000 m²/day, but generally is less than 40,000 m²/day in the recharge zone (Macclay 1995). The aquifer extends 304 km across 12 counties from Kinney County in the west to Bell County in the northeast (see Fig. 1).

Fig. 1 Location and extent of Edwards Aquifer in south-central Texas, USA



The Edwards aquifer is named after the water-bearing carbonate formations belonging to the Edwards Group, a 131–155 m thick lower Cretaceous limestone and dolomite. The Georgetown Formation, primarily comprised of 18 m or less of dense, marly limestone (Pantea and Cole 2004), overlies the Edwards Group (Rose 1972). Because the Edwards Group and Georgetown Formation are hydraulically connected (Rose 1972) they constitute a single aquifer unit known as the Edwards and associated limestones (Arnow 1963). Relatively impermeable marl and limestone of the Glen Rose Formation underlies the Edwards Group and forms the lower confining unit of the Edwards aquifer (Rose 1972). It consists of hundreds of meters of thin, alternating beds of dense limestone, marl and evaporite deposits (Pantea and Cole 2004). South of the Balcones fault zone, the Edwards aquifer is under confined conditions due to the overlying, less permeable, limestone-shale-limestone sequences of the Del Rio and Buda Formations (Arnow 1963).

Uplift and exposure of the Edwards Group is due to discontinuous faults that trend northeast to southwest as part of the Balcones fault zone, which extends about 573 km from Del Rio on the US–Mexico border, eastward towards San Antonio and then northward to northeastern Texas (Ferrill et al. 2004). Many of the faults within this zone act as barriers to groundwater flow, while other fractures and associated joints form local and regional groundwater conduits (Sharp and Banner 1997). High-angle normal faults are the dominant structural feature of the region with most of the faults having a dip angle of greater than 60° (Ferrill et al. 2004) toward the down-dropped side of the fault blocks. Surface water generally flows to the southeast toward the Gulf of Mexico and crosses the

Edwards aquifer recharge zone, which coincides with the surface outcrop of the Edwards Group and is within the Balcones fault zone (shown in Fig. 1).

Description of study area

This study is focused on the incorporated City of Shavano Park in northern Bexar County, Texas (Fig. 2). Located 20 km north of downtown San Antonio, Shavano Park has a total area of 4.7 km² and a population of approximately 1,700. The principal water-bearing formation in northern Bexar County, and Shavano Park, is the Edwards and associated limestones (Arnow 1963). Shavano Park is predominantly located within the Edwards aquifer recharge zone, with near surface and exposed rock outcrops belonging to the cyclic, marine, leached, and collapsed members of the Person Formation within the Edwards Group (Stein and Ozuna 1996). The seven municipal wells in Shavano Park produce approximately 1.7 ML/day from the unconfined Edwards aquifer.

Single-family home lots in Shavano Park range in size from 0.05 to 2.36 ha with a mean of 0.41 ha. Wastewater is processed by septic systems on 700 out of a total of 1,217 single-family home lots, with most of the septic systems being located in the central part of Shavano Park (highlighted in Fig. 3). The density of septic systems is approximately 8.65 systems per hectare, which far exceeds the US Environmental Protection Agency (USEPA) guideline, of 0.15 systems per hectare (Yates 1985). Wastewater from the remaining lots and surrounding properties within the San Antonio city limits is piped to a municipal wastewater treatment facility outside the Shavano Park area.

Fig. 2 Location of City of Shavano Park in northern Bexar County, TX

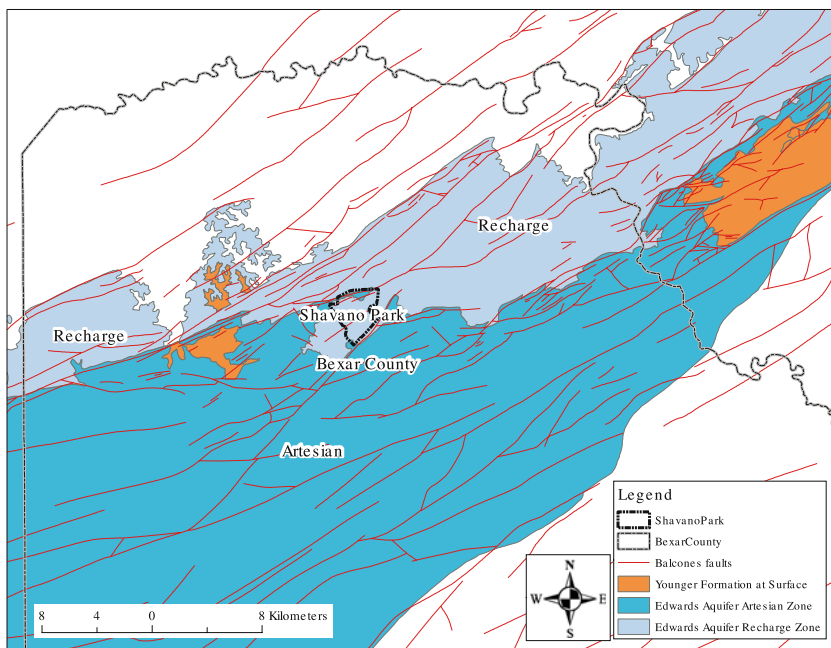
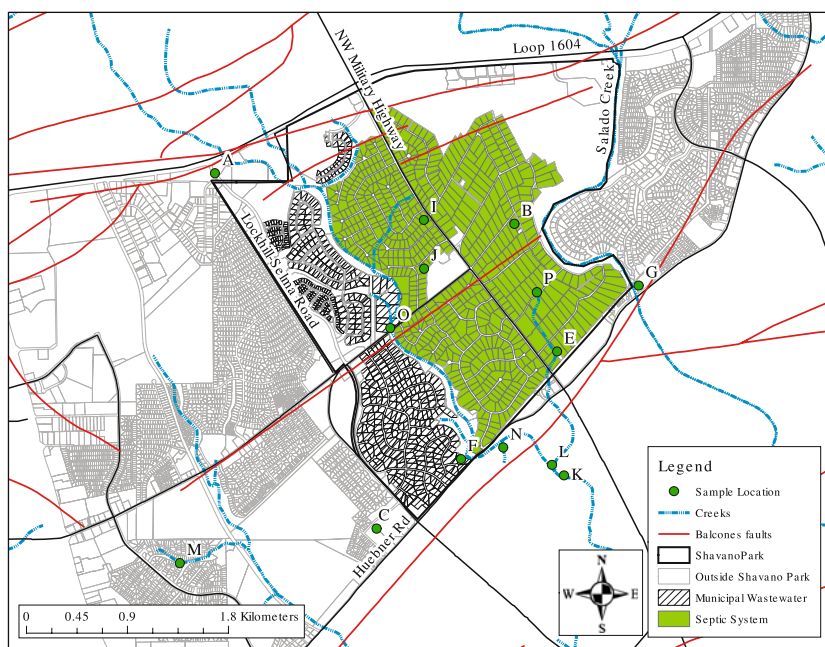


Fig. 3 Distribution of septic systems and single-family home lots in the City of Shavano Park and locations of OB samples



Materials and methods

Synoptic water level measurement

Water levels are measured on an approximate annual schedule in the Edwards Aquifer, including the Shavano Park study area, by the US Geological Survey (USGS) and the Edwards Aquifer Authority (EAA). During April 2005 water levels were measured (in conjunction with the EAA) in eight Shavano Park area wells (Fig. 4).

Sampling

Eleven Edwards aquifer monitoring wells (locations shown in Fig. 5), ranging in depth from 79 to 201 m below the ground surface, were sampled in April 2005 in the Shavano Park area. Two liters of water were collected from each monitoring well using a submersible pump and stored in amber colored glass bottles to minimize photodegradation of OB. Surface water was sampled from three intermittent creeks (locations shown in Fig. 5) within the upper Salado

Fig. 4 Measured water level elevations (m) and equipotential lines for April 2005 in a portion of the Edwards aquifer recharge zone, Bexar County, TX

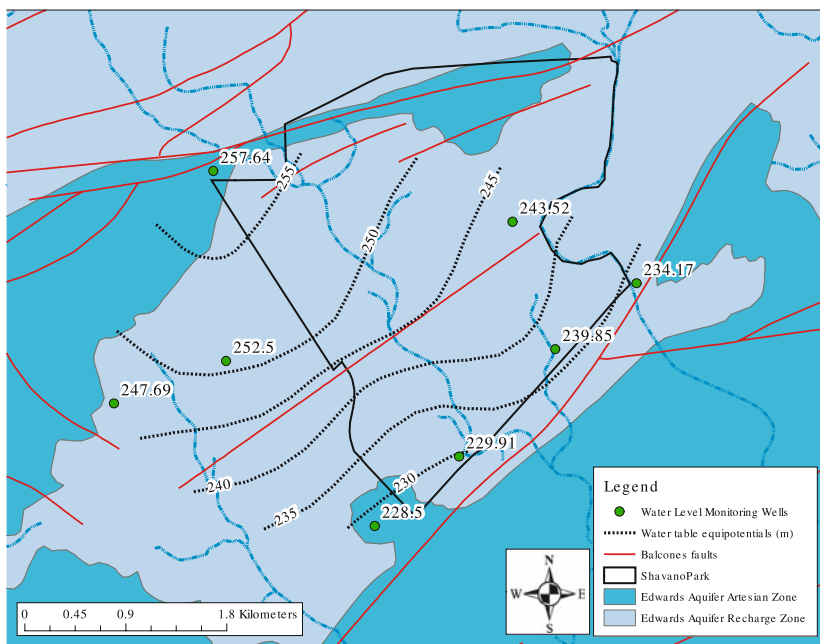
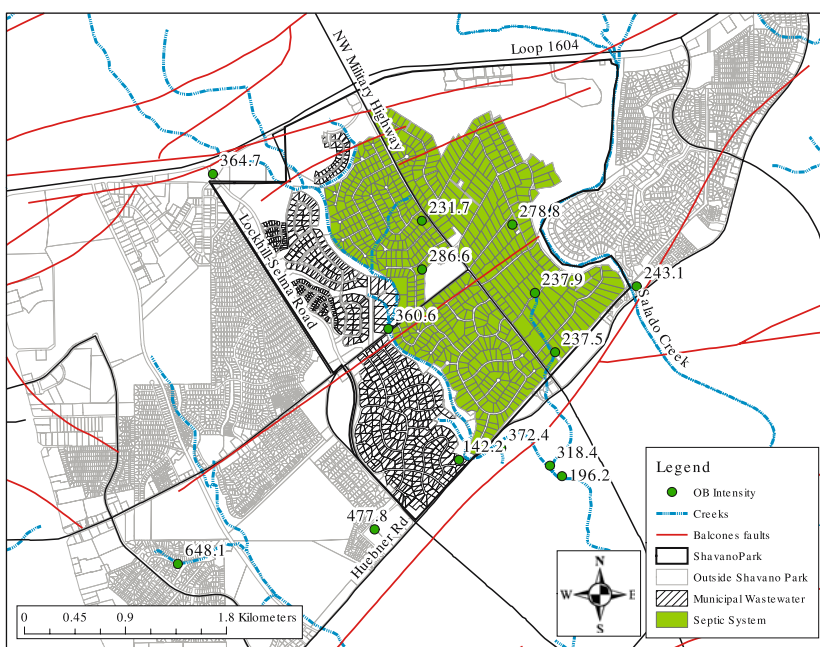


Fig. 5 Groundwater and surface water sampling locations showing peak intensity of OB between 410 and 450 nm



Creek watershed after a heavy rainfall event in August 2005. Samples were collected from the deepest portion of the creeks using polyethylene containers. Surface water samples were transferred to amber colored glass bottles to minimize photodegradation of OB.

Sample filtering and preparation

Each groundwater and surface water sample was filtered using a polyethersulfone (PES) membrane having 1.6 μm

pore diameters. One liter of water was passed through the PES membranes so that the membrane would retain suspended solids to which OB were potentially adsorbed. PES membranes were dried at room temperature, while isolated from sun or artificial light to avoid photodegradation of OB.

Laboratory analysis

A Perkin-Elmer LS-50B spectrofluorophotometer (i.e., spectrometer) was used to analyze PES membranes for the

presence or absence of OB. The spectrometer detected fluorescence, from chemicals absorbed to the PES membranes, by exposing the membrane to light and measuring the wavelength of light subsequently emitted by the membrane. OB absorb invisible ultraviolet light between 300 and 400 nm within the electromagnetic spectrum and emit visible light in the blue/violet portion of the spectrum between 400 and 500 nm (Fay et al. 1995).

Solutions containing various laundry detergents were prepared and scanned with the spectrometer to confirm the wavelength (440 nm) at which maximum (peak) intensities of OB were emitted. Spectrometer settings were optimized, using dilute solutions containing laundry detergent, for measuring OB emission with an excitation slit of 4.0 nm, emission slit of 4.0 nm, excitation of 350 nm, starting wavelength of 350 nm, ending wavelength of 550 nm, and scan speed of 750 nm/min.

Each PES membrane, used to filter the groundwater and surface water samples, was then scanned with the spectrometer using the optimized settings. Graphs of emission intensity on the y-axis versus emission wavelength on the x-axis were developed to illustrate variations in fluorescence over the range of wavelengths of the spectrum.

Results

Depth to the water table ranged from 42 m to 67 m below ground surface and water table elevations ranged from 228 to 258 m in the eight wells that were used for measurement during the month of April 2005. These wells range in depth from 79 to 94 m and lack a discrete screened interval (i.e., open boreholes); therefore, the water table elevations represent an average potential from the members of the Edwards Group that are contributing water to the wells. Table 1 presents the location ID, location description (i.e., state well number), measuring point (MP) elevation, well depth, depth to water, and water table elevations for each of the monitoring wells used for synoptic water level

Table 1 Summary of synoptic water level data (April 2005), and well construction details

Location ID	Location description ^a	MP elevation (m)	Well depth (m)	Depth to water below MP (m)	Water elevation (m amsl)
A	68-28-210	300.8	85.6	45.19	257.64
B	68-28-211	297.2	91.4	53.66	243.52
C	68-28-515	296.0	93.3	67.46	228.50
D	68-28-517	294.1	79.6	41.63	252.50
E	68-28-518	281.9	79.6	42.09	239.85
F	68-28-519	281.9	85.3	52.03	229.91
G	68-28-609	281.6	79.2	47.47	234.17
H	68-28-407	305.4	94.5	57.72	247.69

ID represents identification, *MP* represents measuring point

^a Represents a TX state well number

measurement. These data were used to prepare contours representing the water table surface (Fig. 4), without considering the potential effects of geologic faults on the water table.

The intensities of fluorescence from PES membranes, used to filter water samples from each location, were plotted on the y-axis versus wavelength on the x-axis (example shown in Fig. 6). Nearly all of the plots showed a small spike around the 440 nm wavelengths, which indicated fluorescence from the membrane and presence of OB in the sample. Larger amplitudes on the y-axis represented the presence of a fluorescing chemical on the membrane, while smaller amplitudes indicated background fluorescence of the membrane or an absence of OB in the sample. The maximum intensities of fluorescence in the 410–450 nm range were tabulated because optical brighteners were confirmed to fluoresce within this range. Maximum intensity of fluorescence for 14 samples (11 groundwater and 3 surface water) ranged from 142.2 to 648.1 (shown in Table 2 and plotted on Fig. 5) and had a mean intensity of 314.

Fig. 6 Example of intensity versus wavelength plot of fluorescence from PES pad for location ID M

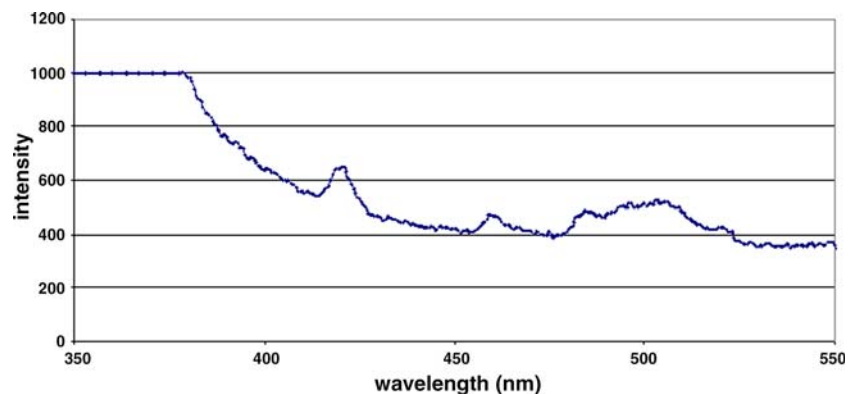


Table 2 Summary of peak OB intensity, between 410 nm and 450 nm, emitted from PES membranes

Location ID	Location description ^a	OB Intensity
A	68-28-210	364.7
B	68-28-211	278.8
C	68-28-515	477.8
E	68-28-518	237.5
F	68-28-519	142.2
G	68-28-609	243.1
I	68-28-203	231.7
J	68-28-205	286.6
K	68-28-513	196.2
L	68-28-514	318.4
M	68-28-516	648.1
N	Creek 1	372.4
O	Creek 2	360.6
P	Creek 3	237.9

ID represents identification

^a Represents a TX state well number or an arbitrary creek number

Discussion

Groundwater flowlines, presented by Maclay (1995), indicate a regional groundwater flow direction of southwest to northeast in the Edwards aquifer and shows local flow directions of northeast to southwest in the recharge zone of Medina County (neighboring Bexar County on the west). The water table surface mapped in this study (shown in Fig. 4) indicates that the water table surface is at the highest elevation in the northwest part and is lowest in the southeast part of the study area. If groundwater flow were controlled only by the hydraulic gradient then groundwater would generally flow from northwest to southeast in this portion of the Edwards aquifer recharge zone, which is inconsistent with both flow directions shown by Maclay (1995). OB intensities from groundwater and surface water samples were used as an alternative measure of groundwater flow direction.

Because the Shavano Park septic systems are likely contributing orders of magnitude more effluent to the shallow subsurface than other potential sources (e.g., sewer line leaks, land applied detergents) any OB intensity above background levels is expected to be a signature of septic tank effluent. OB intensities for the 14 samples had a near normal distribution with only one location ID (e.g., M) being more than two standard deviations (SDs) higher than the mean and one other location ID (e.g., C) being between one and two SDs higher than the mean. Humic and fulvic acids are known to fluoresce within the same wavelength range as OB so they could potentially interfere with the analytical results presented in this study. However, it is

assumed that surface water samples would have higher amounts of humic and fulvic acids than groundwater because these compounds are decay intermediates of natural organic matter (Smart and Karunaratne 2002) and more abundant at the surface. Because intensities of fluorescence, within the 410–450 nm range, of surface water samples (e.g., location IDs N, O, and P) were within one SD of the mean of all samples the effects of humic and fulvic acid are considered negligible. Therefore, higher intensities of fluorescence for the groundwater samples (higher than one SD of the mean) may indicate the presence of OB that originated from septic tank effluent.

Because the highest intensities of fluorescence were in location IDs C and M to the southwest of the septic area of Shavano Park this indicates that effluent from the septic systems is moving from the northeast to the southwest. A groundwater flow direction of northeast to southwest is consistent with the groundwater flow direction presented by Maclay (1995) for the Edwards aquifer recharge zone in northern Medina County. Interpretations by Ferrill et al. (2004) suggest that there is a strong structural geologic control on groundwater flow in this part of the Edwards recharge zone; whereby, downdropped blocks and faulted/fractured geologic units form relay ramps for the transfer of groundwater sub-parallel to the major fault orientation. The pattern of OB detections supports the relay ramp idea presented by Ferrill et al. (2004); therefore, it is concluded that the structural geologic framework and characteristics in the northern Bexar County Edwards aquifer recharge zone are more strongly influencing the local groundwater flow direction than the hydraulic gradient.

Future hydrologic investigations in the Edwards aquifer recharge zone should compare borehole geophysical data to quantitative dye tracer or aquifer tests designed for an anisotropic, fractured media. Water quality studies should also be completed to assess the presence or absence of endocrine disrupting compounds, viability of pathogens (Harris 1995) and other microbial organisms that could originate from septic tank effluent.

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References

Alhajjar BJ, Chesters G, Harkin JM (1990) Indicators of chemical pollution from septic systems. *Ground Water* 28(4):559–568
 Arnow T (1963) Groundwater geology of Bexar County, Texas. US Geological Survey Water-Supply Paper 1588: pp 36

- Davis SN, Thompson GM, Bentley HW, Stiles G (1980) Ground-water tracers—a short review. *Ground Water* 18(1):14–23
- DWAFWRC Department of Water Affairs and Forestry and Water Resources Commission (1996) The philosophy and practice of integrated catchment management: implications for water resource management in South Africa. WRC Report No TT 81/96, Pretoria: pp 139
- Fay SR, Spong RC, Alexander SC, Alexander ECJ (1995) Optical brighteners: sorption behavior, detection, septic system tracer applications. Paper presented at the International association of hydrogeologists XXVI international congress, Edmonton, Alberta
- Ferrill DA, Sims DW, Waiting DJ, Morris AP, Franklin NM, Schultz AL (2004) Structural framework of the Edwards Aquifer recharge zone in south-central Texas. *GSA Bull* 16(3/4):407–418
- Frost FJ, Kunde TR, Craun GF (2002) Is contaminated groundwater an important cause of viral gastroenteritis in the United States? *J Environ Health* 65(3):9–14
- Harris PJ (1995) Water quality impacts from on-site waste disposal systems to coastal areas through groundwater discharge. *Environ Geol* 26:262–268
- Holmbeck-Pelham SA, Rasmussen TC, Fowler LA (2000) Regulation of injected ground water tracers. *Ground Water* 38(4):541–549
- Hutson SS, Barber NL, Kenny JF, Linsey KS, Lumia DS, Maupin MA (2004) Estimated use of water in the United States in 2000. US Geological Survey Circular 1268. Denver, CO, pp 46
- Maclay RW (1995) Geology and hydrology of the Edwards aquifer in the San Antonio area, Texas. US Geological Survey Water-Resources Investigations Report 95–4186, pp 64
- Mull DS, Liebermann TD, Smoot JL, Woosley LH (1988). Application of dye-tracing techniques for determining solute-transport characteristics of ground water in karst terrains. EPA 904/6–88–001. US Environmental Protection Agency Region 4, Atlanta, Georgia
- Pantea MP, Cole JC (2004) Three-dimensional geologic framework modeling of faulted hydrostratigraphic units within the Edwards aquifer, northern Bexar County, Texas. US Geological Survey Scientific Investigations Report 2004–5226, Denver, Colorado pp 10
- Rose PR (1972) Edwards Group, surface and subsurface, Central Texas, University of Texas. Bureau of Economic Geology Report of Investigations No. 74, Austin, Texas pp 198
- Sankaran S, Rangarajan R, Dhar RL (2005) Delineation of hydraulic connectivity across a dolerite dyke through hydrogeological, geophysical and tracer studies—a case study. *Environ Geol* 48:411–419
- Schindel GM, Quinlan JF, Davies G, Ray JA (1997) Guidelines for wellhead and springhead protection area delineation in carbonate rocks. EPA/904/B-97/003, United States Environmental Protection Agency
- Sharp JM, Banner JL (1997) The Edwards aquifer: a resource in conflict. *GSA Today* 7(8):1–9
- Smart CC, Karunaratne KC (2002) Characterisation of fluorescence background in dye tracing. *Environ Geol* 42:492–498
- Stein WG, Ozuna GB (1996) Geologic framework and hydrogeologic characteristics of the Edwards aquifer recharge zone, Bexar County, Texas. Austin, TX. US Geological Survey Water-Resources Investigations Report 95–4030, pp 8
- Stumm W (1985) Clean shirts and clean water. *Environ Sci Technol* 19(11):1013
- USBR United States Bureau of Reclamation (2003) Water 2025: preventing crises and conflict in the West, USBR Fact Sheet, pp 27
- USEPA United States Environmental Protection Agency (2003) Voluntary national guidelines for management of onsite and clustered (decentralized) wastewater treatment systems. EPA 832-B-03–001
- Veni G (1999) A geomorphological strategy for conducting environmental impact assessments in karst areas. *Geomorphology* 31:151–180
- Veni G (2002) Revising the karst map of the United States. *J Cave Karst Stud* 64(1):45–50
- Yates MV (1985) Septic tank density and ground water contamination. *Ground Water* 23(5):586–591