Journal of Hydrology 564 (2018) 230–245

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

The fate of urban springs: Pumping-induced seawater intrusion in a phreatic cave

Robert J. Scharping, K. Michael Garman, Ryan P. Henry, Prahathees J. Eswara, James R. Garey*

Department of Cell Biology, Microbiology, and Molecular Biology, University of South Florida, USA

ARTICLE INFO

This manuscript was handled by G. Syme, Editor-in-Chief, with the assistance of Helge Bormann, Associate Editor

Keywords:
Spring
Karst
Artesian
Coastal groundwater
Hydrographs
Urban

ABSTRACT

Sulphur Springs Cave is an extensive phreatic cavity that produces a large, historic spring in the middle of metropolitan Tampa, Florida, USA. The city of Tampa extracts groundwater from the spring to supplement municipal water supply and to support low-salinity habitat in the estuarine Hillsborough River. Extraction at this site has occurred for many decades, but has intensified since the early 2000s, rapidly increasing the salinity of the spring and cave water. The purpose of this study was to address the potential sources and mechanisms of saltwater intrusion at this site using historical and current hydrochemical data published in the literature and online by government agencies. We also explored the cave to identify point-sources of intrusion, and collected water and biological samples from inside the cave to identify potential ecosystem impacts of increasing cave salinity. From 1946 to present, Sulphur Springs water shifted from being fresh (specific conductance $< 500\ \mu S\ cm^{-1}$) and of calcium-sulfate type to being brackish (specific conductance $\sim 5000\ \mu S\ cm^{-1}$ and higher) and of sodium-chloride type. We found numerous vents in the cave that issue saline, thermal, sulfidic water and host distinct microbial mat communities. These vents are likely connected to bedrock fractures that provide preferential flow-paths along which confined, deep-sourced saline water enters the freshwater portion of the aquifer, probably originating from the coastal mixing zone. Salinity increased at the spring during dry-season pumping activity and after wet-season recharge events, which likely increased artesian pressure in confined saline aquifer units. Salinization of Sulphur Springs may disrupt the cave microbe and stygobite communities and eventually make the spring unsuitable to maintain low-salinity habitat in the Hillsborough River.

1. Introduction

1.1. Coastal aquifers, saline groundwater intrusion, and urban caves

Population density in low-elevation coastal zones is more than five times that of the global average (Neumann et al., 2015). Dense coastal populations often rely on aquifers as primary sources of drinking, agricultural, and industrial water, but current groundwater use in many coastal areas is unsustainable (Michael et al., 2017). Exploitation of coastal aquifers can lead to subterranean seawater intrusion, and even small amounts of chloride contamination from intruding seawater can render groundwater nonportable ($250\ mg\ L^{-1}\ Cl^{-}$; WHO, 2011). Chloride contamination in coastal aquifers can be difficult to remediate, so researchers are working to understand, monitor, and prevent seawater intrusion before it occurs (e.g., Kazakis et al., 2018; Motevalli et al., 2018; Werner et al., 2012). Mechanisms of salinization vary greatly among aquifer systems and types (i.e., granular vs. karstic), so a conceptual understanding of local system behavior is important for the development of coastal groundwater management plans.

An interface between seaward-flowing fresh groundwater and landward-intruding seawater (the coastal mixing zone) is present in many coastal aquifers. Coastal mixing zone shape and behavior are defined by complicated relationships between land surface topography, aquifer hydrogeology, and anthropogenic activity, making some coastal mixing zones difficult to identify and monitor (Weyer, 2018). In a regional flow system with sufficient topographic relief, aquifer recharge can pressurize discharge zones hundreds of kilometers away. For example, coastal discharge zones throughout south Florida are primarily recharged in the central Florida uplands, producing flow systems stretching > 300 km (Weyer, 2018). The seawater wedge intruding into confined aquifers can be pressurized by recharge to exposed topographic highs, causing saline groundwater to seep upward into freshwater portions of the aquifer (as in the Netherlands; de Louw et al., 2010; Van Rees Vellinga et al., 1981), or causing the salinization of

* Corresponding author.
E-mail addresses: scharping@mail.usf.edu (R.J. Scharping), eswara@usf.edu (P.J. Eswara), garey@usf.edu (J.R. Garey).

https://doi.org/10.1016/j.jhydrol.2018.07.016
Received 20 March 2018; Received in revised form 6 July 2018; Accepted 8 July 2018
Available online 09 July 2018

coastal artesian wells, as in southern France (Montety et al., 2008). Anthropogenic aquifer use can deform the mixing zone and perturb natural groundwater salinity stratification, potentially contaminating aquifers where direct seawater intrusion might not otherwise occur (e.g., Giambastiani et al., 2013; Motevalli et al., 2018).

One widespread consequence of coastal groundwater extraction is mixing zone upconing (Garcia-Menendez et al., 2016; Werner et al., 2013). Groundwater extraction generates low-pressure zones directly below wells, causing the saltwater-freshwater interface to cone upward (reviewed by Bower et al., 1999). Based on extraction rate, freshwater head position and sea level, the saltwater cone can reach a stable state some distance below the bottom of the well. If the cone rises past a critical point, it becomes unstable and the well begins to draw saline water. On coasts with more diffuse mixing zones, a well can upcone and draw shallow saline water long before the deeper main interface is deformed (Bear et al., 2001; Werner et al., 2009). Groundwater extraction can therefore expand the vertical thickness of the coastal mixing zone (Jakovovic et al., 2016). Vertical migration of deep saline groundwater is not limited to coastal zones, and can result from extraction-induced head reduction in aquifers overlying confined brines (e.g., Karro et al., 2004). Upward movement of saline groundwater can be caused by human activities other than well-water extraction. In northern Italy, extensive drainage systems have artificially lowered regional aquifer head. This practice disrupted natural vertical head gradients, destabilizing groundwater salinity stratification as deep-sourced saline water migrated upward into fresh groundwater zones (Giambastiani et al., 2013).

Preferential flow-paths can enhance vertical groundwater migration and further complicate interpretations of aquifer dynamics. Conduits of high-permeability sediment, fractures, faults, and karstic voids offer paths of least resistance along which intruding seawater or deep-sourced saline groundwater can infiltrate into freshwater aquifer units. Offshore of North Carolina, USA, Mulligan et al. (2007) found that paleochannels infilled with coarse sediments breached a confined aquifer and could act as preferential flow-paths for landward-intruding seawater. In the Netherlands, sand boils vented deep-sourced coastal mixing zone water through fresh aquifer layers into overlying surface water bodies (de Louw et al., 2010). The boils were fed by sand-filled fractures that penetrated underlying confining units, and a combination of the rapid discharge rate and the low head of the boils caused the underlying seawater wedge to upcone significantly. Anthropogenic aquifer head reduction on the Atlantic coast of Florida, USA caused deep-sourced brines to migrate upward through vertically-persistent bedrock fractures and then laterally through freshwater zones, contaminating a series of confined aquifers (Spechler, 1994). In Israel, decades of extraction activity and head reduction in shallow aquifers led to the vertical migration of confined, deep-sourced brines along regional faults (Rosenthal, 1988). On the Mediterranean coast of Spain, Calvache and Pulido-Bosch (1997) attributed seawater intrusion in the Catell de Ferro aquifer entirely to the influence of preferential flow-paths present in the karstified carbonate component of the aquifer, which amplified the impact of anthropogenic groundwater extraction. Lez Spring in southern France is part of an extensive karst system, and discharges groundwater from multiple aquifer units (Bicalho et al., 2017). After heavy rains, Lez Spring discharge experienced increased contribution from mineralized groundwater, which was sourced from confined evaporites. The mineralized groundwater had migrated upward through faults and then leaked laterally into the main aquifer, where it was later mobilized by the deep groundwater flow-paths induced by intense recharge events. In a limestone aquifer in South Australia, Wood and Harrington (2015) monitored a deep karst feature which intercepted the coastal mixing zone, finding that the salinity of groundwater discharging from the feature showed seasonal variation dependent on mixing zone position, while surrounding groundwater remained fresh.

Caves and other karst features such as the system studied by Wood and Harrington (2015) provide scientists with direct access to coastal aquifers, allowing researchers to identify novel mechanisms of seawater intrusion (e.g., Beddows et al., 2007; Vera et al., 2012) and the extreme extent to which seawater intrusion can occur (Xu et al., 2016). Studies of coastal karst features have also revealed groundwater-dependent ecosystems driven by unique hydrological regimes (e.g., Menning et al., 2015, 2018) as well as extreme, isolated environments which host salinity-stratified water columns (e.g., Garman and Garey, 2005; Garman et al., 2011). Karst features are vulnerable to anthropogenic groundwater quality deterioration (Calijuri et al., 2012; Jiang et al., 2009), especially underwater (phreatic) conduits, which are preferential groundwater flow-paths large enough to rapidly transmit natural and anthropogenic drinking water contaminants (Bicalho et al., 2012). Sulphur Springs Cave is an extensive phreatic conduit developed beneath metropolitan Tampa, Florida, USA. The cave discharges groundwater to a surface pool, from which the city of Tampa extracts water. In this paper we investigate hydrologically-related issues that Sulphur Springs Cave has experienced as a consequence of anthropogenic activity, propose a conceptual model for seawater intrusion at this site, and discuss the potential impacts of salinity increase on the cave ecosystem.

1.2. Sulphur Springs cave

Sulphur Springs Cave is a phreatic void developed in the eogenetic limestone beneath Tampa, Florida (Fig. 1). Eogenetic karst develops in young limestones which have maintained their initial primary porosity, such that diffuse matrix flow and storage occur simultaneously with fracture/karst hydrodynamics (Vacher and Mylroie, 2002). About 1 km of the cave conduit has been mapped by divers. The cave consists of a Main Tunnel which splits into two smaller passages: the Orchid Tunnel and the Alaska Tunnel. The tunnels lie at a water depth of ~30 m. About 25% of Sulphur Springs Cave passageway is higher than it is wide, compared to the 10% exhibited by most Floridan caves (Garman, 2010), suggesting the importance of vertical bedrock fracturing in the speleogenesis of Sulphur Springs Cave.

Groundwater from the confined Upper Floridan Aquifer flows through the Sulphur Springs tunnels toward the cave mouth, producing an artesian spring. The cave mouth is < 1 m high and 2 m wide, and is submerged in a ~10 m deep pool. The pool was impounded by the city of Tampa in the early twentieth century to create a public swimming area. The pool was used as such until the 1980s, when fecal coliforms were detected and the pool was closed to swimming. Pumps were installed at Sulphur Springs pool in 1964, when the city started using spring water to replenish the Hillsborough River Reservoir during droughts. In 2002, the pumping system was modified to allow extracted spring water to be diverted to below the reservoir dam to support the downstream Lower Hillsborough River (Southwest Florida Water Management District SWFWMD, 2004, 2006). Diverted spring water maintains low-salinity habitat and manatee thermal refuge in this estuary. When spring water is not pumped, it overflows from the impounded pool into the Lower Hillsborough River ~4 km downstream of the dam. When pumps are active, the pool level can drop ~1 m and water ceases flowing over the spillway flumes.

The dynamics of the spring pool have been monitored and studied since the 1940s (see Menke et al., 1961; Rosenau et al., 1977; Stewart and Mills, 1984). Specific conductance of the spring water increases when the pool is lowered, regardless of local aquifer head position. Water quality of the spring and cave can thus be maintained by controlling pool depth, yet the specific conductance of the spring water has increased over time.

1.3. Deterioration of Sulphur Springs water quality

North of Sulphur Springs Cave, swallets and sinkholes are present which have historically contributed to Sulphur Springs recharge