A New Focus on Groundwater–Seawater Interactions
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Effect of an offshore sinkhole perforation in a coastal confined aquifer on submarine groundwater discharge

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Abstract In order to explore submarine groundwater discharge in the vicinity of karst features that penetrate the confining layer of an offshore, partially confined aquifer, we constructed a three-dimensional groundwater model using the SUTRA (Saturated–Unsaturated TRAnsport) variable-density groundwater flow model. We ran a parameter sensitivity analysis, testing the effects of recharge rates, permeabilities of the aquifer and confining layer, and thickness of the confining layer. In all simulations, less than 20% of the freshwater recharge for the entire model exits through the sinkhole. Recirculated seawater usually accounts for 10–30% of the total outflow from the model. Often, the sinkhole lies seaward of the transition zone and acts as a recharge feature for recirculating seawater. The permeability ratio between aquifer and confining layer influences the configuration of the freshwater wedge the most; as confining layer permeability decreases, the wedge lengthens and the fraction of total discharge exiting through the sinkhole increases.

Key words submarine spring; sinkhole; submarine groundwater discharge; karst; freshwater; saltwater; transition zone; coastal aquifer; SUTRA; Florida

INTRODUCTION

Florida may have the greatest potential for submarine groundwater discharge (SGD) of any location in the world due to its high precipitation rates, its long coastline, and the high permeability of the Floridan Aquifer (Zektzer *et al.*, 1973; Swarzenski & Kindinger, 2003). The hydrogeological units of the karstified Floridan Aquifer extend to the edges of the Florida Platform, some 100 km on the northeastern side and twice that distance on the western shelf, and are at least partially confined by the predominantly siliciclastic Hawthorn Formation for most of this area. A freshwater wedge extending offshore in such conditions will discharge water in a diffuse manner across the confining layer, creating concentrated discharge points wherever the confining layer is breached.

On the coastlines of Florida, such a breach is likely to be a sinkhole. In places where the Floridan Aquifer is partially confined, the Hawthorn Formation is less than 100 m thick and perforated by sinkholes and collapse features, the majority of which formed during sea level minima of the late Oligocene and early Miocene when the entire shelf was exposed (Stringfield, 1966). Above sea level, these sinkholes provide a route for recharge to the aquifer. When submerged, they connect the aquifer directly with the overlying seawater and create point sources (or sinks) of SGD (Kohout, 1966; Stringfield & LeGrand, 1969; Swarzenski *et al.*, 2003). In breaching the confining layer, Kohout says, the sinkhole acts as an artesian well. Kohout's analogy is echoed by Stringfield & LeGrand (1969, and LeGrand & Stringfield, 1971), who examined the dynamics of freshwater–saltwater systems within karstic conduits that penetrate to the base of the freshwater lens or wedge.

The Crescent Beach Spring just off the coast of Jacksonville, Florida, may be the most spectacular example of a submerged sinkhole spring, ranking among Florida's many first-magnitude springs (Swarzenski *et al.*, 2001). However, as Zektzer and others (1973) pointed out, there must be countless smaller submarine springs that may not be easily observed from the sea surface. Such springs may lack integrated conduit systems and still discharge substantially more water than the areas surrounding them.

The purpose of this study was to examine the magnitude of discharge that might be diverted to a sinkhole or other breach in the confining layer of an aquifer discharging freshwater off shore. We wanted to study the parameters that most affect the proportion of discharge that occurs through these structures and their impact on the configuration of the freshwater wedge and its transition zone.

RELATED STUDIES

SGD often consists of meteoric water from land and recirculated seawater, driven by an array of processes operating at different scales, including terrestrial hydraulic gradients, wave and tidal pumping and set-up, and thermal and density gradients (Burnett *et al.*, 2003). In this paper, we examine only the SGD driven by a flow of freshwater from land and the recirculation of seawater that accompanies it.

A seafloor discharge face has been included in theoretical models of the coastal freshwater wedge since Hubbert (1940). Glover (1959) calculated the width of the seepage face in his potential-theory model of a coastal aquifer that is unconfined beneath the seafloor. Edelman (1972) presented an analytical solution to the problem of the offshore discharge face of a partially confined aquifer. Kooi & Groen (2001) expanded on Edelman's work, addressing the question of how far groundwater can be carried offshore in a confined aquifer.

Along with terrestrially derived freshwater, the SGD associated with an offshore freshwater wedge includes a certain amount of recirculated seawater. Cooper (1959) and Kohout (1960) described the potential for cyclic flow of seawater into the transition zone and corresponding loss of head in the seawater part of the regime. Stringfield & LeGrand (1969) pointed out that vertical karst features that penetrate to this zone of negative head may have water levels lower than sea level and, if open to the sea, could continuously intake seawater in a cyclic flow. They described such features at Tarpon Springs, Florida, and the island of Cephalonia, Greece (Stringfield & LeGrand, 1969).

The coastal freshwater wedge and the flow system associated with it can also be modified by upconing of the freshwater–saltwater transition zone beneath a freshwater sink (usually conceptualized as a pumping well). Many early models utilized the assumption of a sharp interface and a radially symmetrical cone (Bear & Dagan, 1964; Bennett *et al.*, 1968; Haubold, 1975) and are concerned mostly with well contamination.

Numerical modelling is used in later studies to allow for the inclusion of a freshwater–seawater transition zone. Reviews of previous work on upconing beneath pumping wells are included in Reilly & Goodman (1987) and Zhou *et al*. (2005).

DESCRIPTION OF THE MODEL

A simple, three-dimensional aquifer model using the SUTRA (Saturated–Unsaturated TRAnsport) variable-density groundwater flow model (Voss, 1984) allowed us to test the effects of aquifer parameters on the proportion of aquifer discharge coming out of the sinkhole (Fig. 1).

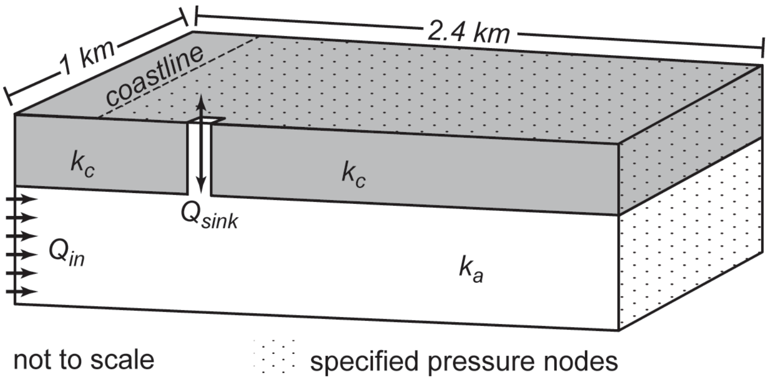

Fig. 1 The model domain, showing boundary conditions and aquifer parameters. Permeability of the confining layer (k_c), aquifer permeability (k_{aq}), freshwater input into the model (Q_{in}), and the discharge (Q_{sink}) through the specified-pressure nodes of the sinkhole.

The aquifer measures 2 km by 2.4 km by 100 m for all simulations and is overlain by a confining layer of 46-m, 66-m, or 86-m thickness. The confining layer was assigned a permeability k_c, except for a 5-by-5 column of nodes representing the sinkhole. The permeabilities of these sinkhole elements are equal to that of the aquifer (k_{aq}). This sinkhole is positioned 440 m from the coast in about 5 m of seawater. We actually ran the model for only half of this model space – the space shown in Fig. 1. We assumed that the model is symmetrical around a vertical plane of symmetry perpendicular to the coastline and passing through the centre of the sinkhole.

Nodes corresponding to the sea floor were assigned specified pressures consistent with those of hydrostatic seawater. Freshwater recharge to the aquifer (Q_{in}) is through specified-source nodes at the landward face of the model. Water discharges through specified-pressure nodes at the top of the confining layer, at the top of the sinkhole (Q_{sink}), and at the seaward end of the model. We ran each simulation to steady state, testing the effects of several recharge rates, the permeability magnitude and ratio of the aquifer (k_{aq}) and confining layer (k_c), and the thickness of the confining layer (b). We constructed a parameter matrix from the following parameters:

(a) Recharge rates: 0.18 m^3/d, 0.15 m^3/d, 0.11 m^3/d, 0.092 m^3/d, and 0.074 m^3/d per metre of coastline.

(b) Permeability of aquifer (k_{aq}): 1.00×10^{-12} m^2, 1.00×10^{-13} m^2.
(c) k_{aq}/k_c ratio: 1, 3, 10, 20, 30, 50, 70, 100, 130, 160, 200, 250, 300, 1000.
(d) Confining layer thickness: 46 m, 66 m, 86 m.

We chose these parameters to fall within acceptable values for a small-scale, coastal flow system. For each parameter set, we ran two simulations: one simulation with the sinkhole in place and a simulation with an uninterrupted confining layer for comparison. The "no sinkhole" cases were essentially two-dimensional models. Of the simulations that we ran, we ended up using about 600 for analysis.

RESULTS

Sinkhole discharge and seawater recirculation

At a steady state, the percentage of freshwater discharging through the sinkhole depends most strongly on the ratio of permeabilities k_{aq}/k_c (Fig. 2(a)), and is at most around 20% of Q_{in} for the parameters that we tested.

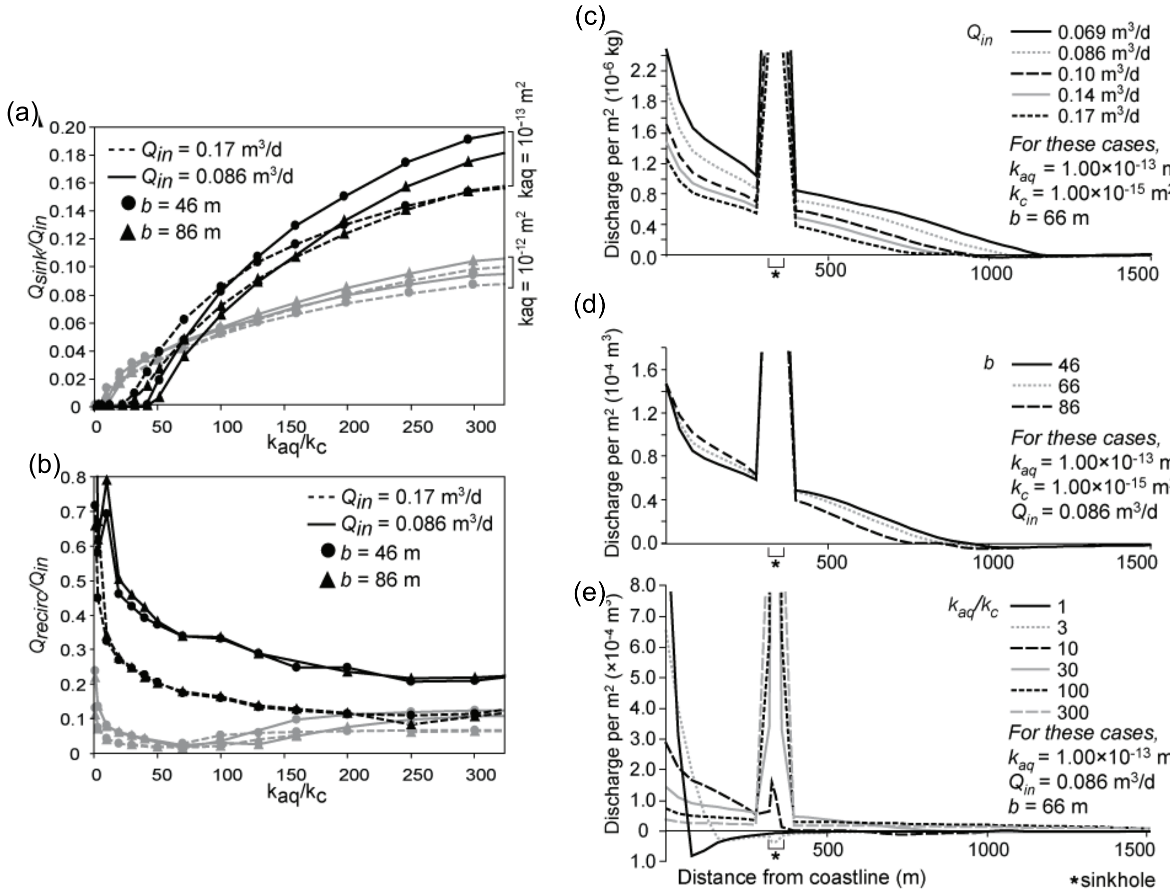

Fig. 2 Results of parameter sensitivity analysis. (a) Proportion of water discharging out of the sinkhole. (b) Amount of recirculated seawater. (c)–(e) Discharge profiles through sinkhole, perpendicular to coastline. (c) The effect of changing freshwater input into the model Q_{in}. (d) The effect of changing aquifer thickness b. (e) The effect of changing the k_{aq}/k_c ratio. This is done by decreasing k_c in six steps from 1.00×10^{-13} m^2 (equal to k_{aq}) to 3.33×10^{-16} m^2 (a k_{aq}/k_c ratio of 300).

Simulations with a higher aquifer permeability k_{aq} generally have a lower discharge through the sinkhole, generally less than 10% of the total freshwater throughput. In most simulations with k_{aq}/k_c ratios of less than 10, the sinkhole discharges nothing.

Total fluxes through the model are often higher than the specified freshwater flux, indicating that seawater is circulating through the model space. The rate of seawater circulation (Q_{recirc}) is inversely proportional to k_{aq}/k_c (Fig. 2(b)), ranging from about 10% to 30% of Q_{in} at higher k_{aq}/k_c ratios.

Discharge profiles

The specific discharge across the sediment-water interface decreases with distance from the coast (Fig. 2(c), (d) and (e)), ending in a very slight negative discharge corresponding with the slow influx of seawater into the aquifer. The profile of discharge perpendicular to the coast is generally stable with a change in Q_{in} or b (Fig. 2(c) and (d)). The k_{aq}/k_c ratio, however, has a far greater effect on the discharge profile. At a k_{aq}/k_c ratio of 1, the freshwater wedge is very short, and the profile has a prominent negative peak corresponding to the intake of seawater (Fig. 2(e)). The freshwater wedge is short enough that virtually all of the recirculated seawater enters the model landward of the sinkhole. Decreasing k_c spreads the discharge out over a larger area and creates focusing of recirculated seawater through the sinkhole. At higher k_{aq}/k_c ratios, the length of the freshwater wedge approaches the length of the model and freshwater starts to discharge out of the outcrop at the end of the model.

Flow regimes

The presence of a confining layer spreads the transition zone out considerably, the parameters of the model determining its shape and position. The magnitude of Q_{in} affects its position (Fig. 3(a)), whereas k_{aq}/k_c completely changes its character (Fig. 3(b)).

The upconing of the concentration contours at the seaward edge of the sinkhole is evident in Fig. 3. Upconing occurs in the upper concentration contours (representing lower fractions of seawater); saltier water remains undisturbed. For $k_{aq}/k_c = 1000$, the concentration contours representing greater than 50% seawater are crowded together near the end of the model.

Flow within the transition zone is largely parallel to the concentration contours (Fig. 3(c)). As expected, the highest velocities occur beneath the sinkhole and within the freshwater portion of the model. Beneath the transition zone, the general flow direction is landward. This flow reverses in the vicinity of the 70%-seawater concentration contour. In this region, flow is imperceptibly slow and vertical in direction.

DISCUSSION

The profiles presented here exhibit a classic freshwater wedge extending offshore with diffuse upward discharge through a confining layer to the sea. Our results are consistent with those of Kooi & Groen (2001), who found that the length of the

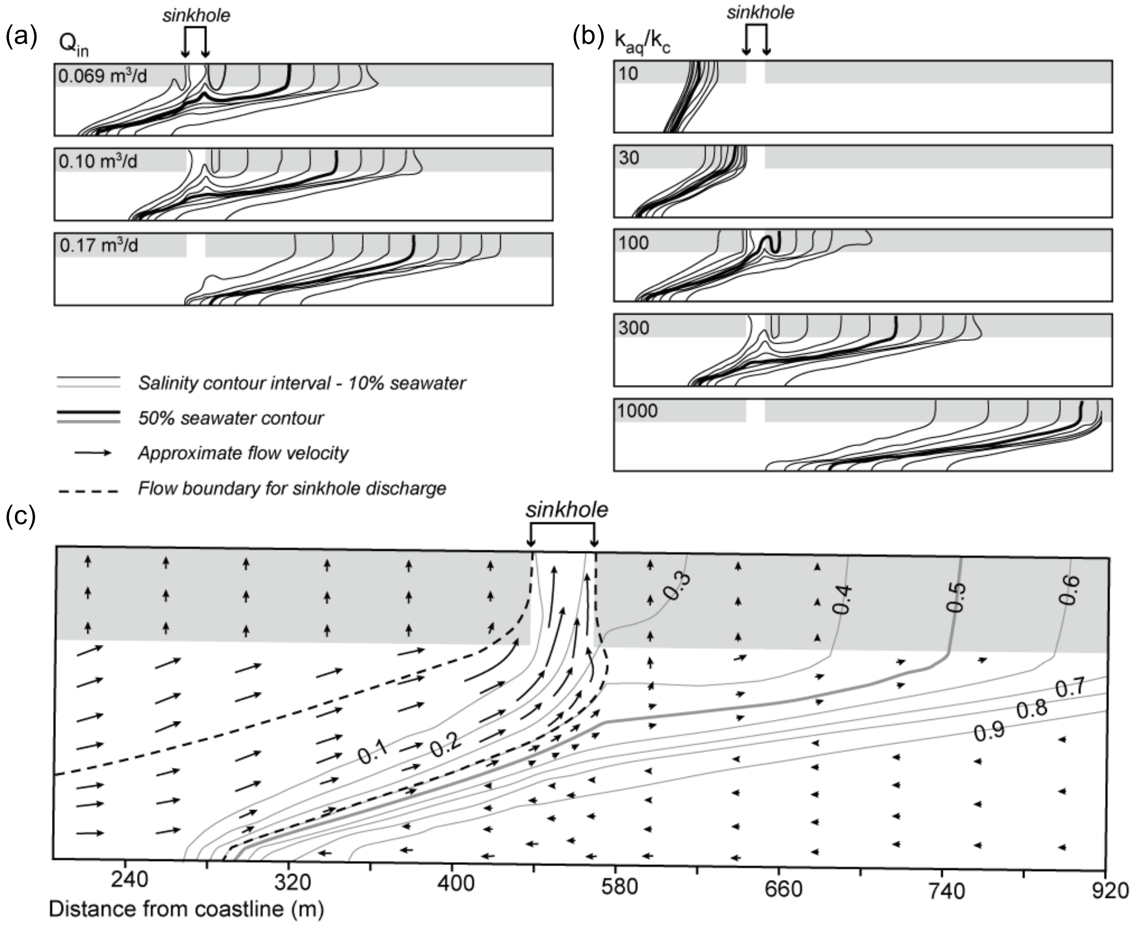

Fig. 3 Salinities and flow regime within the freshwater wedge. (a) and (b) Transition zone profiles through the sinkhole. (c) Flow diagram of profile through centre of the sinkhole. This slice is a no-flow boundary: there is no flow into or out of this section. Except where specified, all of these simulations have Q_{in} = 0.086 m^3/s, k_{aq} = 1.00 × 10^{-12} m^2, k_c = 3.33×10^{-15} m^2, and b = 46.

freshwater wedge depends upon the permeability and thickness of the confining layer and the discharge at the coastline. Generally, thicker and less-permeable confining layers, coupled with high recharge at the coast, produce longer freshwater wedges (Fig. 3(a) and (b); higher k_{aq}/k_c ratio corresponds to less-permeable confining layer).

Kooi & Groen (2001) pointed out that the length of the freshwater wedge is limited by downward dispersive effects at the outflow face, which overcome upward seepage in very long freshwater wedges. It is possible that, like Kooi & Groen's calculated "length of freshwater discharge", our ratio Q_{sink}/Q_{in} may not continue to increase with k_{aq}/k_c but instead may reach a maximum. With this particular model domain, however, the simulations with higher k_{aq}/k_c are too influenced by discharge out of the "outcrop" end of the model for us to be certain that this is the case.

Within our simulations, the sinkhole diverts up to 20% of the freshwater discharge from the freshwater wedge. The discharge through the sinkhole depends mostly on its position relative to the freshwater–saltwater transition zone. In this study, the sinkhole is stationary; the position and shape of the transition zone is largely influenced by the widely varying k_{aq}/k_c ratio. Field values of k_{aq}/k_c may vary by several orders of magnitude in an area such as Florida. We used experimental values that reflect this. In fact, the permeability of the units in the Floridan Aquifer can often be around 10 000 times the permeability of the Hawthorne Formation. The results shown in Fig. 2(a), however, suggest that a percentage greater than 30% would be unlikely, even at very high k_{aq}/k_c ratios.

Recirculated seawater accounts for some fraction of the total flux through the system, adding about 10 to 30% to the specified recharge (Q_{in}) at higher k_{aq}/k_c ratios. Recirculation is higher at lower k_{aq}/k_c ratios which allow seawater to more easily penetrate the confining layer. The freshwater wedge ends landward of the sinkhole in most of these simulations, causing the sinkhole to act as a recharge feature.

The specific discharge of the sinkhole dwarfs that of the diffuse outflow face (Fig. 2(c), (d) and (e)), but the area of diffuse flow is much larger. Without a conduit system feeding the sinkhole discharge, the sinkhole's influence is mostly local, and much of the freshwater in the system will still exit through the diffuse outflow face. However, given that sinkholes tend to exist in clusters and that the k_{aq}/k_c ratio is likely to be much larger than 300, the percentage of Q_{in} exiting the sinkholes is likely to be much larger than 20%. The effect is at least enough to confound SGD measurements in a highly heterogeneous offshore face, especially if spot seepage measurements are integrated across the entire outflow face.

Zhou *et al.* (2005), Johannsen *et al.* (2002) and Oswald *et al.* (2002) reported that in experiments concerning upconing beneath pumping wells, only the part of the transition zone with lower salinities was upconed. The water with higher salinities was not affected by the upconing. We found similar results, with a salinity profile comparable to that of a cased well penetrating the confining layer.

CONCLUSIONS

A sinkhole that perforates a confining layer in a coastal aquifer acts similarly to a cased well into the freshwater wedge, discharging freshwater or pulling in seawater, depending on its position within the flow regime. In the cases we examined, the sinkhole diverts as much as 20% of the freshwater flow through the model. This number is likely to increase with an increase in the ratio of aquifer permeability to confining-layer permeability. At lower k_{aq}/k_c ratios, seawater circulation can double the total water flux through the model compared to specified recharge values. At higher k_{aq}/k_c ratios, the rate of seawater recirculation is an additional 10–30% added to the specified freshwater recharge rate. The lower-salinity concentration contours are upconed at the seaward edge of the sinkhole; however, the sinkhole almost always discharges more than 95% freshwater. Even without a substantial conduit system feeding it, a submarine spring of this type can substantially alter the surrounding flow regime and complicate studies of submarine groundwater discharge.

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