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Application of factor analysis and electrical resistivity to understand groundwater contributions to coastal embayments in semi-arid and hypersaline coastal settings

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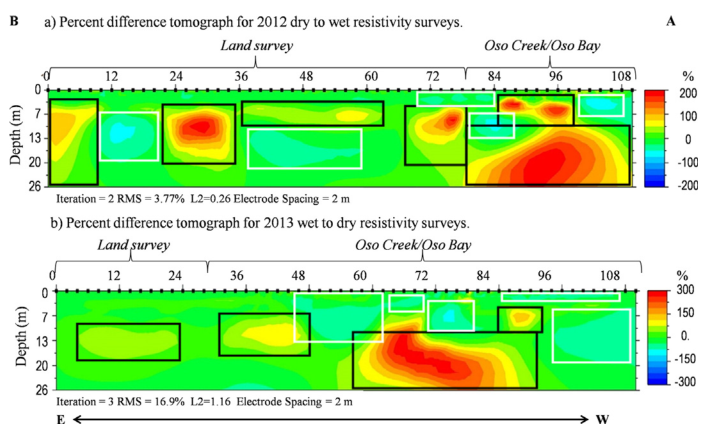
HIGHLIGHTS

- Study of salinity regimes in relation to groundwater in a coastal semiarid setting
- Factor analysis defined dominant factors influencing water quality variations.
- Electrical resistivity methods reveal groundwater–surface water interactions.
- Salinity mass-balance models show that submarine groundwater discharge is variable.
- Groundwater–surface water interaction is dominated by density-difference flow.

GRAPHICAL ABSTRACT



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ABSTRACT

Groundwater contributions and sources of salinity to Oso Bay in south Texas were investigated using multivariate statistical analysis of geochemical data and multitemporal electrical resistivity tomography surveys. Both analysis of geochemical data and subsurface imaging techniques identified two commonalities for the investigated system: 1) hypersaline water occurs near the groundwater/surface water interface during wet conditions creating reverse hydraulic gradients due to density effects. The development and downward movement of these fluids as continuous plumes deflect fresher groundwater discharge downward and laterally away from the surface; and 2) more pronounced upwelling of fresher groundwater occurs during drought periods when density inversions are more defined and are expected to overcome dispersion and diffusion processes and create sufficiently large-enough unstable gradients that induce density-difference convection. Salinity mass-balance models derived from time-difference resistivity tomograph and in-situ salinity data reaffirm these findings indicating that groundwater upwelling is more prominent during dry to wet conditions in 2013 (~545.5 m^3/d) and is less pronounced during wet to dry conditions in 2012 (~262.7 m^3/d) for the 224 m^2 area surveyed. Findings show that the highly saline nature of water in this area and changes in salinity regimes can be attributed to a combination of factors, namely: surface outflows, evapoconcentration, recirculation of hypersaline groundwaters, and potential trapped oil field brines. Increased drought conditions will likely exacerbate the rate at which salinity

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levels are increasing in bays and estuaries in semi-arid regions where both hypersaline groundwater discharge and high evaporation rates occur simultaneously.

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1. Introduction

Submarine groundwater discharge (SGD) and coastal groundwater discharge (CGD) are important components of the hydrologic and biogeochemical systems that link terrestrial waters to marine environments (Moore, 1996; Burnett and Dulaiova, 2003; Cardenas et al., 2010). SGD enables the flow and transport of fluids and solutes from inland groundwater resources into offshore coastal environments (i.e., bays, estuaries, oceans, etc.) whereby CGD occurs from offshore to inland environments (i.e., wetlands, marshes, etc.). CGD and saltwater intrusion are similar in their definition and mechanisms of fluid transport; however, CGD assumes that saline groundwater from seawater intrusion will eventually discharge into adjacent surface waters depending on the hydrogeologic conditions. Bays and estuaries rely on a specific range of salinity and nutrient levels in order to maintain optimal productivity and ecosystem services (Palmer et al., 2011). Inflows from riverine and groundwater resources to estuaries are the dominant source of freshwater inflows that can affect coastal ecosystem structure indirectly by changing salinity regimes, hydrology, and transport of nutrients and contaminants.

The interaction between groundwater and surface water and the importance of SGD in delivering nutrients that affect the ecology of estuaries and coastal water bodies has been investigated extensively (Johannes, 1980; Charette, 2007; Kim et al., 2011; Portnoy et al., 1998; Hu et al., 2006; Lee et al., 2010) especially in coastal environments dominated by high conductive sediments/deposits (Moore, 1996; Katz et al., 1997; Burnett and Dulaiova, 2003; Burnett et al., 2007; Breier et al., 2010; Ni et al., 2011). Nevertheless, research in semi-arid, hypersaline coastal settings with sediments of low hydraulic conductivity has been minimal. Little attention has been directed toward environments dominated by silty-clay and clayey-silt sediments because little exchange of fluids and solutes between groundwater–surface water (GW–SW) is expected. However, studies show that processes such as air entrapment beneath an inverted water table and infiltration into the capillary fringe can cause the water table to rise more than ten times the amount of infiltration in clayey environments (Gerla, 1992; Silliman et al., 2002). Furthermore, studies show that the osmotic flow of fluids through clay soils are influenced by changes in pore fluid chemistry that could ultimately deplete clays integrity as a reliable confining unit (Barbour and Fredlund, 1989).

Additionally, levels of dissolved constituents are highly enriched in subsurface waters and can be important to coastal budgets even where the volumetric contribution is small (Slomp and Van Cappelle, 2004). The salinization of groundwater resources through various mechanisms have also been investigated using a number of techniques (Barica, 1972; Rosenthal et al., 1992; Morell et al., 1996; Sanchez-Martos et al., 2002; Faye et al., 2005), but little is known about the salinization of surface water in relation to groundwater, namely in semi-arid coastal areas with low hydraulic conductivity sediments. Most related studies infer that the observed elevated salinities associated with groundwater discharge to coastal embayments are the result of seawater circulation (Simmons, 1992; Moore and Church, 1996). Few studies, however, provide insight into the groundwater dynamics that drive seawater circulation and/or differentiate between sources of salinity.

Commonly, analyses of groundwater discharge to surface water have been conducted using elemental and isotopic geochemistry (Moore, 1996; Grossman, 2002; Cable et al., 2004; Ni et al., 2011; Dimova et al., 2013) as well as density-dependent flow and transport simulation codes (Guo and Langevin, 2002; Murgulet and Tick, in press). Statistical methods such as analysis of variance (ANOVA), multivariate linear regression (MLR) and factor analysis on environmental data have also produced valuable models that aid in identifying variations in water quality and contamination sources in various hydrologic systems (Morehead et al., 2008; Thareja et al., 2011; Hae-Cheol and Montagna, 2012). Recently, subsurface imaging techniques such as direct current electrical resistivity (ER) surveys have been increasingly used to delineate and quantify groundwater flow paths and discharge rates into surface water bodies (White, 1988; Greenwood et al., 2006; Green et al., 2008). Consecutive ER images conducted along the same survey line during different environmental conditions give groundwater discharge estimates over time (Nyquist et al., 2008; Dimova et al., 2012; Johnson et al., 2012).

The main objective of this study was to improve understanding of groundwater contributions to surface water in a semi-arid coastal environment dominated by low permeability sediments (i.e., fine silt-to-clayey sediment), low precipitation rates and limited freshwater inflows, high evaporation rates, and highly saline groundwaters. The sub-objectives were to: characterize the role of groundwater as a source of salinity to surface water in south Texas; and to define surface water salinity sources and trends associated with SGD and CGD as a function of climatic conditions (i.e., source of salinities spanning from wet to dry conditions). For this purpose, a combination of geochemical, geophysical, and statistical techniques were implemented. Statistical analyses of surface-, pore-, and groundwater major ions, stable and radioactive isotopes, and field parameters were performed to evaluate and source-track water movement and solute transport within the land to water transition zone. In addition, time-difference ER images were used to validate statistical analyses and identify groundwater seepage faces, estimate groundwater discharge rates, and to evaluate salinity inputs to bays and estuaries in the study area. This combination of established methods presents a novel approach to better elucidate sources of salinity to coastal estuaries by linking multiple sources (i.e., surface and groundwater) to climatic conditions (i.e., wet versus dry periods). This work is critically important for understanding the role of hypersaline groundwater discharge in salinity budgets in semi-arid coastal and hypothetical impacts on ecosystem health.

2. Study area

2.1. South Texas: background and importance

In south Texas severe drought conditions caused depletion of freshwater resources and increased salinity contents in surface waters and surficial aquifers (Schmidt and Garland, 2012). Laguna Madre, a naturally hypersaline coastal ecosystem located in the area, is one of only three large hypersaline lagoons in the world. This is due to negligible freshwater inflows and little connection with the Gulf leading to high accumulation rates of salt during high evaporation events (Quammen and Onuf, 1993). Most studies in south Texas show that impaired waterways are the result of high levels of bacteria or other microbes, dissolved oxygen (DO) depletion, and increasing salinity levels (Montagna and Ritter, 2006; Palmer et al., 2011). Although monitoring efforts have been extensive, limited efforts were directed toward identifying the quality and quantity of freshwater inputs. Recent efforts to regulate freshwater inflows for optimal salinity ranges to promote ecosystem health of bays and estuaries along the Texas Gulf Coast do not include groundwater inputs (Alexander and Dunton, 2006; Kim and Montagna, 2012). This study shows that groundwater may have a significant role in delivering total dissolved solids to estuaries in south

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