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Seawater intrusion processes, investigation and management: Recent advances and future challenges

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ABSTRACT

Seawater intrusion (SI) is a global issue, exacerbated by increasing demands for freshwater in coastal zones and predisposed to the influences of rising sea levels and changing climates. This review presents the state of knowledge in SI research, compares classes of methods for assessing and managing SI, and suggests areas for future research. We subdivide SI research into categories relating to processes, measurement, prediction and management. Considerable research effort spanning more than 50 years has provided an extensive array of field, laboratory and computer-based techniques for SI investigation. Despite this, knowledge gaps exist in SI process understanding, in particular associated with transient SI processes and timeframes, and the characterization and prediction of freshwater–saltwater interfaces over regional scales and in highly heterogeneous and dynamic settings. Multidisciplinary research is warranted to evaluate interactions between SI and submarine groundwater discharge, ecosystem health and unsaturated zone processes. Recent advances in numerical simulation, calibration and optimization techniques require rigorous field-scale application to contemporary issues of climate change, sea-level rise, and socioeconomic and ecological factors that are inseparable elements of SI management. The number of well-characterized examples of SI is small, and this has impeded understanding of field-scale processes, such as those controlling mixing zones, saltwater upconing, heterogeneity effects and other factors. Current SI process understanding is based mainly on numerical simulation and laboratory sand-tank experimentation to unravel the combined effects of tides, surface water–groundwater interaction, heterogeneity, pumping and density contrasts. The research effort would benefit from intensive measurement campaigns to delineate accurately interfaces and their movement in response to real-world coastal aquifer stresses, encompassing a range of geological and hydrological settings.

1. Introduction

The management of freshwater reserves is an increasingly important imperative for the custodians of natural resources. Freshwater stored in coastal aquifers is particularly susceptible to degradation due to its proximity to seawater, in combination with the intensive water demands that accompany higher population densities of coastal zones. Seawater intrusion (SI, i.e., the landward incursion of seawater) is caused by prolonged changes (or in some cases severe episodic changes) in coastal groundwater levels due to pumping, land-use change, climate variations or sea-level fluctuations. The primary detrimental effects of SI are reduction in the available freshwater storage volume and contamination of production wells, whereby less than 1% of seawater (∼250 mg/l chloride [355]) renders freshwater unfit for drinking. The considerable threat of SI on the global scale is well documented (e.g., [169,249,35]).

Here, SI refers to the subsurface movement of seawater, although surface water bodies (e.g., rivers, canals, wetlands) are impacted similarly by intruding seawater. Coastal aquifers are complex environments typified by transient water levels, variable salinity and water density distributions, and heterogeneous

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hydraulic properties. Climate variations, groundwater pumping and fluctuating sea levels impose dynamic hydrologic conditions, which are inter-related with the distribution of dissolved salts through water density-salinity relationships. These processes are often important at vastly different spatial and temporal scales, although cumulative small-scale factors (e.g., beach-scale dynamics) can combine to have wide ranging impacts on coastal hydrology and SI (e.g., [60]). A simplified coastal aquifer representation showing a selection of hydrogeological processes of relevance to SI in a shallow unconfined aquifer is given in Fig. 1. Important aspects such as 3D effects, heterogeneity in aquifer properties and geometry, dispersion and diffusion, degree of aquifer confinement, hydrogeochemical processes, etc., are omitted from the figure, but their importance is recognized in the review that follows.

Considerable research effort spanning more than 50 years has been devoted to understand better coastal aquifer flow and transport processes, to enhance coastal water security, and to avoid environmental degradation of coastal systems [101,249]. Indeed, the field of coastal hydrogeology, considered as a sub-discipline of hydrogeology, spans SI, submarine groundwater discharge (SGD), beach-scale hydrology, sub-seafloor hydrogeology and studies on geological timescales involving coastline geomorphology. Despite this, coastal aquifer hydrodynamics and SI remain challenging to measure and quantify, commonly used models and field data are difficult to reconcile, and predictions of future coastal aquifer functioning are relatively uncertain across both regional and local (individual well) scales (e.g., [278]).

Here, we review the literature to outline recent progress in SI research, including both practical and theoretical elements of SI analysis and investigative tools. SI research encompasses a multidisciplinary range of topics due to the complex nature of coastal aquifer flow and transport, which are influenced by unsaturated zone processes, interactions with surface water systems, shoreline geomorphology, microbiological and vegetation functioning, hydrogeochemical reactions, etc. It follows that SI research often involves linkages across traditionally disparate disciplines. Further, much of the SI literature focuses on the optimal use of coastal groundwater and issues of sustainability (i.e., management), including the uptake and application of new knowledge in understanding natural system functioning, and ultimately in the deployment of operational practices for regulating groundwater extraction and in mitigating SI. Given the inherent uniqueness of each real-world incidence of SI, well-documented case studies are an important aspect of SI research.

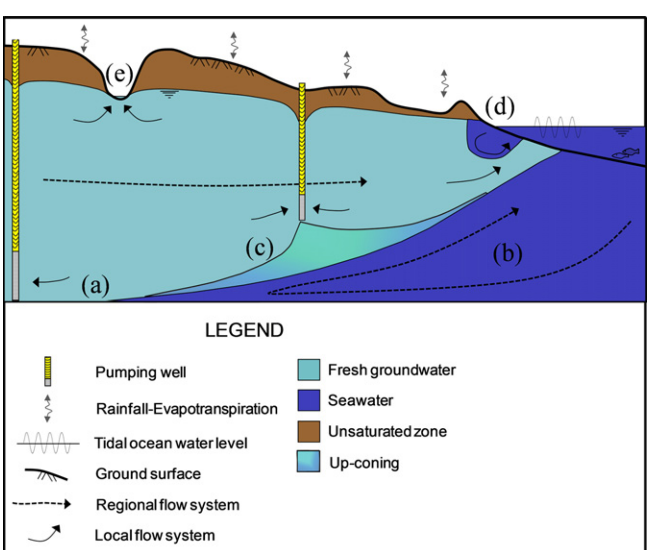

Fig. 1. Simplified diagram of a coastal unconfined aquifer setting, showing (a) seawater wedge toe, (b) density-driven circulation in the seawater zone, (c) seawater upconing due to well pumping, (d) coastal fringe processes, such as tidal seepage face and upper seawater recirculation zone, (e) head-controlled surface expression of groundwater.

The review aims to summarize the evolution and current status of SI research. The following SI research categories are considered: processes (Section 2), measurement (Section 3), prediction (Section 4), and management (Section 5). Finally, we provide a prospective view of gaps in SI knowledge and investigative tools (Section 6). Fundamental aspects of SI theory and management are covered by Reilly and Goodman [266], Custodio and Bruggeman [81], Bear et al. [40], Diersch and Kolditz [101], Cheng and Ouazar [72], and are not repeated here.

2. SI processes

The processes and factors associated with SI are described qualitatively by Custodio [77,78]. These include dispersive mixing, tidal effects, density effects including unstable convection, surface hydrology (e.g., recharge variability and surface–subsurface interactions), paleo-hydrogeological conditions (i.e., leading to trapped ancient seawater), anthropogenic influences, and geological characteristics that influence the degree of confinement as well as aquifer hydraulic and transport properties. The interactions between these and other processes (e.g., geochemical reactions, tsunamis and other episodic ocean events, beach morphological controls on shoreline watertable conditions, unsaturated zone flow and transport) provide for a seemingly infinite array of possible settings in which SI can occur. This poses a significant challenge for water resource managers in identifying the primary SI controlling factors and considering these in both the evaluation and optimization of groundwater use. In many cases, field observations reveal behavior that is unexpected or inexplicable if only a subset of coastal aquifer processes is considered (e.g., [319]). Laboratory and numerical modeling experimentation are typically the tools of choice in seeking to elucidate the influence of individual processes from multifaceted field measurements, and many of the studies reviewed below incorporate these types of approaches.

In all SI situations, controlling factors include buoyancy forces associated with density variations (controlled mainly through solute concentration but sometimes through temperature [90]), advective forces resulting from freshwater discharge, dispersive mechanisms, and hydrological/geometric boundary condition controls (e.g., aquifer thickness and extent and characteristics of sources and sinks). Time lags in SI responses to both cyclic and prolonged fluctuations in aquifer stresses introduce further complexity, and could potentially confound the interpretation of SI from field-based measurements (e.g., [345]). The situation of stable density stratification (freshwater overlying saltwater) is the most common salinity configuration, and is often explored through modified forms of the Henry [142] problem. Dentz et al. [99] defined dimensionless parameters for the Henry problem, representing the interplay between advective and diffusive mechanisms (i.e., the Péclet number; *Pe*), and the ratio of buoyancy to viscous forces (i.e., the Rayleigh number; *Ra*). Convective circulation of seawater, an important component of SI behavior, is demonstrated in the Henry problem. Abarca et al. [3] considered dispersive forms of the Henry problem as more realistic representations of SI, and generated additional dimensionless parameters accounting for dispersive and anisotropic controls. Werner et al. [354] considered confined and unconfined dimensionless parameters representing the mixed convection processes for steady-state situations involving recharge and a sharp freshwater–saltwater interface. The interplays between mechanisms associated with unstable situations (saltwater