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Research Perspectives for Developing Seawater Intrusion Indicators in Changing Environments with Case Studies of Korean Coastal Aquifers: A Review

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ABSTRACT

The global use of groundwater in coastal areas has increased. Events such as seawater intrusion (SWI) are expected to increase along with the acceleration of natural disasters owing to environmental changes such as climate change, resulting in large-scale damage worldwide. Current trends in the research of coastal groundwater and related natural disasters include testing and verifying technologies using major case studies from individual countries. We identified global research trends in coastal groundwater, related these trends to changing environments and climate, and confirmed the qualitative and quantitative growth of these studies. This study describes the theoretical background and techniques for coastal groundwater analysis and details regional-scale SWI indicators based on analytical and numerical studies. This review highlights recent technologies that consider uncertainty and promotes discussions on field data obtained using new technologies. Finally, the research findings and trends for a regional coastal aquifer in Korea are discussed to describe recent SWI approaches for groundwater resources.

Keywords : Seawater intrusion/saltwater intrusion(SWI), SWI indicator, SWI metrics, Vulnerability, Climate-change

1. Introduction

Coastal areas face rapid urbanization, population growth, and natural disasters that degrade fresh groundwater resources. Seawater or saltwater intrusion (SWI) is a representative disaster in coastal aquifers that induces groundwater salinization, reducing available groundwater resources. Globally, the SWI of coastal groundwater resources occurs frequently but remains dependent on local hydrological and topographical characteristics (Ranjan et al., 2006; Werner et al., 2013).

SWI occurs as a natural disaster in coastal aquifers. Because of the high concentration of dissolved salt in seawater, seawater flows into the fresh groundwater aquifer, creating a seawater-freshwater wedge and mixing zone. Anthropogenic factors, such as changes in land use, artificial infrastructure, and excessive abstraction of coastal groundwater, control SWI. These natural and anthropogenic drivers that contribute to SWI in residential, agricultural, and natural areas have become increasingly serious issues in resource management and groundwater environmental fields. Analytical solutions and numerical analyses based on various mathematical models have been widely used in coastal groundwater management and SWI studies to simulate the conditions of coastal groundwater, considering geological diversity and topographic complexity. Prominent research groups worldwide have conducted coastal groundwater research for several decades (Goswami and Clement, 2007; Robinson et al., 2006; Oude Essink, 2001; El-Kadi et al., 2014; Werner et al., 2011).

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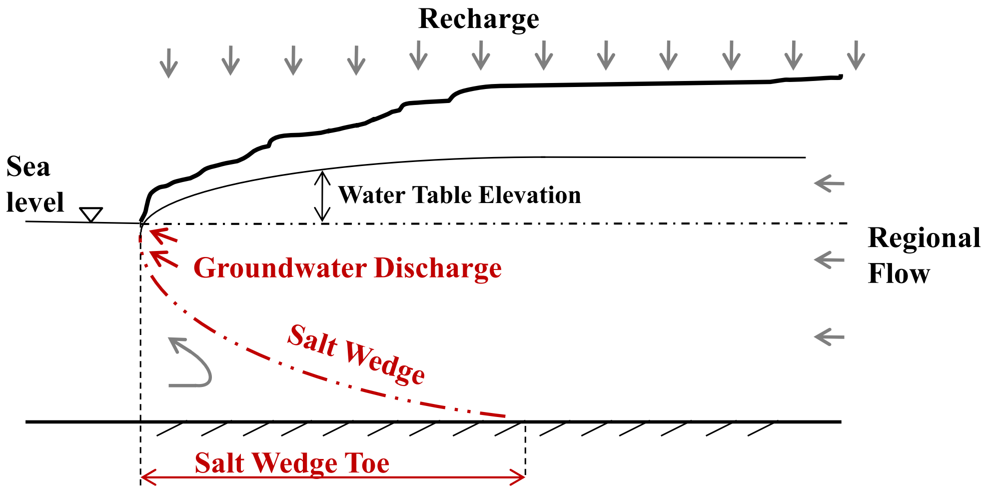

Fig. 1. Schematic Diagram of Coastal Aquifers and the Corresponding Indicators

Uncertainty in the prediction of water resources due to extreme climatic conditions due to climate change, such as sea level rise (SLR) and reduced recharge due to extreme drought, exacerbates the vulnerability of water resources. New diagnostic tools and evaluation methods for protecting coastal water resources and ensuring sustainability are continuously being advanced.

Fig. 1 shows a conceptual cross-sectional diagram describing the groundwater flows that occur near the sea. The figure shows widely used SWI indicators, including the salt wedge, salt wedge toe, and groundwater discharge flow. This analysis of SWI indicators excludes from discussion water table elevation, a common indicator in groundwater studies. Initially, analytical and numerical research was mainly performed using lateral movement as a measure of SWI by analyzing the cross-section of the coastal aquifer. A salt wedge generally refers to a 50 % isochlor salt concentration. The 10 % and 90 % isochlors were used as SWI metrics when dispersion effects were considered. The extent of SWI is defined as the horizontal length of a salt wedge toe. Salt wedges in coastal aquifers divide the groundwater flow into two distinct regions: a freshwater region above the wedge and a saline region below the wedge. Freshwater transport above the wedge is much faster than that below the wedge. Groundwater discharge leaving the aquifer from the coastal aquifer includes fresh local groundwater mixed with saline seawater that has penetrated the aquifer. The SWI creates a typical circulation pattern below the interface.

The vulnerability index describes the risk or impact of SWI on coastal aquifers using a calculated index. By visualizing the vulnerability index, quantitative and qualitative analyses were carried out to see how regional characteristics affected the vulnerability assessment results. Vulnerability index methods using analytical solutions have been widely employed. The analysis method assessed the vulnerability to SWI based on the freshwater-saltwater interface derivation equation using the Ghyben-Herzberg ratio. For example, SWI vulnerability indicators for freshwater lenses on strip islands in Australia were assessed (Morgan and Werner, 2014). In the Netherlands, coastal groundwater vulnerability was assessed using six criteria (sea-level-based freshwater head distribution, presence or absence of agriculture, aquifer thickness, groundwater cultivation capacity, groundwater discharge area, and soil characteristics) to supply fresh water actively and with a focus on vulnerable areas. The GALDIT method, developed by Chachadi (2001), comprehensively identifies the seawater penetration vulnerability index by considering aquifer characteristics, hydraulic conductivity characteristics, groundwater level, distance from the coast, severity of current seawater penetration, and aquifer thickness. The method expresses vulnerabilities through arithmetic calculations after assigning weights to each vulnerability and ranking them using decision-making methods. Geographic information systems (GIS) software was used to map parameter data and check distribution.

The overall trends in SWI and research trends have been reviewed by country (Barlow and Reichard, 2010; Custodio, 2010; Jeen et al., 2021; Werner, 2010). The study characteristics were classified according to the method, code, or area of application. This review examined representative studies from a new perspective, focusing on the indicators used to characterize outputs. To reveal the significance and contributions of each SWI study, we focused on implementing the SWI indicators to analyze the results. The objective of this review is to understand the contributions of previous studies on SWI dynamics. A lot of case studies with conceptual models and discussions of site studies in coastal regions are covered. Each section discusses the SWI analysis method using analytical and numerical models, research trends related to climate change and future research, and Korean studies related to the SWI. Groundwater indicators. This review focused only on quantitatively measured SWI metrics and excluded chemical and geochemical indicators.

2. Diagnosis Using SWI Indicators

2.1 Indicators Used in Analytical Analysis

The mathematical expression of the sharp interface model and related analytical solutions are based on the Ghyben-Herzberg principle. When computing the SWI process, mixing is commonly ignored, and a sharp interface between the saltwater and freshwater zones is assumed. Most analytical models adopt a simplified, sharp interface approximation (Strack, 1976). The equation for the sharp interface model is a single-potential analysis and was derived from a study by Custodio and Bruggeman (Custodio and Bruggeman, 1987). In early studies, Tamai and Shima (Tamai and Shima, 1967) developed an approximate solution based on the Duipuit assumption to predict the transient movement of an intrusion wedge toe. The authors compared the mathematically predicted results to the experimental results and observed a good match when the experiment was conducted using coarse sand. Vappicha and Nagaraja (1976) developed a similar model (Bear and Dagan, 1964), which adopted indicators such as the rate of movement of the interface and the length of intrusion. They compared the mathematically predicted results with the experimental results and observed a good match when the experiment was conducted with coarse sand. Chesnaux and Allen (2008) used closed-form analytical solutions for circular and strip islands, applied the Ghyben-Herzberg relation, and compared the location of the water table and the time of groundwater transport. Werner and Simmons (2009) used analytical models to classify the extent and nature of SWI in aquifers with immediate SLR according to the type of freshwater inflow. To evaluate the SWI extent, they adapted an equation representing the salt wedge toe, originally developed by Strack (1976) and Custodio (1987). The analytical index, considering the representative parameters of the Nile Delta region, showed results consistent with the numerical solution of Sherif and Singh (1999). Nevertheless, the authors recommended using it to manage coastal aquifers impacted by SLR separately rather than proposing a replacement with a numerical solution. Werner et al. (2011) improved the existing analytical solutions to devise new SWI vulnerability indicators using two partial derivatives: 1) the rate of change in the wedge toe and 2) the rate of change in seawater volume when the toe of the wedge and the volume of water are expressed in the analytical solution. The stressors affecting the vulnerability of the SWI include SLR, changes in recharge due to climate change, and changes in seaward discharge. Based on these SWI vulnerability indicators, a national inventory of SWI vulnerability for Australia was introduced based on 28 coastal aquifers in Australia (Morgan and Werner, 2015). As a useful MODFLOW family tool, the SWI package was developed by Bakker et al. (2013). This package is based on sharp interface approximations and is more suitable for modeling systems with negligible dispersion effects.

Recently, researchers have begun to consider uncertainties when studying the extent of SWIs. Ferguson and Gleeson (2012) investigated the extent of the SWI based on the impact of SLR and saltwater inundation. They concluded that saltwater inundation is more important than SLR inundation because of the topographic gradient in low-lying coastal areas. By taking into account the range of one standard deviation of hydraulic conductivity owing to various aquifer types, from coarse-grained classic rocks to coarse-grained unconsolidated sediment, the study included a statistical indicator, the uncertainty of the SWI. Representative analytically modeled

Table 1. Analytical Indicators Used for the Identification and Prediction of SWI

Relevant studies	Model description	Issues of the study (stressors)	Output indicators
Tamai and Shima (1967)	Conceptualized model compared to the laboratory experiment	Dupuit assumption for the movement of the intruding salt wedge toe	Movement of salt wedge toe
Chesnaux and Allen (2008)	Conceptualized unconfined island model	Analytical approach for groundwater travel time	Travel time
Werner and Simmons (2009)	Field-scale analytical model	Impact of hypothetical SLR	Change of salt wedge toe
Morgan and Werner (2015)	Selected Australian unconfined aquifers	SLR, recharge change and change in seaward groundwater flux	SWI vulnerability indicator: 1) The change of salt wedge toe to for the change of SLR 2) Recharge and seaward groundwater flux
Werner et al. (2011)	Adapted from the Gaza Strip (Moe et al., 2001); the Pioneer Valley aquifer (Werner and Gallagher, 2006); the Nile Delta; and the Madras aquifer (Sherif and Singh, 1999)	Analytical approach for SWI vulnerability assessment	SWI vulnerability indicator: 1) Rate of change in the salt wedge toe 2) Rate of change in seawater volume when the salt wedge toe and the volume of water are expressed in the analytical solution according to 1) SLR, 2) change in recharge, and 3) change in the seaward discharge
Ferguson and Gleeson (2012)	1,419 coastal watersheds, USA	Impact of SLR and saltwater inundation	1) Change of salt wedge toe, 2) Uncertainty considering the range of hydraulic conductivity

SWI studies are summarized in Table 1.

2.2 Indicators Used in Conceptualized Numerical Models

The extent of the SWI and movement of the mixing zone depend on the geography, hydrogeological properties of the aquifer, and meteorological parameters, such as precipitation. Rectangular, two-dimensional, and three-dimensional precise numerical simulations are used for density-dependent groundwater flows. The advantage of more sophisticated numerical models is that mixing effects due to dispersion can be simulated across the interface. Numerical models are useful for modeling field-scale problems because they include topographic complexity and geological variability (Dausman and Langevin, 2005; Oude Essink et al., 2010; Praveenaa et al., 2010; Vandenbohede and Lebbe, 2002). A particular set of benchmark problems is solved with tried-and-true analytical, laboratory, and numerical solutions in order to validate a numerical model. The Henry problem (Henry, 1964) is the only density coupling numerical example related to the saltwater-freshwater interface and SWI for which a semi-analytical solution exists in a two-dimensional flow. This solution defines the location and shape of the freshwater boundary, showing that freshwater flow moves toward the ocean boundary. During the data validation process, the isochore, which includes linearized points corresponding to 50 % concentration of saltwater, was used as the main indicator defining the saltwater-freshwater interface. After being introduced as a benchmark solution, the model design and numerical schemes were comprehensively evaluated and modified by researchers. These studies were conducted by verifying the model parameters and modifying a few according to Henry's solution. Pinder and Cooper (1970), Lee and Cheng (1974), Segol and Pinder (1976), Frind (Frind, 1982), Huyakorn et al. (1987), and Voss and Souza (1987) developed several modified solutions. Croucher and O'Sullivan (1995) concluded that Henry's original interpretation may have been slightly erroneous. Segol (1994) reexamined the errors related to Henry's solution and suggested a few corrections. The proposed correction is a 183-term truncation scheme. These solutions to the Henry problem have mainly investigated the steady-state isochore distribution. A criterion for determining the extent of SWI is the locations of additional isochores, like 25 %, 75 %, and 50 % isochores, because of the mixing zone in the domain of the numerically simulated Henry problem. Simpson and Clement (2003) adopted a novel transient indicator for the Henry problem: the transient position of the toe. Simpson and Clement proposed a 293-term truncation scheme (Simpson and Clement, 2004). When Segol (Segol, 1994) recalculated Henry's solution using additional terms, the new solution differed slightly from the original. With this new solution, Segol (1994) showed that numerical codes could reproduce the correct solutions for the Henry problem. The coupling of the flow and transport based on the density difference owing to the high concentration was a key factor in the numerical analysis. Simpson and Clement (2003) compared the isochores of domains for coupled versus uncoupled cases and reported that the coupling process effect of the Henry problem was not evident when the default parameter values were given. Based on these findings, Simpson and Clement (2003; 2004) discussed a modified Henry problem by reducing the dimensionless freshwater flux among the input parameters. Abarca et al. (2007) investigated the heterogeneity of the Henry problem by considering a dimensionless input parameter, and the results illustrated a dimensionless saltwater flux for dispersive and diffusive cases. Kerrou and Jaouher (2010) investigated the two-dimensional and three-dimensional Henry problems by following the dimensionless parameters of Abarca et al. (2007) to avoid scale-dependent analysis. The dimensionless penetration length of the saltwater wedge and the dimensionless width of the mixing zone described the geometry of the saltwater-freshwater interface. The amount of saltwater entering the aquifer system is described by the dimensionless saltwater inflow flux. The results showed that in two dimensions, anisotropy significantly affects the permeability coefficient; however, in three dimensions, the degree of diffusion through the dispersion coefficient changes, changing the length of the SWI. In addition to the dimensionless salt wedge toe, width of the mixing zone, and saltwater flux, recent studies of the Henry problem considered additional dimensionless indicators (Fahs et al., 2016; Fahs et al., 2018).

A laboratory-scale experimental setup was used to analyze the crosscut model in the SWI. The experimental results enabled visualization of the SWI movement under the surface that could not be observed in the field. Oostrom et al. (1992) considered a laboratory experimental setup that is widely used for SWI. In contrast to the Henry problem, which involves a wide mixing zone, most laboratory experimental results indicate a relatively narrow mixing zone. Goswami and Clement (2007) provided the first benchmark problem based on experimental results by specifying the boundary conditions of the experimental model. The numerical simulations using 10 %, 50 %, and 90 % isochores for steady-state simulations were compared with the experimental results. In addition, the authors used only 50 % of the isochores in the transient simulations. An experimental dataset of horizontal and vertical distances with respect to time was provided for use as a benchmark dataset. Abarca and Clement (2009) succeeded in visualizing only the mixing zone, including the freshwater interface, in different colors by setting boundary conditions for freshwater and saltwater with different pH values in a small-scale water tank experiment.

Most benchmark problems, including the Henry problem, exist only as numerical simulations or semi-analytical solutions. Chang and Clement (2012) extracted and quantified the location of the salt wedge in a laboratory experiment and quantified the velocity of the movement of the freshwater–saltwater interface using an exponential function to describe a time-dependent equation. To quantify the difference between the intruding and receding SWI rate, the term $\Delta XT(t)$ was newly defined, which is the distance that remains to be traversed by a migrating saltwater wedge toe to reach the steady-state condition at the end of the simulations. This indicator showed that the wedge rapidly advanced during the early simulation period when the boundary condition was changed and gradually slowed down. Chang and Clement (2013) investigated the movement of contaminants in freshwater and saltwater regions based on the freshwater interface and reproduced the migration of slugs using numerical simulations. This study was extended to a site scale of decades to simulate the movement of a contaminant or nutrient plume. When comparing water circulation patterns between the freshwater and saltwater regions, the results showed that the movement of contaminants or nutrients in the saltwater area was relatively low. Oz et al. (2014) obtained experimental and numerical results from laboratory experiments. The results compared the salinity values of the 40 measuring points; these points were divided into three different ranges based on their salinity values. Sensitivity tests were performed using three dimensionless parameters: density, thickness, and flux.

Many studies have used the detailed vertical movement of the SWI in nearshore aquifers using two-dimensional numerical models. Taniguchi et al. (2002) highlighted the relationship between the extent of SWI inland and the increase or decrease in submarine groundwater discharge (SGD) and the importance of evaluating SGD as a coastal water resource management issue. SGD contributes greatly to the discharge and circulation of nutrients and pollutants near the coast and has attracted the interest of groundwater experts and experts in the marine engineering field. Changes in sea-level oscillations due to tides and waves can influence offshore and large-scale SGD patterns, which can affect the aquifer-ocean interface in terms of the upper saline plume (USP) and saltwater wedge (Li et al., 2008; Li and Jiao, 2003a; 2003b; Michael et al., 2005; Robinson et al., 2007a; 2007b). The shape of sloping beaches has been altered by ocean oscillations, and numerical models have been used to study the effects of wave and tidal forcing. These models have confirmed that surface changes in unconfined aquifers can affect beaches (Horn, 2006; Robinson et al., 2006). Robinson et al. (2006) extracted the vertical hydraulic gradient from numerical simulations to indicate upward flow according to

Table 2. Numerical Indicators Used for the Identification and Prediction of SWI

Relevant studies	Model description	Issues of the study (stressors)	Output indicators
Pinder and Cooper (1970), Lee and Cheng (1974), Segol and Pinder (1976), Frind (1982), Huyakorn et al. (1987), Voss and Souza (1987), Croucher and O'Sullivan (1995)	Conceptualized numerical model for the Henry problem	Numerical validation	1) The dimensionless salt wedge toe 2) The dimensionless spread of the concentration between 10 % and 90 % isochlors
Fahs et al. (2016)	Conceptualized numerical model for the Henry problem	New semi-analytical solution for velocity-dependent dispersion	1) The dimensionless salt wedge toe 2) The dimensionless spread of the concentration between 10 % and 90 % isochlors 3) The dimensionless width of the mixing zone 4) The dimensionless z coordinate of the adverse flow inflection point 5) The dimensionless saltwater flux
Fahs et al. (2018)	Conceptualized numerical model for the Henry problem	Stratification and anisotropy on the Henry problem	1) The dimensionless salt wedge toe 2) The dimensionless width of the mixing zone 3) The dimensionless saltwater flux 4) The dimensionless depth of the zone of groundwater discharge to the sea
Goswami and Clement (2007)	Laboratory experiment	Boundary condition	The steady-state and transient 10 %, 50 %, and 90 % isochlors
Kuan et al. (2012)	Conceptualized unconfined aquifer with a sloping beach	Tidal influence	1) Salt wedge toe 2) Upper edge of the salt wedge 3) Width of the freshwater discharge zone 4) Area of upper saline plume
Robinson et al. (2014)	Conceptualized unconfined aquifer with a sloping beach	Subterranean estuary driven by intensified wave conditions	1) The total salt mass per unit width of the aquifer in the USP 2) The x coordinate of the centroid of the salt plume 3) The z coordinate of the salt plume centroid in the USP of a subterranean estuary
Dausman and Langevin (2005)	Field-scale model for the Biscayne Aquifer in southern Florida	Drought, well-field pumping, SLR, and canal management	1) Salt wedge toe 2) Isochlors for 200, 1000, 5000, 10 000, 15 000, 17 000, 19 000 mg/L of chloride concentrations

tidal cycles. This study further investigated the effects of wave forcing on beach profile evolution using large-scale laboratory experiments with numerical modeling (Bakhtyar et al., 2011) and groundwater dynamics. The tidal influence simulated by Kuan et al. (2012) is indicated by the toe and upper edge of the salt wedge, width of the freshwater discharge zone, area of the USP, tide-induced circulation rate, and root mean square error (RMSE). Here, the RMSE was calculated based on the difference between the x coordinates of the interface given by the Glover solution and the simulation results for a given z value. The aquifer response to waves simulated by Robinson et al. (Robinson et al., 2014) is indicated by 1) the total salt mass per unit width of the aquifer in the USP, 2) the x-coordinate of the centroid of the salt plume, and 3) the z-coordinate of the salt plume centroid in the USP of a subterranean estuary. Boufadel (2000), Boufadel et al. (2006) mesured concentrations of salt water and pressure heads from laboratory-scale experiments on a tidal-induced fresh brine interface.

One of the most intensively studied coastal aquifers in North America is the Biscayne Aquifer in southeastern Florida, USA (Kohout, 1960). For example, Dausman and Langevin (2005) evaluated the relative importance of drought, well-field pumping, SLR, and canal management in SWI. Ranjan et al. (2006) focused on changes in groundwater recharge and SLR due to the loss of fresh groundwater resources in water-resource-stressed coastal aquifers. Masterson (2004) and Masterson and Garabedian (2007) simulated the underground water system of Cape Cod Island, Massachusetts, USA, which is well-known for tourism. Due to the significant abstraction of groundwater from the aquifer, the seawater-freshwater interface continues to move inland. Gingerich and Voss (2005) used the three-dimensional model SUTRA (Provost and Voss, 2019) to simulate SWI in Hawaii, USA. Oki (Oki, 2005) simulated SWI in Hawaii. Langevin (2001) investigated coastal groundwater problems in Biscayne Bay, Florida, USA. Werner and Simmons (2009) studied the SWI problem in Pioneer Valley, Australia. Table 2 provides an overview of representative numerically modeled SWI studies.

2.3 Application of Index in Changing Future Environment

Climate change, which induces environmental changes in coastal aquifers, is a critical issue that significantly increases uncertainty in water resource management due to groundwater salinization (Green et al., 2011). In recent years, increased anthropogenic activities, extreme droughts, and SLR due to climate change have emerged as issues for coastal groundwater management. Climate change can affect long-term groundwater resources by affecting precipitation patterns and recharge pathways. Long-term recharge changes can affect groundwater resources by inducing drought or excessive water supply during rapidly changing or intensified seasonality. Numerous modeling-driven coastal groundwater studies have investigated the effects of climate change on future water resources. Future anthropogenic and natural changes were incorporated into these scenarios. Nicholls et al. (2008) defined a scenario for climate change and coastal vulnerability as “a description of potential future conditions developed to inform decision-making under uncertainty” (Parson et al., 2007).

The SLR boundaries of SWI models were hypothetically simulated or exaggerated in early studies on the effects of climate change on SWI. The results were primarily analyzed using the salt wedge in the aquifer's crosscut or the salt concentration, measured in terms of salinity or total dissolved solids (TDS). Meisler et al. (1984) numerically analyzed the effect of eustatic sea-level fluctuations on the transition zone between freshwater and seawater in the Northern Atlantic coastal plain by lowering the relative sea level from 0 to 150 m. Fesker (2007) simulated an SLR of 0.5 m per 100 years over a simulation time of 250 years by comparing the salt wedge for these three cases. The results showed that a constantly rising sea level resulted in a linear increase in the salt load in the model domain with successive salinization of the marsh area from the coastline towards Geest, which could represent the effect of SLR at the freshwater-saltwater interface. Oude Essink (2001) established three types of simplified SLR scenarios to perform numerical analysis in aquifers in the Netherlands and concluded that a 0.5 m rise in sea level over 100 years would lead to an increase in salinity in all low-lying areas near the sea, providing maps of the freshwater head and the chloride concentrations. By comparing the measured and simulated water levels and the toe positions of 250 mg/L isochores, Dausman and Langevin (2005) concluded that the coastal aquifer of Broward County, Florida, could cause chloride contamination if the sea level exceeded 48 cm over 100 years. By comparing the volumetric loss of freshwater due to SLR in Israel, Melloul and Collin (2006) proved that 77 % of the loss was due to lateral movement and 23 % was due to head change, assuming that the SLR is 0.5 m in the coastal aquifers. Navoy (1991) graphically compared the positions of sharp interfaces from a crosscut model to study aquifer-estuary interactions based on the impact of several hypothetical SLRs and various combinations of hydraulic conductivities in the coastal aquifer of New Jersey, USA.

Aquifers are dynamically linked to the watershed hydrology and SWI studies have been conducted to integrate detailed hydrological analysis results (Chang et al., 2016; El-Kadi et al., 2016). This makes it even more important to generate detailed projection of groundwater recharge based on climatic future stresses. The climatic effect on groundwater resources is considered dependent on local climatic conditions and topography (Green et al., 2011; Ranjan et al., 2006). Ranjan et al. (2006) calculated freshwater loss by considering land-use changes and the hydrological behavior of a catchment in Sri Lanka. Ranjan et al. studied the impact of climate change on high- (A2) and low-emission scenarios (B2) and observed that it may result in a decrease in semi-arid rainfall at the local scale, whereas increased temperatures are projected to increase precipitation at the global scale (Ranjan et al., 2006). These two studies adopted an aridity index to study fresh groundwater loss. Green and MacQuarrie (2014) simulated the impact of climate change and groundwater abstraction in Atalatic, Canada to complete a vulnerability assessment and quantified the impact of SLR and changes after recharge on SWI in coastal aquifers.

Due to the effects of climate change, islands are significant research sites that are greatly impacted by changes in the water resources that are available. Several island regions have geological and terrestrial characteristics that make it difficult to use surface water resources, and most groundwater recharge in these regions relies on rainfall. Therefore, compared to coastal aquifers along the inland coast, groundwater resources on islands are more susceptible to SWI, and the islands can be sensitive to natural disasters depending on the island's hydrology, geology, topography, or shape (van der Geest et al., 2020). Among the island regions, the most vulnerable to SWI are the atoll islands in the Pacific and Indian Oceans, which are in the lowlands less than a few meters above sea level and simultaneously have a relatively small area (Bailey et al., 2009; Kundzewicz and DÖll, 2009; White and Falkland, 2010). In contrast, the impact of groundwater recharge due to rainfall changes will have a greater effect on the freshwater lenses of islands if shoreline erosion by SLR is insignificant (White and Falkland, 2010). Studies have focused on SWIs impacted by climate-related stressors. The impact of changes in precipitation and SLR was reported in the Special Report on Emission Scenario (SRES) from the IPCC 4^{th} report (IPCC, 2007), which showed the movement of the saltwater wedge and change in volumetric freshwater lenses under both the most and least favorable scenarios applied to Shelter Island, USA (Rozell and Wong, 2010). Mapping the water level distribution, impact of SLR, and impact of increased precipitation were projected until 2100 based on the IPCC SRES A2 scenario on freshwater lenses of the North Sea Island of Borkum, Germany (Sulzbacher et al., 2012). The calibration method was illustrated by comparing the measured TDS at several monitoring wells to the computed results and the vertical profiles of electrical conductivities. The impact of a 25 % increase in the recharge rate was reported in Malaysia (Praveena and Aris, 2010), and the impact of future climate and land-use changes during 2070-2099 under the SRES A2 scenario on the entire Jeju Island of South Korea was studied (El-Kadi et al., 2014). Babu et al. (2018) simulated a reduction in freshwater volume on Tongatapu Island under recharge reduction and increased pumping scenarios. Chang et al. (2016) examined the effects of anthropogenic activities and recharge scenarios caused by climate change based on the IPCC SRES on Dauphin Island, USA, and indicated a volumetric reduction in freshwater by indicating changes in the freshwater head, salt wedge in the vertical crosscut of the model, and volumetric changes in freshwater resources.

Loáiciga et al. (2011) simulated SLR scenarios for the city of Monterey, California, USA. The study illustrated numerically simulated locations of the vertically averaged 1000 and 10,000 mg/L isosalinity lines in the plan view of the model, where predictions of mean SLR are expected to range from 0.10 to 0.90 m. The simulation analysis included a detailed resolution of SWI, and its causes were quantified via numerical simulation under scenarios of changes in both groundwater extraction and SLR in the 21st century. One of the most recent studies was conducted by Chun et al. (2018) who simulated SLR and precipitation scenarios under the Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios based on the 5th IPCC report. The results showed the highest salinity increase of 40 % in the case of SLR and a less favorable freshwater recharge rate under RCP 4.5.

Recently, studies have considered more sophisticated climate change scenarios that consider recharge and SLR based on projected changes in precipitation and air temperature from global climate models and emission scenarios. In addition, interdisciplinary research has been conducted to map the SWI vulnerability in groundwater aquifers that are impacted by climate change (Klassen and Allen, 2017; Werner et al., 2013) and to inform the status of groundwater resources using indexed equations, various hydrogeological data, and GIS techniques. Various indicators have been developed in field research to assess the severity of SWI. Giambastiani et al. (2007) conducted a numerical study to investigate SWI in an unconfined coastal aquifer in Ravenna, Italy. By indicating the salt concentration distribution in the aquifer, the results showed that the mixing zone between fresh and saline groundwater shifted 800 m farther inland for an SLR of 0.475 m per century. In addition, the impact of the SLR was illustrated by indicating the seepage rate and salt load. Representative SWI studies related to changing environments are summarized in Table 3.

2.4 Recent Development of New Technology and Perspectives for SWI Indicators

Approaches to SWI research include numerical modeling, analytical solutions, and GIS. Recent modeling includes an uncertainty analysis and assesses the effect of alternative SWI reduction measures. Using new observational data and statistical techniques, uncertainty analysis was performed. Coulon et al. (2021) considered the uncertainties of an observation dataset and quantitatively reported the standard deviation and 95 % confidence intervals obtained from shallow, deep open, and pumping wells on Magdalen Island, Canada. To obtain an optimized extraction rate for pumping, Rajabi and Ketabchi (2017) tested five new formulations for uncertainty-based simulation-optimization approaches, which have the objective function of minimizing the sum of energy distances for various reliability levels in the management plan. Roy and Datta (2020) attempted ensemble-based SWI prediction by combining artificial intelligence-based prediction models and selecting five prediction models: adaptive neuro-fuzzy inference system (ANFIS), Gaussian process regression (GPR), multivariate adaptive regression spline (MARS), support vector regression (SVR), and probabilistic linear regression. The prediction performance was compared to that of the dataset obtained from the five monitoring locations using the following statistical metrics: rRMSE, MAPRE, R, NS, IOA, and KGE. To reduce uncertainty, new observation data or a combination of new and existing data were used

Table 3. Description of Indicators Used to Identify and Predict SWI Related to Changing Environments

Relevant studies	Model description	Issues of the study (Stressors)	Output indicators
Ranjan et al. (2006)	Field-scale numerical model for a catchment of Sri Lanka	Change of recharge, land use, and hydrologic soil condition	Volume of freshwater loss
Sulzbacher et al. (2012)	Field-scale numerical model for freshwater lenses of the North Sea Island	SLR, and the increase in precipitation under IPCC SRES A2 scenario	1) the measured TDS at monitoring well positions 2) the vertical profiles of electrical conductivities
Chang et al. (2016)	Field-scale numerical model for Dauphin Island, USA	Land use, land-use change, and recharge based on IPCC SRES scenarios	1) Salt wedge toe 2) Volumetric reduction of freshwater
Chun et al. (2018)	Field-scale numerical model, Korea	SLR and future precipitation under RCP 4.5 and 8.5 scenarios	Salinity
Giambastiani et al. (2007)	Field-scale numerical model for Ravenna, Italy	SLR with uncertainty based on IPCC scenarios	1) Salt wedge toe 2) Seepage rate 3) Salt load

in the model. For example, uncertainties can be reduced by applying observation data using new electrical signals such as airborne electromagnetic (AEM) (Meyer et al., 2019). The AEM resistivity data in the cross-sectional model was mapped and visually compared to the simulated distribution of TDS. This demonstrated a further application for quantitative comparison with conventional indicators. Goebel et al. (2019) combined offshore AEM and onshore electrical resistivity tomography (ERT) and discovered that this approach was successful in regions previously considered inaccessible by traditional monitoring methods. Hermans and Paepen (2020) combined inland and ocean ERT to improve the reliability of observations.

Studies related to SGD and oceanic oscillations have considered the effects of tidal (Veerapaga et al., 2019) and seasonal changes in confined systems (Qu et al., 2020). Qu et al. (2020) noted that most studies have investigated the effects of oceanic oscillations on unconfined aquifer systems and applied numerical approaches to confined systems using several indicators. To compare the groundwater discharge from the system, seasonally varying fresh submarine groundwater discharge (Q_{FSGD}), recirculated saline groundwater discharge (Q_{RSGD}), and fluxes flowing out of the aquifer across the seaward boundary (Q_{SGD}) were averaged over a seasonal cycle. Comparing freshwater storage capacities showed that an idealized circular system could store much more freshwater than an equivalent strip island. Tang et al. (2020) estimated the temporally varying cumulative volume of the channel (CVC) under different tidal levels from the coastal aquifer caused by surface and groundwater interactions through the river, and the change in the seawater-occupied channel volume, as a prediction and adaptation plan for SWI.

Compared to experimental results, Memari et al. investigated a circular, two-dimensional axisymmetric model for experiments on circular island systems (Memari et al., 2020). Veerapaga et al. (2019) developed new indicators for the validation of simulation results using (a) water level, (b) salinity interface gradient (SIG), which is defined as the slope of a 10 % isoline, (c) salinity intrusion length for a salinity of 10 (SIL10), and (d) salinity intrusion length for a salinity of 5 (SIL5). Table 4 summarizes representative SWI studies that have recently developed SWI indicators.

3. Application of SWI Indicators in Recent Korean Studies

Early SWI studies of regional aquifers in Korea focused on Jeju Island, Korea's largest island, which lies south of the mainland. Groundwater development occurs actively in the watersheds in the eastern and northern regions of Jeju Island (Won et al., 2006). Youn et al. (2003) and Kim et al. (2009) confirmed the presence of a saltwater-freshwater interface in the Handong-ri Watershed of eastern Jeju Island. Kim et al. (2009) calculated the hydraulic characteristics of

Table 4. Recent Indicators Used for the Identification and Prediction of SWI

Relevant studies	Model description	Issues of the study (stressors)	Output indicators
Coulon et al. (2021)	Field-scale analytical model for Magdalen Islands, Canada	Freshwater volume, interface elevation, parameter estimation, uncertainty analysis	The standard deviation and 95 % confidence intervals
Memari et al. (2020)	Radial experimental system	Comparison between circular and strip island systems	1) Salt wedge toe 2) Volume of freshwater lens
Roy and Datta (2020)	Hypothetical heterogeneous coastal aquifer system	Application of artificial intelligence method, weighted average ensemble	Statistical metrics: rRMSE, MAPRE, R, NS, IOA, and KGE
Tang et al. (2020)	Field-scale model for Pearl River Estuary, China	River discharge, mitigation of coastal channel	Temporally varied cumulative volume of the channel (CVC)
Veerapaga et al. (2019)	Field-scale model for Chikugo River estuary, Japan	Tidal effect	1) Water level 2) The salinity interface gradient (SIG), defined as the slope of 10 % isoline 3) Salinity intrusion length for salinity of 10 (SIL10) 4) Salinity intrusion length for salinity of 5 (SIL5)

a coastal aquifer by applying a tidal response technique and concluded that the range of tidal effects on eastern Jeju Island is 3-5 km off the coast. Recently, Shin and Hwang (2020) analyzed the anisotropy of coastal aquifers using borehole data from the eastern part of Jeju Island. The acquisition borehole data included electric conductivity, temperature, and temperature data from the thermal line sensor. Kim et al. (2016) developed a method for predicting the SWI interface using artificial neural networks (ANNs) by observing the seawater-freshwater interface on Jeju Island. Data on the seawater-freshwater interface was collected by installing an interface egg measuring device in the observation well, and past data was collected to predict the location of the seawater-freshwater interface. Groundwater level, tide, and sea level interface data were used to build an ANN model. Two ANN models were constructed and employed to predict the groundwater level and freshwater-saltwater interface. Studies related to SWI observations have been incorporated into the investigation of SGD on Jeju Island. Lee et al. (2016a; 2016b; 2016c) performed chemical and microbial community analyses in groundwater, considering tidal and coastal runoff in the southeastern part of Jeju Island, and used a thermal infrared imager mounted on an unmanned aerial vehicle (UAV) to inspect the SGD Kang et al. (2019) quantitatively evaluated coastal runoff using a thermal infrared sensor mounted on an UAV at two different tidal conditions.

A recent trend in SWI research in Korea is actively employing numerical modeling in inland coastal areas and predicting and evaluating future SWI on reclaimed land (Chang et al., 2020; El-Kadi et al., 2014). El-Kadi et al. (2014) assessed the water resource sustainability of Jeju Island under various climate change scenarios. They used pumping-sustainability yield (P-SY) indicators to represent the changes in spring flow under various recharge and pumping scenarios. To reflect the seasonal characteristics in Korea, the monthly differences in the index have been indicated using GALDIT. Various methods have been attempted, such as analyzing observational data centered on Jeju Island, predicting future situations, and evaluating vulnerabilities through numerical modeling. Chang et al. (2019) applied GALDIT to Jeju Island, South Korea. GALDIT was comparatively analyzed using calculations from observations in 2010 and 2015 on Jeju Island. This is the first study in which the SWI vulnerability of aquifers across Jeju Island was studied using GALDIT, a coastal groundwater assessment method. To analyze the risk of SWI on Jeju Island using long-term observations, parameters such as groundwater reserves across Jeju Island, hydraulic conductivity of aquifers, groundwater levels above sea level, distance from the coastline, effects of existing SWI, and aquifer thickness were analyzed. In addition, Chang et al. (2020) applied future scenarios to the northeastern part of Jeju Island, Korea. Three future scenarios exist in which the amount of pumped water increases, and the scenarios are divided into average, wet, and dry according to the applied climate. The simulations were conducted for a period of 10 years. This was the first attempt to incorporate the spatial distribution of freshwater levels and salinity obtained from numerical simulations as GALDIT input parameters.

The number of SWIs in inland Korea has increased in recent years. Jung et al. (2021) applied an SLR scenario to reclaimed lands in South Korea. Using the RCP scenario, the model SLR was subjected to sea level rise of 4.5, 8.5, and 2050, respectively. The SWI on the reclaimed land showed that when SLR exceeded the fresh groundwater level, it proceeded rapidly inland. Lee et al. (2015) evaluated the effects of SWIs on underground structures in a few areas of Yeosu along the southern coast. The seawater mixing ratio was used to evaluate the effect of the SWI on the underground structure and the effect of the SWI on the chloride concentration in the seepage. Kim et al. (2018) analyzed the effect of the SWI around an artificial waterway in Incheon and Gimpo, Korea. Electrical conductivity was measured and analyzed by installing a multi-depth monitoring sensor in the observation well around the waterway and by SEAWAT modeling. A 10-year predictive model was used to simulate the effect of the SWI due to the inflow of seawater into the waterway around the waterway. The analysis was performed on the data collected using a multi-depth monitoring sensor, and the salinity trend according to the effect of the SWI in the vicinity of the waterway was estimated according to the criteria. Kim and Yang (2018) analyzed the prediction of SWI by 2099 and the effect of applying alternatives to Taean, one of the western coasts of Korea. On the West Coast, areas vulnerable to SWI were identified based on groundwater level, seawater level,

Table 5. Description of Indicators Used to Identify and Predict SWI in Korean Regional Aquifers

Relevant studies	Model	Issues of the study (stressors)	Output indicators
El-Kadi et al. (2014)	Field-scale numerical model for Jeju Island, Korea	Climate change based on the IPCC SRES scenario	Pumping-sustainability yeid (P-SY)
Chang et al. (2020)	Field-scale numerical model for Jeju Island, Korea	Hypothetical future recharge and pumping scenarios	Salt wedge toe
Jung et al. (2021)	West coast reclaimed land, Korea	SLR scenario under IPCC RCP 4.5 and 8.5 scenarios	1) SWI area and rate 2) Soil salinization area and rate 3) Spatial average groundwater level
Kim and Yang (2018)	West Coast aquifer of inland Korea	SLR and recharge scenario under IPCC RCP 4.5 and 8.5 scenarios. Future pumping scenario using linear regression	1) SWI area and rate 2) Reduction of SWI area and rate using countermeasures

groundwater usage, and reclamation trends. The RCP scenario was simulated until 2099. Kim et al. (2021) applied GALDIT to nine administrative districts in the northern region of the western coast of South Korea. To represent seasonal changes in SWI vulnerability, the GALDIT index was divided into dynamic and static indices. For a sensible consideration of the monthly changes, the GALDIT score criterion, divided by the existing quartiles, was changed to a decile and evaluated. The representative Korean SWI studies are summarized in Table 5.

4. Discussion and Conclusion

The sustainability of coastal groundwater resources is threatened by changing environmental stresses. Accurate indicators are required to evaluate aquifer conditions and increase the reliability of interpretations. We discuss how studies indicate SWIs that can identify the occurrence of conceptualized and regional-scale SWIs. Early coastal groundwater simulations were limited to laboratory experiments or conceptualized SWI models; however, an increasing number of field modeling studies have been conducted globally with various and combined approaches to represent the severity or vulnerability of SWI in detail. Thus, significant discoveries and enhanced knowledge exchange have occurred among researchers of different nationalities. This review shows that analytical SWI indicators provide insight into the characterization and understanding of SWI. By using sophisticated coding, the SWI indicators produced by numerical simulation can include complex boundary conditions as well as site-specific heterogeneous and anisotropic parameters. Recent conceptual and regional studies have developed new indicators and updated conventional SWI metrics. For SWI studies in Korea, the quantity and quality of research have increased recently; however, the development of SWI analysis using new indicators is still insufficient.

Research on SWI identification and prediction involves analyzing future situations by simulating future environmental changes. Analysis of the SWI according to future scenarios and optimization of alternatives will require a highly reliable model. The high volume of data and many input parameters have resulted in high levels of uncertainty, so improving the reliability of the observation data is necessary to accurately predict the SWI. In addition to method optimization, alternative probabilistic approaches are required. To increase the reliability of the SWI model and reduce uncertainty, high-quality data from various locations is required for aquifers and coastal areas. Recent technological developments have improved data quality, and densely obtained data is collected using observation techniques such as AEM. The application of management strategies to prevent SWI damage requires location optimization, operating time for climatic characteristics, and water resource requirements.

Regarding the modeling of SWI in coastal aquifers, further attempts are being made to reflect the spatial and temporal heterogeneity of groundwater recharge and SLR scenarios to reflect recently updated climate change scenarios. More sophisticated scenario-based estimations are expected to be produced using a combination of detailed future scenarios and various field data-mining technologies.

In Korea's coastal groundwater research, the GIS-based index & ranking method represented by GALDIT and the numerical approach represented by SEAWAT are increasing. The vulnerability index is suitable to be used as a policy tool when quickly diagnosing the current status of the aquifer. Numerical modeling, such as SEAWAT, have the advantage of enabling mid- to long-term projections. In the future researches, integrated vulnerability diagnosis and numerical prediction for a single study site is expected to become a widely accepted SWI approach.

Finally, effective methods for transforming field data into conceptualized SWI model inputs collected from testbeds should also be devised. In numerical modeling, compared to calibration using groundwater head, calibration and verification methods using SWI indicators are currently applied selectively due to the difficulty of low suitability. Understanding the rapid changes in salinity that occur near the mixing zone and saltwedge and developing a suitable calibration process are expected to be important factors in improving the reliability of the SWI numerical modeling.

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References

Abarca, E., Carrera, J., Sánchez-Vila, X. and Dentz, M. (2007). "Anisotropic dispersive Henry problem." *Advances in Water Resources,* Vol. 30, No. 4, pp. 913-926.

Abarca, E. and Clement, T. P. (2009). "A novel approach for characterizing the mixing zone of a saltwater wedge." *Geophysical Research Letters,* Vol. 36, No. 6.

Babu, R., Park, N., Yoon, S. and Kula, T. (2018). "Sharp interface approach for regional and well scale modeling of small island freshwater lens: Tongatapu Island." *Water,* Vol. 10, 1636, https://doi.org/10.3390/w10111636.

Bailey, R. T., Jenson, J. W. and Olsen, A. E. (2009). "Numerical modeling of atoll island hydrogeology." *Groundwater,* Vol. 47, No. 2, pp. 184-196, https://doi.org/10.1111/j.1745-6584.2008.00520.x.

Bakhtyar, R., Brovelli, A., Barry, D. A. and Li, L. (2011). "Wave-induced water table fluctuations, sediment transport and beach profile change: Modeling and comparison with large-scale laboratory experiments." *Coastal Engineering,* Vol. 58, No. 1, pp. 103-118, https://doi.org/10.1016/j.coastaleng.2010.08.004.

Bakker, M., Schaars, F., Hughes, J. D., Langevin, C. D. and Dausman, A. M. (2013). *Documentation of the seawater intrusion (SWI2) package for MODFLOW: U.S. Geological Survey Techniques and Methods,* Book 6, Chapt. A46.

Barlow, P. M. and Reichard, E. G. (2010). "Saltwater intrusion in coastal regions of North America." *Hydrogeology Journal,* Vol. 18, No. 1, pp. 247-260, https://doi.org/10.1007/s10040-009-0514-3.

Bear, J. and Dagan, G. (1964). "Some exact solutions of interface problems by means of the hodograph method." *Journal of Geophysical Research,* Vol. 69, No. 8, pp. 1563-1572, https://doi.org/10.1029/JZ069i008p01563.

Boufadel, M. C. (2000). "A mechanistic study of nonlinear solute transport in a groundwater-surface water system under steady state and transient hydraulic conditions." *Water Resources Research,* Vol. 36, No. 9, pp. 2549-2565, https://doi.org/10.1029/2000wr900159.

Boufadel, M. C., Suidan, M. T. and Venosa, A. D. (2006). "Tracer studies in laboratory beach simulating tidal influences." *Journal of Environmental Engineering,* Vol. 132, No. 6, pp. 616-623.

Chachadi, A. G. and Lobo-Ferreira, J.-P. (2001). *Sea water intrusion vulnerability mapping of aquifers using the GALDIT method,* Vol. 4.

Chang, S. W., Chung, I.-M., Kim, M.-G., Tolera, M. and Koh, G.-W. (2019). "Application of GALDIT in assessing the seawater intrusion vulnerability of Jeju Island, South Korea." *Water,* Vol. 11, No. 9, 1824.

Chang, S. W., Chung, I.-M., Kim, M.-G. and Yifru, B. A. (2020). "Vulnerability assessment considering impact of future groundwater exploitation on coastal groundwater resources in northeastern Jeju Island, South Korea." *Environmental Earth Sciences,* Vol. 79, No. 22, 498, https://doi.org/10.1007/s12665-020-09254-2.

Chang, S. W. and Clement, T. P. (2012). "Experimental and numerical investigation of saltwater intrusion dynamics in flux controlled groundwater systems." *Water Resources Research,* Vol. 48, No. 9, W09527, https://doi.org/10.1029/2012WR012134.

Chang, S. W. and Clement, T. P. (2013). "Laboratory and numerical investigation of transport processes occurring above and within a saltwater wedge." *Journal of Contaminant Hydrology,* Vol. 147, pp. 14-24, https://doi.org/10.1016/j.jconhyd.2013.02.005.

Chang, S. W., Nemec, K., Kalin, L. and Clement, T. P. (2016). "Impacts of climate change and urbanization on groundwater resources in a barrier Island." *Journal of Environmental Engineering,* Vol. 142, No. 12, D4016001, https://doi.org/10.1061/(ASCE)EE.1943-7870.0001123.

Chesnaux, R. and Allen, D. M. (2008). "Groundwater travel times for unconfined island aquifers bounded by freshwater or seawater." *Hydrogeology Journal,* Vol. 16, No. 3, pp. 437-445.

Chun, J. A., Lim, C., Kim, D. and Kim, J. S. (2018). "Assessing impacts of climate change and sea-level rise on seawater intrusion in a coastal aquifer." *Water,* Vol. 10, No. 4, 357.

Coulon, C., Pryet, A., Lemieux, J.-M., Yrro, B. J. F., Bouchedda, A., Gloaguen, E., Comte, J. C., Dupuis, J. C. and Banton, O. (2021). "A framework for parameter estimation using sharp-interface seawater intrusion models." *Journal of Hydrology,* Vol. 600, 126509. https://doi.org/ 10.1016/j.jhydrol.2021.126509.

Croucher, A. E. and O'Sullivan, M. J. (1995). "The Henry problem for saltwater intrusion." *Water Resources Research,* Vol. 31, No. 7, pp. 1809-1814.

Custodio, E. (2010). "Coastal aquifers of Europe: an overview." *Hydrogeology Journal,* Vol. 18, No. 1, pp. 269-280, https://doi.org/10.1007/s10040-009-0496-1.

Custodio, E. and Bruggeman, G. A. (1987). "Groundwater problems in coastal areas." *Studies and Reports in Hydrology,* 45: UNESCO, Paris.

Dausman, A. and Langevin, C. (2005). *Movement of the saltwater interface in the Surficial Aquifer System in response to hydrologic stresses and water-management practices, Broward County, Florida,* USGS Scientific Investigations Report 2004-5256, https://doi.org/10.3133/sir20045256.

El-Kadi, A. I., Tillery, S., Whittier, R. B., Hagedorn, B., Mair, A., Ha, K. and Koh, G.-W. (2014). "Assessing sustainability of groundwater resources on Jeju Island, South Korea, under climate change, drought, and increased usage." *Hydrogeology Journal,* Vol. 22, No. 3, pp. 625-642, https://doi.org/10.1007/s10040-013-1084-y.

Fahs, M., Ataie-Ashtiani, B., Younes, A., Simmons, C. T. and Ackerer, P. (2016). "The Henry problem: New semianalytical solution for velocity-dependent dispersion." *Water Resources Research,* Vol. 52, No. 9, pp. 7382-7407, https://doi.org/10.1002/2016wr019288.

Fahs, M., Koohbor, B., Belfort, B., Ataie-Ashtiani, B., Simmons, C. T., Younes, A. and Ackerer, P. (2018). "A generalized semi-analytical solution for the dispersive henry problem: Effect of stratification and anisotropy on seawater intrusion." *Water,* Vol. 10, No. 2, 230.

Ferguson, G. and Gleeson, T. (2012). "Vulnerability of coastal aquifers to groundwater use and climate change." *Nature Clim. Change,* Vol. 2, pp. 342-345, https://doi.org/10.1038/nclimate1413.

Feseker, T. (2007). "Numerical studies on saltwater intrusion in a coastal aquifer in northwestern Germany." *Hydrogeology Journal,* Vol. 15, No. 2, pp. 267-279.

Frind, E. O. (1982). "Simulation of long-term transient density-dependent transport in groundwater." *Advances in Water Resources,* Vol. 5, No. 2, pp. 73-88.

Giambastiani, B. M. S., Antonellini, M., Oude Essink, G. H. P. and Stuurman, R. J. (2007). "Saltwater intrusion in the unconfined coastal aquifer of Ravenna (Italy): A numerical model." *Journal of Hydrology,* Vol. 340, No. 1-2, pp. 91-104.

Gingerich, S. B. and Voss, C. I. (2005). "Three-dimensional variable-density flow simulation of a coastal aquifer in southern Oahu, Hawaii, USA." *Hydrogeology Journal,* Vol. 13, No. 2, pp. 436-450, https://doi.org/10.1007/s10040-004-0371-z.

Goebel, M., Knight, R. and Halkjær, M. (2019). "Mapping saltwater intrusion with an airborne electromagnetic method in the offshore coastal environment, Monterey Bay, California." *Journal of Hydrology: Regional Studies,* Vol. 23, 100602, https://doi.org/10.1016/j.ejrh.2019.100602.

Goswami, R. R. and Clement, T. P. (2007). "Laboratory-scale investigation of saltwater intrusion dynamics." *Water Resources Research,* Vol. 43, No. 4. W04418, https://doi.org/10.1029/2006WR005151.

Green, N. R. and MacQuarrie, K. T. B. (2014). "An evaluation of the relative importance of the effects of climate change and groundwater extraction on seawater intrusion in coastal aquifers in Atlantic Canada. *Hydrogeology Journal,* Vol. 22, No. 3, pp. 609-623, https://doi.org/10.1007/s10040-013-1092-y.

Green, T. R., Taniguchi, M., Kooi, H., Gurdak, J. J., Allen, D. M., Hiscock, K. M., Treidel, H. and Aureli, A. (2011). "Beneath the surface of global change: Impacts of climate change on groundwater." *Journal of Hydrology,* Vol. 405, No. 3-4, pp. 532-560, https://doi.org/10.1016/j.jhydrol.2011.05.002.

Henry, H. R. (1964). *Effects of dispersion on salt encroachment in coastal aquifers,* U.S. Geological Survey Water-Supply, Paper 1613-C.

Hermans, T. and Paepen, M. (2020). "Combined inversion of land and marine electrical resistivity tomography for submarine groundwater discharge and saltwater intrusion characterization." *Geophysical Research Letters*, Vol. 47, No. 3, e2019GL085877, https://doi.org/10.1029/2019GL085877.

Horn, D. P. (2006). "Measurements and modelling of beach groundwater flow in the swash-zone: a review." *Continental Shelf Research,* Vol. 26, No. 5, pp. 622-652, https://doi.org/10.1016/j.csr.2006.02.001.

Huyakorn, P. S., Andersen, P. F., Mercer, J. W. and White Jr., H. O. (1987). "Saltwater intrusion in aquifers: Development and testing of a three-dimensional finite element model." *Water Resources Research,* Vol. 23, No. 2, pp. 293-312, https://doi.org/10.1029/WR023i002p00293.

IPCC. (2007). Climate change 2007: Impacts, adaptation and vulnerability. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson (Eds.), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*: Cambridge University Press Cambridge.

Jeen, S.-W., Kang, J., Jung, H. and Lee, J. (2021). “Review of seawater intrusion in western coastal regions of south Korea.” *Water,* Vol. 13, No. 6, 761.

Jung, E., Park, N. and Park, J. (2021). “Composite modeling for evaluation of groundwater and soil salinization on the multiple reclaimed land due to sea-level rise.” *Transport in Porous Media,* Vol. 136, No. 1, pp. 271-293, https://doi.org/10.1007/s11242-020-01511-z.

Kang, K.-M., Kim, D.-J., Kim, Y., Lee, E., Kim, B.-G., Kim, S. H., Ha, K., Koh, D.-C., Cho, Y.-K. and Kim, G. (2019). “Quantitative estimation of submarine groundwater discharge using airborne thermal infrared data acquired at two different tidal heights.” *Hydrological Processes,* Vol. 33, No. 7, pp. 1089-1100, https://doi.org/10.1002/hyp.13387.

Kerrou, J. and Renard, P. (2010). “A numerical analysis of dimensionality and heterogeneity effects on advective dispersive seawater intrusion processes.” *Hydrogeology Journal,* Vol. 18, pp. 55-72.

Kim, D.-G., Shin, K.-H. and Kim, G.-B. (2018). “Suitability analysis of saline water intrusion monitoring wells near a waterway based on a numerical model and electric conductivity time series.” *Geosciences Journal,* Vol. 22, No. 5, pp. 807-824, https://doi.org/10.1007/s12303-018-0001-8.

Kim, I. and Yang, J.-S. (2018). “Prioritizing countermeasures for reducing seawater-intrusion area by considering regional characteristics using SEAWAT and a multi-criteria decision-making method.” *Hydrological Processes,* Vol. 32, No. 25, pp. 3741-3757, https://doi.org/10.1002/hyp.13283.

Kim, I. H., Chung, I.-M. and Chang, S. W. (2021). “Development of seawater intrusion vulnerability assessment for averaged seasonality of using modified GALDIT method.” *Water,* Vol. 13, No. 13, 1820.

Kim, K.-H., Shin, J.-Y., Koh, E.-H., Koh, G.-W. and Lee, K.-K. (2009). “Sea level rise around Jeju Island due to global warming and movement of groundwater/seawater interface in the Eastern Part of Jeju Island.” *Journal of Soil and Groundwater Environment,* Vol. 14, No. 3, pp. 68-73.

Kim, Y., Yoon, H. and Kim, G.-P. (2016). “Development of a novel method to monitor the temporal change in the location of the freshwater-saltwater interface and time series models for the prediction of the interface.” *Environmental Earth Sciences,* Vol. 75, No. 10, 882, https://doi.org/10.1007/s12665-016-5650-1.

Klassen, J. and Allen, D. M. (2017). “Assessing the risk of saltwater intrusion in coastal aquifers.” *Journal of Hydrology,* Vol. 551, pp. 730-745, https://doi.org/10.1016/j.jhydrol.2017.02.044.

Kohout, F. A. (1960). “Cyclic flow of salt water in the biscayne aquifer of southeastern florida.” *Journal of Geophysical Research,* Vol. 65, No. 7, pp. 2133-2141, https://doi.org/10.1029/JZ065i007p02133.

Kuan, W. K., Jin, G., Xin, P., Robinson, C., Gibbes, B. and Li, L. (2012). “Tidal influence on seawater intrusion in unconfined coastal aquifers.” *Water Resources Research,* Vol. 48, No. 2, W02502, https://doi.org/10.1029/2011wr010678.

Kundzewicz, Z. W. and DÖll, P. (2009). “Will groundwater ease freshwater stress under climate change?” *Hydrological Sciences Journal,* Vol. 54, No. 4, pp. 665-675, https://doi.org/10.1623/hysj.54.4.665.

Langevin, C. D. (2001). *Simulation of ground-water discharge to Biscayne Bay, southeastern Florida* (2000-4251). Retrieved from http://pubs.er.usgs.gov/publication/wri004251.

Lee, C. H. and Cheng, R. T. S. (1974). “On seawater encroachment in coastal aquifers.” *Water Resources Research,* Vol. 10, pp. 1039-1043.

Lee, E., Kang, K.-M., Hyun, S. P., Lee, K.-Y., Yoon, H., Kim, S. H., Kim, Y., Xu, Z., Kim, D. J., Koh, D.-C. and Ha, K. (2016a). “Submarine groundwater discharge revealed by aerial thermal infrared imagery: a case study on Jeju Island, Korea.” *Hydrological Processes,* Vol. 30, No. 19, pp. 3494-3506, https://doi.org/10.1002/hyp.10868.

Lee, E., Lim, J.-W., Moon, H. and Lee, K.-K. (2015). “Assessment of seawater intrusion into underground oil storage cavern and prediction of its sustainability.” *Environmental Earth Sciences,* Vol. 73, pp. 1179-1190, https://doi.org/10.1007/s12665-014-3473-5.

Lee, E., Shin, D., Hyun, S., Ko, K.-S., Moon, H., Koh, D.-C., Ha, K. and Kim, B.-Y. (2016b). “Periodic change in coastal microbial community structure associated with submarine groundwater discharge and tidal fluctuation: Changes in coastal microbial community.” *Limnology and Oceanography,* Vol. 62, No. 2, pp. 437-451, https://doi.org/10.1002/lno.10433.

Lee, E., Yoon, H., Hyun, S. P., Burnett, W. C., Koh, D.-C., Ha, K., Kim, D.J., Kim, Y. and Kang, K.-M. (2016c). “Unmanned aerial vehicles (UAVs)-based thermal infrared (TIR) mapping, a novel approach to assess groundwater discharge into the coastal zone.” *Limnology and Oceanography: Methods,* Vol. 14, No. 11, pp. 725-735, https://doi.org/10.1002/lom3.10132.

Li, H., Boufadel, M. C. and Weaver, J. W. (2008). “Tide-induced seawater-groundwater circulation in shallow beach aquifers.” *Journal of Hydrology,* Vol. 352, No. 1-2, pp. 211-224.

Li, H. and Jiao, J. J. (2003a). “Influence of the tide on the mean watertable in an unconfined, anisotropic, inhomogeneous coastal aquifer.” *Advances in Water Resources,* Vol. 26, No. 1, pp. 9-16.

Li, H. and Jiao, J. J. (2003b). “Tide-induced seawater-groundwater circulation in a multi-layered coastal leaky aquifer system.” *Journal of Hydrology,* Vol. 274, No. 1-4, pp. 211-224.

Loáiciga, H. A., Pingel, T. J. and Garcia, E. S. (2012). “Sea water intrusion by sea-level rise: Scenarios for the 21st century.” *Groundwater*, Vol. 50, No. 1, pp. 37-47, https://doi.org/10.1111/j.1745-6584.2011.00800.x.

Masterson, J. P. (2004). *Simulated interaction between freshwater and saltwater and effects of ground-water pumping and sea-level change, lower Cape Cod aquifer system, Massachusetts* (2004-5014). Retrieved from http://pubs.er.usgs.gov/publication/sir20045014.

Masterson, J. P. and Garabedian, S. P. (2007). “Effects of sea-level rise on ground water flow in a coastal aquifer system.” *Groundwater,* Vol. 45, No. 2, pp. 209-217, https://doi.org/10.1111/j.1745-6584.2006.00279.x.

Meisler, H., Leahy, P. P. and Knobel, L. L. (1984). *The effect of eustatic sea-level changes on saltwaterfreshwater relations in the northern Atlantic Coastal Plain,* U.S. Geological Survey Water-Supply Paper 2255, 28 p, https://doi.org/10.3133/wsp2255.

Melloul, A. and Collin, M. (2006). "Hydrogeological changes in coastal aquifers due to sea level rise." *Ocean & Coastal Management,* Vol. 49, No. 5-6, pp. 281-297.

Memari, S. S., Bedekar, V. S. and Clement, T. P. (2020). "Laboratory and Numerical Investigation of Saltwater Intrusion Processes in a Circular Island Aquifer." *Water Resources Research,* Vol. 56, No. 2, e2019WR025325, https://doi.org/10.1029/2019WR025325.

Meyer, R., Engesgaard, P. and Sonnenborg, T. O. (2019). "Origin and dynamics of saltwater intrusion in a regional aquifer: Combining 3-D saltwater modeling with geophysical and geochemical data." *Water Resources Research,* Vol. 55, No. 3, pp. 1792-1813, https://doi.org/10.1029/2018WR023624.

Michael, H. A., Mulligan, A. E. and Harvey, C. F. (2005). "Seasonal oscillations in water exchange between aquifers and the coastal ocean." *Nature,* Vol. 436, No. 7054, pp. 1145-1148.

Moe, H., Hossain, R., Fitzgerald, R., Banna, M., Mushtaha, A. and Yaqubi, A. (2001). *Application of 3-Dimensional Coupled Flow and Transport Model in the Gaza Strip.* Paper presented at the First International Conference on Saltwater Intrusion and Coastal Aquifers—Monitoring, Modeling, and Management, Essaouira, Morocco.

Morgan, L. K. and Werner, A. D. (2014). "Seawater intrusion vulnerability indicators for freshwater lenses in strip islands." *Journal of Hydrology,* Vol. 508, pp. 322-327, https://doi.org/10.1016/j.jhydrol.2013.11.002.

Morgan, L. K. and Werner, A. D. (2015). "A national inventory of seawater intrusion vulnerability for Australia." *Journal of Hydrology: Regional Studies,* Vol. 4, pp. 686-698, https://doi.org/10.1016/j.ejrh.2015.10.005.

Navoy, A. S. (1991). *Aquifer-estuary interaction and vulnerability of groundwater supplies to sea level rise-driven saltwater intrusion.* (PhD Thesis), Pennsylvania State University, USA.

Nicholls, R. J., Wong, P. P., Burkett, V., Woodroffe, C. D. and Hay, J. (2008). "Climate change and coastal vulnerability assessment: scenarios for integrated assessment." *Sustainability Science,* Vol. 3, No. 1, pp. 89-102. https://doi.org/10.1007/s11625-008-0050-4.

Oki, D. S. (2005). *Numerical simulation of the effects of low-permeability valley-fill barriers and the redistribution of ground-water withdrawals in the Pearl Harbor area, Oahu, Hawaii,* U.S. Geological Survey Scientific Investigations Report 2005-5253, 111 p.

Oostrom, M., Hayworth, J. S., Dane, J. H. and Güen, O. (1992). "Behavior of dense aqueous phase leachate plumes in homogeneous porous media." *Water Resources Research,* Vol. 28, No. 8, pp. 2123-2134, https://doi.org/10.1029/92wr00711.

Oude Essink, G. H. P. (2001). "Salt water intrusion in a three-dimensional groundwater system in The Netherlands: A numerical study." *Transport in Porous Media,* Vol. 43, No. 1, pp. 137-158, https://doi.org/10.1023/a:1010625913251.

Oude Essink, G. H. P., van Baaren, E. S. and de Louw, P. G. B. (2010). "Effects of climate change on coastal groundwater systems: A modeling study in the Netherlands." *Water Resources Research,* Vol. 46, W00F04, https://doi.org/10.1029/2009wr008719.

Oz, I., Shalev, E., Yechieli, Y., Gavrieli, I. and Gvirtzman, H. (2014). "Flow dynamics and salt transport in a coastal aquifer driven by a stratified saltwater body: Lab experiment and numerical modeling." *Journal of Hydrology,* Vol. 511, pp. 665-674, https://doi.org/10.1016/j.jhydrol.2014.02.020.

Parson, E., Burkett, V., Fisher-Vanden, K., Keith, D., Mearns, L., Pitcher, H., Rosenzweig, C. and Webster, M. (2007). *Global change scenarios: their development and use,* US Department of Energy Publications. 7.

Pinder, G. F. and Cooper, H. H., Jr. (1970). "A numerical technique for calculating the transient position of the saltwater front." *Water Resources Research,* Vol. 6, No. 3, pp. 875-882, https://doi.org/10.1029/WR006i003p00875.

Praveena, S. M. and Aris, A. Z. (2010). "Groundwater resources assessment using numerical model: A case study in low-lying coastal area. *International Journal of Environmental Science & Technology,* Vol. 7, No. 1, pp. 135-146, https://doi.org/10.1007/BF03326125.

Praveenaa, S. M., Abdullaha, M. H., Arisb, A. Z. and Bidina, K. (2010). Recharge and aquifer response: Manukan Island, s Aquifer, Sabah, Malaysia. *EnvironmentAsia,* Vol. 3.

Provost, A. M. and Voss, C. I. (2019). *SUTRA, a model for saturated-unsaturated, variable-density groundwater flow with solute or energy transport—Documentation of generalized boundary conditions, a modified implementation of specified pressures and concentrations or temperatures, and the lake capability,* U.S. Geological Survey Techniques and Methods, book 6, chap. A52, 62 p, https://doi.org/10.3133/tm6A52.

Qu, W., Li, H., Wang, C., Zheng, C., Wang, X. and Zhang, Y. (2020). "Numerical simulations of seasonally oscillated groundwater dynamics in coastal confined aquifers." *Ground Water,* Vol. 58, No. 4, pp. 550-559, https://doi.org/10.1111/gwat.12926.

Rajabi, M. M. and Ketabchi, H. (2017). "Uncertainty-based simulation-optimization using Gaussian process emulation: Application to coastal groundwater management." *Journal of Hydrology,* Vol. 555, pp. 518-534, https://doi.org/10.1016/j.jhydrol.2017.10.041.

Ranjan, P., Kazama, S. and Sawamoto, M. (2006). "Effects of climate and land use changes on groundwater resources in coastal aquifers." *Journal of Environmental Management,* Vol. 80, No. 1, pp. 25-35, https://doi.org/10.1016/j.jenvman.2005.08.008.

Ranjan, P., Kazama, S. and Sawamoto, M. (2006). "Effects of climate change on coastal fresh groundwater resources." *Global Environmental Change,* Vol. 16, No. 4, pp. 388-399, https://doi.org/10.1016/j.gloenvcha.2006.03.006.

Robinson, C., Gibbes, B. and Li, L. (2006). "Driving mechanisms for groundwater flow and salt transport in a subterranean estuary." *Geophysical Research Letters,* Vol. 33, No. 3.

https://doi.org/10.1029/2005GL025247.

Robinson, C., Li, L. and Barry, D. A. (2007a). "Effect of tidal forcing on a subterranean estuary." *Advances in Water Resources,* Vol. 30, No. 4, pp. 851-865.

Robinson, C., Li, L. and Prommer, H. (2007b). "Tide-induced recirculation across the aquifer-ocean interface." *Water Resources Research,* Vol. 43, No. 7, W07428, https://doi.org/10.1029/2006wr005679.

Robinson, C., Xin, P., Li, L. and Barry, D. A. (2014). "Groundwater flow and salt transport in a subterranean estuary driven by intensified wave conditions." *Water Resources Research,* Vol. 50, No. 1, pp. 165-181, https://doi.org/10.1002/2013WR013813.

Roy, D. K. and Datta, B. (2020). "Saltwater intrusion prediction in coastal aquifers utilizing a weighted-average heterogeneous ensemble of prediction models based on Dempster-Shafer theory of evidence." *Hydrological Sciences Journal,* Vol. 65, No. 9, pp. 1555-1567, https://doi.org/10.1080/02626667.2020.1749764.

Rozell, D. J. and Wong, T.-F. (2010). "Effects of climate change on groundwater resources at Shelter Island, New York State, USA." *Hydrogeology Journal,* Vol. 18, No. 7, pp. 1657-1665, https://doi.org/10.1007/s10040-010-0615-z.

Segol, G. (1994). *Classic Groundwater Simulations Proving and Improving Numerical Models*. Old Tappan, N. J.

Segol, G. and Pinder, G. (1976). "Transient Simulation of Saltwater Intrusion in Southeastern Florida." *Water Resources Research,* Vol. 12, No. 1, pp. 65-70.

Sherif, M. M. and Singh, V. P. (1999). "Effect of climate change on sea water intrusion in coastal aquifers." *Hydrological Processes,* Vol. 13, No. 8, pp. 1277-1287, https://doi.org/10.1002/(SICI)1099-1085(19990615)13:8<1277::AID-HYP765>3.0.CO;2-W.

Shin, J. and Hwang, S. (2020). "A Borehole-Based Approach for Seawater Intrusion in Heterogeneous Coastal Aquifers, Eastern Part of Jeju Island, Korea." *Water,* Vol. 12, No. 2, 609.

Simpson, M. J. and Clement, T. P. (2003). "Theoretical analysis of the worthiness of Henry and Elder problems as benchmarks of density-dependent groundwater flow models." *Advances in Water Resources,* Vol. 26, No. 1, pp. 17-31.

Simpson, M. J. and Clement, T. P. (2004). "Improving the worthiness of the Henry problem as a benchmark for density-dependent groundwater flow models." *Water Resources Research,* Vol. 40, No. 1, W01504, https://doi.org/10.1029/2003wr002199.

Strack, O. D. L. (1976). "A single-potential solution for regional interface problems in coastal aquifers." *Water Resources Research,* Vol. 12, No. 6, pp. 1165-1174.

Sulzbacher, H., Wiederhold, H., Siemon, B., Grinat, M., Igel, J., Burschil, T., Günther, T. and Hinsby, K. (2012). "Numerical modelling of climate change impacts on freshwater lenses on the North Sea Island of Borkum using hydrological and geophysical methods." *Hydrology and Earth System Sciences,* Vol. 16, No. 10, pp. 3621-3643, https://doi.org/10.5194/hess-16-3621-2012.

Tamai, N. and Shima, S. (1967). "Salt-water wedge in unconfined coastal aquifers." *Transactions of the Japan Society of Civil Engineers,* Vol. 1967, pp. 31-38.

Tang, G., Yang, M., Chen, X., Chen, T., Xiaohua, C. and Fang, H. (2020). "A new idea for predicting and managing seawater intrusion in coastal channels of the Pearl River, China." *Journal of Hydrology,* Vol. 590, 125454, https://doi.org/10.1016/j.jhydrol.2020.125454.

Taniguchi, M., Burnett, W. C., Cable, J. E. and Turner, J. V. (2002). "Investigations of submarine groundwater discharge." *Hydrological Processes*, Vol. 16, No. 1, pp. 2115-2129.

van der Geest, K., Burkett, M., Fitzpatrick, J., Stege, M. and Wheeler, B. (2020). "Climate change, ecosystem services and migration in the Marshall Islands: are they related?" *Climatic Change,* Vol. 161, No. 1, pp. 109-127, https://doi.org/10.1007/s10584-019-02648-7.

Vandenbohede, A. and Lebbe, L. (2002). "Numerical modelling and hydrochemical characterisation of a fresh-water lens in the Belgian coastal plain." *Hydrogeology Journal,* Vol. 10, No. 5, pp. 576-586, https://doi.org/10.1007/s10040-002-0209-5.

Vappicha, V. N. and Nagaraja, S. (1976). "An approximate solution for the transient interface in a coastal aquifer." *Journal of Hydrology,* Vol. 31, pp. 161-173.

Veerapaga, N., Azhikodan, G., Shintani, T., Iwamoto, N. and Yokoyama, K. (2019). "A three-dimensional environmental hydrodynamic model, Fantom-Refined: Validation and application for saltwater intrusion in a meso-macrotidal estuary." *Ocean Modelling,* Vol. 141, 101425, https://doi.org/10.1016/j.ocemod.2019.101425.

Voss, C. I. and Souza, W. R. (1987). "Variable density flow and solute transport simulation of regional aquifers containing a narrow freshwater-saltwater transition zone." *Water Resources Research*, Vol. 23, No. 10, pp. 1851-1866. https://doi.org/10.1029/WR023i010p01851.

Werner, A. D. (2010). "A review of seawater intrusion and its management in Australia." *Hydrogeology Journal,* Vol. 18, No. 1, pp. 281-285, https://doi.org/10.1007/s10040-009-0465-8.

Werner, A. D., Bakker, M., Post, V. E. A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C. T. and Barry, D. A. (2013). "Seawater intrusion processes, investigation and management: Recent advances and future challenges." *Advances in Water Resources,* Vol. 51, pp. 3-26, https://doi.org/10.1016/j.advwatres.2012.03.004.

Werner, A. D. and Gallagher, M. R. (2006). "Characterisation of sea-water intrusion in the Pioneer Valley, Australia using hydrochemistry and three-dimensional numerical modelling." *Hydrogeology Journal,* Vol. 14, No. 8, pp. 1452-1469, https://doi.org/10.1007/s10040-006-0059-7.

Werner, A. D. and Simmons, C. T. (2009). "Impact of sea-level rise on sea water intrusion in coastal aquifers." *Ground Water,* Vol. 47, No. 2, pp. 197-204. Retrieved from https://doi.org/10.1111/j.1745-6584.2008.00535.x.

Werner, A. D., Ward, J. D., Morgan, L. K., Simmons, C. T., Robinson, N. I. and Teubner, M. D. (2011). "Vulnerability indicators of sea water intrusion." *Groundwater*, Vol. 50, No. 1, pp. 48-58, https://doi.org/10.1111/j.1745-6584.2011.00817.x.

White, I. and Falkland, T. (2010). "Management of freshwater lenses on small Pacific islands." *Hydrogeology Journal,* Vol. 18, No. 1, pp. 227-246, https://doi.org/10.1007/s10040-009-0525-0.

Won, J.-H., Lee, J.-Y., Kim, J.-W. and Koh, G.-W. (2006). "Groundwater occurrence on Jeju Island, Korea." *Hydrogeology Journal,* Vol. 14, No. 4, pp. 532-547, https://doi.org/10.1007/s10040-005-0447-4.

Youn, J., Kim, G. and Jung, C. Y. (2003). "A hydrogeolgocal study on high saline groundwater of Handong-ri in the eastern part of Jeju Island, Korea." *Journal of the Geological Society of Korea,* Vol. 39, No. 1, pp. 115-131 (in Korean).