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Sea-level rise impacts on seawater intrusion in coastal aquifers: Review and integration

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SUMMARY

Sea-level rise (SLR) influences groundwater hydraulics and in particular seawater intrusion (SWI) in many coastal aquifers. The quantification of the combined and relative impacts of influential factors on SWI has not previously been considered in coastal aquifers. In the present study, a systematic review of the available literature on this topic is first provided. Then, the potential remaining challenges are scrutinized. Open questions on the effects of more realistic complexities such as gradual SLR, parameter uncertainties, and the associated influences in decision-making models are issues requiring further investigation.

We assess and quantify the seawater toe location under the impacts of SLR in combination with recharge rate variations, land-surface inundation (LSI) due to SLR, aquifer bed slope variation, and changing landward boundary conditions (LWBCs). This is the first study to include all of these factors in a single analysis framework. Both analytical and numerical models are used for these sensitivity assessments. It is demonstrated that (1) LSI caused by SLR has a significant incremental impact on the seawater toe location, especially in the flatter coasts and the flux-controlled (FC) LWBCs, however this impact is less than the reported orders of magnitude differences which were estimated using only analytical solutions; (2) LWBCs significantly influence the SLR impacts under almost all conditions considered in this study; (3) The main controlling factors of seawater toe location are the magnitudes of fresh groundwater discharge to sea and recharge rate. Regional freshwater flux entering from the landward boundary and the groundwater hydraulic gradient are the major contributors of fresh groundwater discharge to sea for both FC and head-controlled (HC) systems, respectively; (4) A larger response of the aquifer and larger seawater toe location changes are demonstrable for a larger ratio of the aquifer thickness to the aquifer length particularly in the HC systems; (5) The lowest sensitivity of seawater toe location is found for the density difference ratio of the seawater and freshwater, and also for the aquifer bed slope; (6) The early-time observations show seawater fingers below the inundated lands due to SLR which are diminished and ultimately extinguished; and (7) A less than 2% reversal effect on the seawater toe location after overshoot mechanism is observed in the transient simulations which suggests that this mechanism is an insignificant and impractical factor compared to other more significant factors.

1. Introduction

Groundwater is generally the most important freshwater resource in many coastal regions which are threatened by seawater intrusion (SWI) (Ataie-Ashtiani and Ketabchi, 2011; Ketabchi and Ataie-Ashtiani, 2015b). Climate change impacts such as sea-level rise (SLR) and precipitation variations that change recharge rates are the influential climatic factors that affect SWI (Werner et al., 2013; Ataie-Ashtiani et al., 2013a). The Intergovernmental Panel on Climate Change (IPCC, 2013) predicts that the global mean SLR may rise between 0.26 m and 0.82 m by the year 2100. A SLR in the range of 0.18–0.59 m was predicted by IPCC (2007) for a similar period. This shows a significant upward revision for SLR prediction between IPCC (2007) and IPCC (2013) and highlights the potential importance of SLR impacts on SWI.

Based on the assessments of IPCC (2013), annual mean precipitation can vary up to ±50% in the world. This range includes the

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Nomenclature

SWI	seawater intrusion
SLR	sea-level rise
LSI	land-surface inundation
LWBCs	landward boundary conditions
FC	flux-controlled
HC	head-controlled
HYP	hypothetical aquifer
REAL	real-case aquifer
EXP	experimental-test aquifer
MSL	mean sea level
OoM	order of magnitude
R	ratio parameter to quantify the influence of LSI on SLR-induced SWI
X^s_{Toe}	seawater toe location for post SLR with LSI condition
X^v_{Toe}	seawater toe location for post SLR without LSI condition
X^0_{Toe}	seawater toe location prior to SLR
ΔX_{Toe}	seawater toe changes
X_{Toe}	seawater toe location
X^*_{Toe}	dimensionless seawater toe location
h	hydraulic head
h^*	dimensionless hydraulic head
x	distance taken from the coastline
x^*	dimensionless distance taken from the coastline
dh/dx	hydraulic gradient
K	hydraulic conductivity
h_{LW}	landward hydraulic head
h^*_{LW}	dimensionless landward hydraulic head
h_{SW}	seaward hydraulic head
h^c_{SW}	corrected seaward hydraulic head
h^*_{SW}	dimensionless seaward hydraulic head
Δh_{SW}	sea-level rise value
Δh^*_{SW}	dimensionless sea-level rise value
L	aquifer length
L_{div}	hydraulic divide location
L^*_{div}	dimensionless hydraulic divide location
B	average aquifer thickness
B^*	dimensionless average aquifer thickness
W	recharge rate
W^*	dimensionless recharge rate
Q_f	fresh groundwater discharge to sea
Q^*_f	dimensionless fresh groundwater discharge to sea
q_b	regional flux entered from landward boundary
q^*_b	dimensionless regional flux entered from landward boundary
δ	density difference ratio of the seawater and freshwater
δ^c	corrected density difference ratio of the seawater and freshwater
ρ_s	seawater density
ρ_f	freshwater density
C_s	seawater concentration
C_f	freshwater concentration
μ	fluid dynamic viscosity
D_m	molecular diffusion
S_s	specific storage
φ	angle of impervious aquifer bed against the horizontal
α_L	longitudinal dispersivity
α_T	transverse dispersivity
ξ_0	depth of the interface below the water table outcrop at the coast
χ_0	width of the gap through the submarine outflow
S	land-surface slope
g	gravitational acceleration
t	time
t^*	dimensionless time
ε	effective porosity

estimate of projected uncertainties. The high latitudes and the equatorial Pacific Ocean are likely to experience an increase in annual mean precipitation by the end of this century. In many mid-latitude and subtropical arid regions, mean precipitation will likely decrease, while in many mid-latitude wet regions, mean precipitation will likely increase by the year 2100 (IPCC, 2013; Horton et al., 2014; Bring et al., 2015). Larger uncertainties surround the projections of surface runoff and recharge rate to groundwater resources, which are affected by many climatic factors, include changes in mean precipitation and temperature regimes. Further assessments have been provided by e.g. Holman (2006), IPCC (2013), and Bring et al. (2015).

Ketabchi and Ataie-Ashtiani (2015b,c) developed the efficient and robust decision models which have the superior abilities in terms of both solution quality and computational time criteria. Using such decision models, they highlighted a need for an integrated study to address how the conceptualization of climate change impacts e.g. SLR, land-surface inundation (LSI), and recharge rate variations can be handled on prospective coastal groundwater management strategies. Gorelick and Zheng (2015) emphasized that global changes such as climatic effects led to multiple stresses that should be considered in groundwater management plans. Ojha et al. (2015) assessed the long-term potential influences of climate change, e.g. SLR impacts in aquifers and efficient management of these resources in many regions of the world. They concluded that such studies are yet open challenges concerning uncertainties in modeling and in defining climate change scenarios, heterogeneities, estimation of recharge rate to groundwater systems, data challenges, and addressing the increasing threats from competing demands and mounting hydrologic stresses on groundwater systems, which all indicated a pressing need to develop effective management strategies.

The main objective of this study is to provide a systematic review of numerous previous studies and to then undertake an analysis of the relative importance of the purported influential factors controlling SWI. We present the literature review in tabulated and diagrammatic formats so as to be easily comprehensible and to easily identify what factors previous studies have and have not included. This is the first study that highlights the impacts of all of known SLR-induced influential factors and thus directs us to evaluate the relative importance of these impacts on SWI using both analytical and numerical methods. The SLR impacts on the SWI interface and in particular seawater toe location are the focus of this study. Such an integrated assessment does not exist because each previous study has only assessed a (different) subset of the purported controlling factors.

2. A review of previous studies

In recent years, there has been a growing body of research relating to climatic and hydrogeologic controls on SWI. It is not easy to rapidly discern the similarities and differences in these studies. Furthermore, it is also not immediately clear where current knowledge gaps might exist. Even more importantly, it is not indeed evident that any previous studies have conducted an integrated assessment to analyze the relative importance of the purported range of influential factors.