Practical approaches to seawater intrusion investigation and management

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Summary

Seawater intrusion (SWI) is the encroachment of saltwater into fresh coastal aquifers. It is a complex process that involves variable-density flow, solute transport and hydrochemical processes, which can make SWI assessment relatively difficult and expensive. The aim of this thesis is the development, application and critical assessment of practical (i.e., rapid, inexpensive) analytic modelling approaches for investigating and assisting in the management of SWI.

First, the steady-state, sharp-interface, analytic modelling approach of Werner et al. (2012) is applied to the Willunga Basin, South Australia in order to gain insight into the relative vulnerabilities of aquifers at the site. Vulnerability is assessed both for current conditions and future stresses (i.e., increased extraction, sea-level rise and recharge change). Limitations of the method, associated with the sharp-interface and steady-state assumptions, are addressed using numerical modelling to explore transient, dispersive SWI caused by sea-level rise. The study provides guidance for an ongoing field-based investigation of SWI.

Second, the Werner et al. (2012) approach is extended to the case of freshwater lenses on islands, accounting also for land surface inundation associated with sea-level rise. Equations are developed for both flux-controlled and head-controlled boundary conditions, which is consistent with the categorisation of continental coastal aquifers by Werner et al. (2012). The resulting equations provide general relationships between SWI vulnerability in freshwater lenses and hydrogeological conditions. Example applications to several case studies illustrate use of the method for rapidly ranking

lenses according to vulnerability, thereby allowing for prioritisation of areas where further and more detailed SWI investigations may be required.

The third study of this thesis considers the impact of SWI-induced changes in seawater volume on water-level trends (which are commonly used as a proxy for changes in aquifer storage), and coastal aquifer water balances. A steady-state, sharp-interface, analytic modelling approach was used to generate idealised relationships between seawater volume, freshwater volume and water levels. The approach assumes quasi-equilibrium conditions (i.e., steady-state conditions persist during temporal changes), which were evaluated using a selection of transient, dispersive simulations and found to be valid in the majority of cases. We conclude that changes in seawater volumes should be included routinely in coastal aquifer water balances. Also, temporal trends in coastal aquifer water levels may not provide an adequate measure of freshwater storage trends.

In the fourth study of this thesis, we investigate physical processes associated with transient seawater movement into coastal aquifers. Specifically, we use sand tank modelling to assess whether SWI overshoot is a measurable physical process. SWI overshoot has been recently reported within numerical modelling studies of transient sea-level rise and SWI by Watson et al. (2010) and Chang et al. (2011) and involves the freshwater-saltwater interface temporarily extending further inland than the eventual steady-state position. This implies that steady-state SWI may not be the worst case, as is generally assumed. In this study, sand tank modelling of sea-level rise and SWI was carried out and photographs show, for the first time, that an overshoot occurs under controlled laboratory conditions. A sea-level drop experiment was also carried out, and overshoot was again observed, whereby the interface was temporarily closer to the

coast than the eventual steady-state position. Numerical modelling corroborated the physical sea-level rise and sea-level drop experiments. This work demonstrates that commonly adopted steady-state approaches can under-estimate the maximum extent of SWI, due to the overshoot phenomenon.

Declaration

I certify that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

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Chapter 1

Introduction

1.1 Objectives

Coastal aquifers are major sources of freshwater supply in many countries (Cheng et al., 2004). Under natural, undisturbed conditions, a landward hydraulic gradient exists within coastal aquifers, with freshwater discharging to the sea. A wedge of saltwater extends beneath the freshwater, due to density differences. Changes in the hydrology of the coastal zone can cause landward movement of seawater, a process referred to as seawater intrusion (SWI). SWI causes degradation of groundwater quality through the displacement of fresh groundwater by seawater.

There is increased risk of SWI in the future due to sea-level rise (SLR), climate change and the increasing dependence on coastal fresh groundwater resources for water supply (Barlow and Reichard, 2010; Post, 2005; Werner, 2010; Werner et al., 2013). Some coastal aquifers, such as freshwater lenses of small islands, are especially vulnerable to SWI caused by the aforementioned factors (White and Falkland, 2010). Understanding SWI is therefore very important if coastal freshwater resources are to be managed sustainably.

SWI is a complex process and this makes SWI assessment relatively difficult and expensive (Werner et al., 2013). While management of coastal aquifers will ideally involve field-based investigations and the development of complex numerical models, management decision-making often requires rapid assessments of coastal aquifer vulnerability to SWI. In some instances, a simplified approach may be all that is affordable, for example in the case of large-scale (i.e., national or continental) studies. In such cases, first-order assessment methods involving analytic interface modelling are a practical choice and can be used to identify areas where further, more detailed SWI assessment may be required. Analytic modelling is also a reasonable choice when reliable input data for a sophisticated model are not available. The usefulness of analytic models as instructional tools for providing insights into the mechanical trend of the flow and steady-state interface location has been advocated by many researchers (Bear, 1972; Strack, 1989; Haitjema, 1995; Cheng, 1999; Custodio, 1987).

Analytic interface models, as described by Strack (1976, 1989), simplify the SWI problem by: (1) neglecting mixing processes (i.e., assuming a sharp interface between the freshwater and saltwater); (2) assuming the saltwater to be stagnant; (3) adopting the Dupuit approximation (i.e., neglecting vertical resistance to flow); (4) adopting steady-state conditions. The steady-state interface position can then be estimated using the Ghyben-Herzberg relation (Ghyben, 1888; Herzberg, 1901). The Strack (1976, 1989) single-potential approach differs to others presented within the literature (e.g., Custodio, 1987) because it allows for a mathematically unified solution to a problem where the domain extends beyond the edge of the interface. As such, the Strack (1976, 1989) approach is well suited to regional-scale SWI modelling.

Recently, the analytic sharp-interface equations of Strack (1976) were used by Werner et al. (2012) as the basis for developing SWI vulnerability indicators for a range of conditions. The Werner et al. (2012) method is an improvement on existing large-scale

SWI vulnerability assessment approaches, such as GALDIT (Lobo-Ferreira et al., 2007) and CVI(SLR) (Ozyurt, 2007), because it is theoretically based and therefore incorporates the physical mechanics of SWI, albeit under highly idealised conditions. The basic premise is that partial derivative equations quantify the propensity for SWI, as rates of change in SWI extent, for a range of different stresses (e.g., increased extraction, reduced recharge and SLR). Using this approach, SWI vulnerability (defined as the propensity for SWI to occur) can be easily and rapidly quantified.

This thesis starts (Chapter 2) with a description of the practical application of the Werner et al. (2012) approach within a first-order assessment of SWI vulnerability for the Willunga Basin aquifer system in South Australia. The objective here is to obtain insight into the relative vulnerabilities of the Willunga Basin aquifers, which will assist in the determination of research priorities as part of an on-going field-based investigation of the Willunga Basin. Limitations of the vulnerability indicators method, associated with the sharp-interface and steady-state assumptions, are addressed using numerical modelling to explore transient, dispersive SWI caused by SLR. The SWI vulnerability indicators have subsequently been applied (using the approach described in this chapter) to 28 case study areas as part of a national-scale assessment of SWI vulnerability for Australia, as described in Ivkovic (2012), Morgan et al. (2013b) and Morgan et al. (2013c).

Despite widespread concern regarding the vulnerability of freshwater lenses to SWI (e.g., Chui and Terry, 2013; Church et al., 2006; Mimura, 1999; Terry and Chui, 2012; White et al., 2007; White and Falkland, 2010; Woodroffe, 2008), there is currently little guidance on methods for rapidly assessing the vulnerability of freshwater lenses to the potential effects of climate change. The second objective of this thesis (Chapter 3) is to extend the Werner et al. (2012) vulnerability indicators methodology to freshwater lenses in strip islands. Given the high susceptibility of many low-lying oceanic islands to land surface inundation (LSI) by the ocean (White and Falkland, 2010), the influence of LSI on SWI vulnerability is also considered.

The primary focus of coastal aquifer management studies is most commonly the inland movement of saltwater and associated threats to water supplies (e.g., Mantoglou, 2003; Werner and Gallagher, 2006). The loss of freshwater storage arising from SWI has received considerably less attention. In many cases, the volumes of storage loss caused by SWI are neglected in evaluating coastal aquifer water balances, despite the importance of accurate quantification of water budgets for management purposes (Bredehoeft, 2002; Custodio, 2002). The estimation of SWI-induced storage decline in practice is confounded by difficulties in quantifying interface movements, which are often poorly constrained because salinity measurements are usually sparse and infrequent. Hence, freshwater storage losses from interface movements are often undetected and subsequently not accounted for. The third objective (Chapter 4) is to examine the conditions under which this may be a significant oversight in the assessment of coastal aquifer condition, i.e., where hydrograph trends are adopted as an indicator of storage depletion (e.g., Brown, 2006; Bekesi, 2009) and freshwater-only water balances are used to develop management strategies (e.g., Davidson and Yu, 2006; Schafer and Johnson, 2009; Sun, 2005; Varma, 2009; Voudouris, 2006; Zulfic et al., 2007). A steady-state, sharp-interface, analytic modelling approach is used to generate idealised relationships between seawater volume, freshwater volume and water levels. The approach assumes quasi-equilibrium conditions, which are evaluated using a selection of transient, dispersive simulations.

In recent years, a number of numerical modelling studies (e.g., Chang et al., 2011; Watson et al., 2010) of transient SLR-SWI have reported an overshoot phenomenon, whereby the freshwater-saltwater interface temporarily extends further inland than the eventual steady-state position. SWI overshoot may have significant implications for coastal aquifer management, because it implies that the post-SLR steady-state interface position may not be the worst case, as is generally assumed. The final objective (Chapter 5) of this thesis is to use physical and numerical modelling to address the question of whether SWI overshoot is a measurable physical process, or simple a nuance of numerical modelling.

The following four Chapters are taken directly from a book chapter (Chapter 2) and international journal publications (Chapters 3, 4, 5). Each Chapter can therefore be read independently. The reference for the book chapter and papers is provided as a footnote at the start of each Chapter. Chapter 6 summarises the main results and conclusions of this thesis.