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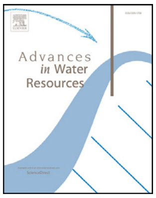

Saltwater upconing zone of influence

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ABSTRACT

In this study, we define and characterize the saltwater upconing zone of influence (SUZI). The SUZI is the region around a pumping well within which significant rise in the saltwater-freshwater interface occurs. While the zone of influence of a pumping well can be clearly defined in terms of hydraulics (e.g., drawdown), the SUZI has not been recognised and characterised, despite its importance for groundwater decision-making in coastal regions. We explore the SUZI under various conditions and compare common methods of investigation using both axisymmetric (1D and 2D vertical cross-section) and 3D simulations of saltwater upconing at the field scale, based on a combination of numerical and analytical approaches. The SUZI was found to be dependent on the relative magnitudes of pumping, regional flow, distance of the well from the coast, and position of the well above the interface, as expected. The three-dimensional coastal setting simulations revealed an asymmetric shape of the lateral extent of the SUZI, which is largest in the direction parallel to the coast. This occurs because the ocean and the inland extent of the seawater wedge limit the propagation of the SUZI perpendicular to the coast. Predictions of the SUZI using the Ghyben–Herzberg approximation, including cases where sloping interfaces occur (i.e., in contrast to the artificiality of horizontal interfaces used in axisymmetric approaches), provide reasonable first approximations of the SUZI. Numerical modelling of dispersive upconing in the 3D inclined interface case is influenced by practical limits to the model domain size and grid resolution. For example, the no-flow boundary condition at 1500 m from the pumping well elongates the SUZI in the direction parallel to the coast. This study extends previous concepts of well interference, which have previously been based on hydraulics only, by introducing the SUZI and characterising its extent, with consideration given to differences in commonly adopted methods of upconing quantification.

1. Introduction

Saltwater upconing is the rise in the freshwater-saltwater interface (i.e., the transition zone between freshwater and saltwater) that occurs beneath pumping wells where fresh groundwater is underlain by saltwater. The salinization of wells due to saltwater upconing is a widespread issue in coastal aquifers (Saeed et al., 2002; Werner et al., 2013). Previous studies of saltwater upconing focus on theoretical analyses (Dagan and Bear, 1968; Rubin and Pinder, 1977; Zhang et al., 1997), laboratory experimentation (Oswald and Kinzelbach, 2004; Werner et al., 2009) and numerical modelling (Diersch et al., 1984; Reilly and Goodman, 1987; Zhou et al., 2005; Jakovovic et al., 2011). Field studies of saltwater upconing are rare. The aspects of upconing that are the focus of previous investigations include the salinity response of pumping wells, the rise of the interface below the well, and the influence of dispersion on upconing processes (e.g., Dagan and Bear 1968; Diersch et al., 1984; Reilly and Goodman, 1987). The lateral extent of salinity impacts due to saltwater upconing has received considerably less attention, particularly for regional scales. To address this, the saltwater upconing zone of influence (SUZI), defined as the zone around a well within which significant interface rise occurs, is introduced and examined in this paper.

While the SUZI has not been characterised previously in the literature, the hydraulic zone of influence of a pumping bore, i.e., the region around a well within which a cone of depression develops, is well defined and routinely used in water management (Dragoni, 1998). The hydraulic zone of influence is usually delineated by the distance from the well to a specific pumping-induced

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drawdown (Osiensky et al., 2006). Kresic (2007) adopts a 0.05 m drawdown for this purpose. The hydraulic zone of influence is commonly obtained using the Theis equation for transient flow problems, or from the Thiem equation for systems where steady-state conditions are an adequate approximation (Chu, 1994; Kasenow, 2000). Alternatively, numerical modelling methods have been widely applied to determine the hydraulic zone of influence (Bair and Roadcap, 1992; Arnold et al., 2003).

While the zone of influence of a pumping well can be clearly defined in terms of hydraulics, the same intuition does not exist for saltwater rise attributable to pumping in a coastal aquifer (i.e., the SUZI). In the absence of previous guidance on defining the SUZI, we adopt an interface rise of 2 m to delineate SUZI extent, given that this is commensurate with a 0.05 m drawdown based on the Ghyben–Herzberg (GH) approximation (Ghyben, 1888; Herzberg, 1901), as follows. The well-known GH relationship, which assumes a steady-state, sharp transition zone between freshwater and saltwater, is commonly used in coastal aquifer studies to obtain a first approximation of the freshwater-seawater interface (e.g., Moore et al., 1992; Guo and Jiao, 2007). The GH depth of the interface, z [L], can be estimated by $z = \delta h_f$, where h_f is the freshwater head above mean sea level (MSL) [L], and δ is the density ratio given by $\rho_f/(\rho_s\text{-}\rho_f)$, where ρ_f and ρ_s are the freshwater and seawater densities [ML^{-3}], respectively. δ is approximately 40. It is noteworthy that our threshold interface rise value of 2 m is a large percentage of the thickness of shallow aquifers.

An important aspect of delineating the SUZI, considering the dispersive interfaces that occur in nature, is to identify the salinity (and rise thereof) that represents upconing extent. While it might seem intuitive to adopt the 50% seawater salinity (e.g., 17,500 mg/L), which is usually used for comparison with sharp-interface analyses, wells become unusable at much lower salinities (e.g., 2000 mg/L; Sherif and Singh, 2002), and hence the vertical rise of lower salinity groundwater also needs to be considered in assessing the SUZI.

Previous studies of pumping impacts on the interface position have applied GH-based approaches, including the Strack (1976) solutions, to investigate critical pumping rates (i.e., maximum permissible discharge without the interface encountering the well), and the steady-state position of the freshwater-seawater interface (e.g., Cheng et al., 2000; Mantoglou, 2003). However, these studies did not characterise the SUZI, but rather, the main focus was on pumping optimization in saltwater-intruded coastal aquifers. The GH approximation is known to lack accuracy in regions of significant vertical flow (e.g., near a partially penetrating well; Rushton, 2004). We apply the GH relationship to obtain a preliminary estimate of the SUZI, and by doing so we focus on regions that are at significant distance from the point of extraction. The accuracy of the GH approximation for this application needs to be assessed, given that upconing in coastal settings involves dispersive processes, transient effects and regional flow impacts, and hence GH-based approaches may be overly simplified and fail to capture important processes in some cases.

Numerical modelling studies of saltwater upconing, aimed at exploring upconing processes in a generalised fashion, have been conducted mainly by considering axisymmetric (1D and 2D vertical cross-section) flow conditions (i.e., Diersch et al., 1984; Wirojanagud and Charbeneau, 1985; Reilly and Goodman, 1987; Holzbecher, 1998; Zhou et al., 2005). Axisymmetric analyses represent radially symmetric flow to a single well, and assume that the initial freshwater-saltwater interface is horizontal (e.g., Langevin, 2008). These assumptions are violated in typical coastal aquifer situations, which involve a seawater wedge and regional flow towards the coast. Hence, three-dimensional flow and transport processes need to be resolved in evaluating the SUZI in coastal aquifer settings (Langevin, 2008), albeit axisymmetric models may provide a rough approximation of the SUZI if superposition principles (see Reilly et al., 1987) apply. The applicability of axisymmetric simulation to evaluate regional-scale upconing impacts requires further investigation.

The current analysis applies both axisymmetric and three-dimensional (3D) models of density-dependent flow and transport to assess the SUZI under a range of conditions. The mathematical simplicity of axisymmetric models allows for an assessment of a multitude of parameter combinations in characterising the SUZI. A selection of coastal aquifer settings are examined using 3D models, and these are compared to idealised axisymmetric models to investigate the role of regional groundwater flow and the associated sloping interface on the SUZI. Also, axisymmetric models are evaluated to ascertain whether they provide a reasonable first estimate of the SUZI (i.e., whereby saltwater rise from an axisymmetric analysis is superimposed onto an undisturbed coastal aquifer situation).

Following the laboratory experiments of Pennink (1915), we expect regional groundwater flow to create complex flow patterns around wells where upconing has been induced. Pennink (1915) used two-dimensional sand-tank models to show that regional flow causes a downstream shift in the saline water below the well. The saltwater interception of the well then occurs from the ocean side, i.e., rather than from beneath the well as expected in the absence of regional flow. Olsthoorn (2010) reproduced this situation numerically. He concluded that regional flow would extend the saltwater-impacted region around the well along the flow direction and cause a higher salinization of the aquifer on the downstream side of the well than on the upstream side, although the extent to which this might occur was not explored. Bear et al. (2001) and Bear and Cheng (2010) numerically modelled a coastal pumping well and also noted asymmetry in saltwater upconing caused by the seaward flow. Further analysis is required to understand and quantify the role of regional flow in modifying the SUZI.

de Louw et al. (2013) in their study of natural saltwater upconing caused by boils suggested that regional flow does not significantly influence the salinities of boils despite that regional flows modify upconing geometry. They modelled an aquifer with a point sink positioned above an initially horizontal transition zone, with regional groundwater flow entering the system at a distance of 1500 m from the boil. They found that regional flow divided the aquifer into a local boil system and an underlying regional flow system, separated by a dividing streamline. This resulted in the boil water coming from shallower depths (i.e., from above the dividing streamline) compared to the situation without regional flow. de Louw et al. (2013) suggested that in coastal aquifers where regional flow is present, leaving the regional flow component out of saltwater upconing studies could be considered as a worst-case scenario. An analysis of the influence of regional flow on the SUZI would add to the study of de Louw et al. (2013) by offering improved understanding of the spatial extent of upconing plumes and associated well salinities.

The objective of this paper is to characterize the SUZI under a range of hypothetical aquifer settings, using parameter ranges based on values from previous publications. We evaluate the applicability of the GH approximation for determining the SUZI, including cases where sloping interfaces occur and where solute dispersion is significant. Both axisymmetric and three-dimensional simulations are used to develop enhanced intuition on both the SUZI extent in coastal aquifers and the processes influencing the SUZI. The comparison of 1D, 2D and 3D models is intended to highlight practical differences between the available methods used in upconing analysis.