Experimental and Modelling Analyses of Saltwater Upconing

submitted by

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As a requirement in full for the degree of

Doctor of Philosophy

in the

School of the Environment

Flinders University of South Australia

November 2013

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Summary

Saltwater upconing is a process that occurs when salty groundwater that underlies fresh groundwater rises towards a pumping well. It is an important problem in many coastal aquifers around the world, leading to the deterioration in water quality of freshwater wells. Once a well is intruded by saltwater, it may require the well to be decommissioned, and hence, controlling bore salinisation through upconing is essential. In this study, the mechanisms of saltwater upconing are assessed to improve the current body of knowledge of the associated density-dependent flow and transport processes.

Saltwater upconing is particularly difficult to measure under field situations, and there are no previous examples of well characterised field-scale saltwater upconing plumes. Prior to the current research, there were also no published observations of upconing under controlled laboratory experimental conditions, notwithstanding previous studies of lateral saltwater intrusion in which incidental vertical movements in saltwater plumes were observed. Laboratory experiments and numerical modelling analyses of saltwater upconing processes were undertaken to provide insight and understanding of the mechanisms responsible for the salinisation of freshwater wells. The research focuses mainly on laboratory-scale upconing, through which saltwater rise under a pumping well and the related impacts in terms of well salinity and plume rise and extent are examined.

Firstly, saltwater upconing observations from four controlled sand-tank experiments were quantified and compared to an existing analytical solution of transient upconing. These results were subsequently extended using a numerical modelling analysis of the laboratory experiments to better understand the flow and transport processes occurring in the sand tank. An important outcome of this work is the numerical reproducibility of the experimentally observed temporal development of saltwater plumes under a pumping bore, albeit for three of the four experiments. The “double peak” upconing observed in one of the laboratory experiments was not reproduced by this model. Numerical modelling results were compared with an existing sharp-interface analytical solution, which

corresponded well with the numerical modelling results for early stages of the four upconing experiments.

Secondly, additional laboratory experimentation and numerical modelling were undertaken to investigate double-peaked upconing that remained unresolved. Laboratory experiments successfully reproduced the double-peaked plume demonstrating that this phenomenon was not an experimental nuance in previous experiments. The modelling undertaken in this analysis demonstrated that sorption is an important consideration when using Rhodmaine WT as a visual aid in sand-tank experiments, especially under slow flow, density-dependent conditions.

The final component of the study extended the laboratory-scale investigation to scales that apply to real-world settings. The aim was to define and characterize the "saltwater upconing zone of influence", which is the extent of saltwater upconing impact, in terms of saltwater rise attributed to pumping, in a largely hypothetical, three-dimensional coastal setting involving a sloping regional freshwater-seawater interface. Both radial and three-dimensional numerical modelling of saltwater upconing at the field scale were undertaken. The results indicate that the sharp-interface approximations of SUZI, for both radial and three-dimensional cases, are larger compared to the numerical model predictions. It was also found that the lateral flow towards the coast significantly influences both the SUZI and the salinity of the extracted groundwater. This part of the study demonstrated that the three-dimensional modelling that includes inclined interfaces and lateral flow towards the coast is essential in studying SUZI in typical coastal areas. That is, radial modelling, which does not capture the lateral flow effects, over-estimates the SUZI extent as well as the pumped water salinity.

Declaration of Originality

I certify that this thesis does not incorporate, without acknowledgement, any material previously submitted for a degree or diploma in any other 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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Acknowledgements

My sincere gratitude and appreciation goes to my supervisors, Assoc. Prof. Adrian Werner, Dr Vincent Post and Prof. Craig Simmons, for their guidance and support through the last four years. In particular, I would like to tank Adrian for his invaluable guidance, numerous ideas, countless reviews, and passionate encouragement for learning, Vincent for his enormous support, patience, inspiration and passionate love of science, and Craig for his support and guidance at initial stages of my PhD.

PhD scholarship by AJ & IM Nylon and conferences funding by the National Centre for Groundwater Research and Training (NCGRT) are sincerely acknowledged.

I gratefully acknowledge help with the laboratory experimentation by Brenton Perkins, Oliver Mannicke, Etienne Lasage, Dirk Eliander, Simon Jacobs and Megan Sebben.

It has been a great experience to work and interact with all the NCGRT Programs 2, 3 and 4 fellow colleagues at Flinders University.

Many thanks to Dr Chunhui Lu, Leanne Morgan, Dr Perry de Louw, Dr Maria Pool and Eugenia Hirthe for many scientific discussions, especially towards the end of my PhD.

My fellow office-226 mates, Carlos Miraldo, Dr Maria Pool, Eugenia Hirthe, Miguel Cambron, Dr Perry de Louw, Charlotte Schmitt, Le Dung Dang, Dr Yueqing Xie, Ty Watson and Anna Seidel: times shared with you are an invaluable part of my PhD experience. Etienne, Daan, Matt and Megs: you are a part of this invaluable experience too.

Goran, your continued encouragement and passion for learning have been a major driving force throughout my PhD. Thank you.

Very special and huge thanks to my family. Your support has been invaluable to me in completing this thesis.

Chapter 1

Background and objectives

In coastal regions, groundwater is often the major source of freshwater, and hence a proper understanding of the processes leading to salinisation of wells is essential. There are numerous processes influencing salt movements in coastal systems, occurring across a wide range of scales, including buoyancy effects due to freshwater-saltwater density contrasts, recharge and regional flow dynamics, and pumping impacts. In the near vicinity of pumping wells, saltwater upconing may occur. Saltwater upconing is the upward vertical transport of salty groundwater towards a pumping well in an aquifer where freshwater is underlain by saltwater. It may lead to considerable deterioration in the quality of extracted water, and is therefore an important problem in many coastal aquifers around the world. Once a freshwater bore is intruded by saltwater, the pumping well is often abandoned (Zhou et al., 2005; Narayan et al., 2006).

Bore salinisation due to saltwater upconing was probably first explored in the 1910s. Pennink (1915) used a sandbox to explore patterns of saltwater movement below a drain and observed brackish and saltwater rise to the bottom of the well. He also examined the influence of lateral flows on up-coning behaviour, and found that these tend to push the saline water downstream of the well. The sand-tank set-up that Pennink (1915) adopted, led to saltwater entering the well from the ocean side, i.e. rather than from beneath, as occurs in the absence of lateral flow (e.g. Diersch et al, 1984; Reilly and Goodman, 1987; Zhou et al., 2005). Dagan and Bear (1968) were among the first to obtain a non-steady solution for saltwater upconing. They adopted the method of small perturbations to obtain solutions for sharp-interface rise below a well, in both two-dimensional cross section and in radial coordinates, in an infinite aquifer. They compared their analytical solution to laboratory results in the form of interface movements inferred from sand-box salinity measurements. The solution was found to be valid for interface rise approximately up to one-third the distance between the bottom of the well and the initial interface position.

The sharp-interface approximation of the freshwater-saltwater mixing zone adopted by Dagan and Bear (1968) has been applied by others in developing subsequent analytical solutions (e.g. Haubold, 1975; Motz, 1992; Zhang et al., 1997; Bower et al., 1999). In these cases, freshwater and saltwater are considered as immiscible fluids separated by a sharp boundary, and head losses and fluxes in the saltwater zone are neglected. While the sharp-interface assumption allows for the development of rapid, first-order methods of analysis, this approach neglects dispersive transport, which was shown by Reilly and Goodman (1987) to be important for the evaluation of well salinities, and in studying upconing processes more generally.

Many studies have implemented the sharp-interface approach, using both analytical and numerical solutions (e.g. Chandler and McWhorter, 1975; Wirojanagud and Charbeneau, 1985; Aharmouch and Larabi, 2001). Based on the sharp-interface approach, it has been shown that, theoretically at least, the interface can be maintained in a position below the well (i.e. a stable saltwater plume can develop below the well) if freshwater extraction is kept below a certain critical pumping rate (e.g. Bear, 1979; Motz, 1992; Zhang et al., 1997). That is, the critical pumping rate can be defined as the maximum permissible discharge for which the interface does not encounter the well. However, the occurrence of stable saltwater plumes below pumping wells has not been demonstrated in real-world settings or under controlled laboratory conditions, and rather, stable upconing plumes have been produced under only idealised (e.g. theoretical, sharp-interface) conditions.

Given that only 2% of seawater mixed with fresh groundwater renders a coastal pumping well unusable for most applications, the behaviour of the transition zone is an essential element of assessing upconing and its potential impacts on groundwater extraction in practical coastal aquifer problems. Previous studies of transition zone behaviour during upconing identified some important observations. For example, the transition zone widens as pumping draws the interface upwards from its initial position (Reilly and Goodman, 1987). Further, it has been shown in lateral seawater intrusion studies that the transition zone is controlled by mechanical dispersion, molecular diffusion, advection, density effects and geological controls (Abarca and Clement, 2009; Lu et al., 2009), and these can affect the salinity of the pumped water.

Diersch et al. (1984) were among the first to numerically model variable-density, dispersive flow and transport processes associated with saltwater upconing. They studied the sensitivity of dispersivity and found that the well salinity is strongly influenced by dispersion (i.e. higher dispersion leads to earlier breakthroughs of low salinity water and a longer transition to the breakthrough of seawater into the pumping well). Reilly and Goodman (1987) simulated a field situation of saltwater upconing using a numerical model of density-dependent groundwater flow and dispersive solute transport. They compared sharp-interface and dispersive transport approaches and concluded that the dispersive transport approach is needed to reproduce upconing situations involving wide transition zones (e.g. under cyclic pumping). Konz et al. (2009) produced saltwater intrusion experimental results for benchmarking variable-density numerical codes. Saltwater intrusion was observed occurring both laterally and vertically (i.e. saltwater upconing), albeit the focus of the study was lateral seawater intrusion. Highly-dispersive upconing was observed in both laboratory experiments and modelling results, i.e. only the 10% isochlor reached the well. The Konz et al. (2009) experiments demonstrated that dispersion may be an important phenomenon when considering bore salinisation processes; further work is needed to explore dispersive processes for a broader range of saltwater upconing conditions.

Saltwater upconing is particularly difficult to measure under field situations, and there are no previous examples of well characterised field-scale saltwater upconing plumes. Prior to the commencement of this thesis, the only examples of published laboratory experimentation of saltwater upconing appeared to be the works of Dagan and Bear (1968) and Oswald (1998). Oswald (1998) produced saltwater upconing in a three-dimensional sand box and salinity plumes were delineated using geophysical interpretations (i.e. there were no direct visual observations of saltwater upconing). Dagan and Bear (1968) provided only a summarised account of their laboratory results (i.e. the shapes of salt plumes were not given and experimental photography was not published), and therefore the salt plume behaviour leading to bore salinisation was not observed directly. Direct observations of saltwater upconing are required to complement previous modelling analyses and to extend the laboratory experimentation of Dagan and Bear (1968) and Oswald (1998) for a broader range of saltwater upconing conditions.

The current research project commences with analyses of four saltwater upconing laboratory experiments undertaken as part of a previous undergraduate research project, which produced experimental photography and a set of laboratory observations. The saltwater upconing results, including water and salt mass balances, boundary condition observations, and saltwater upconing trends are critically evaluated and compared to the analytical solution of Dagan and Bear (1968) for transient, sharp-interface upconing. The results of the analyses of these four laboratory experiments provide the starting point for the remainder of the thesis, which examines saltwater upconing in more detail, including further laboratory experimentation, a closer examination of the transport processes observed under controlled laboratory conditions, and an extension to field-scale upconing problems.

This thesis consists of seven chapters including the current chapter. Chapter 1 provides a basic background to this research and summarises briefly each chapter. Chapters 2, 3, 4 and 5 are based on journal publications, and references to the papers are specified at the start of each chapter. Chapter 6 is not directly related to chapters 2, 3, 4 and 5, and can be read independently. Chapter 7 summarises the main conclusions of this research.

The first stage of this thesis (Chapter 2) involved the investigation of saltwater upconing imagery and experimental data to produce a well-characterised account of laboratory measurements of saltwater upconing, thereby extending the work of Dagan and Bear (1968) and Oswald (1998). This part of the study provided the first published time-series observations of saltwater upconing under controlled laboratory experimental conditions. Following this, a numerical modelling analysis of the laboratory experiments was undertaken (Chapter 3) to better understand the flow and transport processes occurring in the sand tank. An important outcome of this work is the numerical reproducibility of the experimentally observed temporal development of saltwater plumes under a pumping bore, albeit for three of the four experiments. The “double peak” upconing observed in one of the laboratory experiments was not reproduced by this model. This led to additional laboratory experimentation and numerical modelling (Chapter 4) to investigate tracer adsorption effects in sand-tank experiments of saltwater upconing. Laboratory experiments successfully reproduced the double-peaked plume demonstrating that this phenomenon was not an experimental nuance in previous experiments. The modelling undertaken in this analysis demonstrated that sorption is an important consideration when using Rhodmaine WT as a visual aid in sand-tank experiments, especially under slow flow, density-dependent conditions. The previous three chapters led to a discussion on the relevance of the upconing criticality conditions to the current work (Chapter 5). That is, a short analysis was undertaken to assess whether the upconing criticality conditions hold for the saltwater upconing laboratory experiments that were carried out. This chapter aimed rather at opening questions on applicability of the stable plume theory to dispersive upconing. The final component of this study (Chapter 6) extended the laboratory-scale investigation to scales that apply to real-world settings. The aim was to define and characterise the “saltwater upconing zone of influence”, which is the extent of saltwater upconing impact, in terms of saltwater rise attributed to pumping. This concept is explored and demonstrated through three-dimensional numerical modelling, and as such is the first attempt to quantify saltwater upconing zone of influence in coastal areas and hence under the impact of lateral flow towards the coast. Chapter 7 provides the main conclusions of this thesis.