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Automated image analysis for experimental investigations of salt water intrusion in coastal aquifers

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SUMMARY

A novel methodology has been developed to quantify important salt water intrusion parameters in a sandbox experiment using image analysis. Existing methods found in the literature are based mainly on visual observations, which are subjective, labour intensive and limit the temporal and spatial resolutions that can be analysed. A robust error analysis was undertaken to determine the optimum methodology to convert image light intensity to concentration. Results showed that defining a relationship on a pixel-wise basis provided the most accurate image to concentration conversion and allowed quantification of the width of the mixing zone between salt water and freshwater. A high image sample rate was used to investigate the transient dynamics of salt water intrusion, which rendered analysis by visual observation unsuitable. This paper presents the methodologies developed to minimise human input, promote autonomy, provide high resolution image to concentration conversion, and allow the quantification of intrusion parameters under transient conditions.

1. Introduction

Saltwater intrusion (SWI) in coastal aquifers is one of the main challenges for water resources management. Excessive pumping of freshwater to supply the demand of coastal cities can lead to increased intrusion lengths, potentially rendering the supplies unusable if not managed effectively. A growing percentage of the world's population live in coastal areas, and with coastal populations becoming increasingly dependent on freshwater extracted from coastal aquifers, SWI has become a global issue that has promoted a worldwide research effort (Hugo, 2011).

Laboratory-scale aquifers have been widely used to characterise freshwater–saltwater interfaces, and to investigate the behaviour of salt water wedges (e.g. Schincariol and Schwartz, 1990; Zhang et al., 2002; Goswami and Clement, 2007; Konz et al., 2009a,b; Chang and Clement, 2013; Dose et al., 2014; Mehdizadeh et al., 2014). Goswami and Clement (2007) developed a homogeneous 2D SWI experiment with the goal of providing a more robust benchmark for numerical models than the popular, but unrealistic, Henry problem (Henry, 1964). Abarca and Clement (2009) improved on the research of Goswami and Clement (2007) by developing a method to map the mixing zone at the salt water–freshwater interface. The method utilised the colourimetric changes of phenolphthalein with respect to pH in order to visualise the mixing zone. Later experimental studies involved analysing the effects of recharge rate (Chang and Clement, 2012) on SWI dynamics and identifying transport processes above and within a salt water wedge (Chang and Clement, 2013).

Konz et al. (2008) detailed an image analysis procedure for a homogeneous test using the reflective light technique. The quality of their image analysis procedure was determined by comparing the concentration profiles calculated from the images to those of resistivity measurements taken from sampling ports at the rear of their sandbox. Konz et al. (2009a) further investigated the differences between the reflective and transmissive light techniques by calculating the errors involved in determining concentration from image light intensities. They concluded that the reflective light technique provided fewer errors. However, the sandbox used in their experiment was 4 cm thick, which would greatly increase the dispersion of light travelling through the porous media and consequently increase the error calculated for the transmissive case. Furthermore, Mariner et al. (2014) identified strong 3D effects occurring in their sandbox (5 cm thick) by comparing images of the front and back faces for the case of salt water overlying freshwater. While 3D effects do occur in highly unstable test conditions, this is not easily identified in a reflective light system. Transmissive light measurement will aid in the detection of these anomalies and will give a better indication of the overall flow, not just what travels between the porous media and front face.

Lu et al. (2013) is one of few studies that considered the mixing zone in laboratory-scale problems. The study only investigated

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steady-state mixing zones; however, no quantitative analysis was conducted on experimental images. The comparison between experimental tests and numerical simulations was purely qualitative in this case. Kashuk et al. (2014) investigated different methods of image calibration using colour separation in their study of the transport of non-aqueous phase liquids within transparent soils. Chowdhury et al. (2014) considered a heterogeneous domain of three different grain sizes constructed in a regular block-wise pattern. Not only was the hydraulic conductivity heterogeneous in the vertical direction, but also in the horizontal. They also investigated the effect of increasing the length of the blocks in the horizontal direction, effectively increasing the anisotropy of the domain. However, similar to Goswami and Clement (2007), Werner et al. (2009), Luyun et al. (2011), Jakovovic et al. (2012), Shi et al.(2011), Stoeckl and Houben (2012), Morgan et al. (2013) and Lu et al. (2013), the results were manually determined from captured images or made directly on the face of the apparatus.

It is clear from the literature that manual quantification by visual observation is limiting when analysing transient SWI dynamics. Furthermore, most of the previous studies have focused on the toe length and paid little attention to the calculation of the width of the mixing zone, which is small and difficult to measure at laboratory-scale. However, an understanding of the response of the mixing zone to transient boundary conditions is important to effectively manage freshwater resources in coastal aquifers (Abarca and Clement, 2009). To address these existing deficiencies, this study presents a novel high accuracy and fully automated process to determine SWI dynamics at high temporal and spatial resolutions, applicable to a wide variety of experimental cases including homogeneous and heterogeneous configurations.

2. Experimental set-up

Experimental investigations of flow in porous media are, for the most part, conducted within sandbox apparatus. Fig. 1 shows a schematic overview of the sandbox. The tank consisted of a central viewing chamber of dimensions (Length × Height × Depth) 0.38 m × 0.15 m × 0.01 m flanked by two large chambers at either side to provide the hydrostatic pressure boundary conditions for each test. The central viewing chamber (test area) was filled with a clear porous media which allowed visual observation of salt water movement within the aquifer. The left side chamber was assigned to hold clear freshwater and the water levels were maintained in the side chambers through an adjustable overflow outlet, which drained excess water to waste. In a similar manner, dyed salt water solution was introduced into the right side chamber and maintained at the desired level. The 2D nature of this unit allowed the use of backlighting to be employed most effectively, as transmissive lighting provides a better representation of the mixing zone dynamics than the reflective light method (Konz et al., 2009c). To achieve the best uniform lighting across the test domain, a light diffuser was fitted to the back of the rig and two Camtree® 600 LED lights were used to provide the illumination.

Two acrylic fine mesh screens were fixed to the interfaces between the side chambers and central testing area. These meshes provided access for water flowing from the side chambers while still confining the beads to the central chamber. The meshes have 0.5 mm apertures; slightly smaller than the finest beads tested. The hydraulic properties of salt water and freshwater are among the key drivers of the transport processes that occur during SWI. Degassed freshwater was used in the experiment to reduce air bubble formation in the porous media. Air bubbles appear as dark spots in the camera images and subsequently appear as noise in the concentration colour maps. This freshwater was also used as the basis for the dyed salt water solution. A large batch of salt water was produced by dissolving a predetermined mass of food grade salt into 200 l of the freshwater to give a salt water density of 1025 kg/m^3. The density of the salt water was checked prior to testing by measuring the mass of a specified volume of the solution.

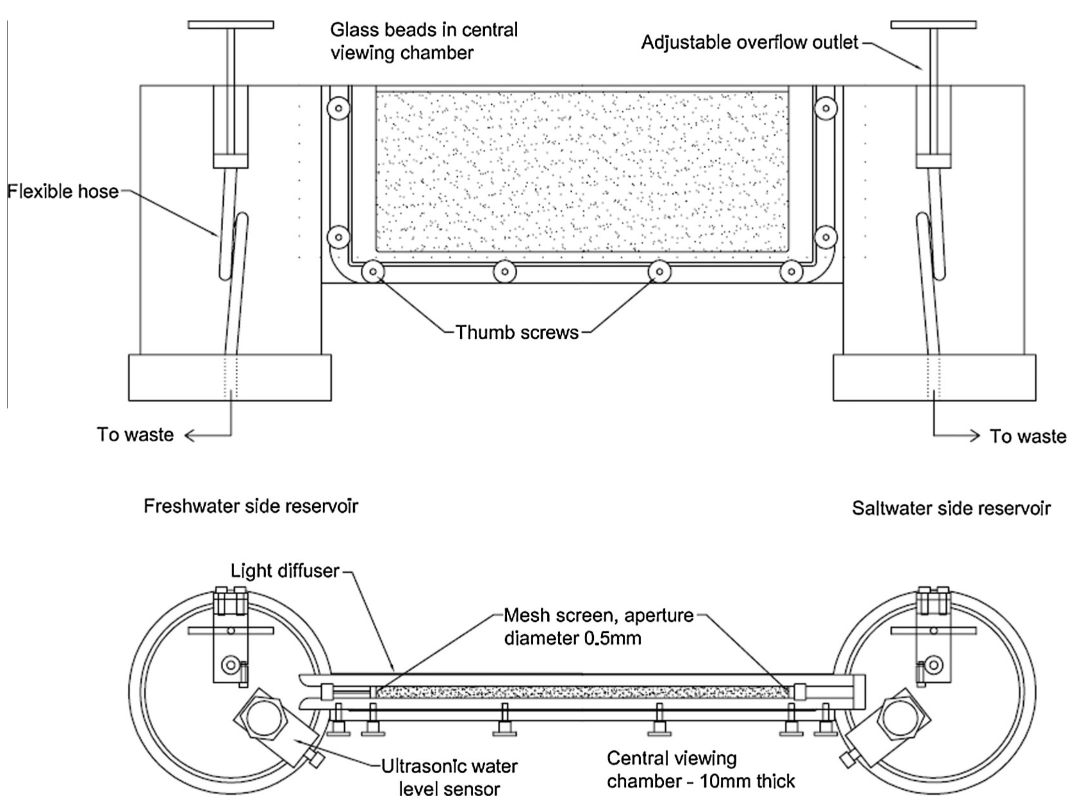

Fig. 1. Schematic diagram of the sandbox experiment tank, front (top) and plan (bottom) elevation.