Automated Image Analysis for Experimental Investigations of Saltwater Intrusions in Coastal Aquifers

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Abstract

A novel methodology has been developed to quantify important saltwater 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 saltwater and freshwater. A high image sample rate was used to investigate the transient dynamics of saltwater intrusion, which rendered analysis by visual observation unsuitable. This paper presents the methodologies developed to minimise human input and promote autonomy, provide high resolution image to concentration conversion, and allow the quantification of intrusion parameters under transient conditions.

Keywords: Saltwater intrusion; Coastal aquifers; Image analysis; Error analysis

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 characterize freshwater-saltwater interfaces, and to investigate the behaviour of saltwater wedges (e.g. Schincariol and Schwartz, 1990; Zhang et al., 2002; Goswami and Clement, 2007; Konz et al., 2009a, 2009b; 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 saltwater-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 saltwater 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 4cm 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 (5cm thick) by comparing images of the front and back faces for the case of saltwater 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 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, similarly 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 Setup

Experimental investigations of flow in porous media are, for the most part, conducted within sandbox apparatus. Figure 1 shows a schematic overview of the sandbox. The tank consisted of a central viewing chamber of dimensions (Length x Height x Depth) 0.38 m x 0.15 m x 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 saltwater 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 saltwater 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 0.5mm apertures; slightly smaller than the finest beads tested. The hydraulic properties of saltwater 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 saltwater solution. A large batch of saltwater was produced by dissolving a predetermined mass of food grade salt into 200 litres of the freshwater to give a saltwater density of 1025 kg/m^3. The density of the saltwater was checked prior to testing by measuring the mass of a specified volume of the solution.

Food colouring has been successfully used in several image analysis experiments in the published literature (Goswami and Clement, 2007; Konz et al., 2009a), and has the benefits of being inert, non-toxic and cheap. A dye concentration of 0.15 g/L was used for all experimental cases. This value was determined through a trial and error process, and provided the most optimal range of light intensities based on the camera properties and illumination setup.

Clear glass beads, from Whitehouse Scientific®, of 1090μm diameter were chosen to represent the porous media. The beads were packed into the central viewing chamber under saturated conditions to form a homogeneous domain. SWI images were captured with an IDT® MotionPro X-Series high speed camera in conjunction with IDT® Motion Studio software. The camera had a capture resolution of 1280x1024 pixels and an 8-bit grayscale pixel depth. The resolution allowed for a pixel size of around 0.3 mm and the grayscale pixel depth provided a range of 256 available light intensities without the need for RGB to grayscale conversion or channel isolation. The main advantage of the high speed camera was to record images in a quick succession to eliminate any variability due to light flickering. A total of 10 images were recorded each time the camera was triggered and the average of the images was used in the analysis procedure. Figure 2 shows the standard deviation in pixel light intensity across the 10 images. It may seem trivial to correct for standard deviations of 2 pixel light intensities, however, particularly dark pixel locations may only have 40 pixel light intensities between 0 % and 100 % saltwater concentration images. This standard deviation could then contribute significant error to the calculated calibration regressions statistics. The camera captured images at a rate of 100 Hz, and these were recorded every 30 seconds to provide information on the transient nature of the intrusion.

The water levels in each side chamber were measured using ultrasonic sensors from the Microsonic® range (Microsonic - mic+25/DIU/TC). Due to the accurate control of water levels required for this experiment, the sensors were sensitive to changes in water level in the order of 0.2 mm.

3. Calibration.

A calibration is required to relate the captured image property, light intensity, to the desired system property, concentration. This relationship is non-linear and has been represented by a range of equations in the published literature (Goswami and Clement, 2007; McNeil, 2006). Calibration images require the entire aquifer domain to be fully flushed with a known concentration of dyed saltwater. Images of the aquifer fully flushed with 8 different concentrations of dyed saltwater (0 %, 5 %, 10 %, 20 %, 30 %, 50 %, 70 % and 100 %) were captured for use in the calibration analysis. The process of flushing the aquifer with the desired saltwater concentration was complicated by the need to maintain fully saturated conditions at all times. Therefore, the calibration procedure began with capturing images of the saturated freshwater aquifer (0 % saltwater concentration), with the 5 % saltwater concentration added to the bottom of the side chamber, displacing the less dense fluid out the overflow outlet at the top. The 5 % saltwater concentration was then allowed to flow until it had fully flooded through the test system. This process was repeated for the increasing density states until a fully saturated 100 % saltwater domain existed. Example images of the fully flushed homogeneous case at 0 %, 20 % and 100 % concentrations are shown in Figure 3. It took around 30 minutes for the beads to become fully saturated and required around 10 litres of saltwater solution for each concentration. The aquifers were flushed with approximately 10 pore volumes to ensure full saturation of the new concentration (Goswami et al., 2008). For these experiments, a power law was adopted to relate light intensity (I) to concentration (C) in the form:

$$C = aI^{b} - c \tag{1.0}$$

where a, b and c are coefficients to be determined from regression analysis.

The calibration of the captured images was undertaken using three different methods: average light intensity method, binned light intensity method and pixel-wise regression method. An error analysis was conducted on each calibration method, following the same methodology presented in Goswami et al. (2008), to ascertain the most suitable method to be used for the experimental case. The method involved a robust statistics based analysis, wherein the total error (σ_{total}) is composed of two error types:

1. Calibration relationship error (σ_{calib}) – The error involved in fitting the regression curve to the calibration data, defined by (Taylor, 1997):

$$\sigma_{calib} = \sqrt{\frac{\sum_{i=1}^{N}(C_m - C)^2}{N-P}} \tag{2.0}$$

where C_m is the actual measured concentration, C is the predicted concentration based on regression analysis, N is the number of data points in the calibration, and P is the number of coefficients used to define the relationship. This is also known as the standard error of the estimate.

2. Experimental Error (σ_{exp}) – The error created by the noise in light intensity of the calibration images. The standard deviation of light intensity was used to represent the image noise, which was related to noise in the concentration field using the equation (Taylor, 1997):

$$\sigma_{exp} = \left|\frac{dC}{dI}\right| \sigma_I \quad 3.0$$

where dC/dI is the gradient of the power law regression equation, and σ_I is the standard deviation of light intensity in the calibration image.

The total error for the calibration is calculated by adding the errors in quadrature:

$$\sigma_{total} = \sqrt{\sigma_{calib}^2 + \sigma_{exp}^2} \quad 4.0$$

The calibration relationship error is representative for all points along the curve, whereas the experimental error is specific to each calibration image. Therefore, the total error was calculated for every calibration concentration and is presented as a percentage of maximum saltwater concentration (100 %).

3.1 Average light intensity method

The simplest calibration regression method that can be employed in the examination of saline intrusion would involve averaging the light intensity values across the entire calibration image. This single light intensity value is deemed representative of the entire domain when conducting the regression analysis. This method works well for highly uniform lighting distributions commonly observed in homogeneous cases. The method is also computationally efficient, as only one set of coefficients needs to be calculated in the regression analysis. However, for the homogeneous images shown in Figure 3, it is clear that there are areas of the aquifer receiving greater illumination than others, despite all attempts to diffuse and spread the lighting system across the full test domain. Furthermore, screw holes in the rear of the tank appear as dark blotches in the centre and sides of the testing area, which further reduces the light uniformity. Figure 4 shows the average light intensity values for a typical calibration image along with the regressed power curve fitted to the data.

From visual observation the curve fits the data well, so the calibration relationship error is expected to be low. However, given the noisy light intensity distribution across the image, the experimental error is expected to be significantly larger. Table 1 shows the results of the error analysis.

As expected, the total error estimate is dominated by the non-uniform light intensity field. This is evident in Figure 5(a), where the regression coefficients are applied to the calibration image light intensities of the 20 % concentration image of Figure 3. A similar distribution of concentration was observed for all other calibration images. Ideally, the concentration colour map should appear uniform at the value of the measured concentration. It is evident that variations in the light intensity fields are still accounted for after conversion of the image to concentration fields, as observed in the higher concentrations calculated at the edges of Figure 5(a). Furthermore, the addition of any heterogeneity would impose greater errors on this method as the light intensity fields become less uniform. This is evidenced by the clear appearance of the three screw positions within the back wall of the rig. Therefore, selecting a single value based on the average light intensity field to represent the entire domain is prone to large errors and is unsuitable for this work.

3.2 Binned light intensity method

A binned light intensity method was investigated to try to account for the large variation in light intensities observed in the images, such that any pixel at a given light intensity, independent of its location in the image, will be affected by the dyed saltwater by the same amount. The method involved selecting pixels of the same light intensity in the 0% concentration images (starting light intensity), and recording their location in the image space. Pixels at these locations are then found in subsequent calibration images and binned in groups together. Similarly to the average light intensity method, the binned light intensities are averaged and a regression analysis was conducted on the results. Therefore, a power relationship was developed for all starting light intensities (SLI) and was applied to the corresponding pixel light intensities of the same value in the test images.

Figure 5(b) shows the result of applying the regression methodology to the 20 % calibration image. It is clear that there is significant improvement over the average light intensity method (Figure 5(a)), as the field is much more uniform and less affected by tank features and lighting heterogeneities. Table 2 shows the average of the error in each bin for each calibration concentration. It is important to note that the experimental error (σ_{exp}) in this case is represented by the standard deviation in each separate bin. This means that the experimental error is zero at 0 % concentration, due to the same SLI values defining how the bins are formed.

As expected, the experimental error is much lower for the binned light intensity method compared to the average light intensity method. Subsequently, the average estimated concentration of each calibration image is much more accurate. The classification of light intensity bins also allowed for the application of regression coefficients to other experimental cases of the same bead class. This reduces the time and labour required to run an experimental test case as no calibration is required. However, a maximum error of 14.4 % still seemed large when considering the fine level of detail that would be required to capture the transient width of the mixing zone dynamics.

3.3 Pixel-wise regression method

It is clear from Table 2 that experimental error accounts for the majority of the total error in the binned light intensity method. The pixel-wise regression method was designed to negate all experimental error, so that only calibration relationship error contributes to the total error. This method involves the determination of power law regression coefficients for every pixel in the image. Therefore, spatial variations in lighting due to bead heterogeneities and tank features are nullified. Figure 5(c) shows the concentration colour map of the converted calibration image at 20 % concentration. It is clear that the pixel-wise regression method produces the most uniform concentration field, and only minor imperfections were observed in the larger concentrations due to errors in fitting the power law relationship.

Table 3 summarises the errors calculated in the pixel-wise regression method. As in the binned light intensity method, the pixel-wise errors are averaged across the image space as reported in Table 3. The total error colour map is shown in Figure 6. With a total error averaging 2.16 %, the pixel-wise regression method provided the most accurate conversion of light intensity to concentration, which allowed the subtle changes in the width of the mixing zone to be analysed. The major disadvantage of the method is that the calibration is entirely specific to the domain test case. This means that a new calibration is required for each synthetic aquifer, increasing the time taken to run each test case.

Nevertheless, the pixel-wise method excelled in accurately predicting concentration fields from image light intensities and was the method adopted in this experimental work.

4. Image Analysis – Code Development

The image analysis code contains 4 main stages:

1. Image preparation – common origin determined, all images are aligned to the common origin, scaled to real world distances and image boundaries are established allowing an image crop to occur;
2. Calibration – determining the regression coefficients which correlate the light intensities captured in the images to concentration values;
3. Analysis – applying regression coefficients determined in the calibration to the experimental test cases, and analysing the images to calculate intrusion parameters;
4. Post processing – Plotting figures from analysis results files for visualisation.

The code was developed in MATLAB® (R2011a) given its ease of use and the fact that it has become the industry standard in academia. All scripts are available free of charge to interested users and can be obtained directly from the lead author.

4.1 Image Preparation

The goal of the methodology developed in this investigation was to establish an automated process by which the concentration mapping of SWI could be achieved. The removal of as much subjectivity as possible from all levels of analysis was the key driver to the methodology implemented. User input is best minimized, although some user input is still required to make sure that the images are ready for analysis.

4.2 Determination of pixel size

Pixel sizing involves determining the dimensions of a single square pixel in order to relate the image space to real space. The mechanism by which it is determined is similar to that employed in any standard flow mapping image analysis system, wherein an object of known size is placed within the image and the user selects pixels across a known measured distance on the object allowing a simple calculation of scale to be applied. The system developed within this research prompts the user to load the required image and asks for the selected points to be identified.

4.3 Spatial Origin and Domain Bounding

Determining an origin for each image in space is essential for image analysis. The calibration regression coefficients are calculated at each specific pixel location, therefore the images need to be synchronised in space. To allow this synchronization to occur a common origin must be identified within all images. The method by which this was achieved involved predicting the edges of the viewing window and extrapolating the bottom and side boundaries to a single point, known as the spatial origin. Initially, a region of interest (ROI) is defined by the user on the first image loaded, wherein the region must contain the bottom edge and right side edge of the viewing window, as shown in Figure 7. In order to determine the right side boundary of the testing area the light intensities along each column of the ROI are averaged while for the bottom boundary the light intensities along each row are averaged. This provides an indication as to whether each column or row of pixels is illuminated or not. The column-wise averaged light intensities are shown in Figure 8 (top right). An edge boundary can be determined by finding the maximum difference between adjacent averaged light intensities. The adjacent differences are shown in Figure 8 (bottom left). The resulting spatial origin is determined where the two boundaries intersect and is shown in Figure 8 (bottom right). The spatial origin coordinates are related back into the full image space and saved for use later in the synchronisation stage.

Another requirement of automated image analysis is to determine the domain area to be analysed. As is shown in Figure 7, the raw images contain large unilluminated areas where analysis is not required. The objective of domain bounding is to speed up analysis calculations by extracting only the information captured in the test area. The domain boundaries are determined using the same method described above for spatial origin calculation. The only boundary unable to be determined this way is the top boundary. The testing area of the tank was not filled entirely with beads, due to the risk of overflow, and is therefore not required to be analysed. Instead, the top boundary is determined by offsetting from the bottom boundary by a specified amount. This offset is defined by the user and is dependent on the experimental setup. The top boundary is not vitally important as it is highly unlikely any intrusion will occur there, therefore this approximate method was deemed suitable. The bottom and side domain boundaries are then offset from the edges of the viewing window to remove any significant light distortion effects occurring here. These offsets are defined at the user's discretion and are specified in the variables section at the beginning of the program script. The final result is shown in Figure 9. Determining domain boundaries only occurs once per test and the same boundaries are applied to all the images of that test. In order for this to be viable, every image in each test case needs to be synchronised in space.

4.4 Spatial Synchronisation and Filtering

It should be noted that during the course of a test case there was minimal physical interaction with the camera; therefore most images tended to be synchronised already. However, image shake may occur when operating a camera, especially a standard digital SLR if a remote shutter release is not used and where mirror movement has not been disabled. Spatial synchronisation seeks to correct such minor camera deviations at the pixel level. Whenever images are synchronised or filtered, data is lost at the image boundaries. Thus, the synchronisation and filtering process utilises the full images, which are then cropped to the domain bounding coordinates. The images are synchronised with each other using the spatial origin parameter. In order to prevent excess loss of data at image boundaries, all calibration images are synchronised to the median spatial origin coordinate. Images are shifted in the vertical and horizontal planes so that each spatial origin coordinate in the calibration data set now lies on the same location as the median spatial coordinate. This synchronisation method does not account for camera pitch, yaw or roll, but its simplicity is warranted due to the low probability of camera movement. Median filtering has been used in previous studies to correct lighting non-uniformities and camera movement (McNeil, 2006; Goswami and Clement, 2007; Konz et al., 2008). However, median filtering blurs the image, reducing the resolution. In this study, as in previous studies, a median filtering level of 5 was set so as to maintain a resolution of roughly one bead diameter (Goswami and Clement, 2007). Figure 10 shows the final bounded, synchronized and scaled image ready for analysis.

4.5 Toe Length and Width of the Mixing Zone Calculation

Toe length (TL) and width of the mixing zone (WMZ) are standard parameters used to describe the intrusion of a saltwater wedge. The TL is defined as the distance between the saltwater boundary and where the 50 % saltwater isoline intersects the bottom boundary. The WMZ is the average of the vertical distance between the 25 % and 75 % saltwater isolines within the range between $0.2 \times (TL)$ and $0.8 \times (TL)$. A reference diagram for how each intrusion parameter is calculated is provided in Figure 11.

In order to facilitate the high time series resolution of the captured images, calculation of TL and WMZ must be automated. The method begins with plotting the 25 %, 50 % and 75 % contour isolines of the concentration images, as shown in Figure 12c. For reference, Figure 12 also shows the bounded domain image being analysed (Figure 12a) and the concentration colour map image after regression coefficients are applied (Figure 12b).

It is clear from Figure 12c that even while using the pixel-wise regression method the concentration values can be noisy. This is particularly evident in the 75 % concentration isoline, where small pockets of low concentration are observed within the wedge despite being fully surrounded by 100 % saltwater concentration. The presence of these anomalies is attributed to localised regression errors and small air bubbles accumulating in the porous media which distort the light intensity field. In order to determine TL and WMZ, the most representative concentration isoline is isolated and all other isolines are considered noise and disregarded.

To achieve this, the coordinates of each isoline are tested against the following rules:

1. Concentration isoline must have a z coordinate at the bottom boundary – it is essential that the isoline intersects the bottom boundary as this is how the TL is calculated.

2. Concentration isoline should have an x coordinate at the right side boundary – the most representative isoline should begin at the saltwater boundary and be present along the full interface.

3. If no x coordinate exists at the right side boundary the longest spanning concentration isoline becomes the most representative.

The results of applying these rules are shown in Figure 13 for the 50 % concentration isoline and for the 25 % and 75 % isolines in Figure 14. Once the representative concentration isolines are located, the TL is assigned to where the 50 % isoline intersects the bottom boundary. The WMZ is calculated by sampling across the 25 % and 75 % concentration isolines and finding the locations of matching x coordinates, as shown in Figure 14. If these matching x coordinates fall into the range of $0.2 \times (TL)$ and $0.8 \times (TL)$ then the difference in z coordinates are calculated and averaged across the interface, giving the final value for WMZ.

5. Test Cases

To show the functionality of the methodology presented, and to test its applicability to automated high resolution analysis, some baseline experimental test cases are presented. These cases involved the investigation of transient SWI intrusion properties in a homogeneous aquifer for both an advancing and receding saltwater wedge. Initially, the aquifer was fully saturated with freshwater. Using the variable overflow outlets, a range of hydraulic gradients were imposed across the aquifer and the resulting transient nature of the intrusion captured until a steady-state condition was achieved. Initially a head difference (dH) of 6 mm between the freshwater side chamber (135.7 mm) and saltwater side chamber (129.7 mm) was imposed to allow the saltwater wedge to intrude into the fully freshwater aquifer. The saltwater wedge was then prompted to intrude further into the aquifer by lowering the water level in the freshwater side chamber (133.7 mm), to a head difference of dH = 4 mm. This test, referred to as 6-4 mm, allowed the analysis of an advancing saltwater wedge without the initial boundary effects observed as the wedge first entered the aquifer. The head difference was then increased to dH = 5 mm by raising the water level in the freshwater side chamber (134.7 mm). This allowed investigation of intrusion parameters within a receding saltwater wedge, and is referred to as 4-5 mm test.

The results from the experimental test cases were compared with numerical simulations using SUTRA (Voss and Provost, 2010). The numerical model consists of a rectangular domain of the same dimensions as the central viewing chamber in the experimental tank. A mesh refinement study yielded element of 1.27 mm as an optimal size for the determination of WMZ while still maintaining reasonable simulation times. The longitudinal and transverse dispersivity values were determined by a trial and error process, but ultimately fell within the ranges specified by Abarca and Clement (2009) for beads of a similar size. The dispersivity values and element dimensions provided numerical stability in the simulations by meeting the criterion for mesh Peclet number (Voss and Provost, 2010). A freshwater (C = 0 %) hydrostatic boundary condition is forced on the left side boundary and a hydrostatic saltwater (C = 100 %) boundary condition applied to the right side (see Figure 11). A head difference of dH = 6 mm was imposed across the domain and the simulated concentration and pressure distributions at steady-state utilised as the initial conditions for the next head difference case (6-4 mm). Similarly, the 4-5 mm case was simulated using the 6-4 mm results at steady-state as the initial conditions. The model was simulated for 50 minutes with a 1 second time step and all cases reached a steady-state condition within this time period. An intrinsic flow test on the experimental domain allowed the calculation of the permeability of the porous media using Darcy's law. The model input parameters are summarised in Table 4.

5.1 Results and Discussion

The transient TL results for the advancing (6-4 mm) and receding (4-5 mm) saltwater wedge cases are presented in Figure 15. Simulations results are shown as data points at 5 minute intervals for clearer visualisation. The numerical and experimental TLs match well, where only minor deviations are observed at the steady-state locations. The numerical simulations under predicts the TL at the dH = 4 mm case (50 mins) and over predicts the TL at dH = 5 mm (100 mins), but generally the transient comparison matches reasonably. This indicates that the experimental saltwater wedge is more sensitive to changes in hydraulic gradient when compared to the numerical saltwater wedge.

The steady-state 50 % saltwater concentration isolines are presented in Figure 16 for both advancing and receding wedge cases. Similarly, only minor deviations between experimental and numerical results are observed, particularly at the toe location and saltwater boundary. The experimental 50 % saltwater concentration isoline appears to be more linear in slope, while the numerical is more curved. It can be reasoned that the experimental wedge slopes are more linear in shape due to minor heterogeneities introduced through small variations in bead diameter. Similar changes in saltwater wedge shape have been reported in numerical studies of heterogeneous effects on SWI (Abarca, 2006; Kerrou and Renard, 2010).

Intrusion timescales have been analysed numerically in previous studies (Chang and Clement, 2013; Lu and Werner, 2013). The general consensus is that a receding saltwater wedge will reach a steady-state condition faster than an advancing wedge. The high temporal resolutions achieved in this methodology allowed the determination of intrusion timescales from experimental results. The time to reach steady-state (T_s) is determined from finding the minimum value of absolute TL difference relative to the steady-state condition, δTL, where $\delta TL(t) = abs[TL_s - TL(t)]$. For easier comparison between head difference cases, the δTL results shown in Figure 17 are presented as a dimensionless ratio of the 6-4 mm case results. It is clear from Figure 17 that the receding saltwater wedge reaches a steady-state (T_s = 18 mins) sooner than the advancing wedge (T_s = 47 mins). It could be argued that the head difference did not return to dH = 6 mm and so the comparison is unfair. However, an additional test case was conducted for a receding saltwater wedge from 5-6 mm, where T_s was calculated at 16 mins. In a worst case scenario the T_s values for both receding saltwater wedge cases are summed, which still results in reaching a steady-state condition sooner. The numerical study by Chang and Clement (2013) revealed a difference in the flow field between an advancing and receding saltwater wedge. In an advancing wedge, the bulk movement of the saltwater opposes the movement of the freshwater. In a receding wedge the flow field switches so that the bulk motion of both fluids is tending seaward. This unidirectional flow field allows the saltwater wedge to retreat at a faster rate and reach a steady-state condition sooner.

The high accuracy calibration methodology adopted in this study allowed quantification of the transient dynamics of the WMZ. Figure 18 shows the results of the transient WMZ for the advancing and receding saltwater wedge. Unlike the TL results, the disparity between experimental and simulation results is fairly pronounced, particularly after a change in hydraulic gradient. When the hydraulic gradient changes, the WMZ expands as is observed shortly after t = 0 mins and t = 50 mins. For the experimental case, an increase in the WMZ is much larger when the saltwater wedge is receding (t = 50-100 mins) compared to the advancing case (t = 0-50 mins). In fact, the WMZ almost doubles in size from the previous steady-state condition during retreat. This is a significant change and questions the validity of the sharp interface assumption adopted in many previous experimental-scale studies. The large increase in experimental WMZ during retreat can be explained by the switch in flow field identified by Chang and Clement (2013). The switch from opposing to unidirectional fluid movements creates a highly disturbed flow field, therefore expanding the saltwater wedge mixing zone. The faster retreat of the saltwater wedge observed in Figure 17 would also promote higher dispersion along the wedge interface and increase the WMZ.

6. Summary and Conclusions

This research presented a novel experimental method for analysing laboratory-scale SWI problems. Rather than using visual observations to calculate standard intrusion parameters as found in previous studies in the literature, this method included an automated image analysis technique to calculate these parameters with minimal human input. Few studies in the literature have focused on the quantification of the WMZ even when visual observations have been used. This study presented a simple yet accurate method to calculate this parameter which should allow further investigation of intrusion dynamics in the future. The proposed methodology has the ability to track both spatial and temporal changes within laboratory-scale SWI. The resolution to which this can be achieved is a function only of the camera used to capture the images. The current system can acquire images at over 4000 frames per second (fps) at 8 bit resolution giving it the ability to track velocities of 100's m/s; there is no lower limit on speed that can be captured. Spatial resolution is a function of the pixel size of the image and focal distance used in the experiment, while sensitivity of the system to measurements of salinity is a function of the bit capacity of sensor, and on the current system this is set to 256 grayscales. Work is underway to deploy this system to modern digital SLR's where typical pixel scales of 1/100th mm per pixel are possible over grayscale, or RGB values, that correspond to over 65k variations of light and thus measurements of salinity.

The experimental study was presented in detail, focusing on the areas of novel contribution most notably:

- The robust error analysis of several different calibration methods to identify the most suitable for application to experimental test cases;
- The development of an image analysis software with a strong focus on automatic quantification of key intrusion parameters, rather than the more qualitative analysis observed in previous studies;
- The increased sampling rate provided crucial detail of TL and WMZ dynamics under the effects of strong transient conditions, which have not been quantified in previous studies;
- The high spatial and temporal resolutions achieved, which allowed analysis of transient intrusion parameters; most notably the WMZ, whose evolution under strong transient conditions had not been mapped in detail in other published experimental work;
- The TL dynamics and intrusion timescales match well with the numerical simulations and with findings from previous studies. The high resolutions in time and space achieved by the presented methodology allowed the quantification of WMZ dynamics. An increase in the width of the mixing zone was observed soon after the head difference across the aquifer was changed. The expansion of the mixing zone was greater for a receding saltwater wedge compared to an

advancing saltwater wedge. This agreed with existing theory of unidirectional flow field in a retreating wedge, providing faster bulk movement of saltwater and increased dispersion.

At present, the authors are investigating different experimental cases that cover wide range of intrusion problems in a sandbox experiment using the methodology described here.

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Figures Captions

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

Figure 2 – Standard deviation of pixel-wise light intensities between 10 images captured at 0.01 s intervals for the 1090 µm homogeneous case.

Figure 3 - Calibration images of 1090 µm homogeneous domain saturated with saltwater concentration 0 % (left), 20 % (middle) and 100 % (right)

Figure 4 – Average light intensities for each concentration calibration image and fitted power law regression curve

Figure 5 Concentration colourmaps of 1090 µm homogeneous domain at 20 % saltwater concentration: (a) Average light intensity method; (b) Binned light intensity method; (c) Pixel-wise regression method

Figure 6 - Colourmap of the total error in the pixel-wise regression method

Figure 7 – Raw camera image with marked ROI (yellow) used in determining spatial origin

Figure 8 - Image ROI analysed to determine spatial origin (top left), column-wise averaged light intensities (top right), adjacent differences of column-wise light intensities (bottom left), image ROI with bottom and right side boundaries (red) and spatial origin (green) marked (bottom right)

Figure 9 – Raw image with predicted domain boundaries shown in red

Figure 10 – Calibration image synchronised and bounded, with median filtering and scaled to real space using the pixel size parameter

Figure 11 – Reference diagram defining the intrusion parameters analysed

Figure 12 – (a) Analysis image for homogenous 1090 um case, (b) concentration colourmap image and (c) 25 %, 50 % and 75 % concentration isolines

Figure 13 – Representative 50 % concentration isoline

Figure 14 – Determination of WMZ from representative 25 % and 75 % isolines.

Figure 15 – Transient toe length for the advancing (t = 0-50 min) and receding (t = 50-100 min) saltwater wedge cases for experimental and simulation results

Figure 16 – Steady-state 50 % saltwater concentration isolines at dH = 4 mm and dH = 5 mm for experimental (dashed line) and simulation (solid line) results

Figure 17 – Transient toe length change relative to steady-state for the experimental advancing and receding saltwater wedge cases

Figure 18 - Transient width of mixing zone for the advancing (t = 0-50 min) and receding (t =50-100 min) saltwater wedge cases for experimental and simulation results