The effect of colour depth and image resolution on laboratory scale study of aquifer saltwater intrusion


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ABSTRACT: Increased water consumption combined with the effects of sea level rise and change in rainfall patterns have intensified seawater intrusion in coastal aquifers. Sandbox setups have been utilized over the years to recreate saline intrusion on a laboratory scale and study the mechanisms of this phenomenon. Recreating saltwater concentration fields from light intensity values is a widely applied image analysis practice in such investigations. The current paper investigates the effect of image colour depth and resolution on this procedure. Glass beads of three different diameters were utilized to recreate three homogeneous and one heterogeneous aquifer in a sandbox setup. High resolution images of saltwater intrusion were acquired using a digital camera. From these images, new ones with modified colour depth (16-bit and 8-bit) and smaller resolution were reconstructed. Deriving regression coefficients for the 16-bit experimental images was 36% ~ 51% faster than doing so for their equivalent 8-bit versions. Nevertheless, utilizing lower colour depth images did not lead to a significant increase in the regression error, constituting their use a viable alternative in cases where data storage limitations apply. Smaller versions of the 16-bit experimental images were processed to derive saltwater concentration flow fields. These fields were compared with those of the original data, and the difference between the basic saline intrusion characteristics was quantified. The toe length of the intruding wedge, the width of the mixing zone and the angle of intrusion were calculated for all four downscaled images. The relative difference from the original images for each parameter is up to 0.36%, 1.63% and 0.35% respectively. This indicates that lower resolution experimental images can be employed to derive accurate estimations of the basic saltwater intrusion characteristics, while minimizing processing time.

KEY WORDS: Saltwater Intrusion; Sandbox; Image Analysis; Regression Analysis

1 INTRODUCTION

Sandbox setups have been widely used to study aquifer saltwater intrusion on a laboratory scale. Image analysis has been successfully utilized to recreate saltwater concentration fields using the values of light intensity (LI) ([1], [2], [3]), enabling the precise calculation of the fundamental saline intrusion characteristics: toe length (TL), width of the mixing zone (WMZ) and angle of intrusion (AOI) [4]. The optimization of data acquisition ([5], [6], [7]) and data processing ([8], [9]) methods has been investigated in multiple studies. The current paper constitutes a contribution to this effort. To the best of the authors’ knowledge this is the first time that the impact of image colour depth and image resolution on the post processing procedure is investigated.

2 METHODOLOGY

2.1 Experimental Setup

The experimental data were acquired in the sandbox setup depicted in Figure 1. It consisted of a central viewing chamber of dimensions 0.38 m × 0.15 m × 0.01 m, with two cylindrical chambers at each side. The left side was filled with freshwater, while saltwater was supplied on the right one. Red food colouring was used to dye the saltwater, with a dye concentration of 0.15 g/L. Water level in the tank was adjusted via two flow outlets at each side chamber. Two ultrasonic sensors by Microsonic® constantly monitored the level with an accuracy of 0.2 mm. Clear glass beads were siphoned into the viewing chamber to recreate the aquifer porous medium. Fine mesh screens were placed between the central and side chambers to immobilize the beads while permitting water flow. Saltwater intrusion was instigated by the head difference between the two cylinders.

Figure 1. 3-d depiction of the utilized sandbox setup

Measurements took place in a totally dark room. Two LED light panels placed on the back of the experimental rig, at a distance of 25 cm, provided illumination. Data were captured using a Nikon D850 Digital SLR Camera. The acquired images had a 14-bit colour depth and a resolution of 7360 × 4912 pixels, corresponding to a pixel size of 0.08 mm.

2.2 Calibration

The pixel wise regression algorithm introduced by Robinson et al. [4] was utilized to derive saltwater concentration using
the values of light intensity in the experimental images. Monochromatic light intensity values were correlated with saltwater concentration values via a non-linear relationship ([2], [4], [10]) employing three regression coefficients a, b, c:

\[ C = aI^b - c \]  

(1)

The calibration method involved the acquisition of eight calibration images of pre-determined saltwater concentration (0 %, 5 %, 10 %, 20 %, 30 %, 50 %, 70 %, 100 %) for every investigated aquifer (Figure 2). Regression analysis in the current investigation was based off of the green colour channel component. Red and blue channel light intensities had either extremely small or big values for the SW = 0% and SW =100 % concentration images. Regression analysis was done on parallel in a 12-core CPU.

In total three homogeneous aquifers, one for each utilized bead diameter (780 µm, 1090 µm, 1325 µm) and a randomly heterogeneous one, comprising of equal quantities of the three bead sizes, were recreated. Calibrations images were acquired for all the experimental aquifers. An intruding saltwater wedge, was initiated by a hydraulic head difference of \( dH = 6 \) mm on the homogeneous 1325 µm and the heterogeneous aquifer (Table 1). In both cases the system reached steady state in approximately 50 minutes.

### Table 1. Acquired experimental datasets

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>8 cal. images</th>
<th>test images</th>
</tr>
</thead>
<tbody>
<tr>
<td>homog. 780 µm</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>homog. 1090 µm</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>homog. 1325 µm</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>heterogeneous</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

#### 2.4 Image post processing

Image post processing was carried out using MATLAB R2018a [11] application and programming language. The utilized algorithms were those proposed by Robinson et al. [4]. Initial post processing included the isolation of the sandbox’s viewing chamber from the rest of the photo and the implementation of median filtering contributing to the removal of outlying pixels. Two different subsets of the originally acquired experimental images were derived in order to investigate the effect of image colour depth and resolution on the derivation of saltwater concentration flow fields.

### Data-subset 1

Colour depth, also called bit depth, equals to the number of bits used to indicate each one of the three colour components (red, green, blue) of a single pixel. 16-bit and 8-bit versions of the original experimental images were derived. 16-bit images express \( LI \) with integer values ranging from 0 to 65535 \( (2^{16}) \), while 8-bit ones, utilize \( 2^8 = 256 \) values respectively. The 8-bit datasets size equalled to 18 % ~ 25 % of the size of the 16-bit ones (Table 2).

### Table 2. Size (MB) of the 16-bit and 8-bit monochromatic green experimental calibration datasets for the four investigated aquifers

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>16-bit</th>
<th>8-bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>homogeneous 780 µm</td>
<td>93.61</td>
<td>17.59</td>
</tr>
<tr>
<td>homogeneous 1090 µm</td>
<td>97.05</td>
<td>24.29</td>
</tr>
<tr>
<td>homogeneous 1325 µm</td>
<td>97.35</td>
<td>23.81</td>
</tr>
<tr>
<td>heterogeneous</td>
<td>96.05</td>
<td>19.44</td>
</tr>
</tbody>
</table>

### Data-subset 2

The effects of image resolution were investigated only for the homogeneous 1325 µm and heterogeneous aquifers. The original 16-bit images were resized to recreate lower pixel resolution datasets. This task was achieved via bicubic interpolation [12]. The dimensions of the derived calibration datasets and their size for the homogeneous 1325 µm aquifer are presented in Table 3. It is worth noticing that image pixel size and file size were not linearly correlated.
Table 3. Dimensions and size of the original and lower resolution monochromatic green 16-bit calibration datasets of the homogeneous 1325 μm aquifer

<table>
<thead>
<tr>
<th>Calibration Dataset</th>
<th>Pixel Size</th>
<th>Size (MB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>original resolution</td>
<td>1579 x 4669 x 8</td>
<td>88.92</td>
</tr>
<tr>
<td>resolution / 4</td>
<td>790 x 2335 x 8</td>
<td>68.00</td>
</tr>
<tr>
<td>resolution / 16</td>
<td>395 x 1168 x 8</td>
<td>21.02</td>
</tr>
<tr>
<td>resolution / 36</td>
<td>264 x 779 x 8</td>
<td>11.96</td>
</tr>
<tr>
<td>resolution / 100</td>
<td>158 x 467 x 8</td>
<td>4.29</td>
</tr>
</tbody>
</table>

3 RESULTS

3.1 Colour depth

In order to find the three coefficients that correlate saltwater concentration with light intensity, regression analysis was carried out using the built-in lsqcurvefit Mat Lab equation. This is a nonlinear curve-fitting solver that utilizes trust region reflective algorithm as its default regression algorithm [13]. It is an iterative procedure that concludes when the minimum function tolerance (1e-06 in this study) is achieved. The more detailed depiction of light intensity in the 16-bit images, using 2^{16} integer values in comparison to only 256 in the 8-bit photographs, resulted in a faster converging search algorithm, with less algorithm iterations executed per pixel (Figure 3), in all four investigated aquifers. Essentially regression analysis for the 16-bit images was 36% to 51% shorter than that conducted for their 8-bit image versions (Figure 4).

No clear correlation between colour depth and regression error was established. Mean squared error was relatively low (less than 1.5) for both the 16-bit and 8-bit images in all the investigated aquifers. The difference between the calculated values of TL and WMZ derived using the two bit depth image versions was less than a pixel size, proving that the recreated flow fields were identical. This is a clear indication that 8-bit images can be successfully utilized in investigations of saltwater intrusion if higher bit depth images are not available or where data storage limitations apply.

Figure 3. Total search algorithm iterations conducted during regression analysis for the 16-bit and 8-bit versions of the homogeneous 780 μm calibration images

Regression analysis was conducted for the five different resolution versions of the homogeneous 1325 μm and heterogeneous aquifers alike. A linear relationship between regression time and image resolution was established (Figure 5). The average regression time per investigated pixel varied between $2.53 \times 10^{-3}$ sec and $4.31 \times 10^{-3}$ sec. Saltwater concentration fields derived for the homogeneous case are presented in Figure 6. The five reproduced fields are indistinguishable from each other through simple visual observation. Three basic saltwater intrusion characteristics, TL, WMZ and AOI were calculated for all the versions of the two test images, and their absolute difference from those in the original images is presented in Figure 7. The change in the values of TL varies from 0.1 mm to 0.6 mm, that is less than the diameter of a single bead (1 mm). Similarly, WMZ was calculated with an accuracy of less than a pixel, i.e. 0.08 mm, while the maximum difference in the calculated AOI was less than 0.1°. This confirms that for most laboratory scale investigations, lower resolution images can be utilized to accurately calculate the various saltwater intrusion characteristics. Since the difference between the presented image versions is so small, no clear trend between the deviation of measured variables and image resolution was established. This variation could be attributed to random experimental
errors and possible shape distortion introduced by the resizing procedure.

Figure 6. Saltwater concentration flow fields of the homogeneous 1325 μm aquifer, generated using the a) full b) four c) 16 d) 36 and e) 100 times less resolution versions of the experimental images.

To further investigate the impact of image resolution in the structure of the generated flow fields, and in particular its effect on the width of the mixing zone, the concentration values of the pixel column at x = 27.5 cm were plotted against each other for the original image and the 16 and 100 times smaller versions of the homogeneous 1325 μm test case (Figure 8). The three curves presented a relatively good fit, but when examined in detail (Figure 8.b), the amount of information loss due to image resizing becomes evident. This indicates that where precise determination of the saltwater freshwater interface is crucial, the use of higher resolution images should be a priority.

Figure 7. Absolute difference between the values of TL, WMZ and AOI calculated from the original resolution experimental images and their lower resolution versions for the homogeneous 1325 μm and heterogeneous aquifer.

4 CONCLUSIONS

This study constitutes an attempt to optimize the image analysis procedures that accompany laboratory scale investigations of saltwater intrusion. The effect of two distinct image characteristics, colour depth and pixel resolution, on the derivation of saltwater concentration fields from the values of light intensity, was quantified. Four synthetic aquifers were constructed in a thin sandbox setup, and seawater intrusion was
Initiated. The acquired experimental data were processed to recreate new datasets of varying bit depth and resolutions. Regression analysis was conducted for all the aforementioned datasets and their concentration flow fields were visualized. Total regression time and regression error per investigated aquifer as well as the precision in the calculated values of TL, WMZ and AOI, were used to assess the impact of colour depth and resolution on the image analysis procedure.

Successful utilization of lower resolution images to recreate new datasets of varying bit depth and resolutions. Total regression time was linearly correlated with image resolution. TL was calculated with an accuracy of 0.1 mm – 0.6 mm, WMZ with 0.016 mm (less than a pixel), while the maximum difference in the calculated AOI was less than a tenth of the degree. This affirms that lower resolution images can be successfully utilized in laboratory investigations of saltwater intrusion.

In order to minimize total regression time and regression error, further work should investigate the use of regression procedures other than trust region reflective least squares algorithm, such as interior point linear least squares or the Levenberg-Marquardt method.

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Figure 8: Vertical saltwater concentration profiles at a) x = 27.5 cm on the dH = 6 mm 1325 μm case, recreated using the original resolution figure and its 16 and 100 time smaller versions and b) detailed depiction along the saltwater freshwater interface of the pixel column.

16-bit and 8-bit laboratory images were tested. The more detailed representation of the LI values in the 16-bit images, expressed with 65536 values in contrast to the limited 256 in 8-bit images lead to significantly less executed search algorithm iterations during regression procedure. This corresponded to a 36% ~ 51 % reduction of the regression time or approximately 5 to 7 hours per experimental image. The flow fields generated by the different colour depth images were identical with each other, the difference on their calculated intrusion characteristics being less than a pixel size.

Four, 16, 36 and 100 times smaller versions of the 16-bit images were constructed. Lower resolution images were successfully utilized to recreate saltwater concentration fields.