CHANGES TO WATER RESOURCES RESULTING FROM SEA LEVEL RISE AND CLIMATE CHANGE

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ABSTRACT

This paper highlights investigation and the impacts of the changes in groundwater table caused by sea level rise due to climate change in Whaiwhetu Aquifer, Lower Hutt, New Zealand. The aquifer is located in coastal zone of almost completely urbanized area of Lower Hutt, north of Wellington City. In the past 100 years sea level raised on average 0.2 m in Wellington region and it is predicted that by the 2090 sea level will increase by 0.8 m and by 2115 almost 1 m. Therefore an investigation has been carried out by developing a three-dimensional hydrodynamic numerical model. Numerical model was developed using comprehensive groundwater modelling package FEFLOW 6.1. Once the model was developed and calibrated, four scenarios were investigated. Scenario 1 assumed the increase of 0.5 m of the mean seawater level (MSL). Scenario 2, Scenario 3 and Scenario 4 assumed an increase of 1.0 m, 1.5 m and 2.0 m MSL respectively. The changes were compared in nine observation bores and the results are presented.

Keywords: Sea level rise, groundwater

1. INTRODUCTION

Within Greater Wellington Region there are three major ground water zones. Those zones are: the Lower Hutt Valley, Kapiti Coast and the Wairarapa Valley (Jones, 2005). Lower Hutt Groundwater Zone (LHGZ) is a system composed of a number of alternating confined and unconfined aquifers. One of them is Whaiwhetu aquifer, known also as Whaiwhetu Artesian Aquifer and Whaiwhetu Gravel Aquifer. It is estimated that only 40% of the catchment is available for the rainfall recharge (Phreatos, 2003). Groundwater system is also recharged through the riverbed in the upper part of the Hutt River, north from the Melling (Stevens, 1956 and Jones, 2005).

In the past 100 years sea level raised on average 0.2 m in Wellington region (Bell and Hannah, 2012). The authors Bell and Hannah (2012) have also predicted that by the 2090 sea level will increase by 0.8 m and by 2115 almost 1 m. Since the Whaiwhetu Artesian Aquifer is the costal aquifer this change will have impact on groundwater table. Therefore an investigation has been carried and presented. In this research the model was built upon conceptual model described by Stevens (Stevens, 1956a and Stevens, 1956b) and on modelling work done by Reynolds for the former Wellington Regional Council (WRC) in 1993 and later revised by Phreatos in 2003.

The purpose of this report is to present investigation on changes in groundwater table due to sea level rise. In order to do such investigation numerical (computer) model was developed. The development of a three-dimensional computer model of groundwater and all steps of the process are presented in detail in subsequent chapters. The numerical model was developed using a comprehensive groundwater modelling software package FEFLOW 6.1 (DHI-WASY, 2012). It has capabilities for pre and post data processing, and very powerful simulation engine.

The groundwater modelling reported on here is fundamental part of the investigation on changes to groundwater table due to sea level rise. The model is built to fit the purpose and that is to estimate change of groundwater level due to sea level rise. This model can be used for any other further investigation on groundwater in Lower Hutt Groundwater Zone (LHGZ) with some improvement to the model. This improvement should mainly focus on obtaining more data on recharge from the Hutt River that will provide better modelling of the recharge to the groundwater from the river.

2. STUDY LOCATION

Lower Hutt Groundwater Zone (LHGZ) is bounded by Wellington fault in the east, on the west by the Eastern Hutt Hills and Taita Gorge in the north. Southern boundary is not well defined and it is assumed that it lies between Somes Island and entrance to Wellington Harbour (Reynolds, 1993; WRC, 1995 and Reynolds, 1993).

Whaiwhetu Aquifer is situated in the Hutt Valley and it is build-up of “water-holding sand, gravel and boulders” (GWRC, 2013). It lies within highly urbanised area and it is one of the sources for the water supply for the Greater Wellington Region. The thickness of the Whaiwhetu Aquifer varies form 20 m at the south-eastern boundary (harbour)
up to 70 m at the western boundary-Wellington fault. From Taita Gorge southward to Kennedy Good Bridge (Melling suburb) Whaiwhetu Aquifer is unconfined and this zone is recharge zone of the Whaiwhetu aquifer (Stevens, 1956 and WRC, 1995). The aquifer becomes confined (artesian) in the zone of the Kennedy Good Bridge and it stays pressurised all the way towards to the southern boundary that lies in the Wellington Harbour.

Model boundary, boundary between confined and unconfined aquifer and discharge zones in the Lower Hutt Groundwater Zone (LHGZ)

Aquifer discharges into the Wellington harbour via submarine springs on the sea floor (Harding, 2000) due to the pressure in the aquifer. Although, discharge zones for the whole Wellington Harbour were identified by Harding (Harding, 2000), in the Figure only discharge zones for the Whaiwhetu aquifer are shown. The main recharge source of the Whaiwhetu Aquifer is the Hutt River. Water leakage from the riverbed in the upper part of the Hutt River (recharge zone) replenishes the groundwater resources of the Whaiwhetu Aquifer and it takes up to a year (GWRC, 2013) for water to reach the aquifer.

Conceptual model of the Lower Hutt Groundwater Zone (GWRC, 2013)
3. RECHARGE

The aquifers in the Lower Hutt Groundwater (LHGW) zone are recharged by losses from the Hutt River, as a primary source and rainfall, as secondary source. The recharge occurs in the upper part of the catchment north from the artesian boundary. This zone is also known as recharge zone and it lies in the area between Taita Gorge and Kennedy Good Bridge (suburb Melling). In this zone Taita Alluvium and Whaiwhetu Artesian Gravels become hydraulically connected and Upper Waiwhetu Artesian Gravels gain water from the Hutt River via Taita Alluvium by vertical infiltration. Lower Waiwhetu Artesian Gravels and Moera Gravels gain less recharge due to lower permeability and hydraulic gradients. Recharge from the rainfall also occurs to unconfined Taita Alluvium aquifer. Since this aquifer is mainly urbanized it is estimated that only 40% of the rainfall is available for the recharge (Reynolds, 1993).

River recharge

Primary recharge source in LHGZ the Hutt River. Losses from the Hutt River contribute to recharge in the unconfined zone of the LHGZ, north of artesian boundary Figure 4. In this area all aquifers, Taita Alluvium, Whaiwhetu Gravel and Moera Gravel, are connected hydraulically due to non-existence of low permeability watertight strata. South of artesian boundary, in the confined zone of deeper aquifers (Lower Whaiwhetu Gravel and Moera Gravel) recharge from the river loss occurs only to Taita Alluvium Aquifer and there is no recharge to deeper aquifers, since overlying confining layer of Melling Peat and Petone Marine Beds is preventing recharge. Due to lack of river flow data estimated values for recharge from the river losses are adopted from (Reynolds, 1993) and (Phreatos, 2003). The authors have developed the relationship between concurrent flow gauging at Taita Gorge (29809), Kennedy Good Bridge (29824) and Boulcott (29811) on the Hutt River.

The relationship developed by Reynolds (1993) was based on records made between 1970 and 1993, at Taita Gorge (29809) and Boulcott (29811): The measurements were taken mostly under low flow conditions varying between 2.3 and 5.7 m3/s:

\[ \text{Boulcott flow} = -595 + (0.975 \times \text{Taita Gorge flow}) \text{l/s (Reynolds, 1993)} \]  
(Equation 1)

During 1995 pumping test was carried out under the normal flows that are ranging between 11 and 30 m3/s (Phreatos, 2003). Regression analysis of the data for the period 1970 -and 1993 and 1995 gave the mathematical relationship for the flow at Taita Gorge and Kennedy Good bridge:

\[ \text{Kennedy-Good Bridge} = 0.974(\text{Taita Gorge}) - 912 \text{ L/sec (Phreatos, 2003).} \]  
(Equation 2)

This equation is similar to the equation that was using only low flow data for the period from 1970 to 1993 developed by (Reynolds, 1993). Therefore losses between Taita Gorge (29809) and Kennedy Good Bridge (29824) are assumed to range between 100,000 to 160,000 m3/day for average river flow conditions and for the flows less than 6 m3/sec (low flows) no less than 80,000 – 85,000 m3/day.

Rainfall recharge

Simple model for the estimate of daily rainfall recharge for deeper aquifers (Lower Whaiwhetu Gravel and Moera Gravel) was developed by (Reynolds, 1993):

\[ \text{Recharge} = \text{Rainfall - Actual Evapotranspiration - Soil Moisture Deficit (Reynolds,1993).} \]  
(Equation 3)

If annual rainfall was greater than 1000 mm, then the annual recharge was calculated using the following equation:

Annual Recharge (mm) = \([0.97 \times \text{Annual Rainfall (mm)}] - 500\) (Reynolds, 1993) (Eq. 4)

where data used in Equation 4 is data accumulated on annual basis from the Equation 3.

Summary of available time series of groundwater levels in the Lower Hutt Groundwater Zone

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Well number</th>
<th>Aquifer</th>
<th>Bore Depth (m)</th>
<th>Available Record period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Somes Island</td>
<td>R27/1171</td>
<td>Upper Waiwhetu</td>
<td>21.2</td>
<td>1968-present</td>
</tr>
<tr>
<td>Hutt Recreation Ground</td>
<td>R27/1115</td>
<td>Upper Waiwhetu</td>
<td>23.5</td>
<td>1968-1979; 1987-present</td>
</tr>
</tbody>
</table>
4. CONCEPTUAL MODEL

The conceptual model, based on the model described in (Phreatos, 2003), consists of seven geological layers. The model domain corresponds to the boundary of the Lower Hutt Groundwater Zone. The northern boundary is at Taita Gorge where gravels thin out. Western boundary of the model domain coincides with Wellington fault. Eastern model boundary is defined by Eastern Hutt Hills. Southern boundary lies within the Wellington Harbour, between Somes Island and entrance to Wellington Harbour.

The upper boundary of the conceptual model is defined by the elevations of the land surface. This was obtained from the University of Otago - 15 m digital elevation model. The lower boundary was set as bottom Moera Gravel Layer. The thicknesses of the layers were determined from the bore logs given in the Revision of the numerical model for the Lower Hutt groundwater zone (Phreatos, 2003). The inflow in the model is the recharge from the rainfall in the onshore zone of the model domain and from the river in the unconfined zone of the LHGZ. Discharge is assumed to be into the Wellington harbour via submarine springs on the sea floor (Harding, 2000).

Conceptual model of the Lower Hutt Groundwater Zone

Modelling Software - FEFLOW 6.1

The modelling software FEFLOW 6.1 (DHI-WASY, 2012) was chosen for building the model. FEFLOW 6.1 is the existing version of software that was first developed in Germany in 1979. It is at a high level of development and refinement and has wide global use by universities, consultants, and government and private research organizations. FEFLOW 6.1 is a three-dimensional finite-element software package for modelling subsurface water flow and contaminant transport. It can be used to build two- or three-dimensional models with steady-state or transient conditions, and includes graphical user interfaces for model building, model input, and post-processing of model output (DHI-WASY, 2012).

Finite-Element Mesh Generation and 3D Discretization
The outer boundary of the framework, called the "supermesh" in FEFFLOW, is defined by model domain (Figure 2). The model domain was drawn using ArcGIS (DHI-WASY, 2012). The two-dimensional finite element mesh was generated using the Gridbuilder mesh generation algorithm in FEFFLOW. The nominal number of elements was specified as 3000, giving an actual number of elements of 4478 (Figure 7). The model was then expanded into 3D, by setting the number of layers to 7, and resulting mesh was applied to each of the slices in the model (ground surface, surfaces between each layer of the model, and lower surface of the Moera Gravel aquifer), giving a total of 31346 elements.

To define the elevations of the slices, the node positions (x and y coordinates) were exported from FEFFLOW as an ESRI point shapefile, and imported into ArcGIS. The Slice 1 elevations (ground surface level, above mean sea level) at the nodes were obtained using bilinear interpolation between the elevations at the centres of the cells of the 15 m digital elevation model (Otago, 2011). To estimate elevations for other slices, a first-order polynomial (planar), linear-regression trend of depth values for each stratigraphic unit from the bore logs of 29 bores (Phreatos, 2003) within the LHGZ. Values of this trend surface were determined at the node positions using bilinear interpolation, and the values were subtracted from the previously estimated Slice 1 elevations to give elevations for all of the remaining slices. Values of all node elevations for each slice were combined into an eight ESRI shapefiles (one shapefile correspond to one slice) containing the node number, x and y coordinates, node elevation, and slice number. These files were imported into FEFFLOW, and the node elevations were assigned using the FEFFLOW data assignment tool. Once the layers have been defined the layer type needed to be defined. The summary of the layer type for each modelled layer is given in the Table.

### Model layers

<table>
<thead>
<tr>
<th>Layer</th>
<th>FEFLOW Layer Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1 - Taita Alluvium</td>
<td>Free</td>
</tr>
<tr>
<td>Layer 2 - Melling Peat and Petone Marine Beds</td>
<td>Dependent</td>
</tr>
<tr>
<td>Layer 3 - Upper Whaiwhetu Artesian Gravels</td>
<td>Confined</td>
</tr>
<tr>
<td>Layer 4 – Interstadial deposits</td>
<td>Confined</td>
</tr>
<tr>
<td>Layer 5 - Lower Whaiwhetu Artesian Gravels</td>
<td>Confined</td>
</tr>
<tr>
<td>Layer 6 - Wilford Shell Beds</td>
<td>Confined</td>
</tr>
<tr>
<td>Layer 7 - Moera Gravels</td>
<td>Confined</td>
</tr>
</tbody>
</table>

The "Free surface" option in FEFFLOW was chosen for modelling the characteristics of the Layer 1 (Taita Alluvium) for the model runs. For Layer 2 (Melling Peat and Petone Marine Bed) the option dependent was chosen, which means that the layer above defines current layer. This means that the Layer 2 property will depend on Layer 1. All the rest layers were set up as confined at all times.

### Boundary Conditions

For the LHGZ model, boundaries were defined as follows (Figure 8):
- Eastern, southern, western and northern boundary: assumed to be no flow boundaries
- Leakage zones: fixed head, set at a value of 0.0 m above sea level;

### Parameter Values

The parameters required for the FEFFLOW input are, for each layer:
- Conductivity values in all directions, Kx, Ky and Kz. It was assumed that all layers of the model are isotropic in the horizontal plane (i.e., Kx = Ky, hence Kxy) drainable/fillable porosity (specific yield).

The apriori conductivity values were set up to be the same as calibrated steady state values in model presented Revision of the numerical model for the Lower Hutt groundwater zone. Drainable/fillable porosity or specific yield values for all the layers were also available in Revision of the numerical model for the Lower Hutt groundwater zone in Table (Phreatos, 2003). Boundary Conditions
Model Calibration

Due to insufficient data regarding river flows in the Hutt River and lack of series of rainfall data, calibration was done only for steady state conditions. Calibration was based on comparison of simulated and observed water levels in nine observation bores. Many runs were performed in order to match the simulated levels with observed ones and for each model run the Nash-Sutcliffe efficiency coefficient (Nash and Sutcliffe 1970) was also calculated. The model was accepted as suitable for further use when there was the same number of overestimated and underestimated water levels in observation bores and when the Nash-Sutcliffe coefficient was a maximum and close to 1.

The best fits were obtained with K values close to the a priori values, with little change in vertical conductivity values for first three layers (Tatita Alluvium; Melling Peat and Petone Marine Beds; Upper Whaiwhetu Artesian Gravels). The calibrated conductivity values are presented in the table.

Comparison of simulated and observed groundwater levels
Calibrated conductivity values

<table>
<thead>
<tr>
<th>Layer</th>
<th>Confined Zone</th>
<th>Unconfined Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k_{XY}$</td>
<td>$k_{Z}$</td>
</tr>
<tr>
<td>Layer 1 - Tatita Alluvium</td>
<td>2600</td>
<td>3</td>
</tr>
<tr>
<td>Layer 2 - Melling Peat and Petone Marine Beds</td>
<td>0.1</td>
<td>0.02</td>
</tr>
<tr>
<td>Layer 3 - Upper Whaiwhetu Artesian Gravels</td>
<td>1120</td>
<td>3</td>
</tr>
<tr>
<td>Layer 4 – Interstadial deposits</td>
<td>0.1</td>
<td>0.002</td>
</tr>
<tr>
<td>Layer 5 - Lower Whaiwhetu Artesian Gravels</td>
<td>600</td>
<td>0.5</td>
</tr>
<tr>
<td>Layer 6 - Wilford Shell Beds</td>
<td>0.1</td>
<td>0.002</td>
</tr>
<tr>
<td>Layer 7 - Moera Gravels</td>
<td>80</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The pattern of simulated groundwater contours is presented in Figure 10. It matches very well with the patterns of the groundwater contours simulated in previous modelling (Phreatos, 2003 and Reynolds, 1993). In the south-western part of the model due to high abstraction rates the local depression is visible.

Pattern of the simulated groundwater levels
1. Somes Island
2. Hutt Recreation Ground
3. Randwick Reserve
4. Petone Centennial Museum (PCM)
5. Port Road
6. Bell Park
7. Hutt Valley Memorial Technical College (H.V.M.T.C.)
8. Mitchell Park
9. Talita Intermediate

5. INVESTIGATION OF CHANGES TO GROUNDWATER TABLE DUE TO SEA LEVEL RISE

Four scenarios were used for investigation of the changes of the water table due to sea level rise. Scenario 1 assumes increase of 0.5 m of the mean seawater level (MSL), Scenario 2 assumes increase of 1.0 m and Scenarios 3 and Scenarios 4 1.5 m and 2.0 m respectively. This increase of the mean sea level in the model was represented by changing fixed head boundary condition at the leakage zones for each scenario. Therefore there were four model runs for each scenario. In Scenario 1 that assumes increase of 0.5 m the average increase of the groundwater levels in the Upper Whaiwhetu Aquifer is 0.07 m. The significant increase is noticeable in the part of the aquifer which lies in the harbour area if the model and in the coastal zone of the LGHZ (Figure 2). The change can be observed in bores Somes Island, Petone Centennial Museum (PCM) and Port Road that are 0.17 m, 0.11 m and 0.13 m respectively. North of the bores
H.V.T.M.C., Randwick Reserve and Bell Park there is no change to the water table due to increase 0.5 m in the mean sea level. Scenario 2 investigates influence of the increase of 1.0 m in the mean sea level. The results of this scenario show that increase in the ground water level will vary from 0.39 m to 0.61 m. The rise in elevation decreases from the south towards the northern part of the aquifer. The increase of the 1.5 m of the mean sea level will cause on average the change of 0.86 m in water table elevations. This change was investigated in Scenario 3. The change in elevations varies from 0.76 m to 0.98 m. Scenario 4 the increase of 2.0 m in the mean sea level. Minimum increase for this case is 1.15 m in the northern part of the aquifer and maximum is 1.39 m in the southern part of the aquifer that lies in the harbour. On average elevations of the ground water table will rise 1.25 m.

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Some Island</td>
<td>0.17</td>
<td>0.61</td>
<td>0.98</td>
<td>1.39</td>
</tr>
<tr>
<td>Hutt Recreation Ground</td>
<td>0.05</td>
<td>0.48</td>
<td>0.85</td>
<td>1.23</td>
</tr>
<tr>
<td>Randwick Reserve</td>
<td>0.11</td>
<td>0.54</td>
<td>0.91</td>
<td>1.31</td>
</tr>
<tr>
<td>Petone Centennial Museum (PCM)</td>
<td>0.13</td>
<td>0.56</td>
<td>0.94</td>
<td>1.34</td>
</tr>
<tr>
<td>Port Road</td>
<td>0.06</td>
<td>0.48</td>
<td>0.85</td>
<td>1.24</td>
</tr>
<tr>
<td>Bell Park</td>
<td>0.07</td>
<td>0.49</td>
<td>0.86</td>
<td>1.25</td>
</tr>
<tr>
<td>Hutt Valley Memorial Technical College</td>
<td>0.04</td>
<td>0.47</td>
<td>0.833</td>
<td>1.22</td>
</tr>
<tr>
<td>Mitchell Park</td>
<td>0.00</td>
<td>0.42</td>
<td>0.78</td>
<td>1.17</td>
</tr>
<tr>
<td>Taita Intermediate</td>
<td>0.00</td>
<td>0.39</td>
<td>0.76</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Once the conceptual model was developed, the numerical model was developed and calibrated by using FEFLOW. The model was accepted as calibrated once the number of overestimated and underestimated levels in observation bores were similar (Figure 9) and when the Nash-Sutcliffe coefficient was a maximum. Calibrated model was then used for investigation of the changes to groundwater table in Whaiwhetu Artesian Aquifer. Four scenarios were investigated for the increase of 0.5 m, 1.0 m, 1.5 m and 2.0 m. The average increase in groundwater levels in Whaiwhetu Artesian Aquifer is 0.07 m, 0.49 m, 0.86 m and 1.25 m respectively.

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REFERENCES