MODELLING AQUIFER RECHARGE WITH STORMWATER IN URBAN AREAS

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ABSTRACT

Urban aquifers have potential for supplying cities with water. Urban development affects both quality and quantity of groundwater recharge and increases flood risk from urban stormwater runoff. Many studies show that traditional stormwater management has failed to mitigate the negative effects of urban expansion.

Recently, the Low Impact Development (LID) approach has been advocated both nationally and internationally, as a sustainable approach for stormwater management. This approach uses distributed, decentralized source controls to manage stormwater runoff. This project explores groundwater aquifer recharge using stormwater as a possible LID option.

The aim of this paper is to explore risks associated with aquifer recharge using stormwater, concentrating on changes in groundwater levels.

The research site is in the Northern Strategic Growth Area, west of Auckland. The bedrock is Waitemata Group rocks, a complex structure of many alternating layers of mudstone and sandstone and localized extreme deformations.

A two layer transient model was built using the three-dimensional finite-element software package FEFLOW 6. The first layer represents a shallow alluvium aquifer and the second layer represents the deep sandstone aquifer.

KEYWORDS

Aquifer recharge, stormwater, 3D numerical model, Waitemata Sandstone

PRESENTER PROFILE

Marija Tutulić is a qualified civil engineer for hydraulic engineering and water resources. She is studying for her PhD degree at the University of Auckland in the field of groundwater hydrology. Marija has 7 years of postgraduate practical experience working mostly in the fields of river engineering and flood management.

1 INTRODUCTION

Artificial aquifer recharge could be described as “any engineered system designed to introduce and store water in aquifer systems” (Reddy, 2008). Artificial aquifer recharge with stormwater is one low impact development (LID) option. It can be regarded as a low cost “source control” option for excess stormwater disposal which aims at maintaining the predevelopment hydrology.

Artificial recharge is an unexplored method in New Zealand. Urban aquifers have a great potential for supplying cities with water. But urban development affects both quality and quantity of groundwater recharge. Furthermore, recharging urban aquifers with stormwater may introduce other problems. These problems include deterioration of groundwater quality and groundwater table rise with resulting damage to buildings.

The aim of this paper is to explore the risks associated with aquifer recharge using stormwater, concentrating on changes in groundwater level. This paper focuses on modeling the groundwater system and explores options for artificial recharge using urban stormwater.

The research area used in this study is located in the Northern Strategic Growth Area (NorSGA), situated in the north - western part of Auckland. Five hypothetical scenarios for aquifer recharge are examined and results are presented.

The majority of urban development in The Kumeu Hobsonville area will take place in the NorSGA within the next 50 years (Figs. 1 & 2). The NorSGA comprises the following areas: Redhills, Massey North, Whenuapai, Hobsonville Road Corridor, Hobsonville Peninsula (including the previous Hobsonville Airbase), and Scotts Point (WCC, 2009). A major city centre is planned to be built at Westgate (in Massey North), and smaller centres are planned for Hobsonville Village, Trig Road, Whenuapai Village and Hobsonville Airbase.

In this paper, we develop a 3D numerical model that increases our understanding of the extent of the aquifer beneath NorSGA and the aquifer’s natural-state dynamics. Once the natural state is known, the impact of urban development can be investigated and measures for maintaining the natural water balance can be proposed.

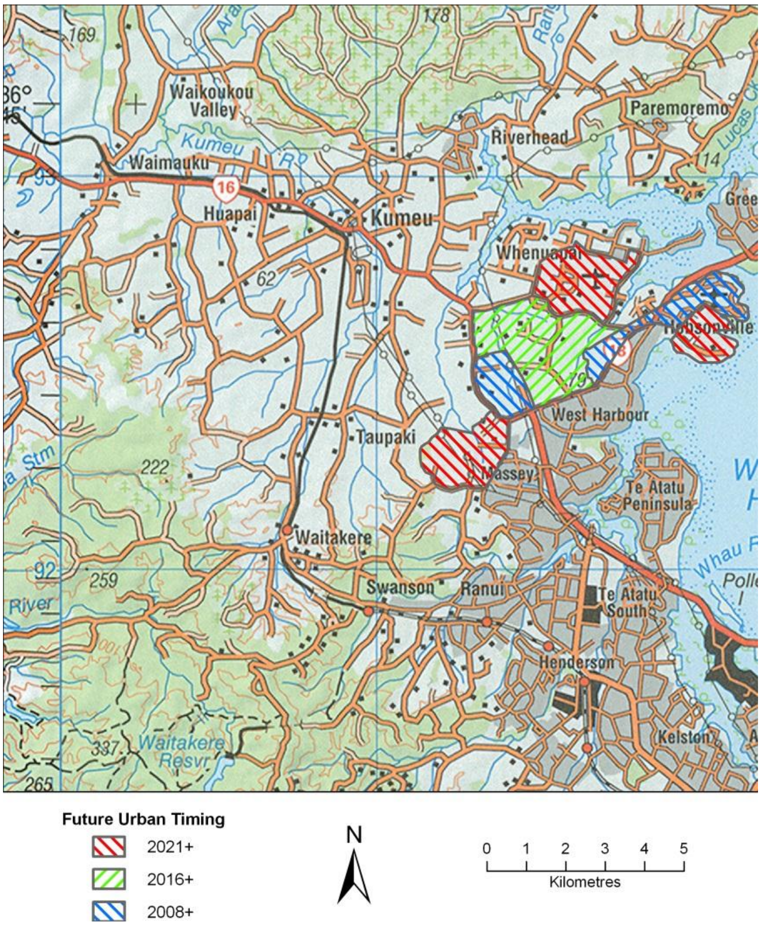

Figure 1: Location of the NorSGA and proposed development

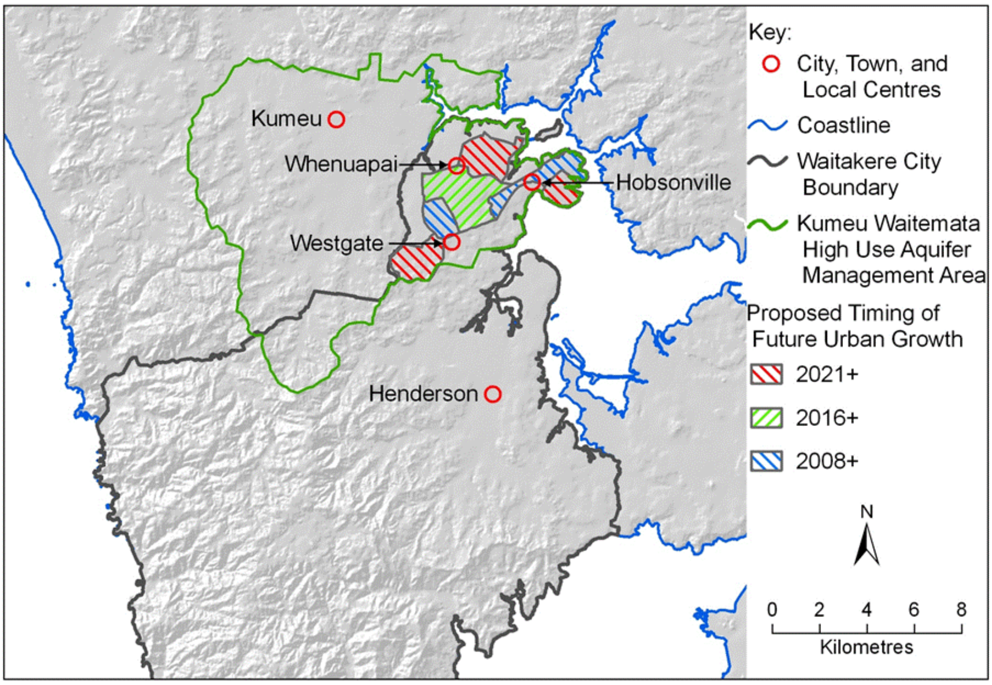

Figure 2: Location of the NorSGA and The Kumeu Waitemata High Use Aquifer Management Area (Adapted from WCC (2009), p. 93)

The bedrock in the NorSGA is Waitemata Group rocks, a complex structure of many alternating layers of sandstone and mudstone (either East Coast Bays or Cornwallis Formations, in the Warkworth Subgroup) and localized extreme deformations.

The NorSGA is within the Kumeu Waitemata [Sandstone] High Use Aquifer Management Area (KWHUAMA) (ARC, 2001). Actual groundwater use within this area is about half of the total available resource, but there are several zones in which actual use is greater than the available resource (Fig. 3).

The sandstone aquifer is used as a source of water for rural domestic supply, stock watering, industry supply and irrigation. Yields are low to moderate (a few cubic meters per day to over 1,000 m^3/day, with most less than 200 m^3/day) and it is mostly drinking water quality. The alluvium aquifer is low-yielding and is prone to contamination from surface water.

Water availability (estimated maximum sustainable extraction) in the KWHUAMA is set by the Proposed Auckland Regional Plan (ARC, 2001). For management purposes, the KWHUAMA is divided into zones (Fig. 3). The zones are determined on the basis of density of bore consents, not on the basis of hydrogeological boundaries. For the reporting year to 31st May 2007, Zone 1 was fully allocated (103% of available water) and use was high at 80% of available. But other zones of the area are less than fully allocated and ground-water use in them is low. Overall, 51% of the aquifer is allocated, and actual use is 27% (ARC, 2008).

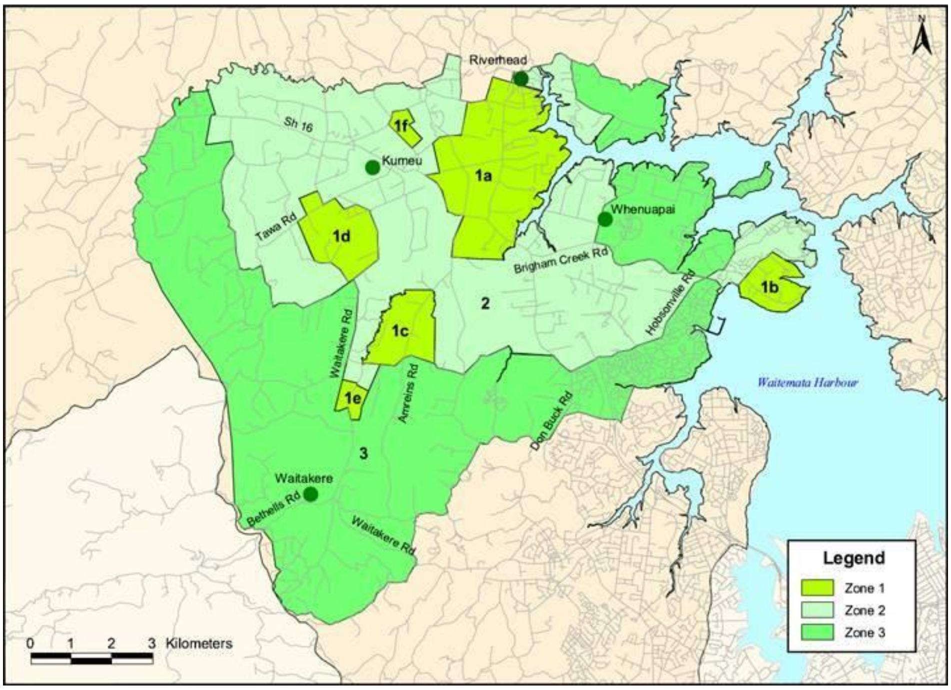

Figure 3: High Use Aquifer Management Area (ARC, 2001)

2 GEOLOGY OF THE KUMEU WAITEMATA AQUIFER

The local basement material (bedrock) under the KWHUAMA is flysch; that is, alternating layers of coarse and fine marine sediments. For nearly all (approximately 95%) of the area of the KWHUAMA, this flysch is interbedded sandstone and mudstone of the Warkworth Subgroup of the Waitemata Group (either East Coast Bays or Cornwallis Formations) and is commonly referred to as Waitemata Sandstone (Fig. 4). On the western fringe of the KWHUAMA the basement material is volcaniclastic flysch of the Waitakere Group (Nihotupu Formation).

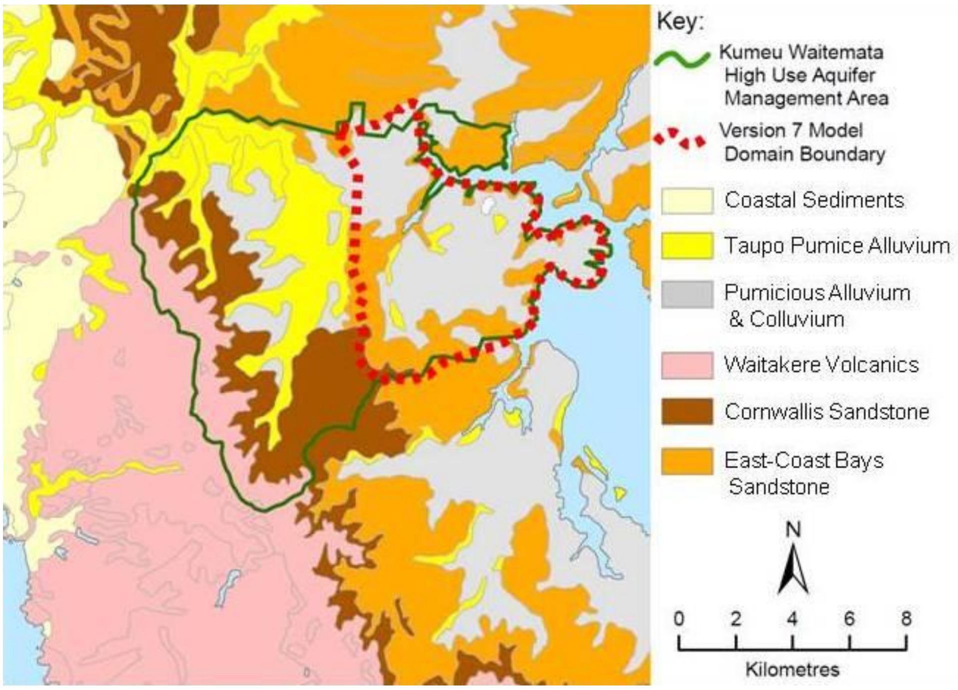

Figure 4: Simplified Geology of the NorSGA Area

The Waitemata Group rocks were formed by a combination of subduction, related volcanic arcs, and compressional tectonics in the Auckland and Northland regions. From the late Oligocene an arc of mainly submarine volcanoes formed to the west of the present West Coast, later producing a line of volcanic islands. In the east there was an arc of younger, more terrestrial, volcanoes, in the line of present-day Coromandel Peninsula and Great Barrier Island. The Waitemata basin, a deep marine basin (1000 to 2000 m deep), formed between them. The basin filled with sediment from higher ground to the north, west and east, to give the present-day rocks of the Waitemata Group.

Most of the sediment in the Waitemata Basin was mud, deposited slowly in the deepening Waitemata Basin, but, intermittently, strong turbidity currents flowed rapidly across the sea floor, depositing layers of silt and sand (Kermode, 1992). The coarse layers can have permeability several orders of magnitude greater than that of the mudstone layers. The Waitemata Group deposits are believed to be up to 2000 m thick. Within the KWHUAMA they are of the order of several hundred metres thick (Kermode, 1992).

Although much of the Waitemata group consists of semi-parallel, gently dipping strata, there is extreme localized folding and faulting of the sedimentary material resulting from submarine slumping of strata during, or soon after, deposition (Strachan, 2008). The combination of alternating layers of fine and course material, deformations that occurred during deposition, and later minor folding and faulting have resulted in a complex geological formation, with variations over small distances.

In the east and centre of the KWHUAMA (and for nearly all the NorSGA), the Waitemata Group is represented by the East Coast Bays Formation, derived from sediment from older rocks in the higher ground to the north and east of the basin (or possibly from volcanic ocean islands - see Shane et al., 2010). The present day expression of the East Coast Bays Formation is the gently rolling topography of generally low relief over much of the Auckland Region. In the west of the KWHUAMA, the Waitemata Group is represented by the Cornwallis Formation, derived from sediments from the contemporaneous volcanic area to the west of the Waitemata Basin. The Cornwallis Formation overlies and interdigitates with Warkworth Subgroup rocks to the east. The present day expression of the Cornwallis Formation is the north-eastern foothills of the Waitakere Ranges.

On the western fringe of the KWHUAMA, the volcaniclastic flysch of the Waitakere Group (Nihotupu Formation) formed during the Early to Mid-Miocene as marine sediments at some distance from the contemporaneous volcanic arc. The sandstones and mudstones of the Nihotupu Formation are derived from erosional material from volcanic rock, and were formed in a similar manner to the Waitemata Group. The present day expression of the Nihotupu Formation is in the eastern part of the Waitakere Ranges. The Waitakere Group overlies the Waitemata Group.

Beneath nearly all the NorSGA, the local basement material is the East Coast Bays Formation. Beneath about 1% of the area of NorSGA (the south-west corner of the Massey post-1921 development area), the basement material is the Cornwallis Formation.

In areas of low relief in the lower parts of stream catchments, much of the material overlying the sandstone is composed of relatively recent (less than 2 million years old), thinly bedded alluvial deposits. These alluvial deposits are mainly re-worked, pumiceous material, the original source of which is volcanic material from the Taupo Volcanic Area. There are also beds of peat and lignite. The alluvial deposits are up to 60 m thick in the NorSGA area (Kermode, 1992), but the average thickness is about 20 m. Soils that have formed in-situ on the Waitemata Sandstone are clay rich and only a few meters thick.

The general form of the Waitemata Sandstone layers is known, but the detailed form in the KWHUAMA is not known. Bore logs available for bores within the KWHUAMA are of variable quality, but in general lack sufficient accurate information to infer detailed stratigraphy. It is not known if localised complex structures, resulting from faulting or from debris flows or turbidity currents (Strachan, 2008) are present in the KWHUAMA. It is also not known if any such structures would inhibit or enhance groundwater flow through the aquifer.

3 DEVELOPMENT OF THE 3D GROUNDWATER MODEL

Developing a numerical model is an iterative procedure (Fig. 5) which includes numerous modifications to the conceptual model and parameter values.

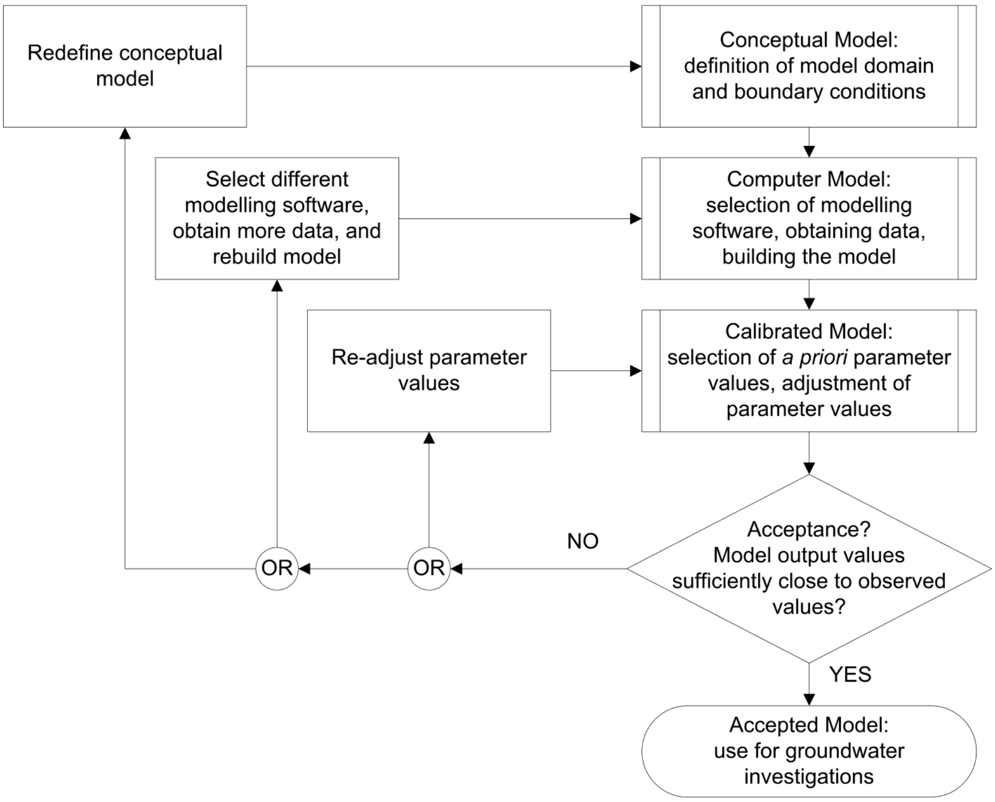

Figure 5: Modeling Stages

The first and most important step in developing a numerical groundwater model is development of a conceptual model and it is not unusual to repeat this stage and redefine the conceptual model several times.

Validation of the model using input data not used in calibration was not possible in this case due to lack of data. Acceptance was based on the credibility of both the model output and the calibrated parameter values and on the perceived usefulness of the model for investigating scenarios.

3.1 CONCEPTUAL MODEL

The conceptual model used in this study consists of two geological layers (alluvium above sandstone) with unconfined aquifers and saturated conditions (Fig. 6). This is a simple conceptual model, but appropriate for the current state of knowledge of the Waitemata Sandstone aquifer and for the amount of data available for model calibration.

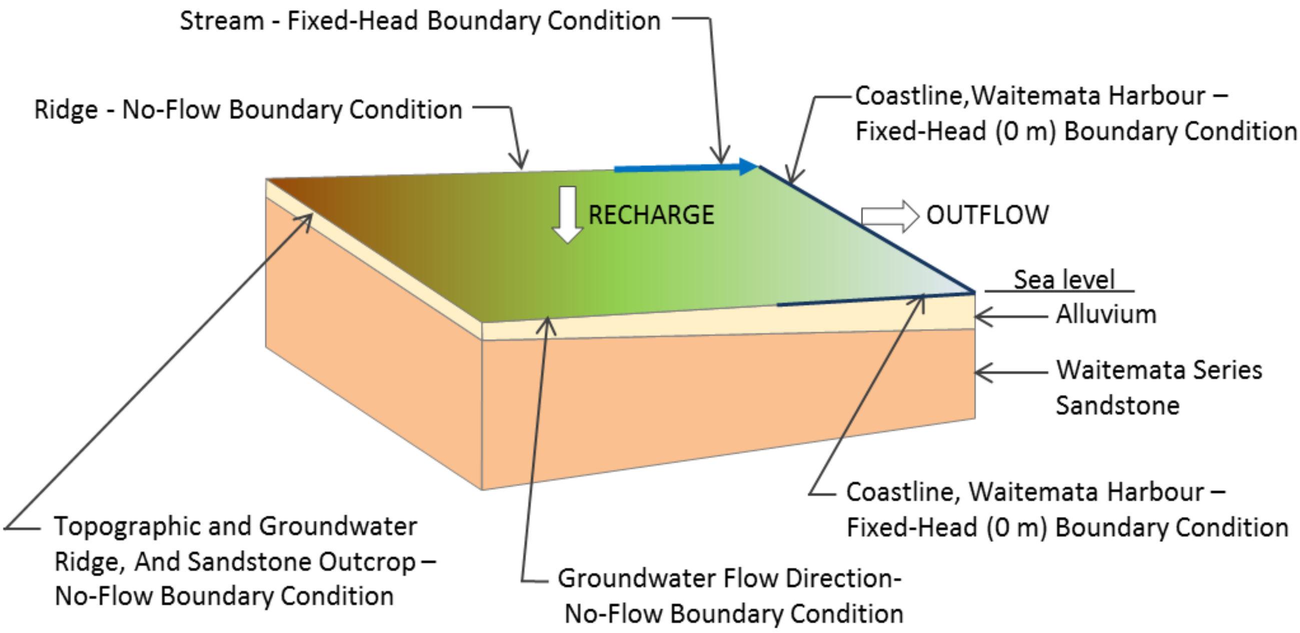

Figure 6: Conceptual model

The domain of the adopted model was determined from the topography (Fig. 7), the geology (Fig. 4), and the shape of the water table surface (Fig. 8). The boundary of the KWHUAMA also encloses the NorSGA (Fig. 2). Early modelling, with the domain boundary approximately the same as the KWHUAMA, failed to simulate the high ground-water ridge just to the west of the NorSGA (Fig. 8).

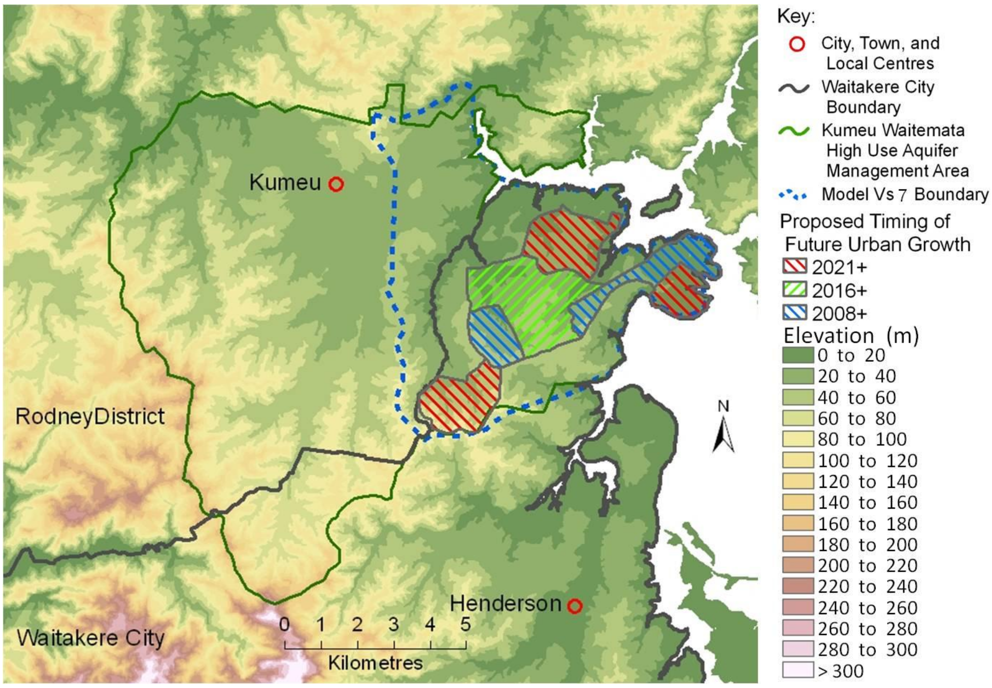

Figure 7: Topography of the NorSGA

Perusal of the topographic map revealed a ridge just to the west of the NorSGA, with ground surface levels ranging between about 40 and 115 m. This ridge coincides with an outcrop of Waitemata Sandstone. The western boundary was, therefore, defined by the best fit to the groundwater ridge, the topographic ridge, and the outcrop of sandstone (Figs. 4, 7, and 8).

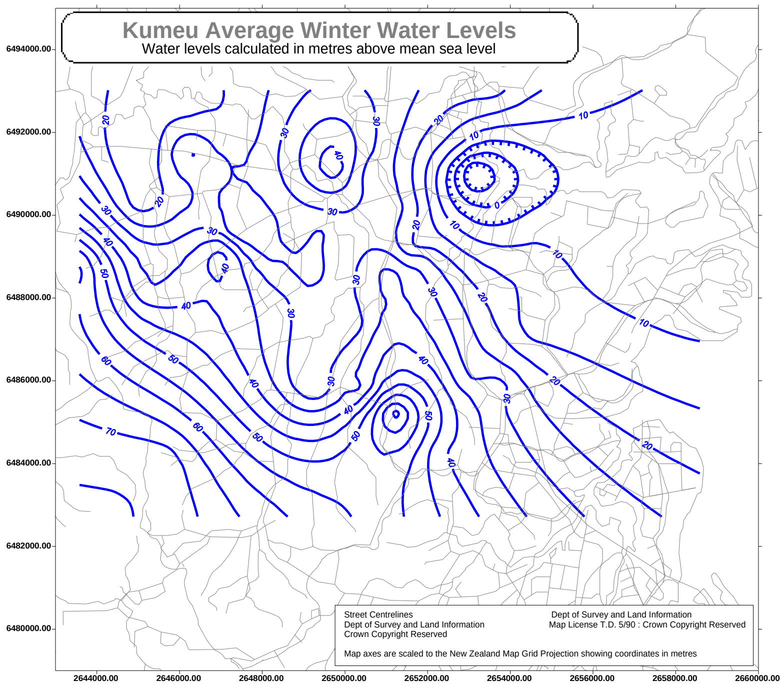

Figure 8: Averaged winter water levels contour plot (Scoble and Millar (1995))

The western end of the southern boundary of the domain was also defined by groundwater levels, topography, and geology; it is the best fit to the ground-water flow direction (assumed to be at right angles the groundwater surface contours) and the topographic ridge. The resulting southern boundary is located within an outcrop of Waitemata Sandstone. The eastern end of the southern boundary is the northern coastline of Lawsons Creek estuary.

The short northern boundary of the model domain is defined at its western end by a small spur coming off the ridge that defines the western boundary, and at its eastern end by a small un-named stream to the north of Riverhead. The eastern boundary is defined by the coastline of the Waitemata Harbour.

The model domain defined by these boundaries encloses NorSGA.

Although the Waitemata Sandstone consists of many alternating layers of fine and coarse material, there is insufficient data to model this complexity. It was decided, as a first approximation, to include only two layers in the model, a top layer approximately 20 m thick representing the alluvium aquifer and a lower layer approximately 445 m thick representing the sandstone aquifer (Fig. 9). It was assumed that both aquifers are unconfined.

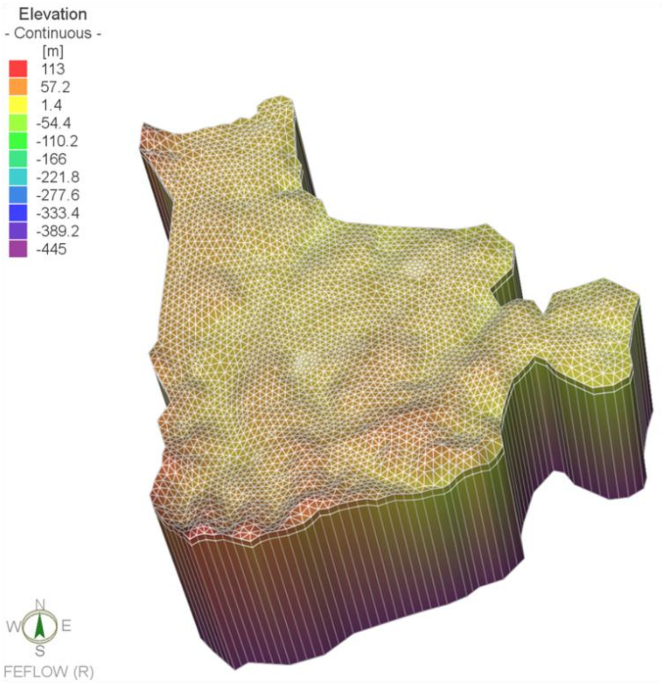

Figure 9: Three dimensional model of the NorSGA

3.2 AVAILABLE DATA

The former Auckland Regional Council (ARC) have records of about 530 bores within the domain of the earlier versions of the ground-water model; i.e., approximately the boundary of the KWHUAMA (pers. comm., R. Samuel, ARC, Dec 2009). Within the model domain there are about 210 bores for which the ARC have records, and bore logs were obtained from the ARC for 109 of these. Most of the stratigraphic information recorded in the bore logs is of poor quality. Strata recorded in the different bore logs, with descriptions such as "sandstone" or "mudstone", could not be correlated along a transect across the model domain (transect not shown). This reflects the difficulty of logging complex formations, such as those in the Waitemata Group, from rotary wash drilling. It also highlights the general poor quality of logging by drillers.

The bore logs do, however, provide two types of useful information:

- estimates of the depth from ground level to the top of the sandstone aquifer (i.e., the thickness of the alluvium aquifer)
- a lower limit to the thickness of the sandstone aquifer (from total depths of bores).

Ground-water levels for model calibration were available from two sources:

- Time-series of ground-water levels
- Contours of mean summer ground-water levels and winter ground-water levels.

Time series of ground-water levels were available from the ARC for ten bores within the KWHUAMA. Groundwater levels are also available as contours of mean summer and mean winter ground-water levels. The contours were derived from measurements made in private bores and ARC monitoring bores during the period 1988 to 1994 (Scoble & Millar, 1995).

Groundwater levels are mainly controlled by topography, but with local depressions in areas of high abstraction rates. There are two groundwater divides, both trending north-east to south-west. One of the divides is in the general vicinity of Huapai and Kumeu, and the other is in the Whenuapai, Hobsonville, West Harbour area. It appears that regional groundwater flow is generally towards the West Coast, the Ngongetepara Stream (western Whenuapai), and the Upper Waitemata Harbour.

A search of the ARC paper-based files revealed several pumping tests for wells within the KWHUAMA, and a summary of most of these tests. From the values in the summary for transmissivity and storativity, the means of the summarized values were calculated, giving an estimate of transmissivity of 2.43 m^2/day and an estimate of storativity of 0.0014.

3.3 MODELLING SOFTWARE

The modelling software FEFLOW 6 (DHI-WASY, 2010a) was chosen for developing the model. FEFLOW 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 is a three-dimensional finite-element software package for modeling subsurface water flow and contaminant transport. It can be used to build one-, 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, 2010b).

FEFLOW was chosen for this research because of the steep slopes in the foothills of the Waitakere Ranges, the large elevational difference across the modeled area, and the complex geology. These factors can result in numerical instability in finite difference models such as Modflow (USGS, 2010), but they are handled more effectively by finite-element software (Brown, 2002).

3.4 MODEL BUILDING

3.4.1 FINITE ELEMENT MESH GENERATION

The model domain forms the outer boundary of the framework (called the "supermesh" in FEFLOW) for generation of the finite element mesh. The model domain was based on the conceptual model and was developed using ArcGIS (ESRI, 2010). The outline was smoothed, particularly around the coastline and around the north-eastern, northern and southern boundaries which follow streams, to eliminate complex fine detail such as acute re-entrant or salient angles which could result in distorted elements (i.e., triangles with large obtuse angles). Distorted elements such as these can cause numerical problems during model runs. The two-dimensional finite element mesh was generated using the Gridbuilder mesh generation algorithm in FEFLOW. The nominal number of elements was specified as 3000, giving an actual number of nodes of 3151. The mesh was adjusted by applying the mesh smoothing tool in FEFLOW to the whole model domain. The mesh smoothing tool adjusts the triangular elements so that they are closer in shape to an isosceles triangle. Mesh smoothing was applied repeatedly, until no further improvements could be observed. The resulting mesh was then applied to each of the three slices in the model (ground surface, surface between the alluvium and sandstone aquifers, and lower surface of the sandstone aquifer), giving a total of 9453 nodes.

The Slice 1 elevations were set as ground surface level, above mean sea level. To estimate Slice 2 elevations (surface between the alluvium and sandstone aquifers), a first-order polynomial (planar), linear-regression trend of values of depth to sandstone was obtained from the bore logs of 55 bores. Values of this trend surface were determined at mesh nodes and the values were subtracted from the previously estimated Slice 1 elevations to give Slice 2 elevations. The levels of all nodes in Slice 3 (lower surface of the sandstone aquifer) were given the value -445 m.

3.4.2 BOUNDARY CONDITIONS

For the current version of the model, boundaries were defined as follows (Fig. 10):

- north-eastern: fixed head, with the nodal values set at the mean of values from average winter and average summer water level contours (Scoble and Millar, 1995);
- eastern boundary (coast line): fixed head, set at a value of 0.0 m above sea level;
- northern, southern and western boundaries: assumed to be no flow boundaries.

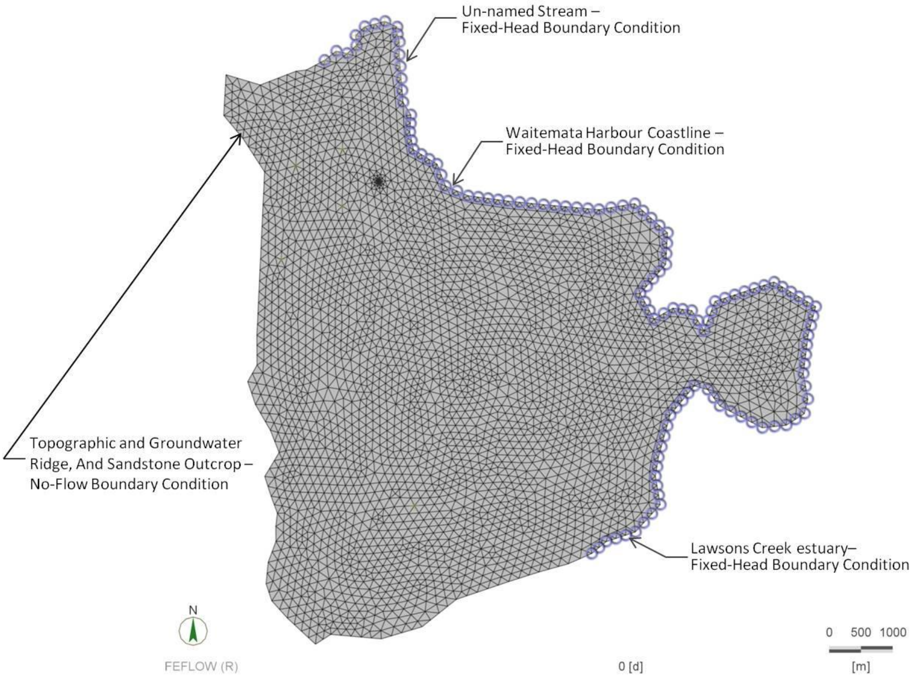

Figure 10: Boundary conditions

3.4.3 RECHARGE ESTIMATION

Steady State Model Method

Initially, the model was calibrated as a steady state model (see Section 3.5.1) and for that purpose recharge was calculated using the following method:

1. A spatially uniform surface recharge was estimated using data in ARC's TP60 (Scoble and Millar, 1995);

2. To allow for extraction of groundwater, the recharge estimated in step 1 was reduced in each of the KWHUAMA management zones (Fig. 3) by the amount of actual ground-water use in that zone (Scoble and Millar, 1995), subtracted as a uniform depth over the zone.

The resulting surface recharge differed between management zones, but was spatially uniform within each zone.

Transient Model

Monthly recharge was estimated for each KWHUMA management zone within the model domain using a spreadsheet-based Thornthwaite-type (Thornthwaite & Mather, 1955) monthly water-balance model developed by Dingman (2002). Monthly values of rainfall, potential evapotranspiration (PET) and streamflow for the period 1998 to 2008 were required for estimation of the monthly recharge values. Rainfall and PET data were obtained from the NZ National Climate Database (CliFlo) (NIWA Science, 2010). Streamflow data were obtained from the Auckland Regional Council. The model was operated in continuous mode for the period January 1998 to December 2008, with the 1998 year used for spin-up. Available water capacity was set at 75 mm for all calculations (Coulter, 1973).

The water balance can be written as (all terms in mm):

$$P = AET + Q + G + dS$$

Where: P is monthly rainfall ; AET is actual monthly evapotranspiration (obtained from the water balance model); Q is monthly water yield; G is monthly deep-aquifer recharge; and dS is the change in soil-water content during a month (obtained from the water balance model)

Monthly deep-aquifer recharge, in the absence of groundwater abstraction, was estimated as:

$$G = P - (AET + Q + dS).$$

To allow for groundwater abstraction, mean values of water use were estimated for each calendar month and for each KWHUAMA management zone within the model domain, using data presented by Scoble and Millar (1995).

The monthly mean usage values were subtracted from the monthly recharge values (as estimated above) to give a time series of net monthly recharge values for years 1998 to 2008 (the monthly mean usage values were repeated for successive years).

3.4.4 PROBLEM SETTINGS

Initially the model was set as a steady state problem, to determine approximate saturated hydraulic conductivity values (K_{sat}) for the Waitemata Sandstone Aquifer. These K_{sat} values were then used as initial values for calibration of the transient model.

The "phreatic surface" option in FEFLOW was chosen for modeling the water table for steady state and transient model runs. For this option, FEFLOW estimates unsaturated hydraulic conductivity by linear interpolation between zero when a layer is completely dry and the specified value of saturated hydraulic conductivity when the layer is saturated. To ensure that the there is a residual conductivity in each model layer, a minimum water content, as a total depth of water in the layer, must be specified. A value of 0.1 m was specified for both layers in the NorSGA model.

3.5 CALIBRATION

3.5.1 STEADY STATE CALIBRATION

Calibration was based on comparison of simulated and observed water levels in five observation bores. The Nash-Sutcliffe efficiency coefficient (Nash & Sutcliffe, 1970) was also calculated for each model run.

The model was accepted as suitable for use when the pattern of simulated and observed groundwater contours had similar shape, when there was the same number of overestimated and underestimated water levels in observation bores (Fig. 11), and when the Nash-Sutcliffe coefficient was a maximum.

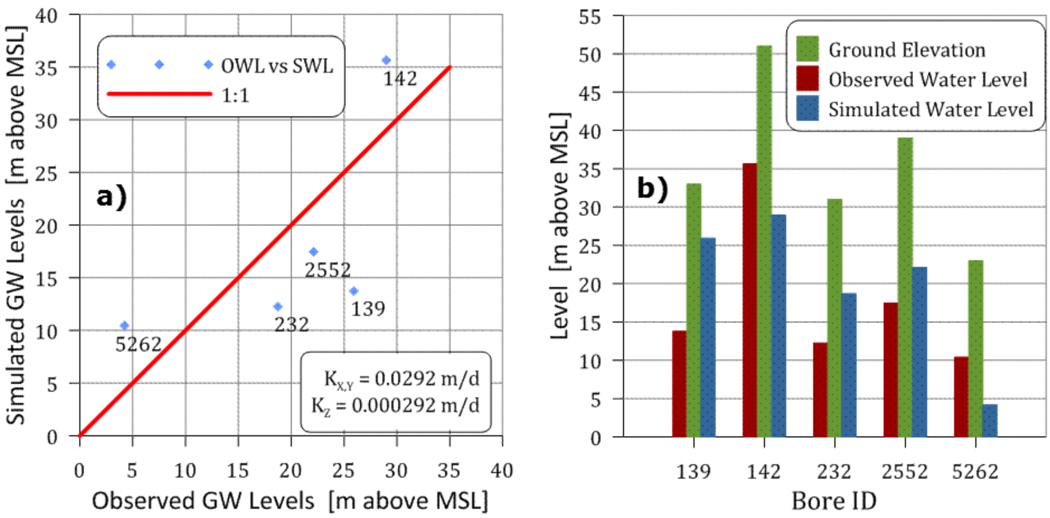

Figure 11: Results for Steady State Model: a) Comparison of simulated and observed groundwater levels b) Comparison including ground elevations

The steady state modelling increased our understanding of the extent of the aquifer beneath NorSGA and aquifer natural dynamics, and provided initial conductivity values.

3.5.2 TRANSIENT CALIBRATION

The transient calibration was based on the same principle as in the steady state calibration. Calibration used the time-series for the period from January 1999 till December 2008 and the period from January 1998 till December 1998 was used for initialization of the system.

Transient calibration provided better results, in that simulated water levels were closer to observed levels (Fig. 14).

Transient calibration was done in order to observe seasonal changes and to calibrate the model when the groundwater table is at its highest elevation, at the end of the winter period.

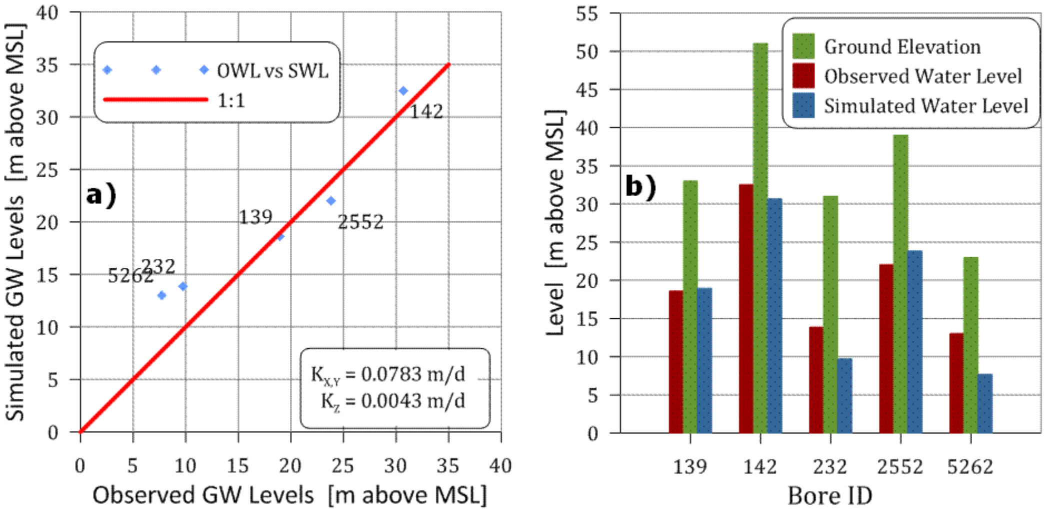

Figure 12: Results for Transient Model: a) Comparison of simulated and observed groundwater levels b) Comparison including ground elevations

4 SCENARIOS OF PROPOSED URBAN DEVELOPMENT

Five scenarios were used for investigation of the changes of the water table. Scenario 1 assumes a decrease of recharge, due to increased runoff caused by urbanization.

In Scenarios 2 and 3, managed artificial recharge of the shallow alluvium aquifer is proposed. In both scenarios, the aquifer is recharged through widely distributed soakage areas within development zones, with uniform surface recharge assumed. This results in indirect recharge of the deep aquifer through the shallow surface aquifer. In Scenario 2 the managed artificial recharge is 20% of the estimated increase in runoff; in Scenario 3 it is 80%.

Scenarios 4 and 5 assume direct recharge with treated stormwater into the deep sandstone aquifer using injection wells on a 1 km grid. In Scenario 4 the managed artificial recharge is 20% of the estimated increase in runoff; in Scenario 5 it is 80%.

In Scenarios 2 to 5, recharge starts in the first year of the development (Fig. 13) (i.e., 2009 for zone 2008+, 2017 for zone 2016+, 2022 for zone 2021+).

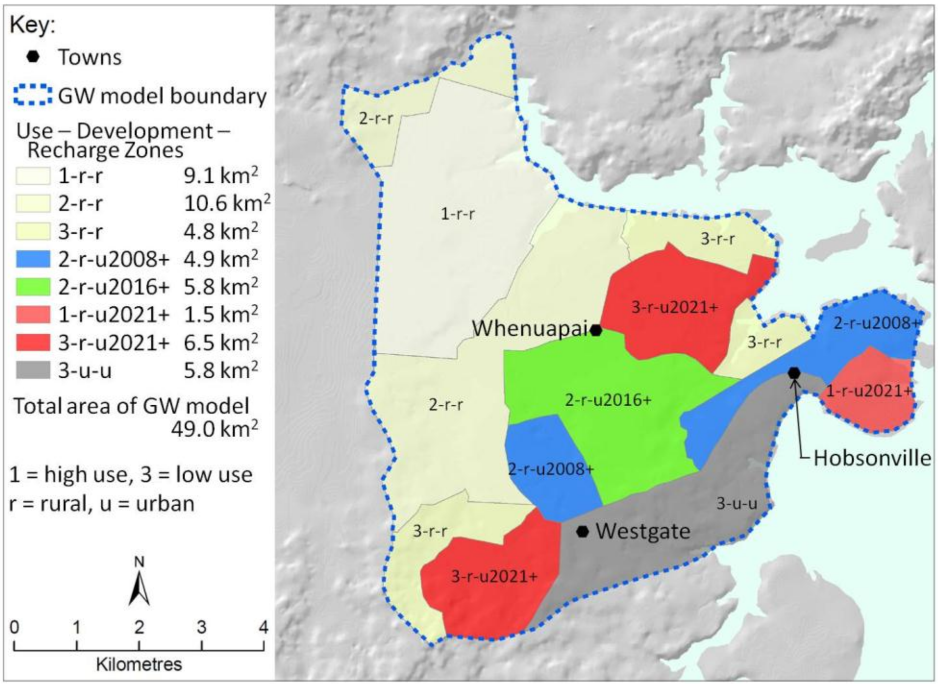

Figure 13: Ground-Water Use – Development – Recharge Zones

5 RESULTS

Results for Scenario 1 are shown in Figure 14. This scenario explores the effects caused by decrease of natural recharge, due to urbanization. The figure shows that decrease of recharge will cause lowering of the groundwater table in zones that are urbanized first (in the coastal area near Hobsonville (see Fig.13)) and which are also high use areas (see Fig. 3).

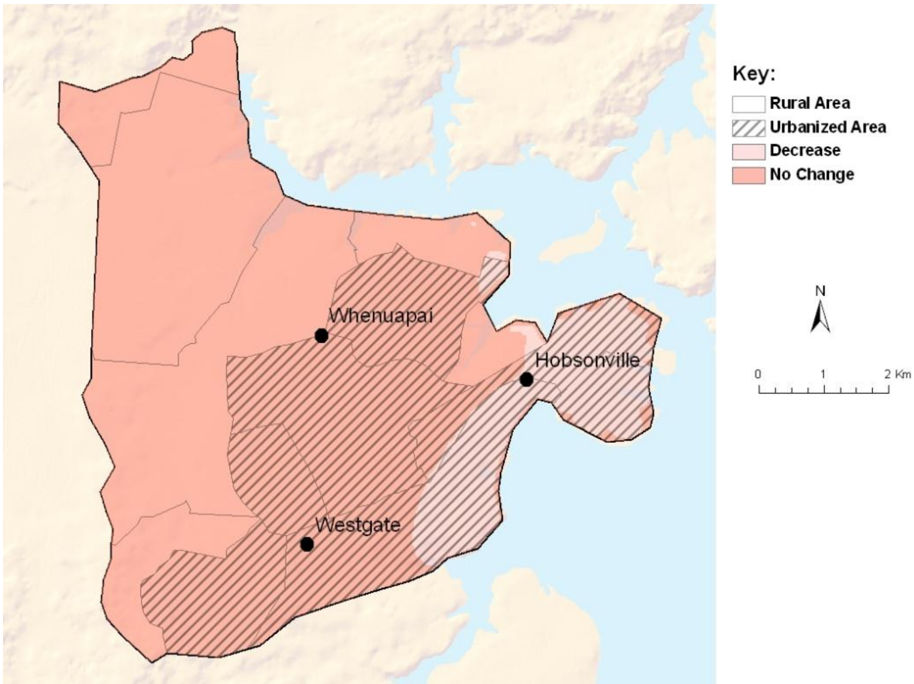

Figure 14: Scenario 1 - Decrease recharge caused by urbanization

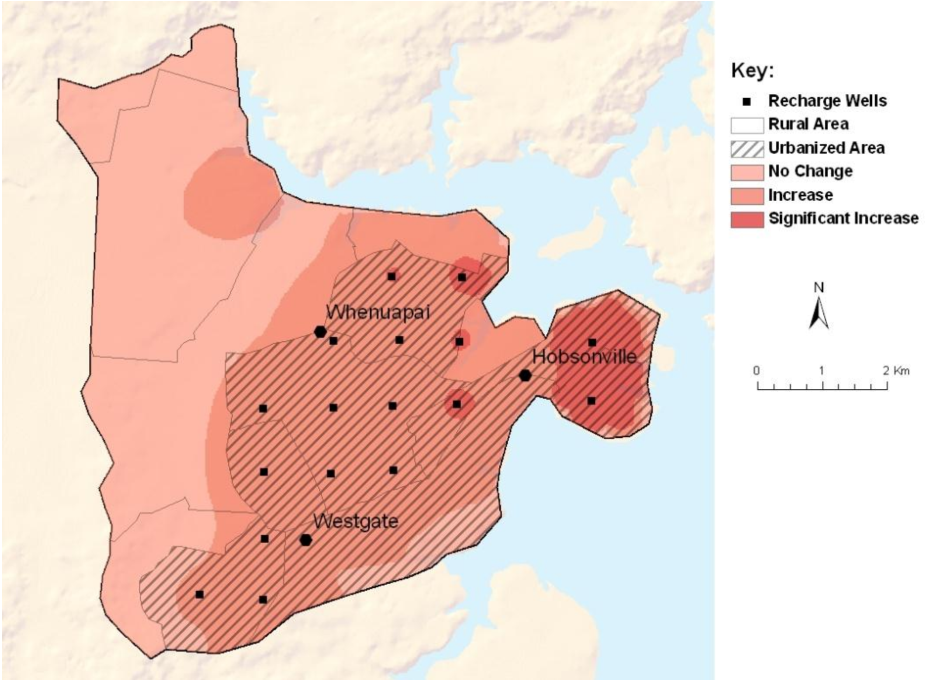

Figure 15: Scenario 2 - Managed artificial recharge to the shallow surface aquifer with 20% runoff

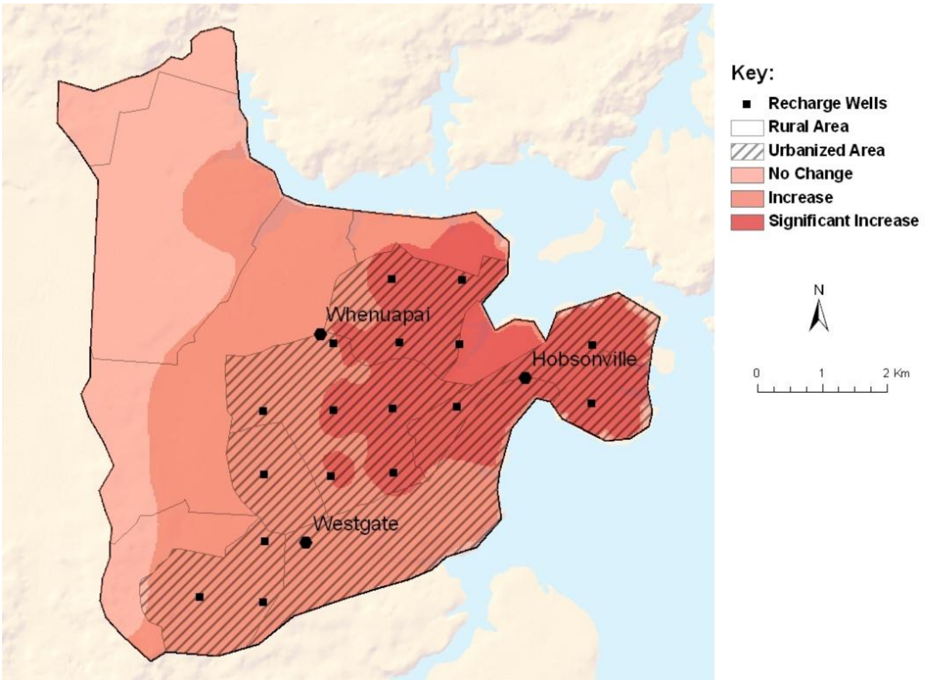

Figure 16: Scenario 3 - Managed artificial recharge to the shallow surface aquifer with 80% runoff

Results for Scenario 2 (Fig. 15) and Scenario 3 (Fig. 16) show that there is a significant raising of groundwater table in zones of artificial recharge, in lower parts of the aquifer (see Fig. 7) towards the coastline. In higher parts of the aquifer towards Waitekere range (see Fig. 7) there was a rise in groundwater, but because the direction of the flow is towards the harbour the effect was moderate.

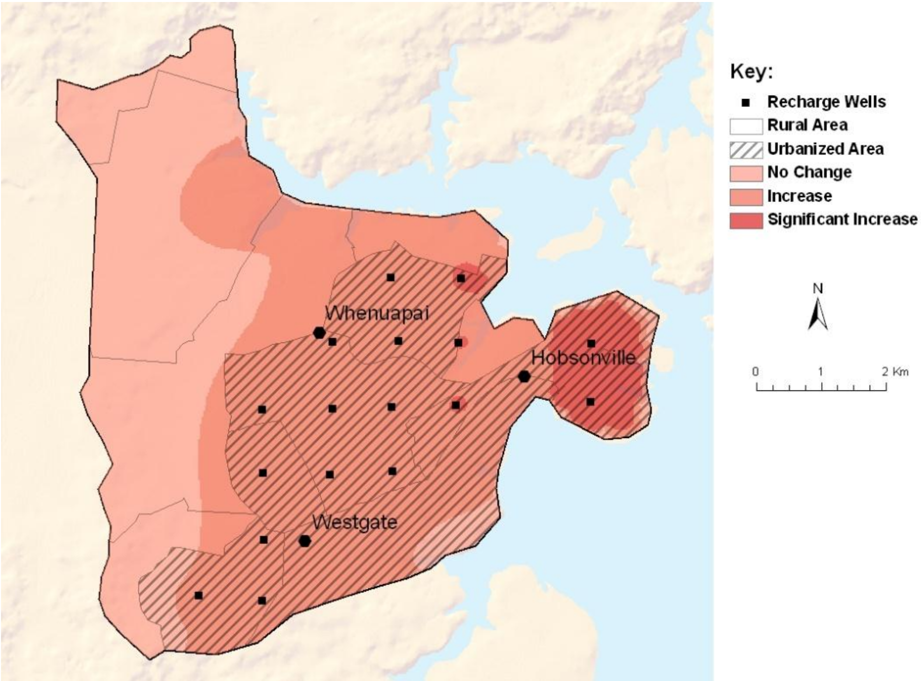

Figure 17: Scenario 4 - Managed artificial recharge to the deep sandstone aquifer with 20% runoff

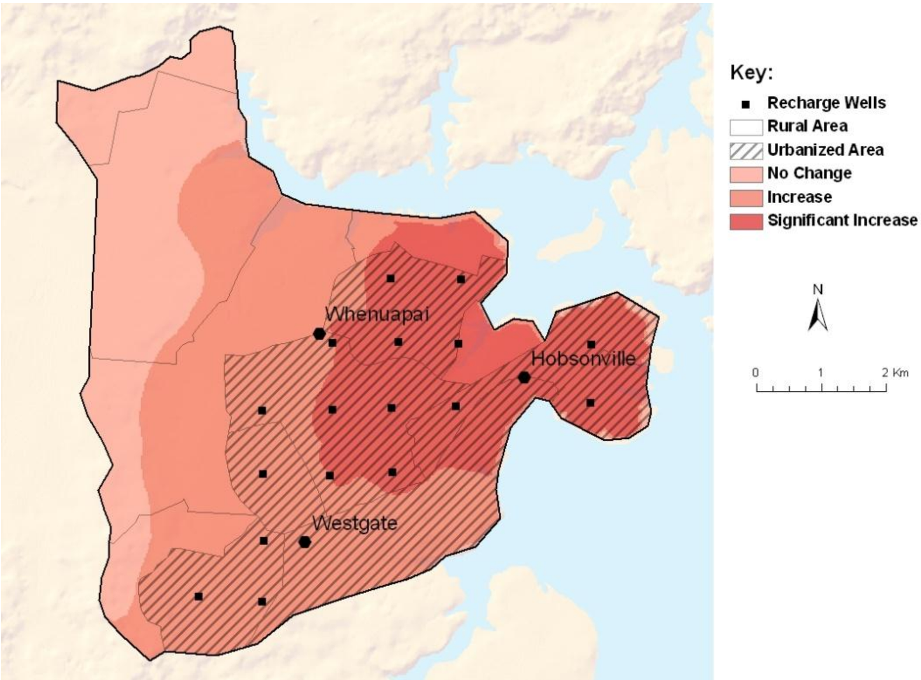

Figure 18 - Scenario 5: Managed artificial recharge to the deep sandstone aquifer with 80% runoff

Scenarios 4 and 5 gave results (Fig. 17 and Fig.18) similar to those for Scenarios 2 and 3 (artificial recharge into the shallow aquifer). The figures show that there is significant raising of the groundwater table in zones of artificial recharge in lower parts of the aquifer towards coastline (see Fig. 7).

Preliminary results obtained in research for this paper also suggest that there is a strong stream-aquifer interaction and that artificial recharge can enhance base-flow in the streams.

6 CONCLUSIONS

From our analysis of the position of the groundwater table, the following conclusions are drawn:

- The increase of urbanized area will cause a lowering of the groundwater table. As this lowering is located in the area near the coastline, saltwater intrusion could occur, resulting in deterioration of the quality of water used for domestic purposes, and stock watering, and agriculture
- Preliminary results suggest that there is strong stream-aquifer interaction and that artificial recharge can considerably enhance stream base-flow and aquifer yield.

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