Groundwater Behaviour in a Fractured Basalt Aquifer under Existing and Future Climate and Land Use in Auckland City (New Zealand)

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Abstract

Existing and expected future groundwater behaviour in a fractured basalt aquifer system is presented for Auckland City (New Zealand), considering current and future climate scenarios (using historic and stochastic rainfall) and impervious surface land use changes. The Auckland Isthmus is comprised of unconfined basalt aquifers and semi-confined Waitemata and Tauranga Groups (sandstone and mudstone) aquifers. The basalt aquifers are used to dispose stormwater via drilled soakholes, serve as groundwater supply in the Onehunga aquifer and disperse industrial and commercial sites across the city, and feed important springs in Western Springs and Onehunga. Regional groundwater models were developed in Visual MODFLOW and MIKE-SHE, covering approximately 45 km^2 with a north-south grid alignment and 100 x 100 m grid cells. Vertically the models are divided into a single basalt aquifer hydrogeological unit. Three scenarios were investigated with combinations of rainfall and land use: (1) existing conditions (current climate and existing land use), (2) future wet year (most probable 2050 climate and maximum possible 2050 land use), and (3) future dry year (most probable 2050 climate and maximum probable 2050 land use). Model results indicate that the aquifer has spare capacity to accommodate recharge under all scenarios examined. Base flows in principal streams and springs will not be compromised unless many dry years occur in succession. A major issue to resolve will be to find practical ways of capturing and injecting large volumes of stormwater generated over short, high intensity storms.

Keywords: aquifers, groundwater, basalt, climate change, land use change, Auckland City (New Zealand)

Introduction

The Auckland Region is situated on the North Island of New Zealand, with mainland Auckland City occupying 15,300 hectares on an isthmus between the Waitemata and Manukau Harbours (Figure 1). Nearly 40% of the city is served by soakage, including thousands of drilled soakholes providing public and private stormwater discharge to underlying aquifers.

Expected existing and future groundwater behaviour in a fractured basalt aquifer system is presented for Auckland City (New Zealand), considering existing and future climate scenarios (using historic and stochastic rainfall) and impervious surface land use changes. This work was undertaken as part of a larger Integrated Catchment Study in Auckland City whose focus is to provide information to decision-makers to enable identification of a works programme to improve drainage service and mitigate adverse environmental effects produced by drainage discharges. Of particular interest in the groundwater study is the investigation of the capacity of aquifers to receive additional stormwater discharge without compromising existing and future groundwater and aquifer uses.

Auckland City Groundwater Aquifers

Volcanism in the Auckland area produced basaltic tuff rings, scoria cones and lava flows. Erosion of the Waitemata and Tauranga Group rocks (sandstone and mudstone) by streams and sea level changes prior to the eruption of the Auckland volcanics contributed to the current

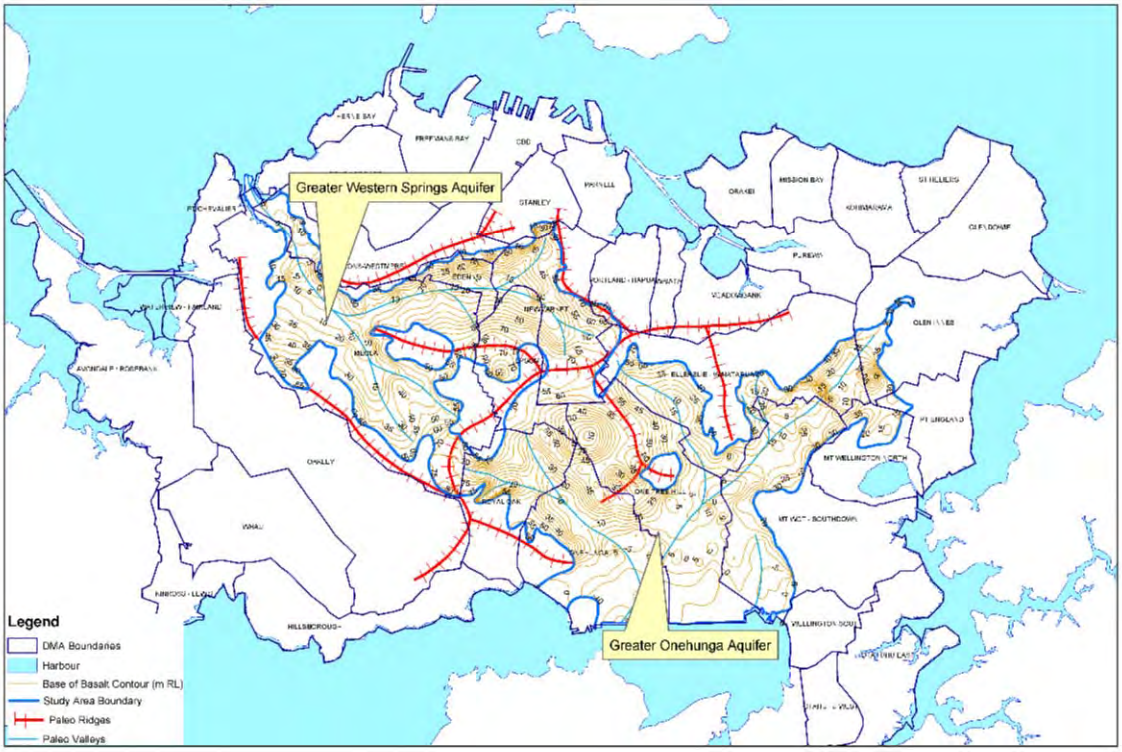


Figure 1. Auckland Isthmus Volcanic Aquifers

landform. These original ridges and valleys affect surface and groundwater drainage to the present day. Subsequently, volcanic materials covered areas of low-lying Waitemata and Tauranga Group rocks, infilling valleys and blocking stream channels. The result is that the Auckland Isthmus is comprised of unconfined basalt aquifers and semi-confined Waitemata and Tauranga Groups aquifers. Groundwater movement mainly occurs in the shallow basalt aquifers due to their higher hydraulic conductivity. The main route for groundwater flow, from recharge areas to discharge zones in the basalt aquifers, is along the paleovalleys in the Waitemata Group through which lava originally flowed. The lava fields on the Auckland Isthmus are divided into seven principal aquifers based on the main volcanoes of origin, grouped into the two main divisions: the Greater Onehunger aquifer that discharges to the Manukau Harbour and the Greater Western Springs that discharges to the Waitemata Harbour (Figure 1). Additional small pocket aquifers exist outside of the two greater aquifer systems. They are not used extensively and were not studied.

Aquifer recharge occurs via open spaces, soakholes and quarries. The aquifers are used to dispose stormwater via thousands of drilled soakholes. Groundwater supply is extracted from the Onehunga aquifer, supplementing the main water distribution network whose supply originates primarily from surface water sources. Other private, industrial and commercial extractions exist across the city. Approximately 4.6 million cubic metres per year are abstracted from the Greater Onehunga aquifer, while annual extraction from Greater Western Springs is approximately 176,000 cubic metres. Important spring areas include Western Springs, located in a large reserve that serves as a community recreation area, and two smaller springs of ecological importance located amongst commercial-industrial areas in Onehunga.

New Zealand and Auckland Region Climate

New Zealand’s location at 34 to 47°S in the Southwest Pacific means that it lies largely within the prevailing westerlies of the mid-latitude Southern Hemisphere. The travelling anticyclones, depressions, and fronts within this flow predominantly govern the progression of weather. However, weather systems that originate from within the tropics can also have an influence (Sturman and Tapper 1996). Thus, New Zealand precipitation varies with fluctuations in both the prevailing westerlies and the strength of the subtropical high-pressure belt (Salinger *et al.* 2001).

The Auckland climate is warm temperate. Being surrounded by ocean, land temperatures are largely controlled by sea surface temperatures. The average annual temperature varies between about 15 and 16°C in the city, with a range of about 9°C between winter and summer. Average annual rainfall totals in the Auckland City area are reasonably uniform and range from just under 1200 mm to about 1400 mm (Salinger *et al.* 2001).

Auckland’s heaviest rainfall occurs with warm moist north to northeasterly wind flow over the city when there is a ‘low’ (depression) to the north or northwest of northern New Zealand, and a slow-moving anticyclone to the east. These flows are typically responsible for about 60 percent of the annual rainfall total. In contrast, southwesterly flow produces showery weather, especially in winter. Stormy westerlies also produce rainfall. When these are strong they may be accompanied by thunderstorms, and sometimes tornadoes (Salinger *et al*. 2001).

Shorter duration rainfalls in Auckland City are often very local because of small-scale weather systems such as a wind convergence. These can also occur in northeast airflows, with embedded thunderstorms. In the Whenuapai area 148 mm of rain fell in a 3.5 hour period, with falls a few kilometres away much lighter, with no rain recorded 8 km away. The localisation of extreme rainfalls in Auckland City is a result of the interaction of small-scale meteorological phenomena with Auckland's orography. Sometimes very localised falls occur mid-afternoon in summer when sea breezes from the main east and west coasts sweep inland and converge over Auckland City (Salinger *et al.* 2001).

In producing future scenarios of Auckland City rainfall for 2050, there are two factors that are considered: the Interdecadal Pacific Oscillation (IPO) phase changes and the influence of global warming. The IPO causes abrupt "shifts" in Pacific weather circulation that persist for several decades, and also affect New Zealand climate. About 1950 following one shift temperatures rose in New Zealand by an average of 0.5°C with the prevailing westerly and southwesterly winds weakening, and with more northeasterlies over northern New Zealand. Another shift in 1977 caused a strengthening of westerlies over New Zealand. Both these produced changes in annual rainfall totals and temperatures over northern New Zealand. The southwesterly phase of the IPO is known as the positive phase, and the northeasterly phase the negative phase of the IPO. It appears likely that the IPO switched into the negative phase around 2000, and before 2050 two further phase changes of the IPO may occur. However, there is no way of predicting which phase might be present in 2050, and to limit the number of scenarios considered, this study does not explicitly take account of the IPO influence on Auckland rainfall (Salinger *et al*. 2001).

Mullan *et al.* (2001a) analysed results from six global climate model (GCM) simulations. Implications for future New Zealand temperature and precipitation were assessed by "downscaling" the GCM grid-point changes (at a scale of several degrees latitude spacing) to the local scale relevant to New Zealand sites. The GCMs predict an increase in temperatures in New Zealand, although at a somewhat slower rate than the global average, and also an increase in the strength of Southern Hemisphere westerly winds. In the Australasian region, precipitation generally decreases in the subtropics just north of New Zealand, and increases in higher latitudes, with New Zealand near the "cross-over" latitude (Salinger *et al*. 2001).

When these model projections are downscaled to the local New Zealand scale (taking account of the influence of orography), the increasing westerlies means that precipitation tends to increase in the west of the country and decrease in the east (Salinger *et al.* 2001). Thermodynamic considerations indicate that for temperatures typical of New Zealand conditions, the water-holding capacity of air increases by 5% for every degree Centigrade. Given a most probable climate scenario of a 1ºC increase, for the current study a 5% increase in mean rainfall in Auckland City was assumed (Mullan and Salinger 2002).

Stochastic Rainfall Model

Due to the need to model at fine time scale and lack of historic, spatial data for surface drainage modelling, as well as the desire to model projected future climate scenarios, a stochastic rainfall model was developed for Auckland City (Cowpertwait 2002). Stochastic rainfall was generated with a spatial-temporal Neyman-Scott Rectangular Pulse (NSRP) model at hourly intervals and subsequently disaggregated into 5-minute time steps (Cowpertwait 2002). The NSRP model represents application to Auckland City of a model developed originally for the United Kingdom and subsequently used in Sweden and Italy (Cowpertwait 1995, 1998; Cowpertwait *et al.* 1996, 2002; Threlfall *et al.* 1999).

100-years of probable current climate rainfall and 100-years of most probable 2050 rainfall were stochastically generated at 12 spatial locations in the city corresponding to permanent rain gauge sites (Cowpertwait 2002). 2050 rainfall was produced by modification of calibrated parameters in the Auckland City NSRP model to reflect a reduction of 5% (per 100 years) of wet days and rescaling of rainfall on the remaining wet days to provide a total 5% increase of total annual rainfall (Cowpertwait 2002; Mullan and Salinger 2002). From the 100-years of most probable 2050rainfall, a single wet year and a single dry year were selected to investigate extremes values.

The stochastic rainfall time series were aggregated into monthly totals for use in groundwater simulations. Accuracy of aggregation of hourly data into larger time blocks was investigated previously (Cowpertwait 2003).

Regional Groundwater Model

One regional groundwater model of the two main (greater) aquifer systems was developed in Visual MODFLOW (Waterloo 2003) and MIKE-SHE (DHI 2004). The models assume that the fractured basalt aquifer can be simulated with an equivalent porous medium approach. The hydrogeologcal investigations carried out by Namjou (1997) in the Mt Wellington region showed that joints and fractures in lave flows are sufficiently uniform and randomly distributed that groundwater system within the basalt can be modelled as a porous medium at a scale of 10’s to 100’s of meters.

Visual MODFLOW was used for the initial steady state calibration due to its advanced steady state solver capabilities for heterogeneous media, while MIKE-SHE was used for transient simulations. MIKE-SHE is one of the few groundwater models available which can handle the transformation between wet and dry cells without destabilizing the model.

System Geometry The model domain is approximately 45km^2 with a north-south grid alignment (Figure 2). The aquifer is subdivided into 130 rows (E-W) and 175 columns (N-S) to create rectangular elements (or grid cells) of 100 x 100 m. The aquifer was simulated with a single layer representing the basaltic aquifer. The grid orientation is parallel to the dominant groundwater flow direction. The models consist of 5164 computational points in the basalt aquifer (including boundary cells). The upper surface of the model was defined from half metre contour survey data. The bottom of the aquifer is defined from interpretation from over 820 borehole logs.

Groundwater Levels and Recharge Groundwater levels from approximately 60 existing and new piezometers from 1998 to 2003 were used to provide steady state and transient groundwater levels for model calibration. The data varied from monthly levels recorded manually to levels recorded every 15 minutes using transducers. All the data was normalised to provide monthly levels. The recharge fraction rates adopted were based on the land use dependant values developed by Pattle Delamore Partners (PDP 1991), applied to the regional model (Figure 3).

Hydraulic Properties The aquifer hydraulic properties used in the model are based on existing pumping test data and data gathered from the investigation phase of the study (PDP 2004). A total of 32 pump test data points are used for the model calibration. The hydraulic conductivity values vary from 2 x 10^{-1} m/s to 5 x 10^{-5} m/s depending on fracture density, with a geometric

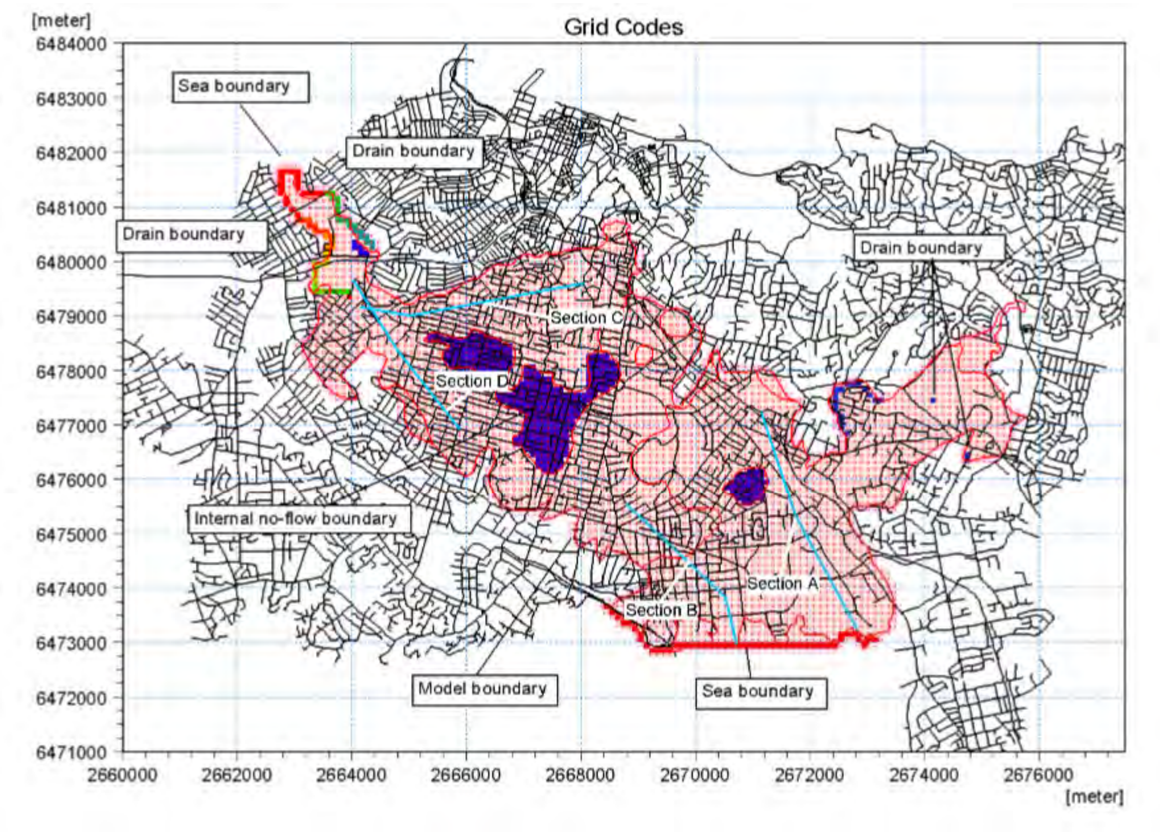
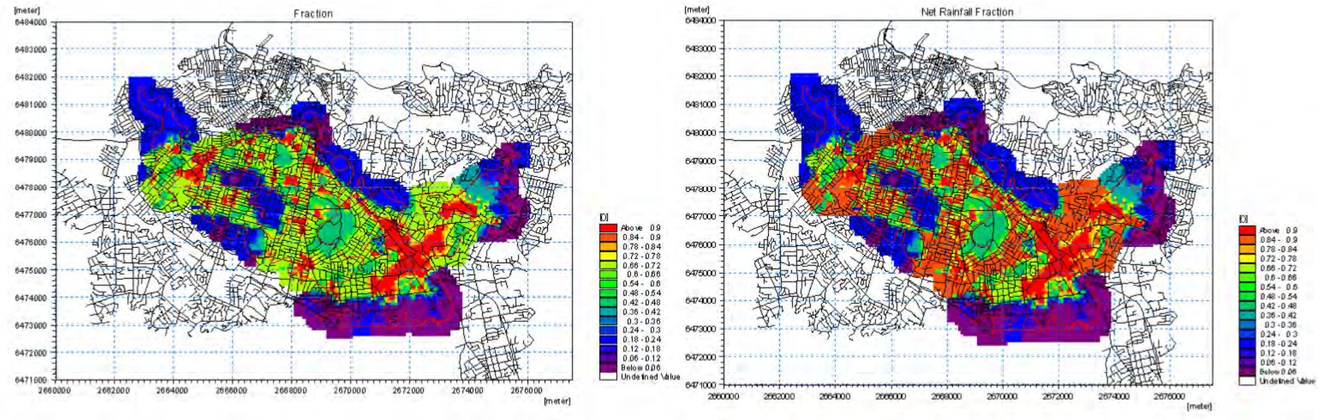


Figure 2. Regional Model Domain



(a)

(b)

Figure 3. Recharge Fraction for (a) Existing Land Use and (b) Future (Maximum Probable) Land Use

mean of 9 x 10^{-4} m/s. Vertical and horizontal hydraulic conductivities are assumed to be equal. The storage coefficient (specific yield) in basalt is variable and can range between 0.01 and 0.3 (Davis and De Wiest 1966). The storage values between 0.03 and 0.2 were obtained from pumping test data.

Model Calibration and Validation The Visual MODFLOW model was calibrated for steady state using long term average piezometric heads from monitored boreholes, the long term average baseflow of Meola and Motion Streams (from the edge of the Greater Western Spring aquifer) and the Mt Wellington Quarry dewatering pumping rate located in Greater Onehunga aquifer.

Initial hydraulic conductivity values were allocated to aquifer zones based on pumping test data. During calibration the zone coverage were altered to provide a match of field and model results. The zone boundaries were changed based on geological interpretation. The first estimate of recharge was based on land use dependant values. This produced the best match between measured and calculated groundwater discharge from the aquifer. Therefore no changes in the initial recharge estimates were necessary. Groundwater discharge rates were available for Meola and Motion Creeks (baseflow measurements) and Mt Wellington quarry dewatering pump rates.

A Normalised Root Mean Squared (NRMS = Root Mean Squared / (maximum observation head-minimum observation head)) and mass discrepancy errors were used to check the goodness of fit for steady state conditions using Visual MODFLOW (Table 1). The calibration results for average groundwater discharge from Greater Western Spring Aquifer and the Mt Wellington-quarry dewatering are given in Table 2.

The transient calibration was undertaken using MIKE-SHE. Initial hydraulic heads were derived from the steady state simulation. The storage coefficients were adjusted until the modelled groundwater fluctuation from 1998 to 2003 mimicked the measured levels with minor discrepancies in the groundwater levels during peaks and troughs. Variations in groundwater levels were between 0 to 1 metres. The large rain event of 2 February 2004 was also used to calibrate the model. In addition, short interval data from four boreholes equipped with automatic recorders were used for calibration of short-term rainfall events. The calibrated storage coefficient of 0.08 provides the best match, however, lower storage values (0.01 to 0.03) had to be applied in a few local zones.

Modelled groundwater discharge to streams at the edge of the basalt (Meola and Motion Creeks) was compared against the measured stream baseflow. The close correlation between the modelled and measured groundwater discharge (baseflow) indicates that the recharge rates applied to the model are satisfactory (Figure 4).

Model Sensitivity and Validation Sensitivity analyses were undertaken to determine the range of uncertainty in the calibrated model. Parameters subject to sensitivity analyses were: (a)

Table 1. Model Water Balance

Model input (m3/d)	Model output (m^3/d)	NRMS (%)	Model mass balance discrepancy (%)
73483.52	73426.83	5.6	0.08

Table 2. Groundwater Flow Calibration Results

Groundwater Discharge Zones	Calibrated Model (m3/d)	Measured (m3/d)
Meola and Motions Creeks	28,000	26,000*
Mt Wellington Dewatering	2,100	2,200-2400**

Notes:

* Based on the ARC stream flow monitoring stations. Note that these stations are located 1km from the harbour edge and therefore do not capture all groundwater throughflow.

** Based on groundwater discharge measurements (PDP 1991 and Namjou 1997).

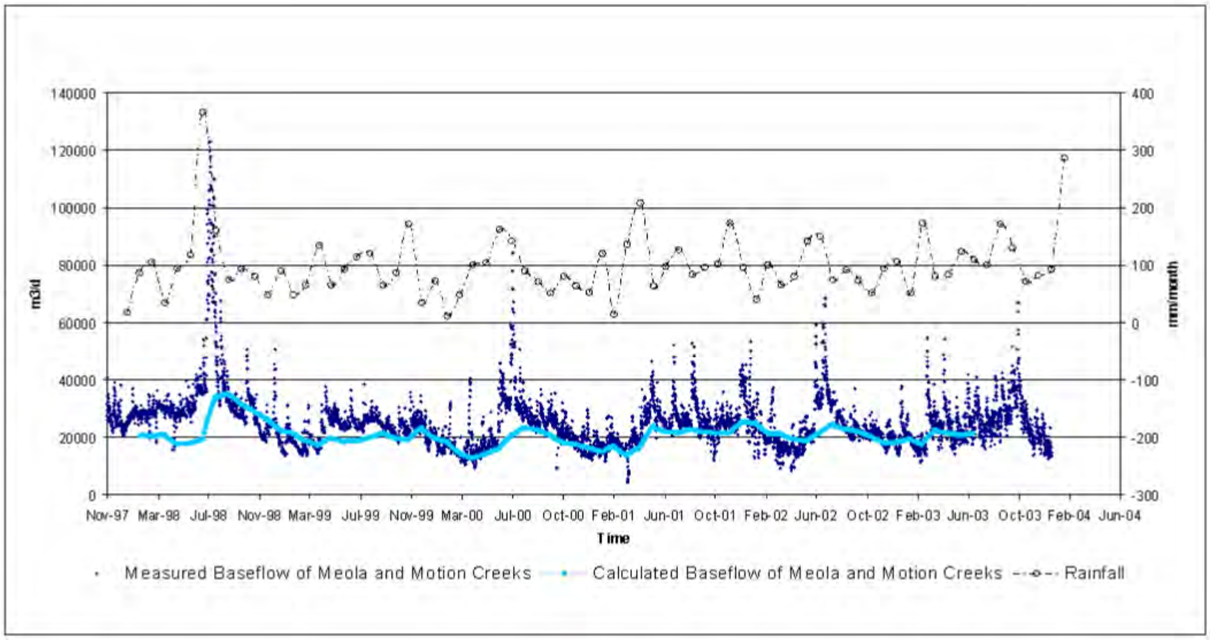


Figure 4. Comparison of Monitored and Modelled Groundwater Discharge (Baseflow)

hydraulic conductivity (b) land use infiltration rates and (c) storage. The results of the sensitivity analyses indicate that the model is sensitive to lower hydraulic conductivity and higher recharge rates. The values used during the calibration of the steady state model are well within the plausible range and can be supported by available data. The model was also validated using 1997 rainfall data.

Groundwater Simulations

Effects of various climatic conditions and land use on groundwater infiltration and groundwater levels were assessed using MIKE-SHE transient simulations. Simulated groundwater levels along four long sections of the aquifer were studied (Figure 2).

The following three scenarios were assessed: (1) existing conditions, (2) future wet year (2050 climate scenario) with maximum possible recharge (recharge fraction=1) and (3) future dry year (2050 climate scenario) with maximum probable land use recharge.

(1) Existing conditions For this scenario six-years of recent rainfall record (1998-2003, with average rainfall of 1179mm) and existing recharge distribution based on current land use were investigated to assess aquifer performance under existing climate and land use conditions (Figures 3a and 5a).

(2) Future wet year (2050) with maximum possible recharge (recharge fraction=1) In this scenario the entire recharge coefficient for all landuse types was set to unity, that is all rainfall falling within the aquifer boundaries enters the aquifer. This is an extreme scenario reflecting maximum possible groundwater inflow for a future wet year (2050) with rainfall of 1546mm.

(3) Future dry year (2050) with maximum probable land use recharge Permitted changes to land use are identified in the city's District Plans (Metrowater 2004). Land use changes result in impervious surface increases due to continued growth, consisting of targeted strategic growth areas and an increase in infilled housing (Metrowater 2004). Increased impermeable area require additional stormwater disposal measures, including potentially increased stormwater disposal to aquifers. Taking the above criteria into account, a new recharge distribution based on future land use (maximum probable) was estimated in conjunction with dry 2050 rainfall year of 746mm (Figure 3b and 5b), providing an estimation of low groundwater levels for future dry conditions. The groundwater level profiles predicted by Scenario 2 and 3 indicate the range of expected maximum groundwater levels under most probable 2050 climate and future land use scenarios.

Simulation Results

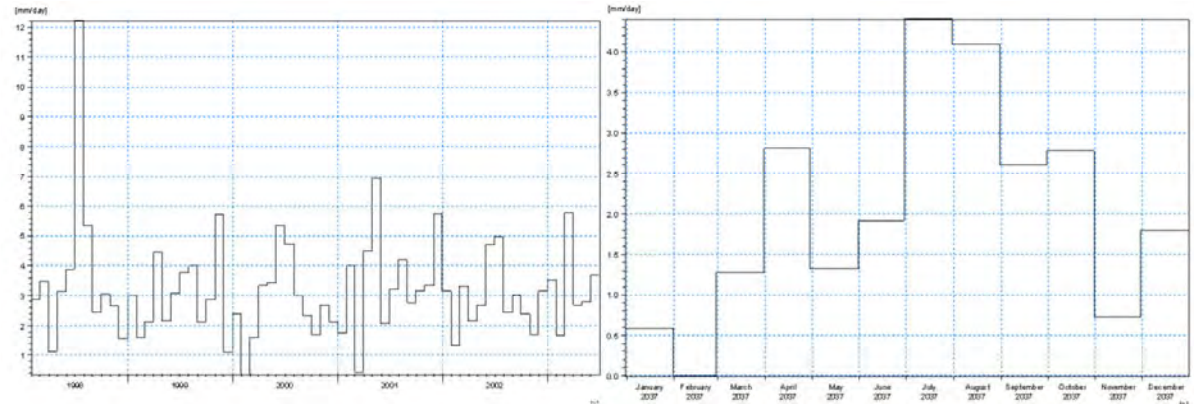
The results of the three scenarios investigated are provided in Table 3 and Figure 6 and are discussed below.

Groundwater Infiltration and Surface Discharge Groundwater infiltration rates for the above scenarios are shown in Table 3. The results indicate that in a future wet year (2050) with maximum possible recharge, groundwater infiltration into the basalt aquifer increases by more than 100%. In such extreme conditions, groundwater discharge to Meola and Motion creeks increases by 85%. In the dry future year and maximum probable development scenario, groundwater discharge to Meola and Motions creeks decreases by 25%.

Groundwater Levels Groundwater level profiles along four sections (Figure 2, Sections A-D) for each major lava flow valley system and for each scenario are shown in Figure 6. Results indicate that maximum groundwater fluctuation occurs in upper catchment areas away from discharge zones as the coastal areas have a dampening effect on groundwater fluctuation.

Table 3. Groundwater Recharge and Discharge

Scenarios	**Groundwater recharge (m^3/d)**	**Groundwater discharge to Meola and Motion Creeks (m^3/d)**
Current climate (1998-2003) with existing land use recharge	73,000	28,300
Future wet year (2050 climate) with maximum possible recharge (recharge fraction=1)	160,000	52,300
Future dry year (2050 climate) with maximum probable development land use recharge	49,000	21,700



(a) (b)

Figure 5. (a) Current Climate and (b) Future Climate (2050) Dry Year

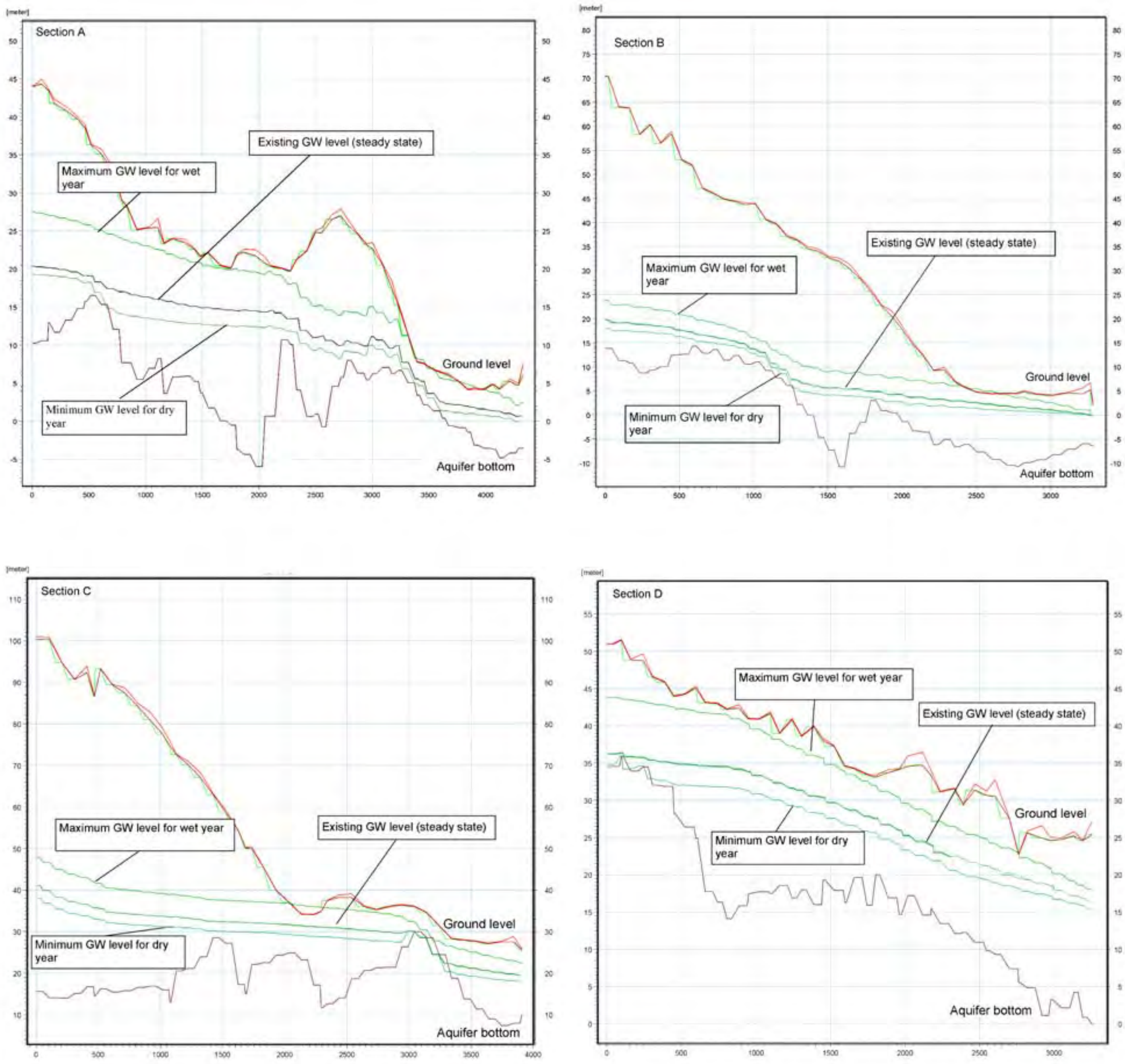


Figure 6. Groundwater Level Profiles (Sections A, B, C and D) for Three Scenarios

The future wet year scenario (2050) with maximum possible recharge (recharge fraction=1) causes less than a 2m groundwater level rise in lower catchment areas (shallow groundwater zones) compared with maximum existing groundwater levels.

Groundwater flooding in this scenario, representing an extreme case where all rainfall infiltrates to the aquifers (i.e, no land use management and complete stormwater disposal via groundwater), increases the spatial extent of the groundwater induced flood hazard by about 10 times in low-lying topographic areas in Onehunga (e.g., Section A). However, this extent represents less than 1% of the entire basalt aquifer areas and a small fraction of surface water induced flood hazard in the city (Metrowater 2004).

The result shows that even under future wet conditions with maximum possible recharge, a large volume of unsaturated basalt is still available in mid to upper catchments for higher infiltration, e.g., stormwater disposal via soakholes.

Discussion and Conclusion

From the scenarios modelled it is clear that there is additional capacity in both the Greater Western Springs and Onehunga aquifers to accept greater recharge in upper catchments under future rainfall and likely changes to land use. Even under extreme recharge conditions, areas of groundwater breakout are limited.

Potential flood hazards produced by elevated groundwater levels are already identified by Auckland City as flood prone areas. Such local flood prone zones with shallow groundwater potentially can be mitigated with implementation of upgraded stormwater drainage systems (e.g., drainage trench to harbours or groundwater pumping wells), some areas of which have already have been identified as requiring stormwater system upgrades.

The future landuse increases the groundwater volume by allowing a greater recharge rate to the aquifer via soakage. Thus existing water supply uses should not be compromised unless many dry years occur in succession. Similarly, base flows in principal streams and springs should not be adversely effected unless many dry years occur in succession.

In summary, the aquifer has spare capacity to accommodate the existing and potential future recharge from rainfall events well into the future and can accommodate the potential changes to land use on the Auckland Isthmus. However a major issue to resolve will be to find practical ways of capturing and injecting large volume of stormwater generated over short, high intensity storms.

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