The Integrated Catchment Study of Auckland City (New Zealand): Long Term Groundwater Behaviour and Assessment

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Abstract

Long term groundwater behaviour under existing and future scenarios in a fractured basalt aquifer system is presented for Auckland City (New Zealand). 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 soakholes, provide groundwater supply in Onehunga and other industrial and commercial sites, constitute baseflow in Motions and Meola Creeks, 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. The models were calibrated to five years of historical records. Two long term scenarios were simulated: (1) existing conditions (20-year simulation with current climate and existing development land use) and (2) future conditions (15-year most probable 2050 climate and maximum probable development 2050 land use). Spare capacity exists in the aquifers to accommodate additional stormwater disposal. Additional groundwater breakout (surface flooding) is predicted in expected areas during high rainfall years. Stream and spring

flows, and groundwater supply are not anticipated to be adversely affected by groundwater management recharge practices. A major unresolved issue is to find practical ways to capture and inject large volumes of stormwater generated by short, high intensity storms.

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

Introduction

Long term groundwater behaviour in a fractured basalt aquifer system was investigated as part of the Integrated Catchment Study (ICS) for Auckland City (New Zealand). Additional aspects of the ICS are provided in companion papers in these conference proceedings: overview (Sharman *et al.* 2006), computation of contaminant loads (Davis *et al.* 2006) and fate of contaminants in coastal receiving environments (Bogle *et al.* 2006).

Auckland City lies on a 14,500 hectare isthmus between the Waitemata and Manukau Harbours (Figure 1). It is home to 400,000 residents within Greater Auckland of 1.2 million residents. Greater Auckland includes Auckland City, Manukau City, North Shore City and Waitakere City. Greater Auckland is the largest metropolitan area and population centre in New Zealand and location of much commercial and industrial activity.

The NZ$23.5 million ICS was a computer modelling focused planning study to assist Auckland City Council (Auckland City) and Metro Water Limited (Metrowater) to develop robust solutions to address:

- Habitable floor flooding and stormwater disposal that can produce economic loss and public health issues;
- Wet weather combined and wastewater overflows that can create short-term public health issues;
- Stormwater quality that can produce long-term environmental health issues;
- Provision for growth, which can exacerbate drainage issues.

Nearly 40% of the city is served by soakage, including thousands of drilled soakholes providing public and private stormwater discharge to the underlying basalt aquifers. Expected existing and future groundwater behaviour in the basalt aquifers are presented, considering existing and future climate scenarios and impervious surface land use changes. Of particular interest was investigation of aquifer capacity and ability 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 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

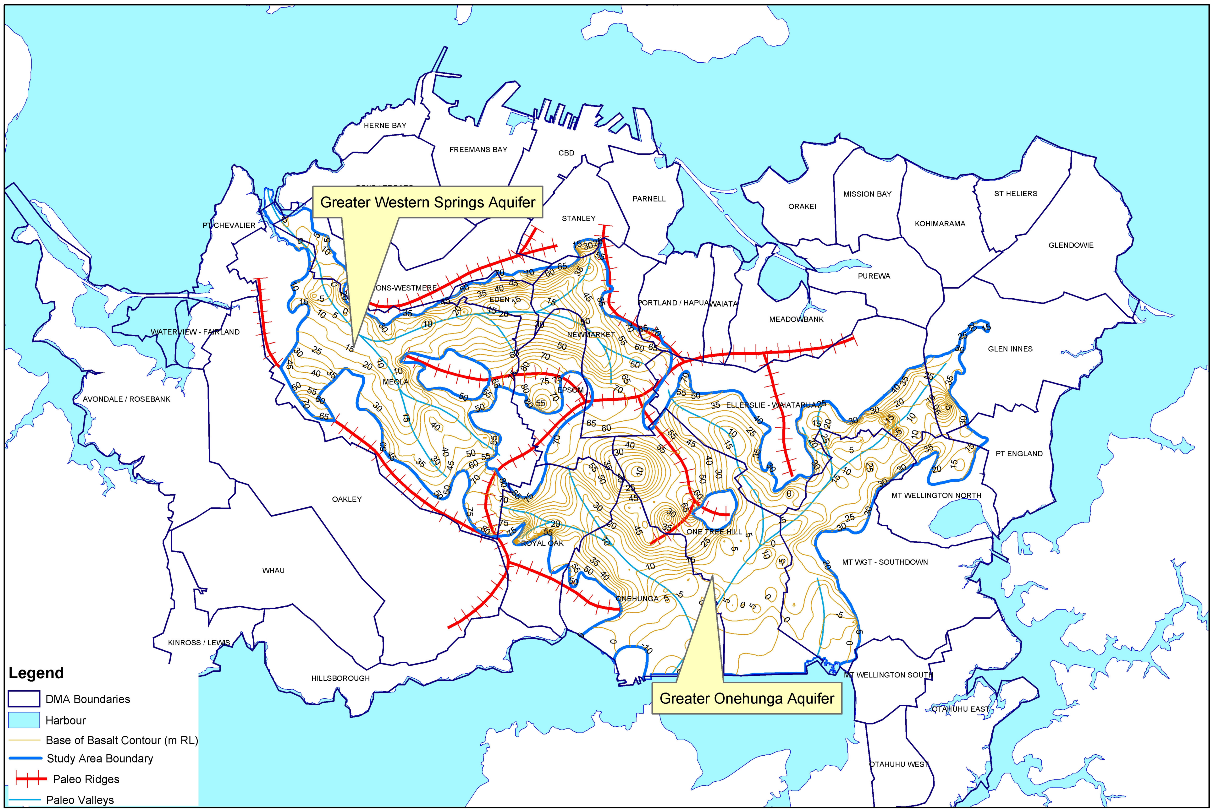
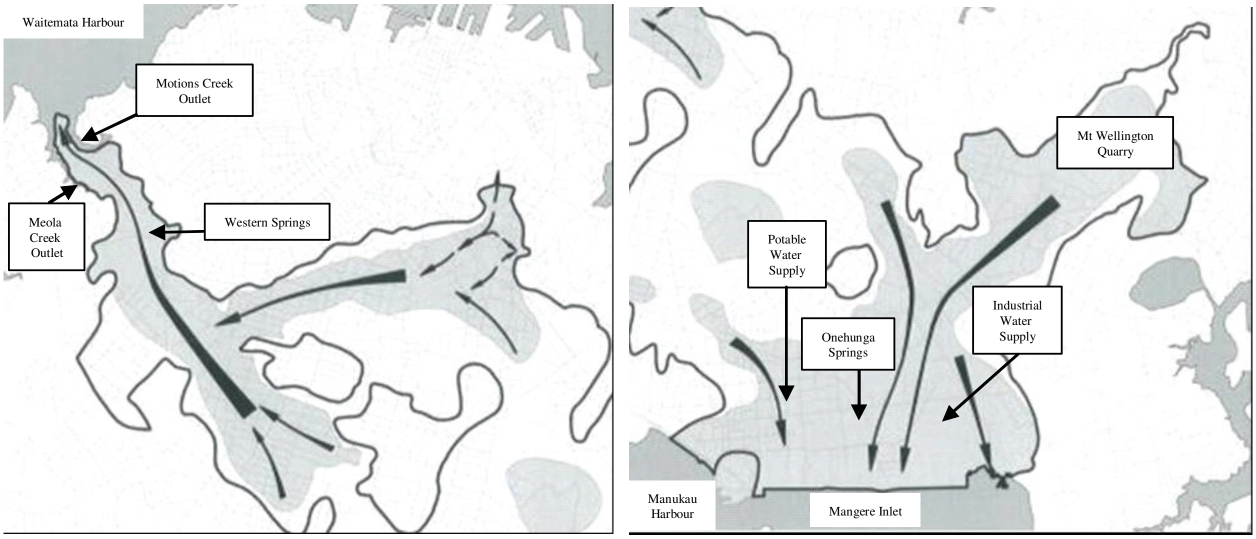


Figure 1. Auckland Isthmus Volcanic Aquifers

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 aquifer that discharges to the Waitemata Harbour (Figure 1).

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 fromthe 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. Further groundwater is dewatered from the Mt Wellington Quarry, located on the border of the Glen Innes and Ellerslie-Waiatarua Drainage Management Areas (Figure 2).

Natural discharge occurs along downstream reaches of Meola and Motions Creeks from the Greater Western Springs aquifer. Discharge also occurs along the Mangere Inlet waterfront from the Greater Onehunga aquifer. In addition, important spring areas include Western Springs, located in a large reserve that serves as a community recreation area, and two small springs of



(a) Greater Western Springs Aquifer (b) Greater Onehunga Aquifer

Figure 2. Flowpaths and Principal Discharge and Extraction Points

of ecological importance located in close proximity to one another amongst commercial-industrial areas in Onehunga (Figure 2).

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 & 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).

In producing future scenarios of Auckland City rainfall for 2050, two factors were 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. For long term simulations, rainfall does not explicitly take account of the IPO influence on Auckland rainfall (Salinger *et al*. 2001). Positive and negative IPO influences on surface flooding during extreme rainfall events were studied separately (Dayananda et al. 2004).

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 & 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 for use in urban drainage (pipe network and surface system) (Cowpertwait 2002). The NSRP model represents application to Auckland City of a model originally developed 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 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 modifying Auckland City NSRP model parameters to reflect a reduction of 5% of wet days (per 100 years) and rescaling of rainfall on the remaining wet days to provide a total 5% increase of total annual rainfall (Cowpertwait 2002; Mullan & Salinger 2002).

The stochastic model is described further and selected surface modelling results are presented in Cowpertwait *et al.* (2004) and Lockie *et al.* (2003). The stochastic rainfall time series were aggregated into monthly totals for use in groundwater simulations. Previously, aggregation of stochastically generated hourly rainfall was investigated and not found to differ significantly from model and gauge rainfall statistics (Cowpertwait 2003).

Regional Groundwater Model

A regional groundwater model of the two main (greater) aquifer systems was developed in Visual MODFLOW (Waterloo 2003) and MIKE-SHE (DHI 2004). It was assumed that the fractured basalt aquifers can be simulated with an equivalent porous medium approach. Hydrogeological investigations carried out in the Mt Wellington area showed that joints and fractures in lava 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 (Namjou 1997).

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, as described below (PDP 2005b). MIKE-SHE is one of the few groundwater models available that can handle the transformation between wet and dry cells without model destabilization (DHI 2004).

System Geometry The model domain is approximately $45km^2$ with a north-south grid alignment. The aquifer is subdivided into 130 rows (E-W) and 175 columns (N-S) to create square grid cells of 100 x 100 m. The aquifer was simulated with a single layer representing the basalt 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 of over 820 borehole logs (PDP 2004, 2005b).

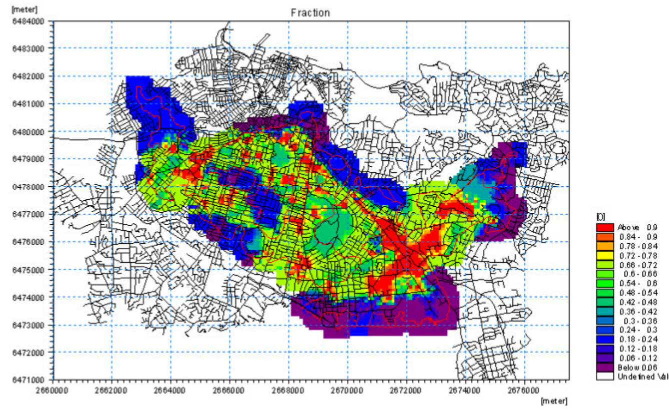
Groundwater Recharge Groundwater recharge occurs through open areas, soakholes and quarries. At the regional scale (generally 100 x 100 m grids), recharge is simulated through recharge fraction rates (PDP 2005b). The recharge fraction rates adopted were based on the land use dependant values developed by Pattle Delamore Partners (PDP 1991) (Figure 3).

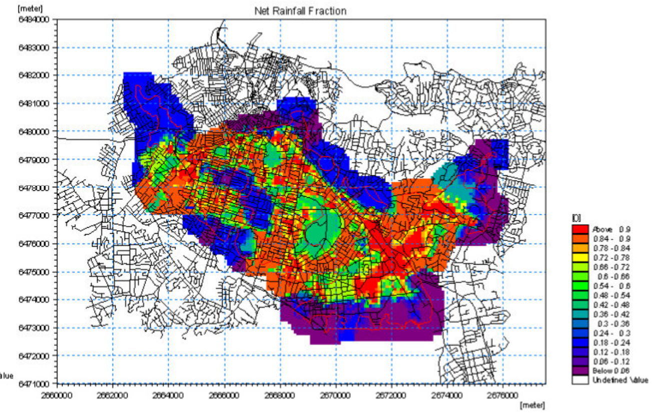
Groundwater Levels Groundwater levels from approximately 60 existing and new piezometers from 1998 to 2003 were used to provide steady state and transient groundwater levels for model calibration. The data varied from monthly levels recorded manually to levels recorded every 15 minutes using transducers. All data was normalised to provide monthly levels (PDP 2004, 2005b).

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 this study (PDP 2004). A total of 32 pump test data points were used for model calibration. The hydraulic conductivity values vary from 2×10^{-1} m/s to 5×10^{-5} m/s, depending on fracture density, with a geometric mean of 9×10^{-4} m/s (PDP 2005b). Vertical and horizontal hydraulic conductivities were assumed to be equal (PDP 2005b). The storage coefficient (specific yield) in basalt is variable and can range between 0.01 and 0.3 (Davis & De Wiest 1966). The storage values between 0.03 and 0.2 were obtained from pump tests (PDP 2004).

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 Creeks (from the edge of the Greater Western Spring aquifer) and the Mt Wellington Quarry dewatering pumping rate located in Greater Onehunga aquifer (PDP 2005b).

Initial hydraulic conductivity values were allocated to aquifer zones based on pumping test data. During calibration the zone coverage was altered to provide a match of field and model results. The zone boundaries were changed based on geological interpretation. Initial recharge rates were based on land use dependant values.





(a) Existing (b) Future

Figure 3. Recharge Fraction for (a) Existing Land Use and (b) Future (Maximum Probable) Land Use (PDP 2005b)

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 level fluctuation from 1998 to 2003 mimicked monthly measured levels with minor discrepancies during peaks and troughs. Variations in groundwater levels were ± 1 metre. Refinement of shorter term groundwater response was undertaken through calibration of the large rain event of 2 February 2004 and short interval data from four boreholes equipped with automatic recorders. A storage coefficient of 0.08 provided the best match. However, lower storage values (0.01 to 0.03) were applied in a few local zones (PDP 2005b). Modelled groundwater discharge to streams at the edge of the basalt (Meola and Motion Creeks) was compared against the measured stream baseflow (Figure 4).

Table 1. Model Water Balance

Model input (m^3/d)	Model output (m^3/d)	NRMS (%)	Model mass balance discrepancy (%)
73484	73427	5.6	0.08

Source: PDP 2005b.

Table 2. Groundwater Flow Calibration Results

Groundwater Discharge Zones	Calibrated Model (m^3/d)	Measured (m^3/d)
Meola and Motions Creeks	28,000	26,000 [a]
Mt Wellington Dewatering	2,100	2,200-2400 [b]

Source: PDP 2005b.

Notes:

a Based on the ARC stream flow monitoring stations.

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

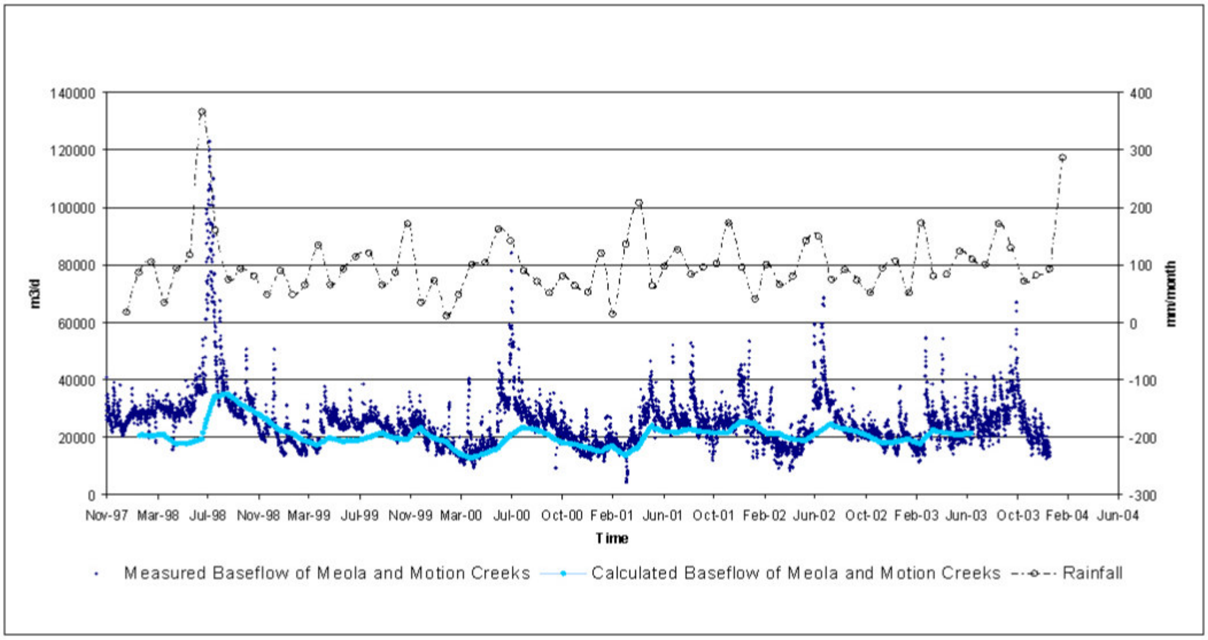


Figure 4. Comparison of Monitored and Modelled Groundwater Discharge (Baseflow) (PDP 2005b)

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) 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 (PDP 2005b).

Groundwater Simulations Scenarios

Groundwater behaviour effects of climatic conditions and land use were assessed using MIKE-SHE transient simulations. Two long term scenarios and were simulated: (1) existing conditions (2005) and (2) future conditions (2050).

(1) Existing conditions (2005):

- Current climate (20-years of monthly stochastic rainfall (Cowpertwait 2002));
- Existing land-use and imperviousness (2002 aerial survey (City Design 2003)).

(2) Future conditions (2050):

- Most probable future climate (15-years of monthly stochastic rainfall (Cowpertwait 2002));
- Most probable land use and imperviousness (maximum probable development allowed in the District Plan (Auckland City 2005)) (PDP 2005a).

Simulation Results

Long-term water balances for dry, average, and wet years are presented in Table 4. Groundwater migrations velocities are presented in Table 5. Groundwater level results from the long-term simulations at twelve points are shown in Figures 5 - 7.

Table 4. Groundwater Mass Balance

Scenario & Rainfall Year Type [1]	**Annual Rainfall (mm)**	**Annual Recharge (m^3)**	**Annual Discharge (m^3)**
Existing (2005) – Dry	1,003	23,636,305	23,636,305
Existing (2005) – Average	1,300	29,651,505	29,651,505
Existing (2005) – Wet	1,665	37,923,500	37,923,500
Future (2050) – Dry	1,038	25,696,000	25,696,000
Future (2050) – Average	1,340	32,667,500	32,667,500
Future (2050) – Wet	1,556	38,398,000	38,398,000

Source: Based on PDP (2005a).

Note: [1] Year types are divided in three (30% of rainfall years are classified as dry, 40% average and 30% wet). They reflect the years within the simulation period and represent a typical dry, average and wet year rather than the statistically driest, average or wettest year within the stochastic rainfall time series.

Table 5. Groundwater Migration Velocities

Main aquifer	**Sub-aquifer (DMA)**	**Predominant Land-use**	**Groundwater Velocity (m/day)**
Greater Onehunga	Royal Oak (Royal Oak)	Residential	14.3
Greater Onehunga	Penrose (Onehunga / One Tree Hill)	Industrial/Commercial	17.6
Greater Onehunga	Mt Wellington (Glen Innes / Ellerslie / Mt Wellington North / Pt England)	Industrial/Commercial	8.2
Greater Onehunga	Southdown (Mt Wellington Southdown)	Industrial	0.8
Greater Western Springs	Mt Eden (Mt Eden)	Residential/Commercial	20.9
Greater Western Springs	Three Kings (upper Meola)	Residential/Commercial	7.0

Source: PDP (2005a).

Discussion

Future impervious land use results in increased stormwater runoff than currently exists. In soakage areas, the increased volume is directed to the aquifers (e.g., 2005 wet year versus 2050 wet year in Table 5).

Additional capacity exists in both the Greater Western Springs and Onehunga aquifers to accept increased stormwater disposal in upper catchment areas. Even under an extreme future, wet rainfall year, groundwater breakout (surface flooding) areas are limited.

Expected flood hazards produced by elevated groundwater levels are already identified by Auckland City as flood prone areas. The local flood prone zones with shallow groundwater potentially can be mitigated through implementation of upgraded stormwater drainage systems

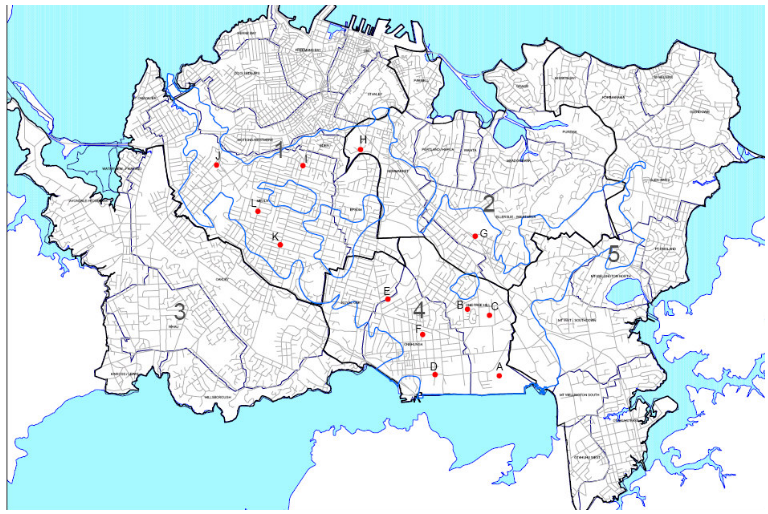


Figure 5. Groundwater Level Monitoring Points

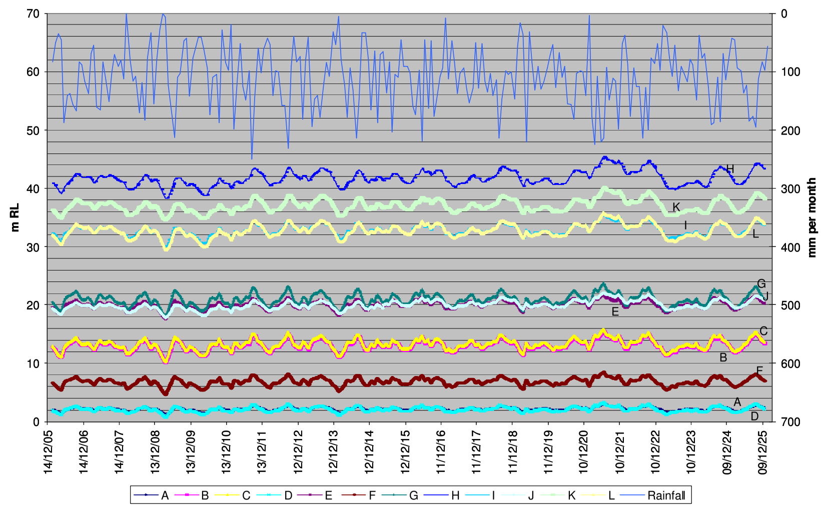


Figure 6. Modelled Groundwater Level - Existing Scenario

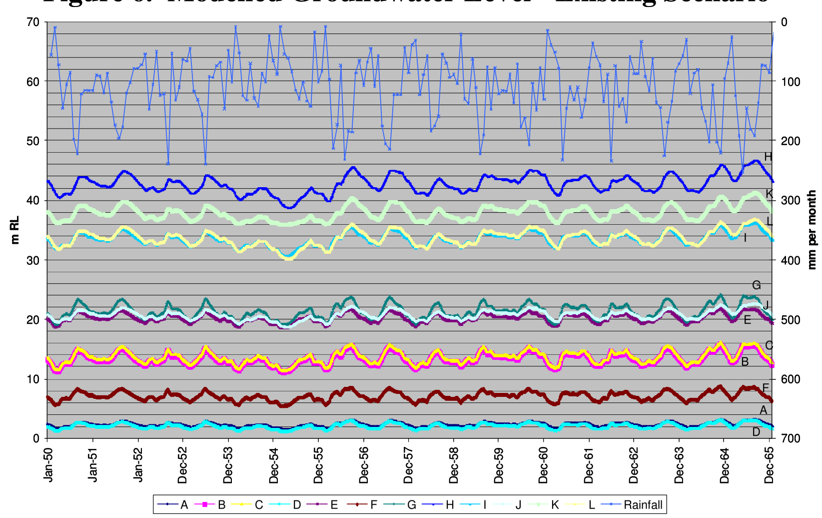


Figure 7. Modelled Groundwater Level - Future Scenario

(e.g. drainage trench to harbours or groundwater pumping wells), some areas of which have already have been identified as requiring stormwater system upgrades.

Under all scenarios, aquifer groundwater volume and levels remain relatively similar. Thus, existing water supply uses may only be trespassed upon temporarily if many dry years occur in succession, which is very uncommon in Auckland. Similarly, base flows in principal streams and springs should not be temporarily affected 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 expected land use on the Auckland Isthmus. However a major issue to resolve will be to find practical ways of capturing and injecting large volumes of stormwater generated by short, high intensity storms into the aquifers.

Conclusion

The groundwater aquifers play an important role in disposing stormwater in Auckland City. In the Greater Onehunga aquifer groundwater provides potable and industrial water. The aquifers feed springs in Western Springs and two springs in Onehunga, providing community and environmental amenities.

To assess existing and long term effects on the aquifer and groundwater uses, regional groundwater models were developed in Visual MODFLOW and MIKE-SHE. A stochastic rainfall model was developed to support surface and network modelling assessments that required finer resolution rainfall (5-minute) and the ability to assess future climate. This fine resolution rainfall data was aggregated into monthly rainfall for simulation in the groundwater models. Field investigation was undertaken to enable improved assessment of aquifer characteristics and to provide calibration and validation data. The models were calibrated to steady state and five years of historical data.

Subsequently, two long term scenarios were assessed: (a) existing (2005) and (b) future (2050). The long term simulations have enable Auckland City and Metrowater to better understand long term groundwater behaviour. Important findings include that the aquifers and other groundwater uses have not and are not expected to be affected adversely by existing land use and climatic factors. Moreover, the aquifer has capacity to accept up to twice as much stormwater disposal, which would result in limited groundwater breakout (surface flooding) that could be managed through engineered drainage works.

Acknowledgements

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