SUSTAINABILITY ASSESSMENT FOR STORMWATER SOAKAGE IN AUCKLAND

Gerald Strayton[1], Parviz Namjou[1], Alan Pattle[1] Peter Kinley[2], Matthew D. Davis[2] and Greg Paterson[3]
[1] Pattle Delamore Partners, Auckland, [2] Metro Water Limited, Auckland City, [3] Auckland City Council – Utility Planning

ABSTRACT

The basalt lava flows of the Auckland volcanics have been used from the earliest time for stormwater disposal. Approximately 40% of the Auckland Isthmus is covered by basalt. This rock has proven to contain good natural soakage characteristics due to plentiful cracks and fissures which transport soakage water from elevated areas of the isthmus to springs, wetlands or under sea discharge zones in the Waitemata and Manukau harbours. Over the years this natural feature has become a major part of the stormwater disposal system on the Auckland Isthmus. An understanding of the underground receiving environment is important requirement for ongoing management of the stormwater soakage system as decisions on its future development could impact users of the groundwater resource such as water supply utilities and natural conservation areas.

This paper reviews the work undertaken as part of Auckland City Council and Metro Water's Global Aquifer Study, discusses the results of the fieldwork and modelling that was undertaken, and presents conclusions on the results. This paper addresses issues relating to the potential capacity of the aquifer to accommodate soakage disposal, methods of finding soakage and injecting the stormwater into the aquifer, treatment of stormwater prior to discharge, the sustainability of the resource, the continued abstraction of the groundwater and other issues relating to the preservation of springs and creeks.

It is the aim of this paper is to present the findings of the work done to date and to provide an assessment on the sustainability of the use of soakage on the Auckland Isthmus. It is also the intention of the paper to provide information for discussions regarding the future of soakage and how the basalt aquifer can be used in a sustainable manner.

KEYWORDS

groundwater, soakage, basalt, aquifer, sustainability, Auckland City (New Zealand)

1 INTRODUCTION

The Global Aquifer Study (GAS) was undertaken as part of the Integrated Catchment Study (ICS) undertaken by Auckland City Council and Metro Water Limited. The main aim of the ICS study was to develop a comprehensive understanding of the Auckland City Isthmus drainage system and receiving environments. In the same way the aim of the GAS project was to develop an understanding of the soakage fields and the sustainability of this form of stormwater disposal.

Auckland City is located on the North Island of New Zealand with the isthmus section of the city occupying 15,300 hectares between the Manukau and Waitemata Harbours. Over 40% of the isthmus is covered by basalt lava from a number of volcanoes over the last 150,000 years.

Specific requirements and objectives of the GAS project comprise the following:

- Identify potential sources of contaminants into the aquifer for assessment of their transport through the aquifer and their potential impact on the environment.
- Evaluate the long-term, sustainable and optimal disposal of stormwater via soakage and identify new areas of soakage.
- Provide means for evaluating groundwater flow through regional and local models.
- Model the optimal and prioritised remedial works
- Support the resource consent process as required.

This paper focuses on the work undertaken as part of GAS project and in particular the sustainability of soakage and the groundwater resource. Issues addressed relate to the potential capacity of the aquifer to accommodate soakage disposal, methods of finding soakage and getting the stormwater into the aquifer, treatment of stormwater prior to discharge, the sustainability of the resource, the continued abstraction of the groundwater and other issues relating to the preservation of springs and creeks

2 FIELD INVESTIGATION

2.1 DRILLING INVESTIGATION

The results of the field investigation have added considerably to the body of knowledge on the Auckland basalt aquifers. The findings have changed previous conceptual models and have improved the understanding of the extent, shape and flow paths of the main aquifers. Significant new findings include a more precise location of the main Waitemata ridge that divides the two main aquifers, definition of the areas of basalt under tuff, an improvement in the definition of all the paleovalleys and in particular the definition of the groundwater flow paths from Newmarket which flows down the Mt Eden paleovalley. Key areas that have been re-conceptualised are:

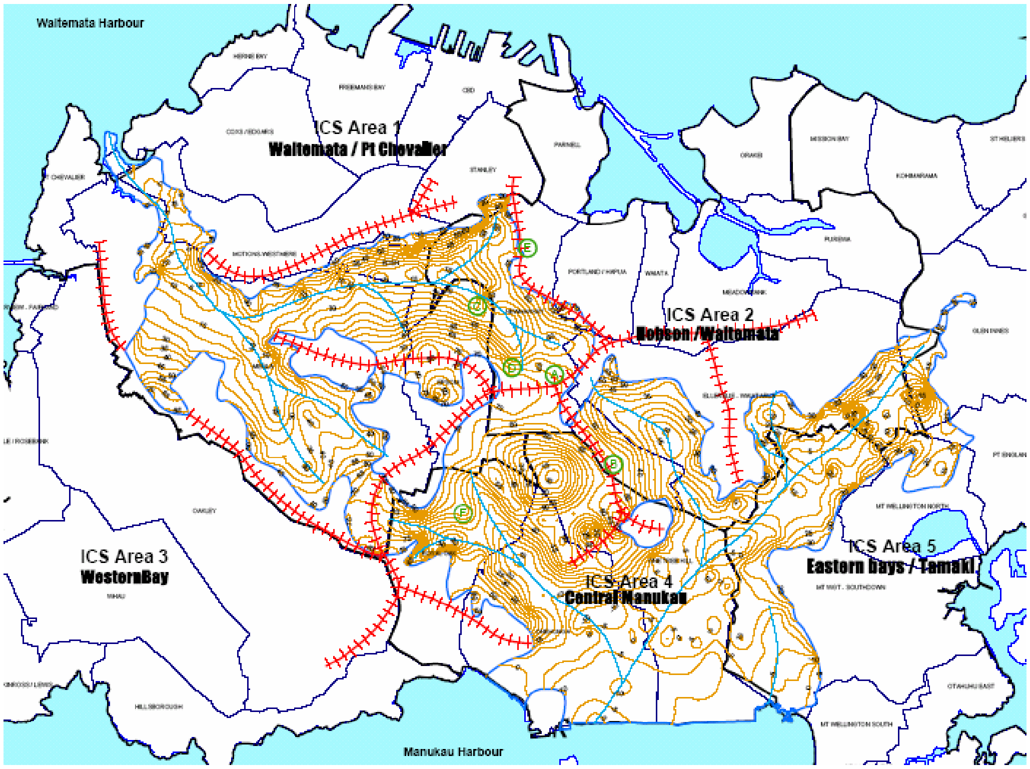
- The area to the north and north east of Mt Eden
- The area around One Tree Hill

The improvement in the definition and delineation of the Waitemata dividing ridge has enhanced the understanding of the direction of the lava flows from Mt St John, Mt Hobson and One Tree Hill. Initial concepts predicted that groundwater within the basalts in Newmarket decanted over the Waitemata ridge on the eastern side of the Newmarket DMA. This has been shown to be only partially correct as the majority of groundwater flows down the Mt Eden paleovalley with groundwater decanting over the Waitemata ridge to the east when groundwater levels rise due to recharge from significant rain events.

Significant areas within the Royal Oak DMA were considered to be founded on tuff and therefore soakage was regarded as problematic. However results of the fieldwork have shown that there exists a significant body of basalt under the tuff which could be utilised for stormwater soakage with deeper soakholes.

The last phase of the fieldwork has also enhanced the understanding of the One Tree Hill area which is a significant point of recharge to a portion of the Greater Onehunga aquifer. The investigation has been able to delineate the extent of the permanent water table within the basalt aquifer and the difference between the original concept as defined at the start of the project and the current state of knowledge is illustrated on Figure 1.

Figure 1: Base of Basalt contours within the study area



The overall geological concepts for the remainder of the GAS area, postulated by Searle (Searle, 1981) have also been confirmed and proven by the fieldwork.

In addition the drilling has defined basalt geology in the key areas of Newmarket, Meola, Greenlane, One Tree Hill and Mt Eden where previously aquifer boundaries were unknown. In Mt Eden and Newmarket overlapping lava flows from Mt Eden and One Tree Hill, each with separate groundwater systems, have been confirmed.

The seven pumping bores were drilled using 150mm diameter percussion hammer or PQ sized coring bit with a 122mm diameter hole. Pumping test bore depths varied from 24.4m to 59.2m. On completion of testing the bore was backfilled and reinstated.

The drilling of each pumping bore was preceded by drilling of a nearby cored piezometer hole (approximately 5 to 15m from the pumping well) which provided information on ground and groundwater level conditions at the site and acted as a monitoring borehole to record groundwater levels during the subsequent pumping test.

The bores were tested by pumping for up to 24 hours (where possible) at a constant flow rate using a 100mm diameter down-hole pump. Water levels were monitored in the pumping bore and all suitably located adjacent piezometers at each pumping well.

Of the seven pump tests, four were conducted over the full 24 hour period while the other three were pumped for periods of between 12 and 16 hours.

2.1.1 SOAKAGE TESTING

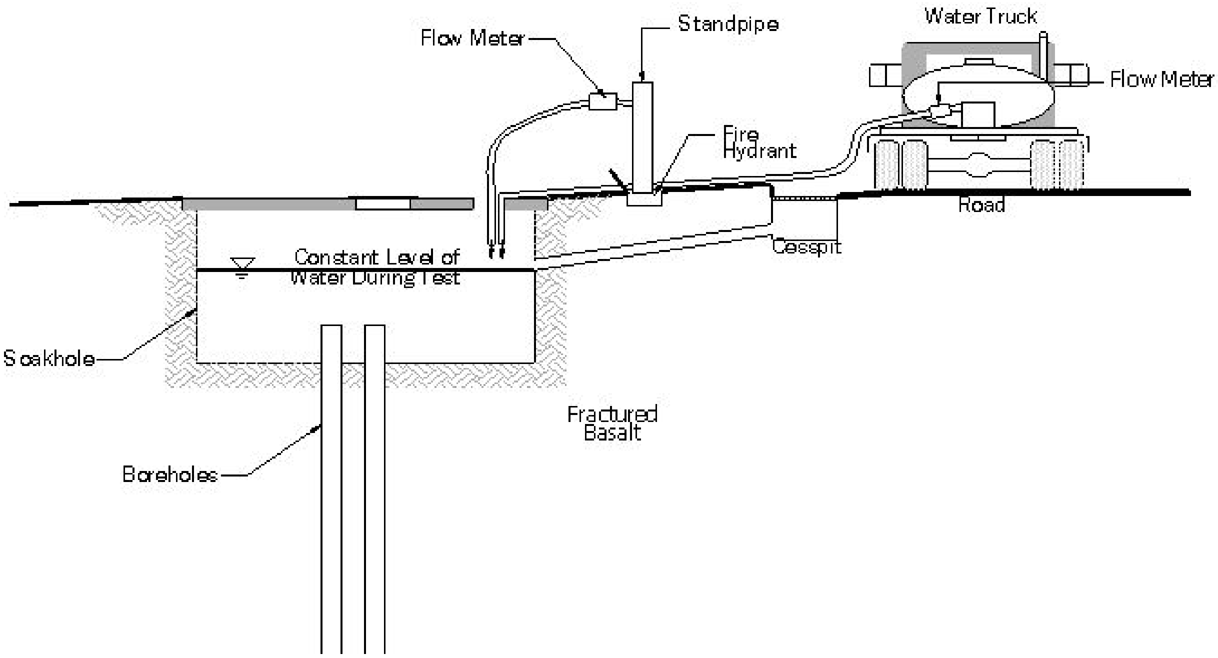
Over 200 soakholes were flow tested as part of the GAS fieldwork. The soakholes for testing were selected based on the following criteria guidelines:

- A 1 km x 1 km grid spacing;

- A reasonable spread across the extent of the lava flows within the study area such that there were soakholes to be tested along the edge as well as in the centre of lava flows;
- Choice of existing soakholes sited close to boreholes with good geological logs;
- Avoidance of soakholes in known tuff zones and sedimentary rocks.
- Known flood prone areas

The soakage testing programme indicated that the capacity of soakholes to dispose of stormwater can vary widely depending on geology (tuff, scoria, fractured and unfractured basalt), weather conditions (antecedent and current conditions), soakhole size, design and maintenance condition, the presence of deciduous trees nearby and their leaf type, long-term clogging and stormwater quality. It is not straightforward to determine potential "good soakage areas" from soakage tests, as the natural characteristics of the ground are often masked by factors related to soakhole design and condition. The testing methodology is illustrated in Figure 2.

Figure 2: Soakage testing configuration

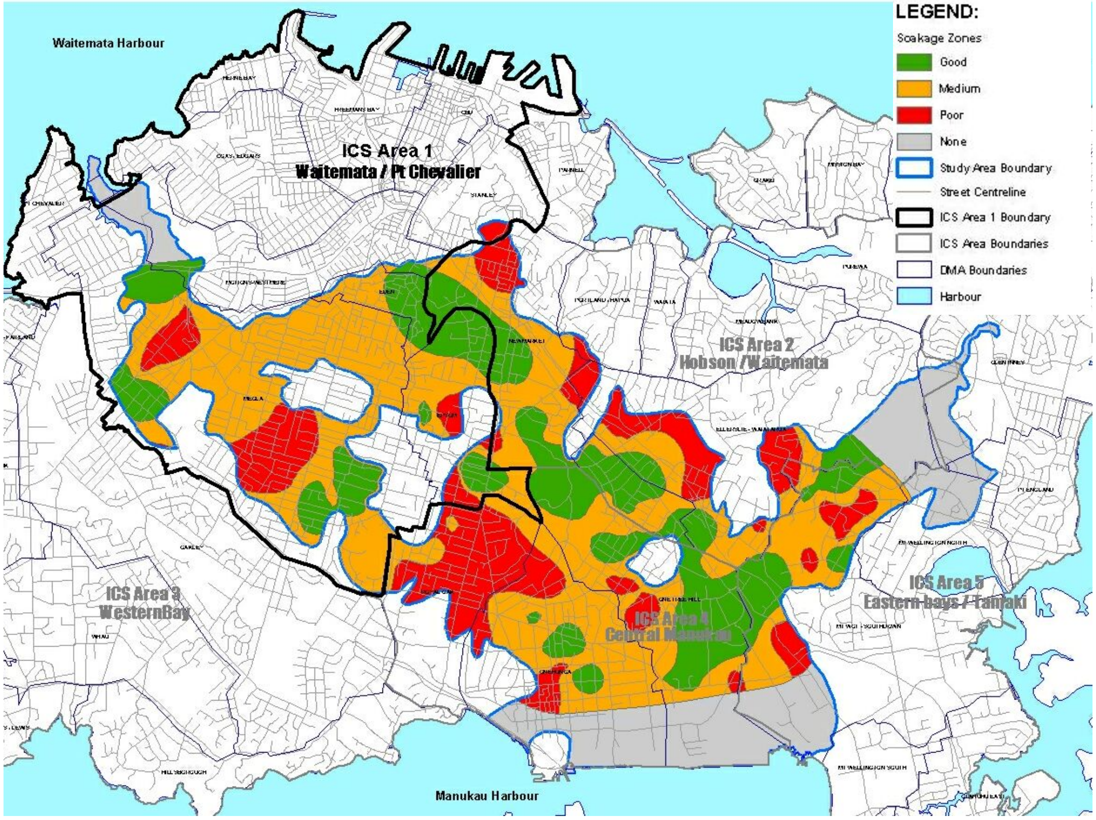


The soakhole test results were plotted as a contour map within the aquifer boundaries. Zones of good, medium and poor soakage were defined.

In attempts to derive a suitable method of grouping or classifying soakage areas, the data was analysed by comparing the soakage rates against age, degree of cleanness, depth of soakholes or bores and geology. This showed no clear correlation between any of these parameters. The soakage rate was also "normalised" by correcting the soakage rate from the actual rate measured to a soakage rate per square metre of face of exposed basalt. The exposed face of basalt was calculated from the dimensions taken during the test and assuming a 10 metre deep bore for each bore if present and using the observed diameter of the bore(s) as measured during the testing.

The normalised soakage rate points were then contoured using the Surfer version 8.0 computer program. Although the results are not clear, areas of poor, medium and good soakage could be identified (Figure 3).

Figure 3: Soakage Contours



The soakage zones given in Figure 3 are an indication only and that this does not preclude the possibility of soakholes or other zones with soakage rates greater or less than that of the area defined. Figure 3 indicates “poor” soakage in the Royal Oak area but from the field work it was found that there exists basalt under the poor draining tuff and therefore soakage in this area could improve with deeper soakholes.

A review of all available borehole data in areas of “good” and “poor” soakage indicates no discernable geological trend except the correlation between soakage and the presence of fractures. The “good” soakage areas generally have a greater occurrence of fractures compared with “poor” soakage areas. The location and aerial and depth extent of fractures is, however, highly variable.

The GAS testing has found that there is often very bad soakage in flooding areas, but that conversely there is very good soakage in other areas that have recorded flooding in the past. This suggests that the areas could dispose of large volumes of water through soakage, but that other factors are preventing this from happening, and hence flooding results. These factors could include inadequately sized soakage infrastructure, inadequate pipes and catchpits, poor design of cesspits and leaves or litter blocking cesspit entrances.

In summary, the results of the soakage testing provide, at best, an approximation of the soakage potential. The results cannot be used to accurately delineate areas of defined soakage rates e.g. for property developers looking for areas suitable for disposing of stormwater into the aquifer. Instead site specific assessment of the on-site soakage will be required.

3 REGIONAL GROUNDWATER MODEL

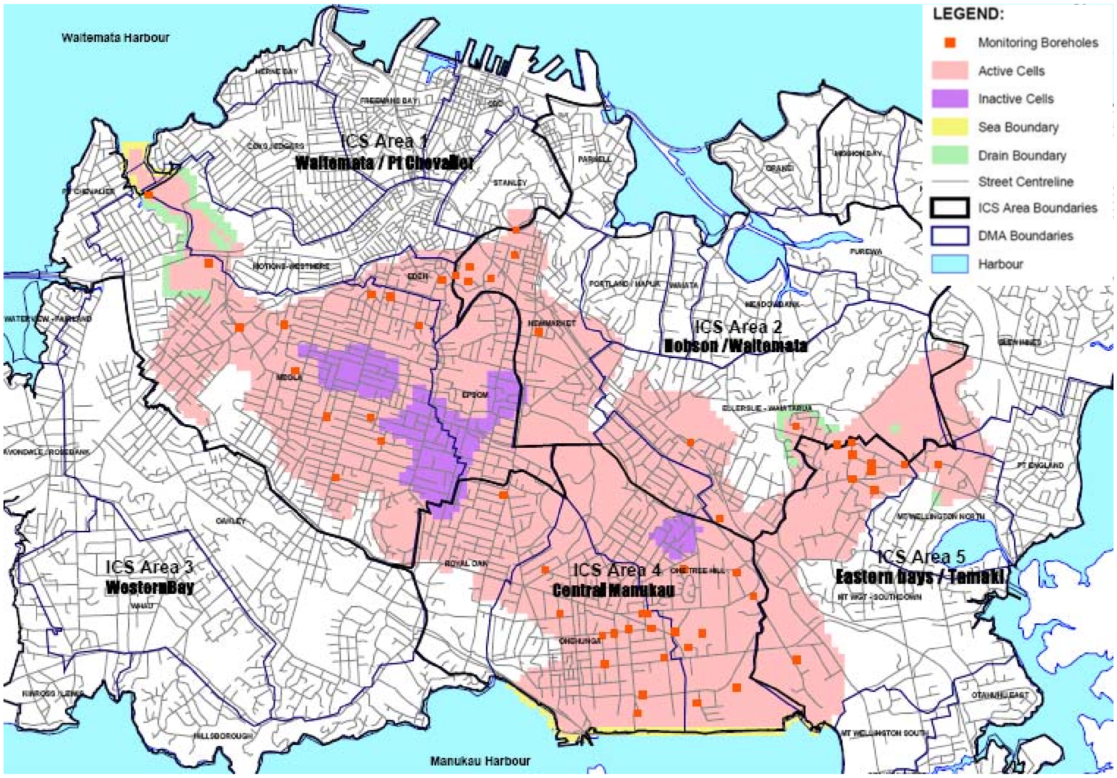
One regional groundwater model of the two main (greater) aquifer systems was developed in Visual MODFLOW (Waterloo 2003) and MIKE-SHE (DHI 2004). The models assume that the fractured basalt aquifer can be simulated with an equivalent porous medium approach. The hydrogeologcal investigations carried out 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.

3.1.1 SYSTEM GEOMETRY

The model domain is approximately 45km^2 with a north-south grid alignment (Figure 4). 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.

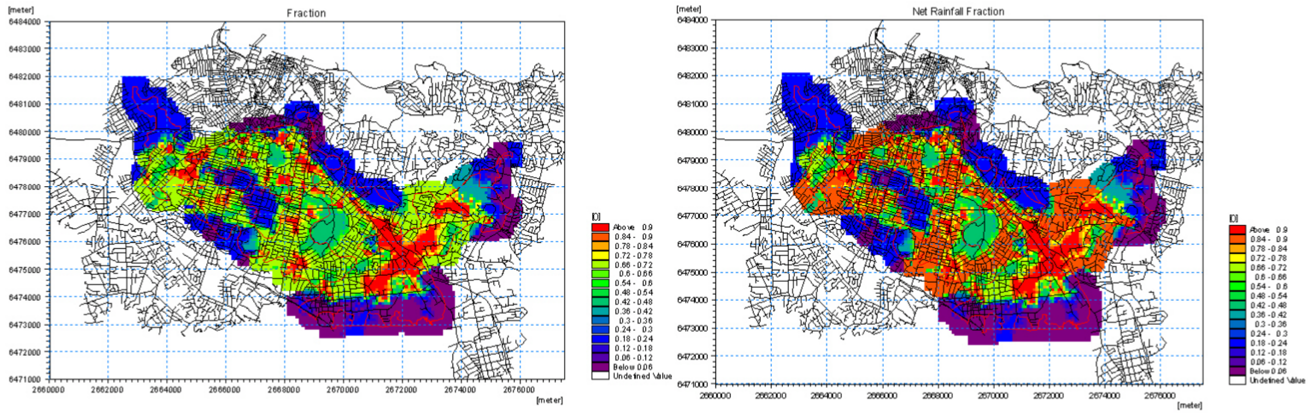
Figure 4: Regional Model with boundary conditions



3.1.2 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 5).

Figure 5: Recharge Fraction for (a) Existing Land Use and (b) Future (Maximum Probable) Land Use



a *b*

3.1.3 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 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.

3.1.4 MODEL CALIBRATION

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.

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).

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

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.

For a more detailed description of the calibration process, including sensitivity and validation analyses see Namjou et al. (2005).

4 RESULTS

A number of scenarios were modelled covering various recharge options. The scenarios modelled are summarised in Table 2 below

Table 2: Summary of Recharge Options

Option	**Description**
1	All existing rainfall infiltrates the aquifer
2	All future wet year rainfall infiltrates the aquifer
3	Recharge based on future landuse (MPD) and existing rainfall
4	Recharge based on existing landuse and wet future year rainfall
5	Recharge based on future landuse and wet future year rainfall
6	Recharge based on future landuse and dry future year rainfall
7	Hypothetical recharge only in Upper catchment

The options are each evaluated in accordance with the purposes for which each was chosen and are discussed below. A summary of the results for the six options analysed is given in Table 3 below.

Table 3 – Summary of Results

Scenario		**Existing**	**1**	**2**	**3**	**4**	**5**	**6**
Recharge	m3/day	73,000	130,000	160,000	77,500	93,200	99,400	49,000
Groundwater discharge	Waitemata m3/day	28,300	48,700	52,300	30,000	34,600	36,000	21,700
	Manukau m3/day	36,500	69,000	83,000	38,800	47,000	49,800	26,600
Groundwater discharge to other boundaries (including pumping and aquifer storage)	m3/day	8,200	12,300	46,700	8,700	11,600	13,600	700
Area of Elevated Groundwater levels within 2m or less of surface	% of Total Area	4%	10%	11%	4%	5%	5%	1%

A scenario involving a localised large additional pulse of recharge to the upper catchment of the Greater Onehunga system was run to determine down aquifer wave transmission velocity. The time taken for recharge pulses to migrate to lower catchment areas is important to feasibility assessment for new soakage facilities. Migration of the water level rise as a pressure wave is of interest. The results indicate that this wave has a velocity of approximately 150 m per day and takes in the order of a week to pass from Epsom to Onehunga.

Groundwater level data monitored through rainfall events at boreholes situated within the mid catchment area indicates that groundwater levels continued to increase for between 3 to 7 days after the rainfall event.

This increase can be attributed to a number of factors such as:

- Hydraulic pressure wave propagation from up catchment and/or
- Local lag and attenuation effects in the unsaturated zone and/or
- Delayed surface water inputs from pipes and ponds

Based on the above, the maximum zone of influence from upgradient recharge pulses on the peak groundwater levels will be between 500m to 1000m

The results also indicate the differential increase in groundwater levels within the lower catchment where the bulk of the groundwater volume is stored, from upper catchment recharge is minimal (Namjou et al. 2005).

5 SUSTAINABILITY OF SOAKAGE

Sustainability concepts have long been used to some degree in managing groundwater. In particular the concept of limiting groundwater extraction to sustainable yield reflects using aquifer resources sustainably. While a universal definition and agreement of sustainability and sustainable water resource management remains somewhat illusive, improved concepts and guidelines are emerging. The concept of sustainable water use (SWU) was promulgated recently. It is defined as use that supports social objectives into the indefinite future without undermining hydrologic and ecological integrity (ASCE & UNESCO 1998; Gleick et al. 1995).

A Sustainable Water Resource Roundtable was convened to help further define and develop criteria to measure and design systems to manage water in a more sustainable manner (Kranz et al, 2004). Heintz (2004) summarises one outcome of the roundtable by advocating a capital maintenance approach to assessing sustainable water resource management. Capital includes both renewable natural resource systems and non-renewable resources. It includes the environmental capacity to absorb and disperse waste and the capacity of the biosphere and its various subsystems to adapt and involve.

ASCE & UNESCO's earlier work (1998) developed guidelines for the development and assessment of sustainable water systems. These guidelines have been grouped in six categories:

(1) the environment and ecosystems

(2) health and human welfare

(3) economics and finance

(4) institutions and society

(5) planning and technology

(6) the design, management and operation of the physical infrastructure

It can be argued that underlying ASCE & UNESCO's sustainable water use definition and guidelines are a capital maintenance approach. It should be emphasized that while a water resource system may be sustainable, a particular component of the system may not be. This paper however does not cover a full assessment of the sustainability of the groundwater resource in the Auckland basalt aquifer.

Assessment of groundwater aquifer use in Auckland City is generally based around a *de facto* capital maintenance approach and assessment of the six categories. The GAS project focuses particularly on categories (1) and (2). Within GAS, the existing state of the aquifers and expected state under varying future management scenarios were investigated, including quantity and quality. Specific assessment was made of the environmental effects of aquifer use for stormwater disposal and the long term sustainability of continued or increased use on ecological, human and social well being.

5.1 CLOGGING

Disposing of stormwater by soakage allows the water to recharge the underlying aquifer as it would have done prior to urban development. Within soakage networks, however, stormwater enters the aquifer directly through pores and fractures in soakholes and tunnels, and does not percolate through soil. Suspended solids in stormwater are therefore more likely to enter the aquifer, potentially impacting on groundwater quality.

Clogging of the aquifer is the term given to the reduced ability of the aquifer to transmit groundwater. This clogging takes the form of the development of a layer of low permeability within the surface of the recharge zone of the aquifer by physical, chemical or biological processes. Sediments and detritus in the stormwater infiltrating into the aquifer are the main contributors to the formation of this layer on the faces of the fissures and fractures within the basalt aquifer.

Clogging layers can vary in thickness from a couple of millimetres to a layer of several centimetres. These layers generally have a much lower hydraulic conductivity than the fractured basalt, which reduces the rate of flow of groundwater through the layer, and consequently reduces, or even prevents, recharge to the groundwater system.

Pattle Delamore Partners (PDP, 2002) noted that from the Epsom study, long-term disposal of stormwater to soakage is sustainable and that stormwater should receive pre-treatment to:

- achieve a reasonable economic life for the soakage assets;
- reduce the rate of aquifer clogging; and
- reduce the risk to groundwater quality.

While there is extensive literature concerning artificial recharge systems and the clogging processes related to soils and sediments (PDP, 2002), little research has been focused on fractured bedrock recharge. In the Auckland Isthmus, the concept of aquifer clogging is of particular interest because of

- the extensive use of disposal of stormwater to soakage;
- the fractured nature of the rock to which the stormwater is typically disposed; and
- the suspended sediment loads that potentially enter the aquifer in high concentrations, and can potentially clog the fractures.

Pattle Delamore Partners (PDP, 2002) from the Epsom study, concluded that while physical clogging of the aquifer, was likely to occur, it has not significantly reduced the ability of the fractured rock basalt aquifer as a whole to transmit groundwater.

Assuming uniform siltation within the aquifer and given estimated parameters for suspended solid concentration within stormwater, the model used in the Epsom Study, predicted that 0.3 m of aquifer depth would have been filled over the 100 years of soakage operations in Epsom. Assuming that the solids settle out in the area immediately surrounding a soakhole or soakage tunnel, the model predicted a 5 m sludge depth in a 5 m radius around a typical soakhole serving 100 m of road and footpath, and an average sludge depth of 5 m in a 40 m radius around the Epsom Avenue soakage tunnel. Overall, urban soakage activities over the last 100 years have probably led to siltation of less than 2% of the groundwater aquifer volume. This assumption of clogging being limited to a 5m radius is corroborated by G Bird (pers. comm.) who noted the finding of detritus within the investigation boreholes drilled within 2-3 m of existing soakholes in heavily fractured basalt.

The effects of clogging in this study have been modelled by effectively changing the permeability of the aquifer. This was done during the sensitivity analysis and the analysis indicated that the model is highly sensitive to changes in hydraulic conductivity of the aquifer. Increasing hydraulic conductivity by 50% without changing any other parameters results in up to 6.5m drop in measured hydraulic heads. However, a 50% reduction in hydraulic conductivity, increases the calibrated heads by up to 11m. Therefore the model is more sensitive to reduction of hydraulic conductivity i.e. clogging. One order of magnitude reduction of hydraulic conductivity causes 167m increase in the model head.

From this it follows that any significant clogging of a soakage area will result in elevated groundwater levels. From the monitoring done to date this has not occurred which would confirm the deductions made based on the studies conducted in the Epsom catchment by PDP.

It is however also true that some existing soakholes do perform better following cleaning and the removal of sediment from the soakhole. In some cases this performance once again decreases over time as the soakhole collects more sediment. This reduction in performance is an indication that the soakhole does not intersect an adequate number of fissures and fractures and therefore the accumulation of sediment does block the fissures and fractures present to some degree. Such soakholes are likely to be a poor performing soakhole from inception. From the fieldwork of the GAS project it has become clear that the aquifer is both a part of the stormwater disposal system and a receiving environment. As stormwater enters the fractured basalt it is “treated” by the fact that the sediment within the stormwater is filtered out in the soakholes and tunnels in the fractured basalt. These soakholes and tunnels should be cleaned regularly to remove the sediment as the contaminants within the sediment could become available to stormwater entering the soakhole/tunnel.

5.2 GROUNDWATER QUALITY

There has been some work done on assessing the effect of stormwater infiltration on groundwater quality in Mt Eden (Rosen et al., 2000). Rosen et al. concluded:

- there had only been a minimal effect on the groundwater from 60 years of infiltration in the Mt Eden area;
- proper cleaning and maintenance of the soakholes (i.e. sediment removal) was key to preventing serious contamination to the groundwater; and

- further research is required to determine if stormwater infiltration will clog the aquifer and/or reduce the groundwater quality.

Smaill (Smaill, 1993) noted that the disposal of stormwater to groundwater is likely to negatively affect the groundwater quality by introducing the potential contaminants from the surface stormwater.

Concerns regarding the degradation of the groundwater quality in the Penrose-Mt Smart area were expressed by Smaill in the One Tree Hill – Onehunga Groundwater Resource Report and Management Plan (Smaill, 1993). The findings were that the groundwater quality had been compromised, predominantly in the Penrose-Mt Smart area and that the most likely source of the contamination would have been from contaminated stormwater being disposed of to ground without treatment.

Comparison of the electrical conductivity results from the 1993 One Tree Hill – Onehunga Groundwater Resource Report and Management Plan with results from this investigation indicate a lowering in the level of dissolved solids within the groundwater. In general, the affected zone of groundwater in the Penrose-Mt Smart area had a range of conductivity results of between 48 to 55 mS/m in 1993 and these have reduced to a range of 20 to 45 mS/m in 2003.

It is thought that this improvement is a direct result of improved stormwater management practices implemented by the ARC, Auckland City and the owners of the industrial premises. The area still remains at risk from the disposal to ground of contaminated stormwater, in particular from the sediment entrained in the stormwater. Treatment and the implementation of silt control measures for stormwater prior to disposal to soakage will ensure that ground soakage remains a long term disposal option.

5.3 GROUNDWATER LEVELS

The groundwater level monitoring programme has confirmed the seasonal movement of the groundwater table as well as providing baseline data for the calibration of the regional model. The monitoring when compared to historical data shows similar levels for long periods.

From the modelling, the areas affected by the groundwater breakout and zones where the groundwater levels are within 2m of surface covers less than 208ha (4%) of the aquifer area of 4347 ha for the existing scenario increasing to approximately 483ha (11%) for the scenario of 100% recharge. As such it is therefore clear that the aquifers can accommodate double the existing recharge with a slight increase in groundwater breakout. These areas affected by groundwater breakout will have to be addressed in conjunction with increasing the development of soakage further up in the aquifer catchments. Drainage systems could be engineered to accommodate this extra stormwater and to pipe the stormwater to the two harbours.

6 CONCLUSIONS

The ability of the aquifer to accommodate more stormwater via soakage also presents an opportunity to use this form of stormwater disposal for flood prone areas outside the aquifer boundary. The major issue which requires resolution is that of how to practically capture and inject large volumes of stormwater generate from short, high intensity storms, into the aquifer.

Conceptual options at this stage are:

- Utilisation of underground chambers/lava tunnels.
- Large scale trenches filled with scoria.
- Short lengths of pipe networks to convey stormwater to areas of better soakage and using the volume of the network as surge capacity.

The effect of increased recharge in the upper catchment has on the groundwater levels in the lower catchment as modelled indicates that the zone of influence around areas affected by elevated groundwater levels is between 500 to 1000m and the at the differential increase in the groundwater levels in the lower catchment is negligible.

The main conclusions can therefore be summarised as:

- The aquifers have the capacity to accept greater than double the existing recharge.
- Less than 1 to 10% of the aquifer area is affected by groundwater breakout.
- Disposal of stormwater generated outside the aquifer catchment boundary is possible
- Aquifer groundwater volumes remain similar in all scenarios and thus the existing water supply users will not be affected.
- The disposal of groundwater to soakage is sustainable considering the existing body of evidence subject to the continued maintenance of the soakage systems and control and management of the quality of water entering the aquifer.

Further work is required to determine the extent of shallow groundwater zones in local areas and the rates and extent of clogging due to the retention of sediment within the basalt aquifer.

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