Lower Hutt Aquifer Model Revision (HAM3): Sustainable Management of the Waiwhetu Aquifer

Greater Wellington Regional Council

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EXECUTIVE SUMMARY

The groundwater resource of the Lower Hutt Valley provides up to about 40% of the water supply for the greater Wellington metropolitan area. Greater Wellington Regional Council (GWRC) is responsible for bulk water supply and is required to sustainably manage the Lower Hutt groundwater resource to ensure a secure and continuous water supply for the city. This responsibility has necessitated the construction of an updated numerical groundwater flow model for the Lower Hutt aquifer system. The Hutt Aquifer Model 3 ('HAM3') represents an evolution of previous models in response to the need for a more accurate simulation. Specific objectives of the HAM3 project are:

- Review of the sustainable yield of the Waiwhetu Artesian Aquifer, including saline intrusion risk;
- Development of a revised saline intrusion risk management framework;
- Development of an abstraction operational tool for assessing the yield of the aquifer and forecasting resource availability during periods of climatic stress;
- Assessment of the potential effects of sea level rise (or land subsidence as a result of seismic activity) on water supply security from Waiwhetu Aquifer.

Hydrogeological setting and HAM3 development

The hydrogeology of the Lower Hutt Valley has been intensively investigated over the past 40-50 years and large groundwater and surface water monitoring datasets are available. Information gaps and data veracity concerns identified during the HAM3 project were addressed through fieldwork activities. Fieldwork included concurrent river flows gaugings, high-accuracy GPS elevation surveying, and the construction of new multi-level monitoring piezometers adjacent to the Hutt River. A revised three-dimensional geological model of the Lower Hutt basin, extended to incorporate its offshore continuation, has formed the framework of the HAM3.

Conceptually, the groundwater system beneath the Lower Hutt valley floor and Wellington Harbour takes the form of a layered sequence of unconsolidated sediments filling an 18km long wedge-shaped and fault-bounded basin which is up to 350m deep at the Petone foreshore and in excess of 600m deep beneath the harbour. Several gravel aquifers occur in the sediment sequence – the most productive being the confined Waiwhetu Artesian Aquifer which is exploited for Wellington's water supply. The confined Waiwhetu Aquifer extends from about Boulcott down-valley and then continues beneath Wellington Harbour where it remains confined and under artesian pressure. As such, it does not appear to have an open contact with the sea, being overlain by a low-permeability marine aquitard. Recharge to the aquifer system occurs principally through seepage from a 5km stretch of the Hutt River downstream of Taita Gorge where unconfined aquifer conditions prevail. The aquifer system is therefore almost entirely dependent upon its connection to the Hutt River and it is evident through modelling that the leakage rate from the river is significantly increased by groundwater abstraction. Discharge from the aquifer occurs via diffuse leakage beneath the harbour and locally small discharges occur from discreet submarine springs where the artesian pressure has burst through the aquitard.

The HAM3 has been constructed using the USGS MODFLOW three-dimensional numerical groundwater flow code. Calibration has been assisted by using the automated inverse estimation algorithm PEST to remove some of the subjectivity of

manual calibration and provide an insight into model non-uniqueness. The HAM3 calibration meets the criteria for a high confidence level simulation capable of meeting its objectives and has been endorsed as such through peer review.

Revised saline intrusion risk management framework

The sustainable management of the Waiwhetu Aquifer is primarily focussed upon managing the saline intrusion risk at the Petone foreshore. A revised and expanded saline intrusion risk management approach incorporates a combination of water level, hydraulic gradient and water quality thresholds within a monitoring framework. Such an approach will provide a higher degree of saline intrusion protection and wellfield operational confidence, particularly during periods of high water demand and stressed aquifer conditions. Three saline intrusion groundwater level thresholds for the Upper Waiwhetu Aquifer are recommended: Review Level: 2.5m, Alert Level: 2.3m and Minimum Level: 2.0m. These are consistent with the three current management levels, but they will provide a more structured management and tiered monitoring response framework. Electrical conductivity (EC) monitoring from five foreshore wells with associated trigger levels will provide warning of water quality changes. The monitoring of onshore and offshore hydraulic gradients is also an integral component of the management framework. Implementation of the framework will require the construction of two replacement monitoring wells on the foreshore, maintenance of existing monitoring sites and scheduled checking and calibration of all EC sites. The development of a remote monitoring display incorporating all components of the saline intrusion management framework is required.

Sustainable yield assessment – Waiwhetu Aquifer

The sustainable yield of the Waiwhetu Aquifer is dependent upon aquifer storage/head conditions in the unconfined part of the aquifer and upon the recharge potential from the Hutt River. The yield is also constrained by the foreshore saline intrusion groundwater level thresholds which in effect define the 'sustainable yield' of the Waiwhetu Aquifer. A somewhat different approach to the yield management of the Waiwhetu Aquifer is advocated, one which is based upon an dynamic evaluation of aquifer storage and river recharge potential using a level indicator in the unconfined aquifer at the Taita Intermediate monitoring site. The groundwater level range at Taita Intermediate is an indicator of the short-term sustainable yield of the Waiwhetu Aquifer which ranges from 100 ML/day (100,000m^3/day) when the Taita Intermediate level is low, to 140 ML/day when the level is high. The induced recharge from the Hutt River has also been calculated to range from 500 to 600 L/sec under the recommended yields. This effect should be taken into account in the management of surface water allocation from the river. It is recommended that the mean daily allocation from the Waiwhetu Aquifer for resource management policy is 100ML (12 month mean), and 36,500 ML/year (the current allocation is 33ML/year). The maximum recommended daily yield is 140ML. In practice, under stress conditions, the yield from the aquifer will be governed by saline intrusion level constraints at the foreshore. Based on the HAM3 re-assessment of aquifer yield, there is clearly scope to increase both the mean and maximum consented abstraction rates if required by GWRC for bulk water supply.

Yield optimisation and prediction tool (HADC)

The Hutt Aquifer drawdown calculator (HADC) has been developed as a simple and adaptable tool to assist in the operational management of the Waiwhetu Aquifer. HADC is a user friendly proxy for the HAM3 and is able to forecast and optimise the yield of the aquifer based upon the state (level) of the unconfined aquifer (and implicitly, the Hutt River) and a specified foreshore minimum groundwater level. The principal benefit of the HADC lies in its ability to forecast the sustainable wellfield yield when the aquifer system becomes stressed and is in recession – i.e. during an anticipated dry period when the river remains at low flow and the unconfined aquifer storage slowly drains. The HADC calculates the recession of the unconfined aquifer using an exponential decay equation and then calculates the sustainable pumping rate from the Waiwhetu Aquifer whilst maintaining a specified saline intrusion risk groundwater level at the foreshore. Because the foreshore groundwater level in the Waiwhetu Aquifer responds very quickly to changes in the pumping rate at Waterloo, the HADC can be used to help 'steer' the foreshore level so that minimum levels are not breached.

Sea level rise impact assessment

The HAM3 has been used to assess the effects of a sea level rise of up to 1.5m above the current sea level on the yield of the Waiwhetu Aquifer. Aquifer levels at the foreshore are predicted to rise, or 'lift', about 30% of the total sea level rise magnitude (i.e. about 0.4m for a 1.5m rise) due to the confined and pressurised nature of the offshore aquifer. The HAM3 predicts that the sustainable yield from the Waiwhetu Aquifer will decline as sea level rises. If the minimum foreshore level of 2.0m is implemented, the yield from the Waiwhetu Aquifer is predicted to drop from 110 to 93 ML/day for a 0.75m sea level rise, and then to 76ML/day for a 1.5m rise. This equates to an 15% reduction in yield for a 0.75m sea level rise, and a 31% reduction for a 1.5m sea level rise.

State of aquifer reporting and forecasting

GWRC require a means of assessing and reporting the 'state of the aquifer' in simplistic terms, both to assist in the operational management of the water supply and for communicating the 'health' of the aquifer with the wider community. Two indicators are recommended which provide information on the resource stress state and yield availability – the Waiwhetu Aquifer level at Petone foreshore (McEwan Park), and the unconfined aquifer level (at Taita Intermediate). Each depicts a different aspect of the aquifer – McEwan Park shows the saline intrusion risk status, whilst Taita Intermediate shows the recharge/storage status. Smoothed 24-hour mean monitoring data for these sites can be portrayed on an envelope plot which shows monthly maxima, minima, and lines indicating one standard deviation from the mean derived from the historical monitoring record. The method provides a good visual way to put the current levels into the context of the historical record. Four coloured status levels are proposed for each site. The envelope plots can also be used to project forecast aquifer levels using the HADC model.

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1 INTRODUCTION

1.1 PROJECT BACKGROUND AND PURPOSE

The groundwater resources of the Lower Hutt valley constitute a vital component of the public water supply system for the greater Wellington area, providing up to about 40% of the water demand. The groundwater system beneath the valley floor (known as the Lower Hutt Groundwater Zone) takes the form of a layered sequence of unconsolidated sediments filling a 4.5km wide, 14km long wedge-shaped and fault-bounded basin up to 350m deep at the Petone foreshore. Several gravel aquifers are present in the sediment sequence; the most productive is the Waiwhetu Artesian Aquifer which is exploited for Wellington's water supply.

Greater Wellington Regional Council (GWRC) is responsible for bulk water supply to the Wellington municipal area and, as the principal user, is required to sustainably manage the Lower Hutt groundwater resource whilst ensuring a secure and continuous water supply for the city. The latter responsibility additionally requires that the vulnerability of the groundwater resource to natural hazards, such as sea level rise and sea water intrusion, is assessed to inform and guide contingency planning.

These management responsibilities have necessitated construction of an updated numerical groundwater flow model for the Lower Hutt aquifer system. The Hutt Aquifer Model 3 ('HAM3') represents an evolution of previous work in response to the need for a more accurate model incorporating an updated geological analysis of the groundwater basin, additional monitoring data and a more robust model calibration methodology.

Specific objectives of the HAM3 modelling project are as follows:

- Review and update the conceptual hydrogeological model for the Lower Hutt aquifer system (Chapters 2-5).
- Develop a high confidence level, calibrated simulation of the Lower Hutt groundwater system (HAM3), capable of predicting or forecasting its response to potential future stresses (Chapters 6-7) .
- Review and revise the management framework for the Waiwhetu artesian aquifer, including saline intrusion risk monitoring and management (Chapter 8).
- Develop a simple operational management tool based on the HAM3 to assess and forecast the sustainable yield of the Waiwhetu Aquifer (Chapter 8).
- Assess the potential effects of sea level rise on water supply security from Waiwhetu Aquifer (Chapter 9).
- Recommend a methodology of forecasting the 'state of the aquifer' and predicting the sustainable yield ahead of summer/stress periods (Chapter 10).

1.2 Previous work and data sources

The Lower Hutt groundwater environment has an extensive history of geological and hydrogeological investigation over the past half a century. Some of the principal geological and hydrogeological resources that have informed the present study are:

- Stevens (1956a,b) –the first interpretation of the geological history of the Hutt Valley and the artesian aquifer system.
- Donaldson and Campbell (1977) produced a seminal hydrogeological study entitled *Groundwaters of the Hutt Valley – Port Nicholson Alluvial Basin* which represented the most complete compilation and analysis of information at the time. It also presented a conceptual hydrogeological model which, with adaptations, remains valid.
- The 1:50 000 Geological map of the Wellington Area including memoir (Begg and Mazengarb, 1996).
- Recent geological modelling of the Hutt Valley in: It's our Fault – Geological and Geotechnical Characterisation and Site Class Revision of the Lower Hutt Valley (Boon et al., 2010).
- Wellington Regional Council (1995) – Hydrology of the Hutt Catchment, vol 2: Groundwater

The Moera Gravel Investigation Bore (Brown and Jones, 2000), drilled to a depth of 151.3m in Lower Hutt, was used to supplement the interpretation of the hydrostratigraphy for the Lower Hutt Groundwater Zone through detailed geological and geophysical logging, pump testing and chemical analysis of groundwater. Although the bore represents a single geospatial point, the information derived from it has facilitated the re-interpretation of the hydrostratigraphic sequence and depositional characteristics of the Lower Hutt Groundwater Zone.

The geophysical study of Wellington Harbour by Wood and Davey (1992) is an invaluable source of information relating to the interpretation of offshore geology and the extension of the Waiwhetu gravels into the harbour. Also, in relation to offshore hydrogeology, an important and unique study of the submarine spring discharges in Wellington Harbour was undertaken during a master's programme at Victoria University of Wellington by Harding (2000). This work has provided helpful information on the offshore discharge from the Waiwhetu Aquifer.

1.2.1 Principal data sources

The data used in this study were derived principally from databases managed by the Greater Wellington Regional Council (GWRC).

A large number of geological logs from boreholes drilled in the Lower Hutt Groundwater Zone over the past century are stored in the GWRC Wells database. Additional geological data from geological maps and geological modelling work were also used to develop the HAM3 (Begg and Mazengarb, 1996; Boon et al., 2010). The geophysical survey data and interpretations of Wood and Davey (1992) provided supplementary information on the offshore geology.

A number of automatic and manual groundwater level monitoring sites are operated throughout the Lower Hutt valley by GWRC. The monitoring records for many of

these extends back for up to 40 years and are stored on the council's Hilltop database. The same database also stores flow monitoring data for the Hutt River – the long-term gauging site at Taita Gorge being the principal source of data for setting up the river boundary condition in the model.

GWRC carry out cross-section surveys of the Hutt River about every 5 years which have been used to set the river bed levels in the HAM3. Cross-section surveys are carried at approximately 100m intervals and were conducted in 1897, 1993, 1998, 2004 and 2009, and a partial survey of the lower 8.7km or so of the river was carried out in 2012. Gravel analysis surveys are reported in two Hutt River Floodplain Management Plan reports (GWRC 2005, 2010).

Climate data for the rainfall recharge model was derived from the NIWA climate model produced for the Wellington Region. Rainfall and potential evapotranspiration were interpolated onto a 500m grid using all available climate station data (from NIWA and GWRC).

Harbour bathymetry data were derived from a high accuracy bathymetry survey carried out by NIWA for GWRC and the Department of Conservation as part of the 'Beneath the Waves' project (NIWA, 2009).

1.2.2 PREVIOUS MODELLING WORK

There have been at least three previous groundwater flow models of the Lower Hutt Groundwater Zone, all based on various versions of the USGS MODFLOW three-dimensional groundwater flow modelling code (Reynolds 1993, PDP 1999, Phreatos 2001). The purpose of these models was to optimise abstraction from the Waiwhetu Aquifer for public water supply and manage saltwater intrusion risk. Prior to the current HAM3 model rebuild, the most recent version of the Hutt Aquifer Model (HAM2) was developed in 2001 by Greater Wellington Regional Council and represented the most recent evaluation of the Lower Hutt Groundwater Zone. The HAM2 incorporated several improvements over previous models – notably it was based on a re-interpretation of Lower Hutt geology, it was extended into Wellington Harbour to incorporate the offshore extension of the aquifer and submarine spring discharges, and simulated the Hutt River recharge with greater accuracy.

Since the HAM2 was constructed, model calibration methodologies and tools have advanced significantly. There is now a heavy focus on assessing the reliability and confidence levels of calibrated model parameters using parameter optimisation methods to reduce predictive uncertainty. Parameter non-uniqueness plagues most groundwater models and is of importance in terms of evaluating and improving the predictive reliability of the model. The grid and temporal resolution, model complexity and calibration robustness of the HAM2 are therefore important aspects of the existing model which could be significantly improved using current methodologies and tools.

1.3 Field activities

Field investigations were carried out to support and fill gaps in existing data-sets and to check the veracity of data upon which model calibration is heavily dependent. Much of this work was focussed around achieving a better understanding river-aquifer interactions, since flow loss from the Hutt River is the principal recharge mechanism for the deeper confined aquifer systems. The fieldwork programme comprised the following activities:

- Drilling of piezometers
- River concurrent gauging during low flow conditions
- Piezometric surveys
- Installation of temporary water level monitoring sites in decommissioned wells
- Differential GPS surveying

1.3.1 Piezometer construction

Two multi-level piezometer clusters were constructed on the bank of the Hutt River along the reach known to recharge the confined aquifer system (between Taita Gorge and Kennedy Good Bridge). These were named 'Mabey Road' and 'Nash Street' and their locations are shown on Figure 1.1. Each site comprises a nest of three piezometers at depths of about 7, 12 and 20m. The multi-level bankside piezometers will fill groundwater monitoring gaps in the unconfined aquifer area and improve understanding of the dynamics of river-aquifer interaction. They will also provide information regarding the vertical hydraulic gradients in the unconfined aquifer adjacent to the river to assist in model calibration and estimation of river bed properties and leakage rates.

1.3.2 Supplementary low flow gaugings

Even though a good knowledge of the loss-gain characteristics of the Hutt River exists, and a number of concurrent gauging surveys were carried out between the 1960's and 2003, more recent surveys were regarded to be necessary, particularly since the river bed is very mobile and gravel extraction activities are occurring in the recharge reach. Two additional concurrent gauging surveys were carried out on 2/11/2011 and 31/1/2012.

1.3.3 Piezometric surveys in unconfined aquifer

A series of groundwater level surveys were carried out in the unconfined aquifer area (north of Lower Hutt City) to fill gaps in the GWRC groundwater monitoring network (there being only one long-term monitoring site at Taita Intermediate). Groundwater levels were measured in selected suitable shallow wells on 19/1/2012 and again on 21/3/2012. The data were used to assist in the calibration of the HAM3.

1.3.4 Installation of temporary water level monitoring sites

Several closed GWRC groundwater level monitoring sites were temporarily re-instated in early 2012 for about 12 months by installing pressure transducers with data loggers. Four sites were selected down the eastern side of the valley to fill gaps in the active GWRC monitoring network; these were (see Figure 4.1 for locations):

- Bell Park (R27/1123) – Waiwhetu Aquifer
- Trafalgar Park (R27/1121) – Waiwhetu Aquifer
- Birch Lane (R27/6097) – Waiwhetu Aquifer
- Thorneycroft Ave (R27/6982) – Taita Alluvium

1.3.5   DIFFERENTIAL GPS SURVEYING

The HAM3 calibration process is based upon the groundwater level monitoring data which must be reduced to the vertical survey datum used in the Lower Hutt Valley (Wellington Vertical Datum-1953, or WVD-53). Although the GWRC groundwater level monitoring database is reduced to this datum using a high standard of historic surveys, a review of the veracity of the survey heights was considered necessary to reduce any uncertainty regarding the head monitoring data used to calibrate the HAM3.

A survey company was therefore commissioned to carry out a differential GPS survey on all GWRC groundwater level monitoring sites to provide accurate elevation data. Several sites required adjusting following the survey and these have now been incorporated into the GWRC Hilltop database.
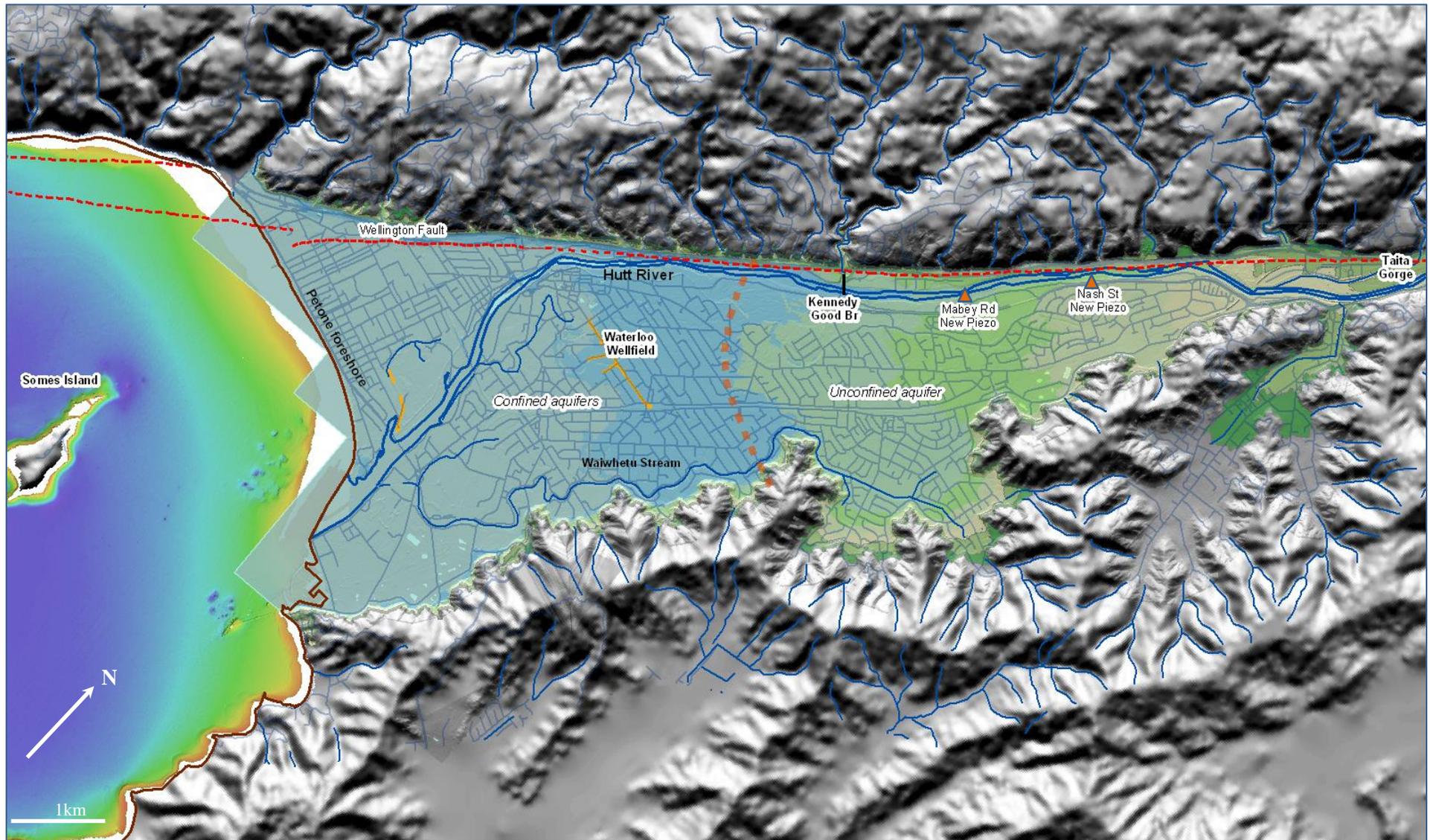
Figure 1.1: Map of the Lower Hutt valley showing main geographical features, topography, harbour bathymetry and the location of the approximate boundary between confined and unconfined aquifers (orange dashed line). The locations of the new piezometer nests at Mabey Road and Nash Street are also shown. Topographic contours are at 5m intervals, from DTM model (colour flood).

2 HUTT CATCHMENT AND OFFSHORE EXTENSION

2.1 HUTT RIVER

The original name given to the river by the Ngāi Tara is Te Awa Kairangi. 'Te Awa' means river, and 'Kairangi' can be translated to mean esteemed or precious. The river's higher mountainous catchment and the coastal plains were originally forested and the swampy plains and waterways associated with the main river and the Waiwhetu Stream were a particularly rich source of food. In the late 19th century, with the arrival of European settlers, the valley floor was completely cleared of natural kahikatea and rimu forest, which would have affected runoff characteristics of the valley. Uplift associated with the 1855 earthquake also had a dramatic impact on the hydrology of the Lower Hutt valley. The landscape and hydrological system have therefore undergone significant changes in response to both natural and human influences in recent times.

The Hutt River is central to understanding the hydrogeological functioning of the Lower Hutt groundwater basin since it is responsible both for the deposition of the aquifer sequence and for being the principal recharge source to the underlying aquifer system. The Hutt River is a steep alluvial river which rises in the southern Tararua Range and flows in a southwest direction for around 45km through the Hutt Valley to its mouth at Petone foreshore on Wellington Harbour. It has a relatively small catchment of about 650 km^2. The upper and lower parts of the Hutt Valley are divided by a gorge at Taita; the floodplain of the Lower Hutt valley extends for about 12km from Taita Gorge (25m amsl) to the coastline at Petone (Figure 1.1).

GWRC and NIWA operate several flow monitoring stations on the Hutt River. Of most relevance to the HAM3 is the site 'Hutt River at Taita Gorge', which was installed in 1979. The long-term monitoring record at this site shows that the mean river flow is 24.9 m^3/sec and the 7-day mean annual low flow is 3.8m^3/sec (GWRC, 2011). The maximum flow recorded since 1979 is 1,562 m^3/sec. The lowest flows of the year tend to occur in late summer, and while prolonged low flows are known to occur, the river generally has a reliable baseflow due to the influence of the forested Tararua Range catchment. Flows in the lower part of the river are affected by Greater Wellington's abstraction for public water supply at Kaitoke in the upper reaches of the river.

Within the Lower Hutt valley, a significant proportion of the river flow is lost through the river bed in the reach between Taita Gorge and Kennedy Good Bridge / Boulcott (Figure 1.1). Seepage through the river bed to the underlying aquifer has been gauged to be in the range of about 700 L/sec and 1,200 L/sec depending upon the depth of the groundwater table beneath the river and downstream groundwater abstraction rates (it appears that there is a relatively poor correlation between river flow and loss). Therefore, up to 30% of the mean annual low flow leaves the river through its gravel bed between Taita Gorge and Boulcott to recharge the underlying aquifers. Further detailed discusson of the river loss characteristics is provided in Section 4.4.1.

The river is currently incising into previously deposited material – reworking and transporting material down the river – rather than deriving it from high catchment erosion (GWRC, 2010). Flood protection policy enacted by GWRC requires that the river flood capacity is actively managed through the extraction of gravel at specific

locations. In the Lower Hutt valley, extraction is focussed along the reach from just upstream of Kennedy Good Bridge downstream to Ewen Bridge. Since the bed is highly mobile and gravel is constantly being transported down the river – particularly during flood episodes – changes in bed level are monitored by using cross-section surveys conducted about every 5 years. This data forms the basis of gravel extraction and general river management activities. Cross-section surveys are carried out at approximately 100m intervals and were conducted in 1897, 1993, 1998, 2004 and 2009, and a partial survey of the lower 8.7km or so the river was carried out in 2012. Figure 2.1 shows the survey cross-section locations and Figure 2.2 shows the surveyed profile of the Hutt River between Taita Gorge and the coastline.
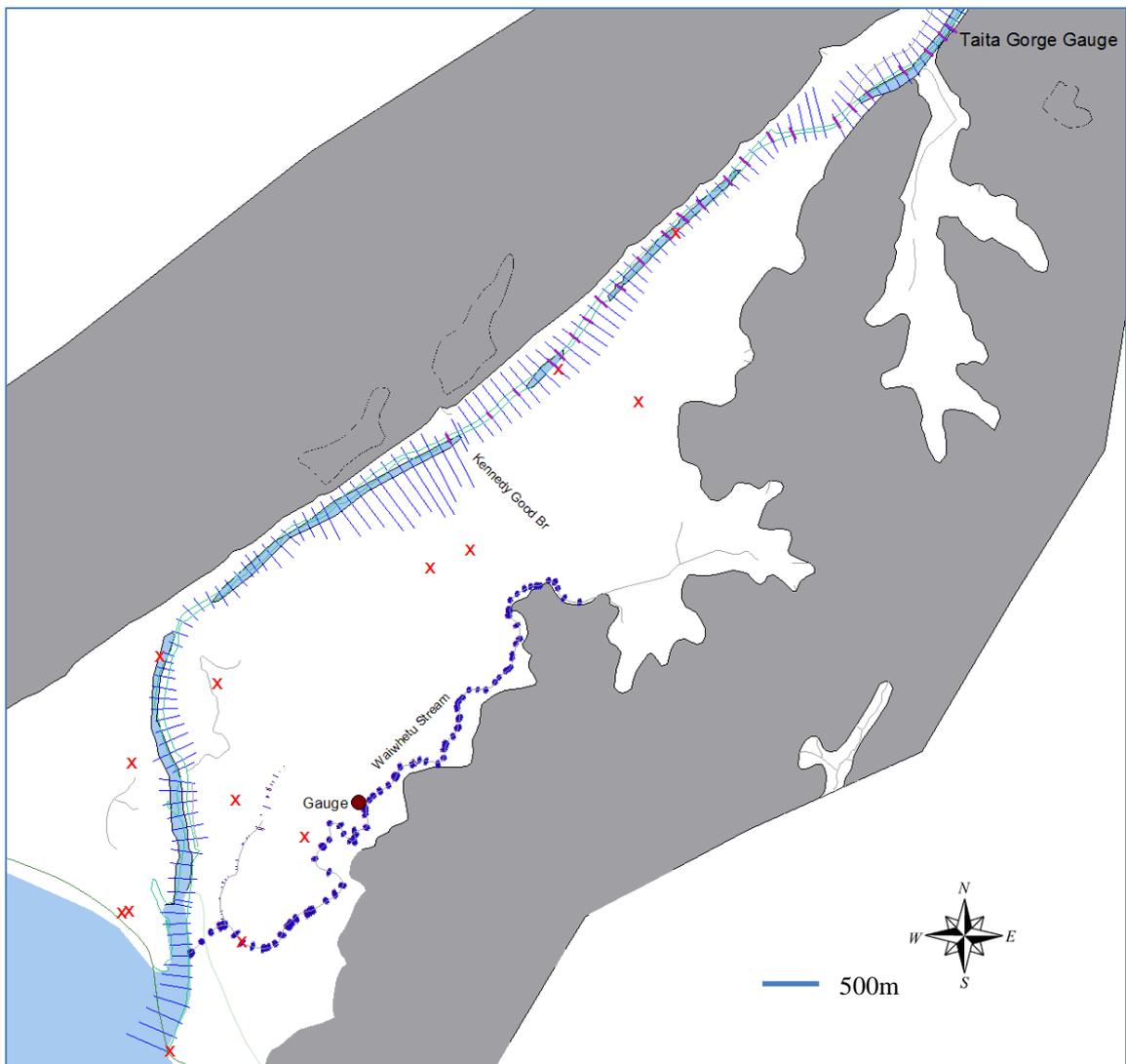
Figure 2.1: Hutt River and Waiwhetu Stream GWRC flood protection survey cross-section locations. Groundwater level monitoring sites shown as red crosses.
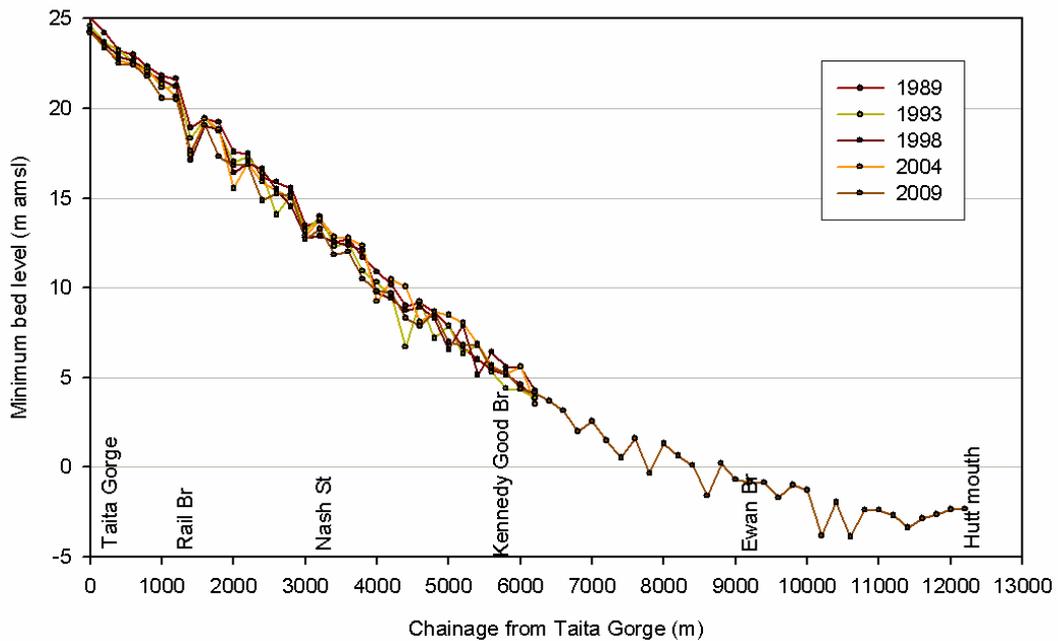
Figure 2.2: Bed elevation profile of the Hutt River between Taita Gorge and the coastline for various GWRC surveys between 1989 and 2009.

The surveys show a fairly consistent annual accumulation of gravel averaging about 50,000m^3/year. In 2005 the extraction rate was increased to 80,000 m^3/year following the January 2005 flood (during which the maximum recorded flow occurred). The objective of the current gravel extraction policy is to maintain the bed to approximately 1998 levels. The implications of gravel abstraction and bed level management on the recharge dynamics to the groundwater environment will be explored using the HAM3 groundwater model.

2.2 WAIWHETU STREAM

The Waiwhetu Stream (Figure 2.1), a small tributary of the Hutt River in its lower reach, was an historically significant, navigable watercourse prior to the uplift associated with the 1855 earthquake. Sourced in the Eastern Hutt hills above the suburb of Naenae, where the stream emerges into the valley floor, the catchment is now highly urbanised and stormwater is diverted into the stream. Baseflow is regarded to be derived from groundwater, both on the valley floor and in the upper parts of the catchment. The GWRC gauge is located at Whites Line East about 3km upstream of the confluence with the Hutt River (shown on Figure 2.2), so it is not possible to evaluate the groundwater input to the stream on the valley flats. The mean flow at the gauge is about 300 L/sec (affected by urban runoff) and the 2-year low flow is 50 L/sec, which may be indicative of the groundwater-sustained baseflow.

2.3 MARINE ENVIRONMENT

The Lower Hutt groundwater basin extends offshore and lies beneath Wellington Harbour. Characterisation of the offshore physical marine environment in terms of bathymetry, sedimentation and submarine groundwater discharge are therefore important considerations in the analysis of the onshore part of the groundwater environment.

The National Institute of Water and Atmospheric Science (NIWA), in association with GWRC and DOC, have mapped the harbour bathymetry using high-accuracy multibeam sonar (NIWA, 2009). Figure 2.3 shows the results of the survey to illustrate the morphology of the harbour floor. The maximum water depth of 20-25m occurs in the central part of harbour, whilst along the northern edge and at the harbour entrance it shallows to 10-15m or so. Figure 2.3 (and also Figure 1.1) highlights the locations of freshwater spring vents – particularly around the Hutt River mouth, off Point Howard wharf and around Somes Island. The spring vents represent freshwater discharge from underlying confined aquifers; their location and characteristics are important in the management of the onshore groundwater resource.
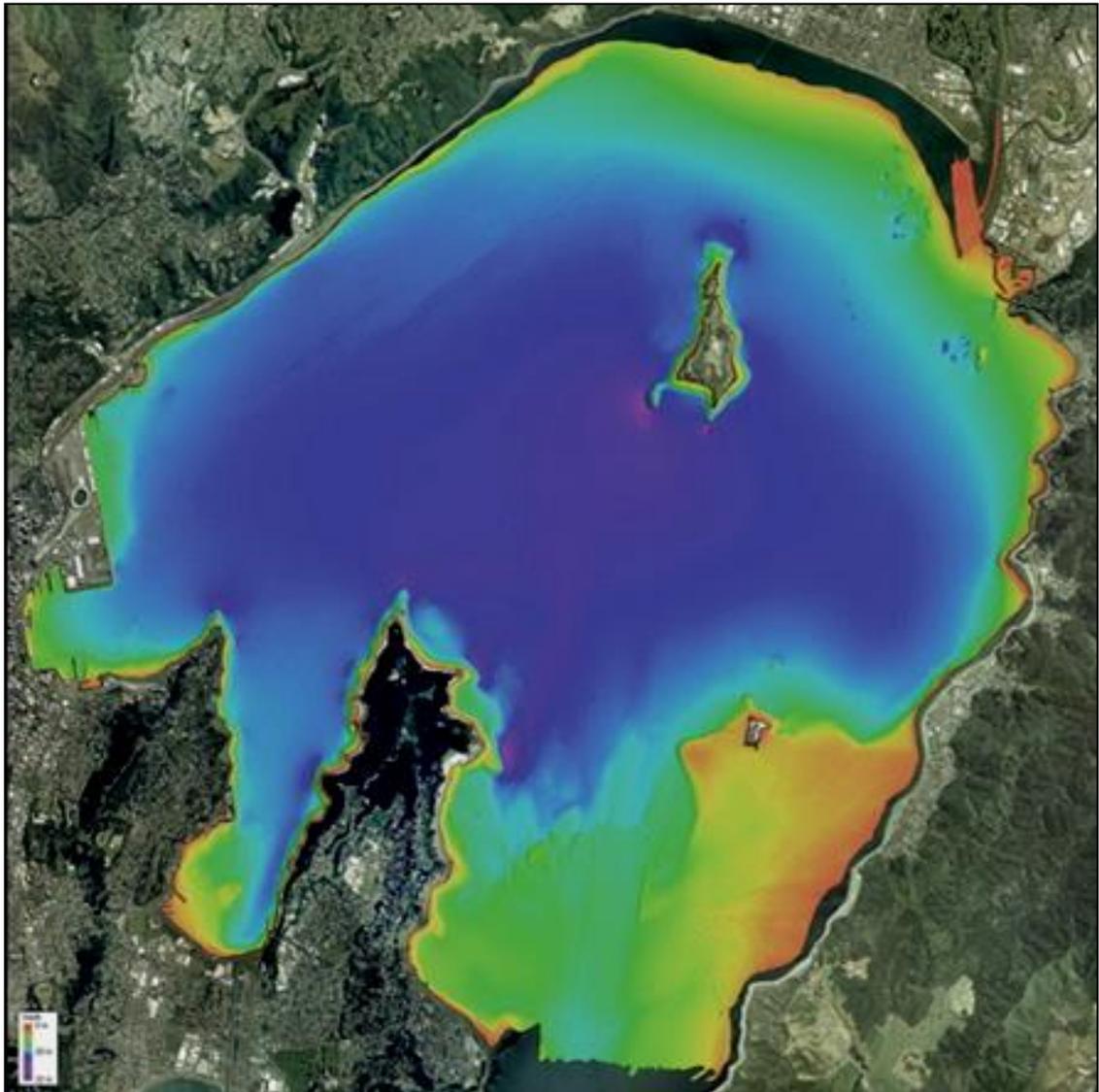
Figure 2.3: Wellington harbour bathymetry image (darker colours – blues – represent deeper water). Submarine spring vents can be clearly identified close to the Petone foreshore and around Somes Island (from NIWA, 2009).

The harbour receives sediment primarily from the Hutt River, mostly in the form of silt and clay, thereby thickening the low-permeability harbour substrate. Currents also bring sand and gravel into the harbour entrance from Cook Strait. Wind, tides, currents and longshore drift help to redistribute the sediment and wind direction determines where most sediment from the Hutt River is deposited. Northerly and southerly winds

mostly confine sediment to the northern and eastern parts of the harbour, although fine sediment gets circulated by tides. The present sedimentation rate off the Petone foreshore is estimated to be about 60mm/year whilst the average for the harbour is about 30 mm/year (Goff and Dunbar, 1996).

Coarse sediment brought in through the harbour entrance by longshore drift tends to move along the submarine platform on the eastern side of the harbour assisted by southerly storms and interfingers with mud from the Hutt River in the vicinity of Ward Island. The sand-mud boundary is located in the vicinity of Ward Island.

Groundwater discharge in the form of submarine springs is of particular interest to the present study. The harbour bathymetry data is especially useful in determining the locations and morphology of spring vents and has helped to determine that the likely source of freshwater is the Waiwhetu artesian aquifer. Harding (2000) investigated spring vent activity and tentatively quantified the flow rates. Section 4.5.1 provides further detailed discussion on submarine aquifer discharge.

3 LOWER HUTT GROUNDWATER ZONE – GEOLOGY AND HYDROSTRATIGRAPHY

3.1 INTRODUCTION

The Lower Hutt Groundwater Zone occupies a sedimentary basin which encompasses the floodplain area of the Lower Hutt valley floor and most of Wellington harbour – extending from Taita Gorge in the north to the harbour entrance area in the south. Gravel-rich horizons in thick sequence of alluvial and glacial outwash sediments infilling the basin host a significant groundwater resource. The confined Waiwhetu Aquifer is an extraordinarily transmissive and laterally extensive alluvial gravel sheet which sustains a significant proportion (>40%) of the municipal water demand for the Wellington Region.

Figure 1.1 shows the spatial extent of the Lower Hutt Groundwater Zone including primary surface water features, flow gauging sites, groundwater level monitoring sites and major abstraction wells.

3.2 GEOLOGICAL SETTING

The geology of the Wellington Region has been intensively investigated and a good summary is contained in the memoirs accompanying the 1:50,000 geological map (Begg and Mazengarb, 1996), and the 1:250, 000 scale 'Q map' (Begg and Johnson, 2000). These maps, along with the accompanying documentation, represent the base geological data used in this study.

Geological data in the form of bore logs, combined with an analysis of the depositional environment, have been used to define the geometry of the groundwater zone and characterise the constituent hydrogeological units.

3.2.1 BASIN MORPHOLOGY

The Hutt Valley – Wellington Harbour alluvial basin is the southernmost and largest of a series of basins associated with the Wellington Fault. The total length of the basin between Taita Gorge and the harbour entrance is approximately 23km. It is a broadly wedge-shaped structure tapering from its widest extent of around 9.5km across the harbour, to about 5km wide at the Petone foreshore and then narrowing to only a few hundred metres in width at Taita Gorge. The western and deepest side of the basin is controlled by Wellington Fault where subsidence has created a sub-vertical basin margin more than 300m deep in places. It is probable that the Wellington Fault has disrupted and displaced the basin fill sediments adjacent to the fault. The Somes Island ridge is a notable basement high which is a fault-bounded horst structure that traverses the basin obliquely and displaces younger sediments (Begg et al., 2008).

The basin bedrock is composed of Permian to Jurassic (280-200 million years old) Torlesse greywacke – a hard metamorphosed sandstone, siltstone and mudstone sequence. Although the greywacke is extensively fractured, it exhibits low permeability and is not regarded to significantly contribute to regional groundwater circulation (WRC, 1995).

3.2.2 QUATERNARY BASIN FILL SEQUENCE AND HYDROSTRATIGRAPHY

The Hutt River has deposited sediment into the Lower Hutt-Wellington Harbour basin over a considerable period of time from about the middle and later Quaternary period to the present (over the last 500,000 years). The sedimentary sequence is associated with the progradation of a delta into a subsiding basin centred on the harbour. Marine sediments were also deposited further up the valley during periods of higher sea level (interglacial periods) and as a result of tectonic subsidence. A c.350m thick wedge-shaped package of alluvial-deltaic-marginal marine sediments at the Petone coastline becomes thicker offshore where it exceeds 600m between Somes Island and the Wellington Fault.

The onshore basin fill succession was first characterised by Stevens (1956) using the large quantity of subsurface information available at that time. He called the fill sequence the 'Hutt Formation' which is comprised of six members:

- Taita Alluvium (Q1[1])
- Melling Peat (Q1)
- Petone Marine Beds (Q1)
- Waiwhetu Artesian Gravels (Q2-4, last glacial)
- Wilford Shell Beds (Q5, last interglacial)
- Moera Basal Gravels (Q6-7, penultimate glacial)

An older, undefined sequence of basal gravels (Q8-Q10?) is present in the deeper parts of the basin, and is associated with earlier glacial and interglacial cycles.

Figure 3.1 shows a three-dimensional representation of the sediments of the Lower Hutt basin from the Petone foreshore to Knights Road based on drillhole information (from Begg and Mazengarb, 1996).

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[1] 'Q' numbers refer to oxygen isotope age stages (Imbrie et al., 1984). 18O is assumed to vary with climate and sea level - even values represent cold periods (eg Q2, Q4, Q6), and odd numbers (eg Q1, Q5) represent warm periods of maximum sea level.
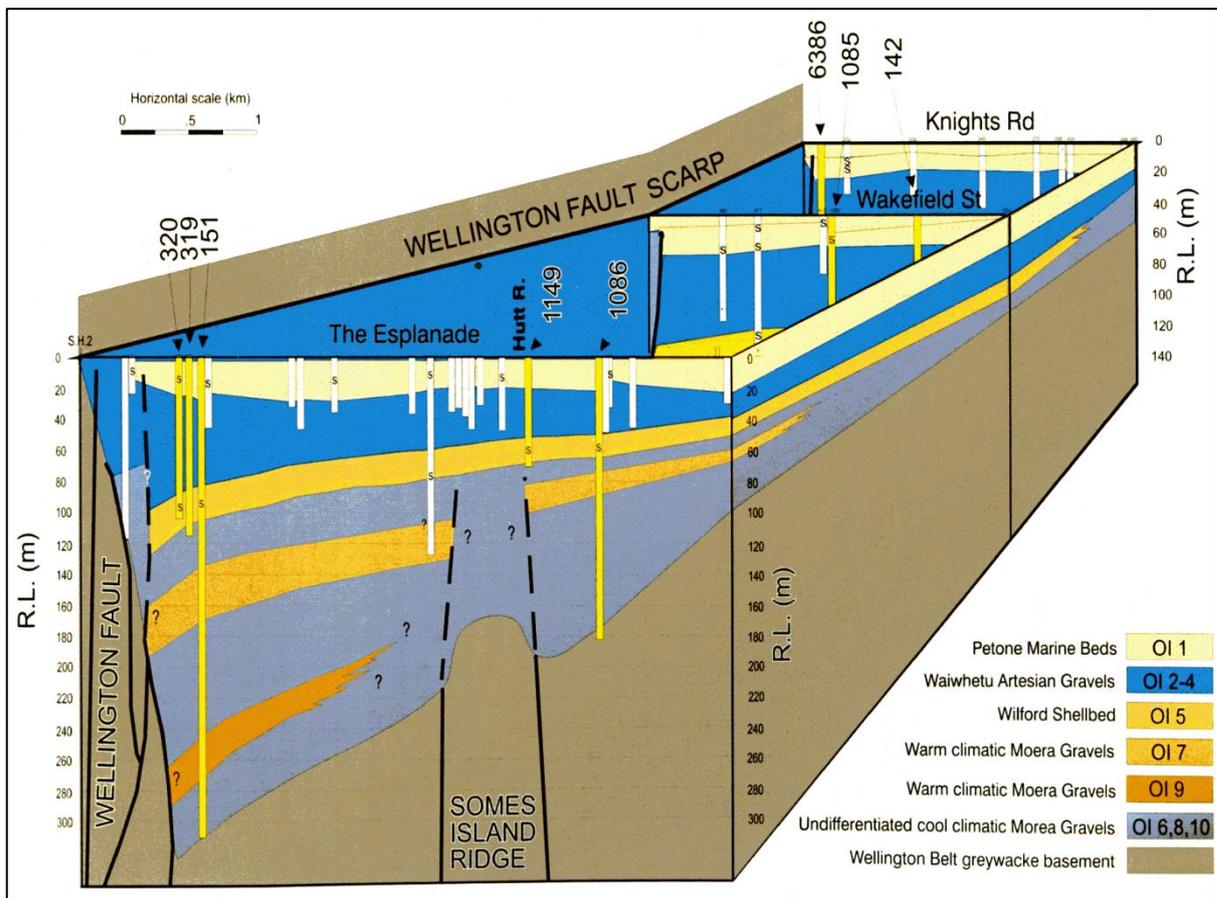
Figure 3.1: Three-dimensional representation of the sediments of the Lower Hutt basin from the Petone foreshore to Knights Road based on drillhole information (Begg and Mazengarb, 1996).

3.2.2.1   **Holocene deposits – Taita Alluvium, Melling Peat and Petone Marine Beds (Q1)**

The youngest three units of the Hutt Formation – Taita Alluvium, Melling Peat and Petone Marine Beds – are of postglacial Holocene age (<10,000 years old) and are semi-contemporaneous since they exhibit a degree of lateral equivalence in response to changing depositional environments. The Petone Marine Beds and Taita Alluvium continue to be deposited at the present time on the harbour floor and on the Hutt River floodplain respectively.

The postglacial Taita Alluvium deposits were defined by Stevens (1956) to include all postglacial fluvial deposits filling the Hutt Valley downstream of Taita Gorge, including the recent river alluvium. The alluvium consists mainly of buried river channel and fan gravel deposits but also includes sand, silt and clay deposited by the river as flood and over-bank deposits. Donaldson and Campbell (1977) interpreted an average thickness of 12m for this unit which dips gently to the southwest.

The Taita Alluvium grades laterally into Melling Peat which outcrops in the bed of the Hutt River for about 400m upstream of Melling Bridge (about 4.5km inland from the coastline). The peat represents a fossil forest which, along with sand, gravel and silt, youngs towards the coast (Boon et al., 2010). South of Melling Bridge, around Lower Hutt City, the peats grade laterally into the Petone Marine Beds which are dominated by

clays, shelly silts and sandy silts. The marine beds are about 30m thick at the Petone foreshore and extend into the harbour where they continue to accumulate.

3.2.2.2 Last Glacial Deposits – Waiwhetu Gravels (Q2-4)

Extensive cold-climate alluvial deposits known as the Waiwhetu Gravels underlie the Holocene sediments at a depth of around 20-30m below ground surface in the foreshore area. These gravels form the principal aquifer in the Lower Hutt valley and are confined by the younger Petone Marine Beds and Melling Peat. The confining beds pinch out between Ewen Bridge and Kennedy Good Bridge (Figure 1.1) in the Mitchell Park area – further to the north the aquifer becomes unconfined.

 The Waiwhetu Gravels accumulated in a braided fluviatile environment and comprise coarse, well-sorted, rounded water-bearing river gravels deposited under high energy conditions during the last glaciation (Otiran, oxygen isotope stages Q2-4). They extend from Taita Gorge to the Petone foreshore and under much of the harbour. Onshore, the formation attains a maximum thickness of about 55m on the western side of the Hutt Valley but elsewhere it is typically between 30m and 50m thick. Beneath the harbour the gravels are thicker in the north and west, and shallower in the south and east as a result of concentrated deposition in the deeper part of the basin along the Wellington Fault. Offshore geophysical interpretations (Davy and Wood, 1993) suggest that the gravels are around 20m thick on the eastern side of the harbour, thickening to as much as 70m alongside the fault in the west of the harbour. Evidence of prominent palaeochannels from the seismic surveys suggests that the river has historically remained close to the Wellington Fault depositing a large thickness of gravels in this area. However, the river appears to have later shifted to the east of Somes Island as shown by the presence of a major palaeochannel towards the top of the gravels.

Donsaldon and Campbell (1977) noted that although extensive in area and depth, the water-bearing capacity of the Waiwhetu Gravels seems to decrease with depth and in most wells only the upper c.20-25m of the layer has a high flow capability. This observation was supported by the detailed logging and water quality sampling of a deep exploration well at Marsden Street near Ewen Bridge (Brown and Jones, 2000) and through re-interpretation of bore logs by Brown during the HAM2 project (Phreatos, 2000). These studies revealed a laterally persistent silt and clay unit within the Waiwhetu Gravels effectively dividing it into two distinct parts – loosely termed the *Upper Waiwhetu* and the *Lower Waiwhetu* gravels. The Lower Waiwhetu Gravels have a gritty clay, silt and sand matrix and down-hole neutron logging in bore R27/6386 shows higher silt and sand content compared with the Upper Waiwhetu Gravels.

An intra-Waiwhetu aquitard is identified at a depth interval of 46.3 to 54.0m in bore R27/6386 (Marsden Street; Brown and Jones, 2000) and consists of sand, silt and clay with interbedded carbonaceous material. The unit is recognisable some other deep bores, being typically up to 10m thick and occurring at a depth range of 40 to 70m, although it does not appear to be present everywhere. It is probably associated with deposition during a period of warmer climate (interstadial – possibly Q3) and a higher sea level stand. The similarity in heads between the upper and lower parts of the Waiwhetu Gravels (at McEwan Park and Tamatoa on the foreshore) suggests that the interstadial unit does not form an effective aquitard. However, different hydraulic properties in the Lower Waiwhetu Gravels appear to significantly affect groundwater

flows as shown by differing chemical and isotopic signatures of groundwater above and below the aquitard (Brown and Jones 2000). Small increases in anions and cations are evident in the Lower Waiwhetu Gravels together with a slight increase in conductivity and pH. Tritium dating of groundwater from the Upper Waiwhetu Gravels indicates an age of < 2.5 years (42.3 m), whilst groundwater below the aquitard has been dated at about 45 years (66.4 m).

No deep test bores have been drilled inland of Lower Hutt City. As a result there is no direct knowledge of the Waiwhetu Gravel characteristics in this area.

3.2.2.3 Last Interglacial Deposits – Wilford Shell Beds (Q5)

The Wilford Shell Bed is a 15-30m thick marine, shelly, silty sand which can be traced across the lower part of the valley beneath the Waiwhetu Gravels. The unit is recorded at depths of 70 to 83m at the Petone foreshore, decreasing in depth and thickness inland – presumably on-lapping the northern and eastern basin margins where it pinches out against older sediments. The geographic distribution of the 12 drillholes penetrating the Wilford Shell Bed is restricted, but the inland extension of the unit appears to be around Knights Road about 4.5 km inland from the Petone foreshore.

The Wilford Shell Bed was deposited during the high sea levels associated with the last interglacial period (Q5, Kaihinu). An estuary tidal channel depositional environment is indicated by the shells present within these deposits and associated interglacial peat, peaty sand, silt and clay (coastal swamp/estuary palaeoenvironment) occur inland as far as Mitchell Park.

A distinctive change in the hydraulic properties, hydraulic head and water chemistry recorded in bores screened above and below this unit is apparent. This suggests that the Wilford Shell Bed is continuous and acts as a low-permeability aquitard separating the Lower Waiwhetu Gravels from the underlying Moera Gravels.

3.2.2.4 Older sediments

Stevens (1956) termed the non-marine weathered gravels beneath the Wilford Shell Bed the 'Moera Basal Gravels'. Begg and Mazengarb (1996) identified this unit as being associated with the Waimea Glacial age (Q6, 130,000 -180,000 years BP) and preceding interglacial period (Q7), and occurring between about 100 and 160m depth at the Petone foreshore. The term 'Moera Basal Gravels' is used here to refer to only these two units. Below this, Boon et al. (2010) postulate an older sequence of glacial and interglacial deposits (Q8-Q10) lying on top of the greywacke basement surface. WRC (1995) and Hutton (1965) also identified two groundwater units within the basal gravels on the basis of hydrogeological and hydrochemical properties. These were an upper unit of between 16 and 60m thick and a deeper unit containing brackish or saline water. The units have comparable hydraulic pressures indicating a complete hydraulic connection.

3.2.3 HYDROSTRATIGRAPHY SUMMARY

The geological sequence described above provides a hydrostratigraphic framework for the Lower Hutt Groundwater Zone as a basis for the numerical modelling of the groundwater system. Distinctive and laterally continuous litho-stratigraphic units can be identified in the basin, essentially representing a sequence of confined aquifers and aquitards in the lower part of the Hutt Valley, and a coalescing unconfined to semi-confined gravel-dominated sequence in the upper part of the valley. On the basis of the geological characterisation, the seven hydrostratigraphic units listed in Table 3.1 are recognised.

Table 3.1: Hydrostratigraphic Units of the Lower Hutt Groundwater Zone

Unit	General hydrogeological nature	Distribution	Max thickness (m)	GNS geological model unit no. (Boon et al., 2010)
Taita Alluvium	Highly variable laterally semi-contemporaneous. Taita Alluvium is locally a loose coarse gravel with high transmissivities forming an unconfined aquifer in the north.	Forms floor of the Hutt valley.	~ 25-30	2
Melling Peat Petone Marine Beds	Melling Peats and Petone Marine Beds are dominated by organic sediments, silts, sands and local gravels; overall represent leaky aquitard unit.	Deposits thicken as a low permeability wedge from about 5km inland of Petone foreshore. Petone Marine Beds form harbour floor and continue to accumulate.	0-30	2
Upper Waiwhetu Gravels	Coarse highly permeable gravels – principal aquifer	Throughout entire valley and sub-harbour	20-55	3
Lower Waiwhetu Gravels	Matrix-rich gravels, significantly lower permeability than Upper Waiwhetu Gravels.	Throughout entire valley and sub-harbour basin	10-20	3
Wilford Shell Beds	Predominantly silts and sands, an aquiclude separating the Waiwhetu and Moera Basal gravels.	From around Knights Road (3km from foreshore) extending into sub-harbour basin	~ 30	4
Moera Basal Gravels	Matrix-rich gravel aquifer, moderate resource potential	Throughout entire valley and sub-harbour	~60	5
Older Deposits	Sequence of compact gravels, silts, sands and clays	Sub-harbour basin, extending onshore at depth	>100	6
Basement Greywacke	Hard rock, minor fracture-controlled secondary permeability, generally regarded to be 'groundwater basement'.	Entire basin		7

3.2.4 THREE DIMENSIONAL GEOLOGICAL MODEL

The abundance of onshore historic drilling information (mostly water wells) and the results of onshore and offshore geophysical surveys enable the basin morphology and geological sequences to be modelled with relative confidence. A three-dimensional geological model for the Lower Hutt Basin, developed by GNS Science (Boon et al., 2010) for the purposes of geotechnical characterisation and seismic hazard assessment, represents the most recent analysis of the basin. This model integrates all reliable pre-existing and newly acquired geological, geotechnical and geophysical data into a 7-layer 3D engineering model based on a network of cross-sections. The primary data source for the model was the GNS Hutt Valley Drillhole Database which contains some 846 drillhole records – largely derived from GWRC databases. The construction of geological model also utilised a Digital Terrain Model (DTM) to represent the ground surface based on aerial LIDAR, in addition to topographic data of the valley floor collected by GWRC.

The layer boundaries and unit definitions used in the geological model are listed in Table 3.2 and Figure 3.2 shows an exploded view of the model.

Table 3.2: GNS 3-D geological model unit definitions

Unit no.	Stratigraphic name	Approx. age (years)	Max. modelled thickness (m)
Unit 1	Reclaimed land	0-100	5-30
Unit 2	Taita Alluvium Melling Peat Petone Marine Beds Alluvial fans	Holocene (Q1) < ~ 10ka	~40
Unit 3	Waiwhetu Gravels	Otira Glaciation (Q2-4) 10 -70ka	~60
Unit 4	Wilford Shell Bed	Kaihinui Interglacial (Q5) 70-128ka	~30
Unit 5	Waimea Glacial ('Moera Gravels')	Waimea Glacial and Karoro Interglacial (Q6-7) 128-245ka	~60
Unit 6	Older sediment infill sequence	Q8-10 245->380ka	~210
Unit 7	Greywacke basement	159-290Ma Permian-Mid Jurassic	300-600
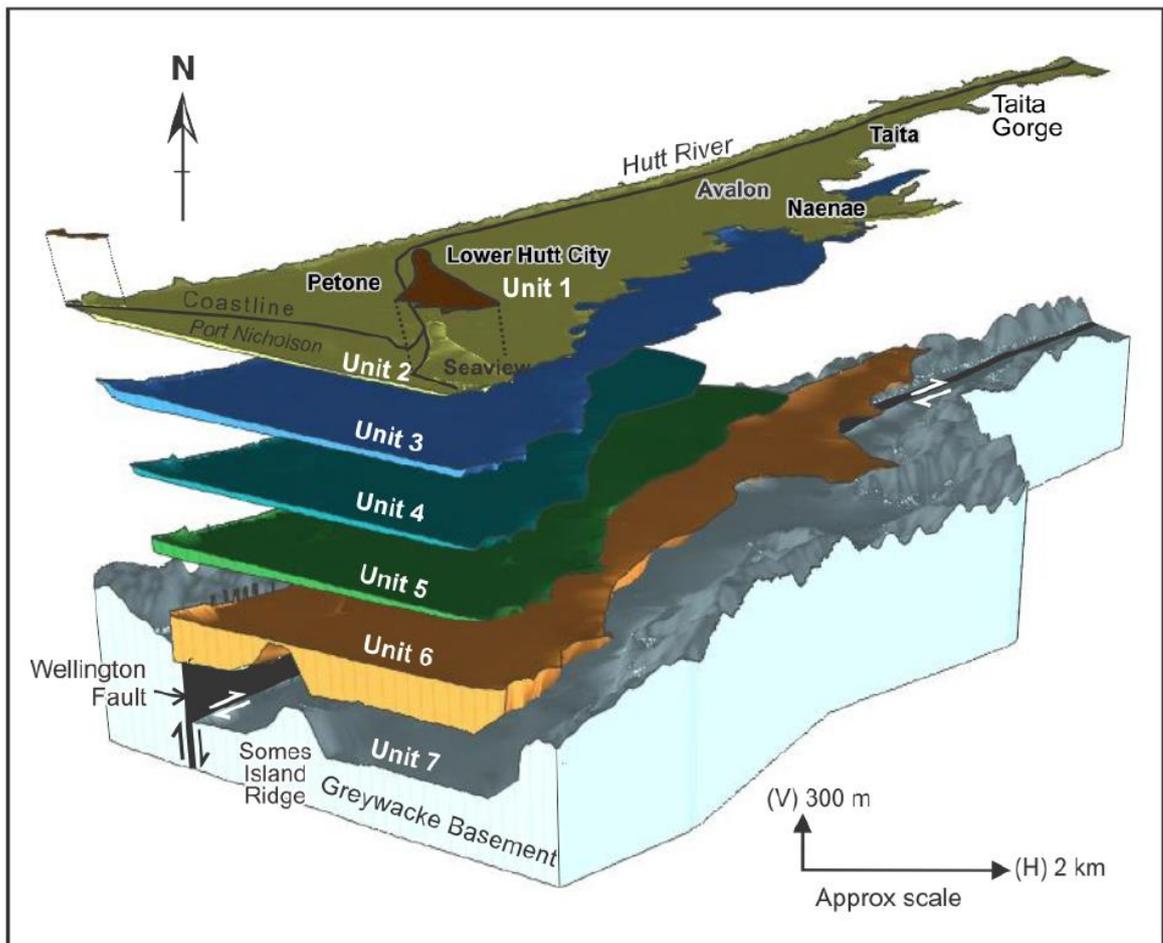
Figure 3.2: Exploded view of the GNS Lower Hutt valley engineering model looking north (Boon et al., 2010).

The GNS geological model incorporates the best information available for mapping the internal layer structure of the onshore portion of the basin and has been used to assist the construction of the new groundwater flow model (HAM3). The offshore, sub-harbour, part of the basin has been characterised by the extensive seismic reflection geophysical surveying carried out by Wood and Davey (1992) to define the basement structure and trace the location of the Wellington Fault.

Figure 3.3 shows the Lower Hutt – Wellington Harbour basin structure (top of greywacke basement, Unit 7) interpreted by combining the onshore GNS model with the offshore geophysical interpretive model (Wood and Davey, 1992; Davey and Wood, 1993). The combined model shows a significant offshore deepening of the basin to more than 600m on either side of the prominent Somes Island basement ridge. The basin shallows considerably to the south which is likely to be associated with a rising structure between Rongotai (the former harbour entrance) and the present harbour entrance around Falcon Shoal (Stevens, 1956; Wood and Davey, 1992).
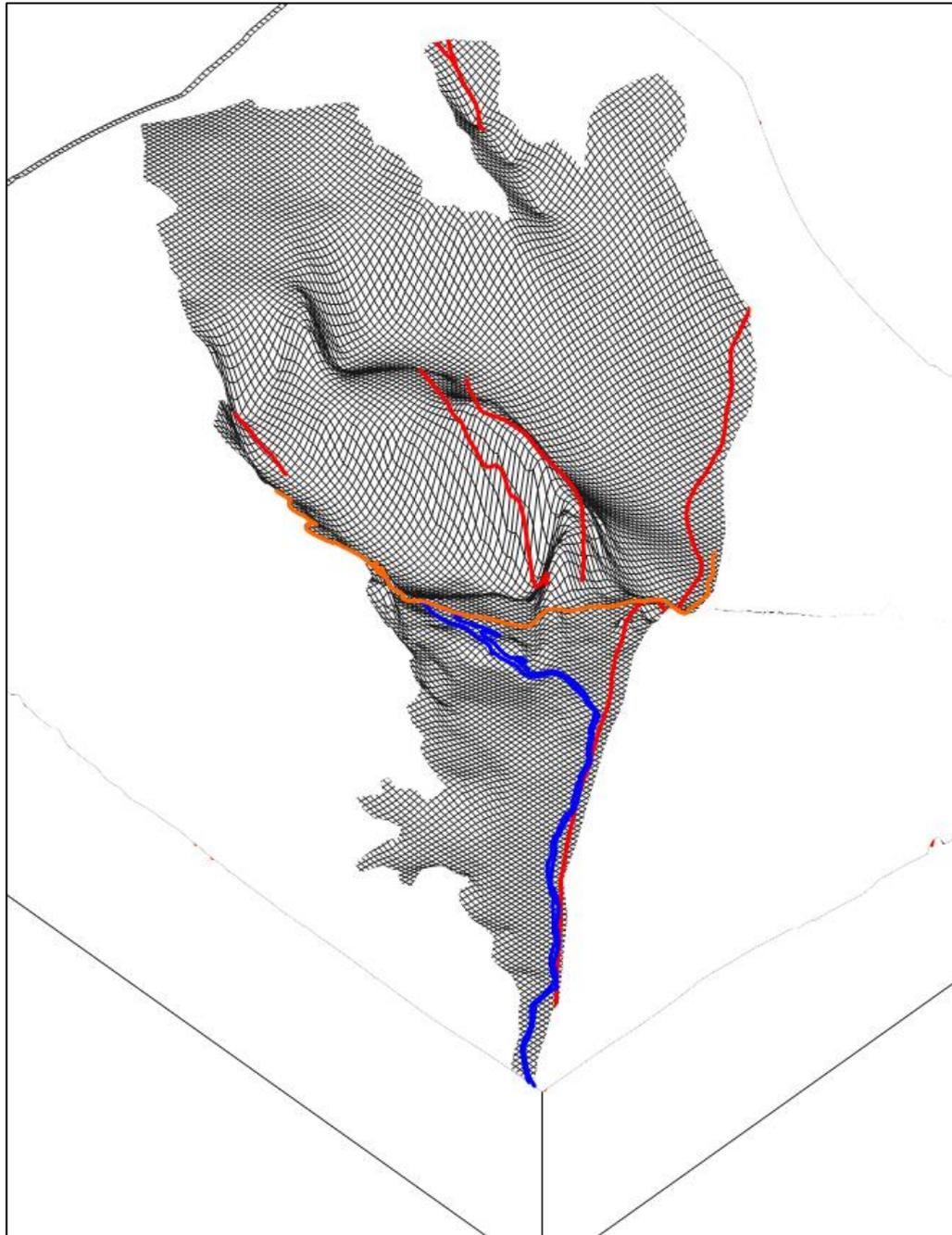
Figure 3.3: Modelled greywacke basement surface (top of Unit 7) based on onshore GNS 3D geological model and offshore geophysical survey interpretations. View looking to the southwest from Taita Gorge in foreground. The Hutt River is shown in blue, coastline at Petone in orange, and red lines are active faults.

4 LOWER HUTT GROUNDWATER ZONE – HYDROGEOLOGY

4.1 GROUNDWATER LEVELS AND FLOWS

4.1.1 MONITORING

The GWRC maintain a groundwater level monitoring network for the Lower Hutt Groundwater Zone comprising automatic and manually recorded observation bores. Additional groundwater level sites were established to assist the HAM3 project (see Section 1.3.1 on project fieldwork activities) which entailed the installation of water level logging equipment in existing bores (mostly dis-established monitoring sites), and the construction of new piezometers. Table 4.1 lists the 29 groundwater monitoring sites used in the HAM3 project; their locations are shown on Figure 4.1.
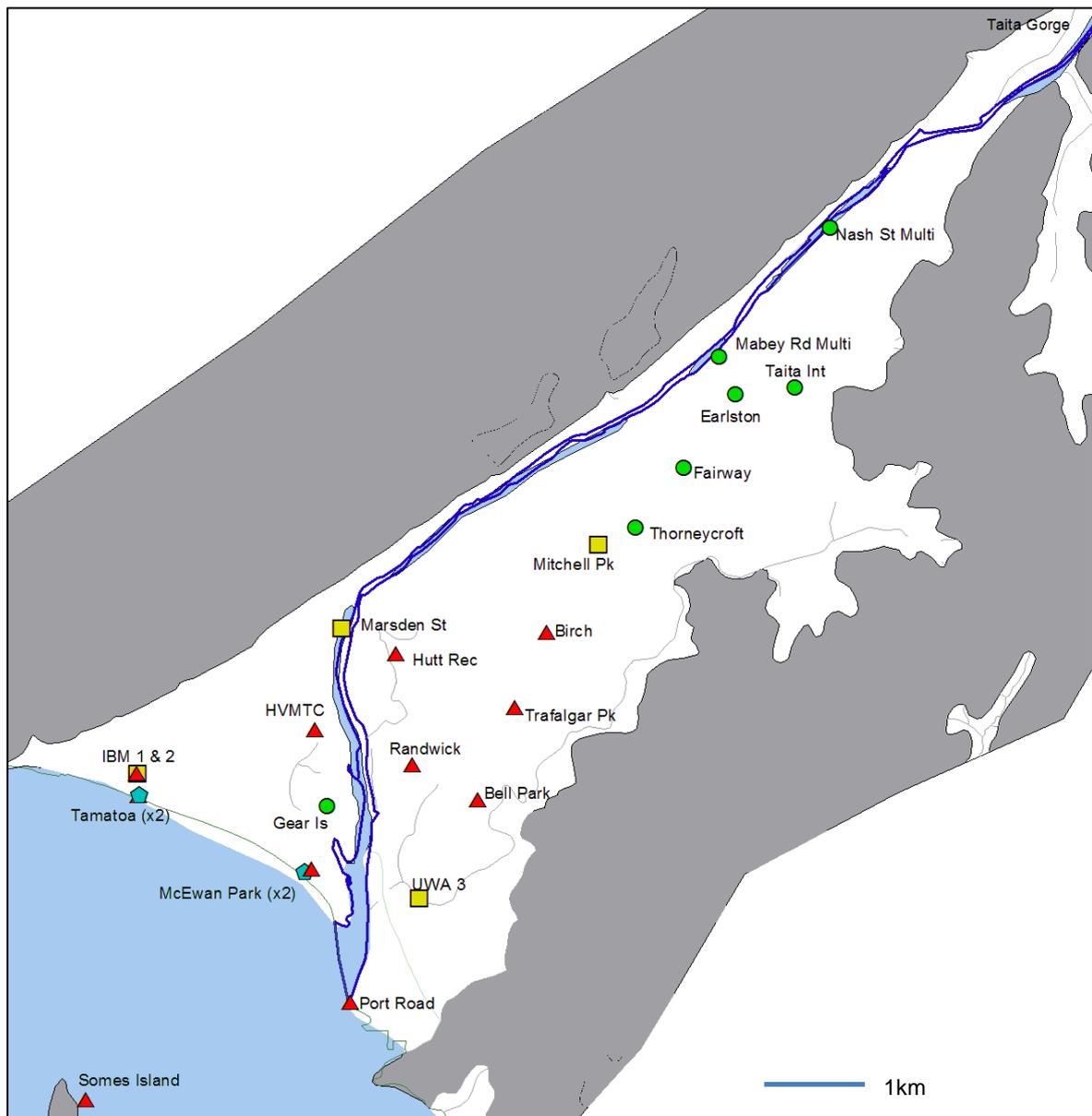
Figure 4.1: Locations of groundwater level monitoring sites in Lower Hutt. Green circles – Taita Alluvium; yellow squares – Moera Gravels; red triangles – Upper Waiwhetu Aquifer; blue hexagons – Lower Waiwhetu Aquifer.

Table 4.1 : Groundwater level monitoring sites in the Lower Hutt Groundwater Basin

Bore ID	Site Name	Depth (m)	Aquifer	Type*	Record length
R27/1123	Bell Park	23.2	Waiwhetu (U)	Auto (closed) Temp (HAM3) – Auto	23/7/75-6/12/95 29/2/12-30/1/13
R27/6097	Birch Lane	47.	Waiwhetu (U)	Auto (closed) Temp (HAM3) – Auto	23/7/75-25/5/94 18/4/12-10/10/12
R27/6980	Earlston	8.4	Taita Alluvium	Man (closed)	11/2/93-2/9/04
R27/6981	Fairway Drive	10.1	Taita Alluvium	Man (closed)	11/2/93-18/5/05
BQ32/0041	Gear Is U/C	7.6	Taita Alluvium	Temp (HAM3) – Auto	25/4/12-30/1/13
R27/1115	Hutt Rec	23.5	Waiwhetu (U)	Auto (open)	15/12/67-
R27/0120	HVMTC	29.6	Waiwhetu (U)	Auto (open)	24/8/68-
R27/0320	IBM1	106-112	Moera	Auto (open)	30/9/92-
R27/1265	IBM2	37.48	Waiwhetu (U)	Auto (open)	8/7/92-
BQ32/0031 BQ32/0030 BQ32/0020	Mabey_7 Mabey_13 Mabey_20	7 13 20	Taita Alluvium- Waiwhetu (U)	New (HAM3) – Auto	7/3/12-
R27/6386	Marsden St	106-115	Moera	Auto (open)	1/5/00-
R27/7153	McEwan Park (Deep)	33.44	Waiwhetu (L)	Auto (open)	14/3/08-
R27/0122	McEwan Park (Shallow)	28.4-29.6	Waiwhetu (U)	Auto (open)	1971-
R27/1116	Mitchell Park	51.8	Moera (?)	Auto (open)	24/8/68-
BQ32/0029 BQ32/0028 BQ32/0023	Nash_7 Nash_13 Nash_20	7 13 20	Taita Alluvium- Waiwhetu (U)	New (HAM3) – Auto	29/2/12-
R27/1223	Nevis St*	46.9?	(leaking?)	Man (open)	8/7/92-
R27/0121	PCM	26.2	Waiwhetu (U)	Auto (closed)	1968-29/5/96
R27/1118	Port Road	28.7	Waiwhetu (U)	Auto (closed) Temp (HAM3)	2/5/70-1997 29/2/12-30/1/13
R27/1122	Randwick	24.4	Waiwhetu (U)	Auto (open)	4/6/75-
R27/1171	Somes Is	23.2	Waiwhetu (U) offshore	Auto (open)	1969-
R27/1117	Taita Int	14.4	Taita Alluvium	Auto (open)	24/9/68-
R27/7215	Tamatoa (Deep)	56.2-57	Waiwhetu (L)	Auto (open)	5/2/08-
R27/7154	Tamatoa (Shallow)	44-45	Waiwhetu (U)	Auto (open)	5/2/08-
R27/6982	Thorneycroft Av	9.3	Taita Alluvium	Auto (closed) Temp (HAM3) – Auto	11/2/93-26/10/05 29/2/12-30/1/13
R27/1121	Trafalgar Park	23	Waiwhetu (U)	Temp (HAM3) – Auto	29/2/12-30/1/13
R27/1086	UWA3	65.75	Moera	Auto (open)	24/2/97

Auto – automatic, continuously monitored; Man – manual, monthly; Temp (HAM3) – site temporarily established for HAM3 project; New (HAM3) – new permanent site installed for HAM3 project.
* Nevis Street monitoring bore is probably leaking – heads indicate a shallow unconfined aquifer response.

4.1.2 GROUNDWATER LEVELS

Groundwater levels in the Lower Hutt Groundwater Zone are influenced by a range of factors including river stage, rainfall recharge and abstraction rates. Tidal and barometric pressure variations also significantly affect levels in the confined aquifers.

4.1.2.1 Taita Alluvium

Groundwater level has been measured continuously at the Taita Intermediate site (R27/1117) since 1968. There has also been short-term monitoring at other sites between 1993 and 2005 and new permanent recording sites were constructed in 2012, as part of the present study, at Mabey Rd and Nash St adjacent to the river (Figure 4.1). Since the unconfined aquifer (Taita Alluvium) and the connected Hutt River constitiute the recharge sources for the downstream confined Waiwhetu Aquifer, it is important to enhance the hydrogeological characterisation of the unconfined aquifer area.

Long-term and short-term variations in groundwater levels in the Taita Alluvium are strongly influenced by the level in the Hutt River and, to a lesser extent, by localised rainfall. Figure 4.2 shows the long-term monitoring record for Taita Intermediate using 30-day and annual mean levels. The plot shows large amplitude fluctuations in mean groundwater level of about 0.7m. These long-term fluctuations can be related to changes in the Hutt River bed level which experiences cycles of degradation and aggradation. The cross-section survey information discussed in Section 2.1 shows a complex temporal and spatial bed level history.

The changes in the Hutt River bed and associated effects on the levels in the unconfined aquifer are of interest in terms of downstream effects on levels in the Waiwhetu Aquifer – particularly at the foreshore where management levels are set. Due to the masking effects of abstraction, evaluation of such downstream effects is not possible using monitoring data; the HAM3 model will, however, be used to explore the sensitivity of the confined aquifer levels to river bed levels in the unconfined aquifer (recharge) area.
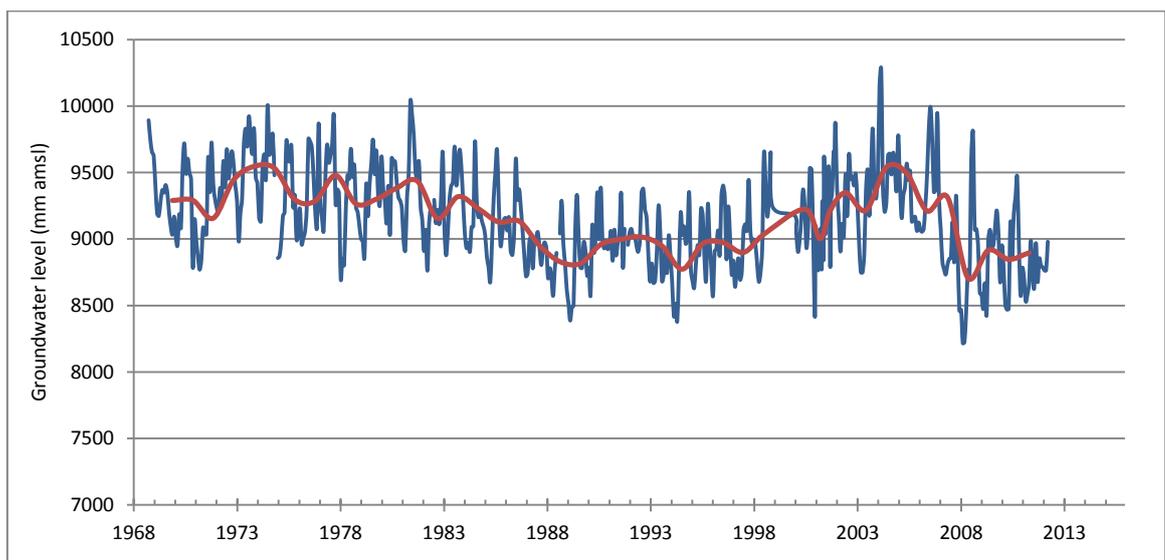
Figure 4.2: Long-term groundwater level record for Taita Intermediate site (30d and annual means plotted)

The Hutt River also exerts both short-term and seasonal effects on the groundwater level in the Taita Alluvium as shown in Figure 4.3. The unconfined aquifer reaches a summer low between about February and April each year corresponding to low river levels and low rainfall. The groundwater level variation between summer lows and winter highs is 1-2m. Figure 4.3 also shows that the aquifer is very responsive to peaks in river flow illustrating a high degree of connectivity between the river and the aquifer.
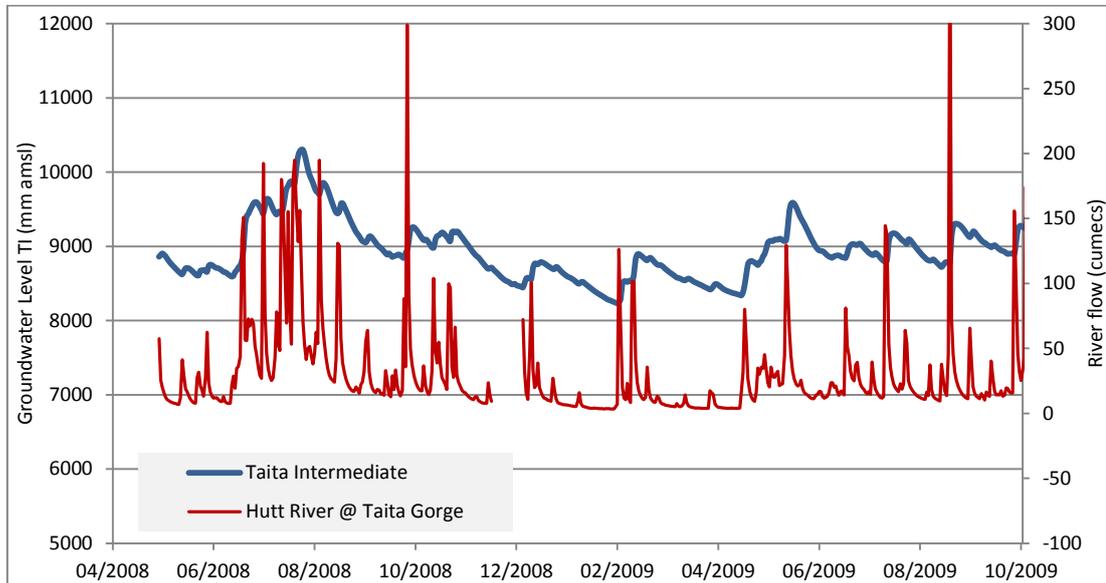
Figure 4.3: Seasonal groundwater level variation in the Taita Alluvium and correlation with flow in the Hutt River

The monitoring results from multi-level piezometers adjacent to the river at Mabey Road and Nash Street, which were installed as part of this project's fieldwork programme (Section 1.3), enable a closer and more detailed examination of the relationship between the Hutt River stage and groundwater levels in the unconfined Taita Alluvium. Figure 4.4 shows monitoring data for August 2012: groundwater levels in the three Mabey Road piezometers (7, 13 and 20m depths), groundwater level at the Taita Intermediate monitoring site located some 850m from the river, and the stage in the Hutt River next to the Mabey Road piezometers (measured using a temporary pressure transducer in the river which was surveyed to the same datum as the groundwater monitoring sites). The Mabey Road piezometers demonstrate a downwards vertical gradient beneath the river bed; this section of river is known to lose significant flow to groundwater (Section 2.1). The head difference between the river level and the 7m and 13m piezometers is about 0.5m which equates to a vertical gradient across the river bed of about 0.18 (the vertical distance between the river bed level and the piezometer screen being about 2.8m). As expected, the Mabey Road groundwater levels mirror the river levels closely – the groundwater level response range being about 80% of the river level range. The more distant Taita Intermediate monitoring site exhibits a much more attenuated and lagged response to river level changes.
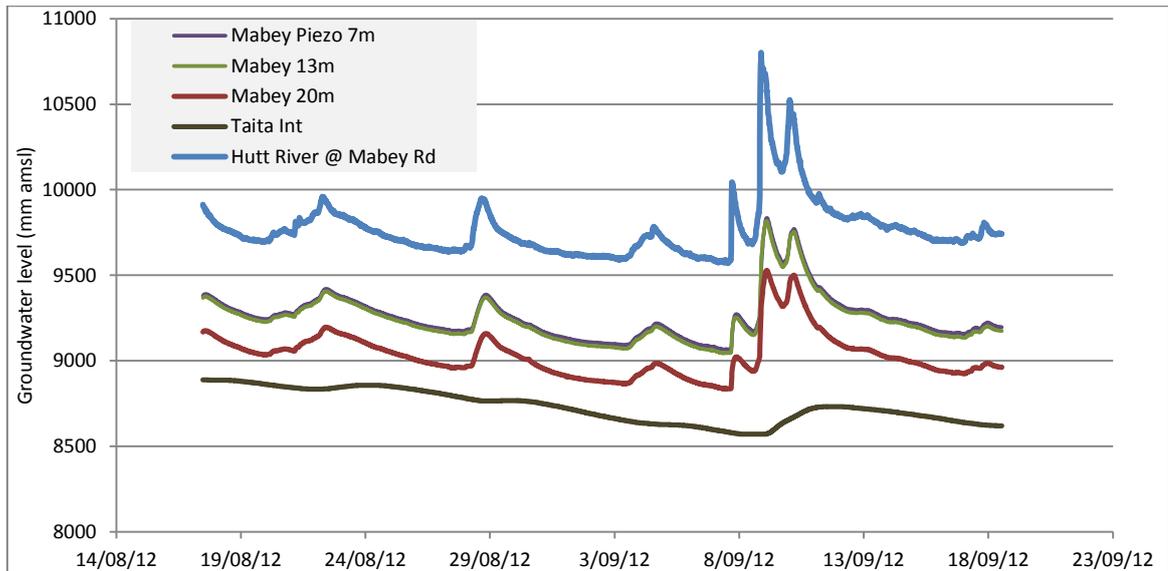
Figure 4.4: Monitoring of groundwater level in the new Mabey Road piezometers, groundwater level at Taita Intermediate and stage in the Hutt River adjacent to the riverside piezometers illustrating the vertical hydraulic gradients adjacent to the river (note: Mabey 7m and 13m overlie each other).

4.1.2.2 Waiwhetu Aquifer

The Waiwhetu Aquifer has an extensive network of 11 permanent groundwater level monitoring stations including the Somes Island monitoring site some 3km offshore (Figure 4.1 and Table 4.1). Most of these sites are screened in the top 10m of the aquifer (Upper Waiwhetu Aquifer) except for the new foreshore sites at McEwan Park Deep (R27/7153) and Tamatoa Deep (R27/7215) which are screened in the Lower Waiwhetu Aquifer adjacent to counterparts screened in the Upper Waiwhetu Aquifer. McEwan Park Deep and Tamatoa Deep were constructed in 2008 primarily to enhance saline intrusion monitoring.

The important point to note in terms of groundwater levels in the Waiwhetu Aquifer is that they are significantly masked by abstraction drawdown effects which extend across the entire valley and propagate into the unconfined area (levels are also influenced by tidal effects as discussed in detail below). It is therefore difficult to assess the natural groundwater level variability of the Waiwhetu Aquifer. The numerical groundwater flow model (described later in this report) can however be used to simulate a 'no-pumping' scenario to explore the natural behaviour of the groundwater system.

Figure 4.5 shows the long-term monitoring record for the McEwan Park monitoring site (R27/0122) on the Petone foreshore (plotted as 7-day and 12-month means) and also the available abstraction record for the municipal supply wells (monitoring commenced in 1994). The gradual rise in levels between 1970 and 1982 is associated with a progressive decrease in abstraction from the Waiwhetu Aquifer. Since the early 1980's consented abstraction has remained between about 113,000 and the current 95,000m^3/day. In 1981 the municipal bulk water supply bores were moved from the foreshore area at Gear Island and Seaview almost 3km inland to Waterloo (Figure 1.1). Therefore, the continued rise in foreshore piezometric levels between 1981 and 1984 may be attributable to the inland shift in abstraction. The abstraction monitoring record shown in Figure 4.5 shows the sensitivity of foreshore groundwater levels to abstraction

Lower Hutt Aquifer Model Revision (HAM3): Sustainable Management of the Waiwhetu Aquifer

volume, particularly when the bores at Gear Island near the foreshore are operational. In 1999 public water supply abstractions near the foreshore (Gear Island and Buick Street) ceased and there is a noticeable recovery in foreshore groundwater levels despite increasing total municipal abstraction from the inland Waterloo Wellfield.
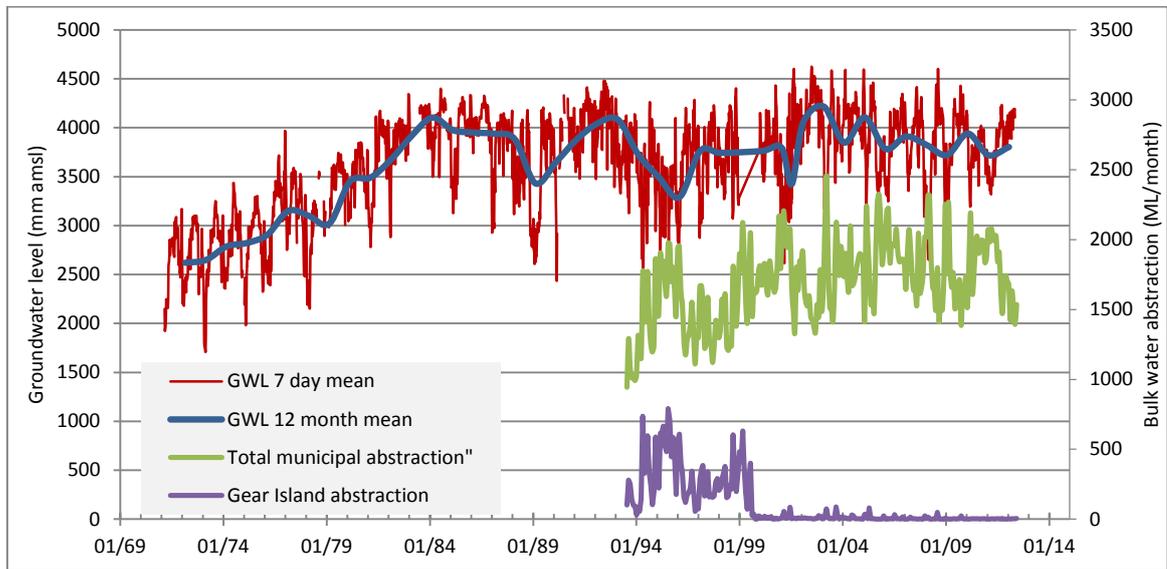
Figure 4.5: Piezometric levels at McEwan Park (R27/0122) and bulk water abstraction record, including Gear Island abstraction at the foreshore (plotted as monthly totals). Note private users are not included in the abstraction plots.

The McEwan Park and Tamatoa groundwater level monitoring sites on the Petone foreshore are both dual-level and screened within the Upper Waiwhetu and Lower Waiwhetu aquifers. Figure 4.6 shows the data for the two McEwan Park recorders, illustrating that there is a negligible head difference between the upper and lower parts of the Waiwhetu Gravels; the negligible head difference indicates that they have a good hydraulic connection even though they are lithologically distinct (see Section 3.2.2.2). The seasonal fluctuations shown in Figure 4.6 are influenced by both natural recharge variability and abstraction from the Waterloo Wellfield (which tends to peak in summer).
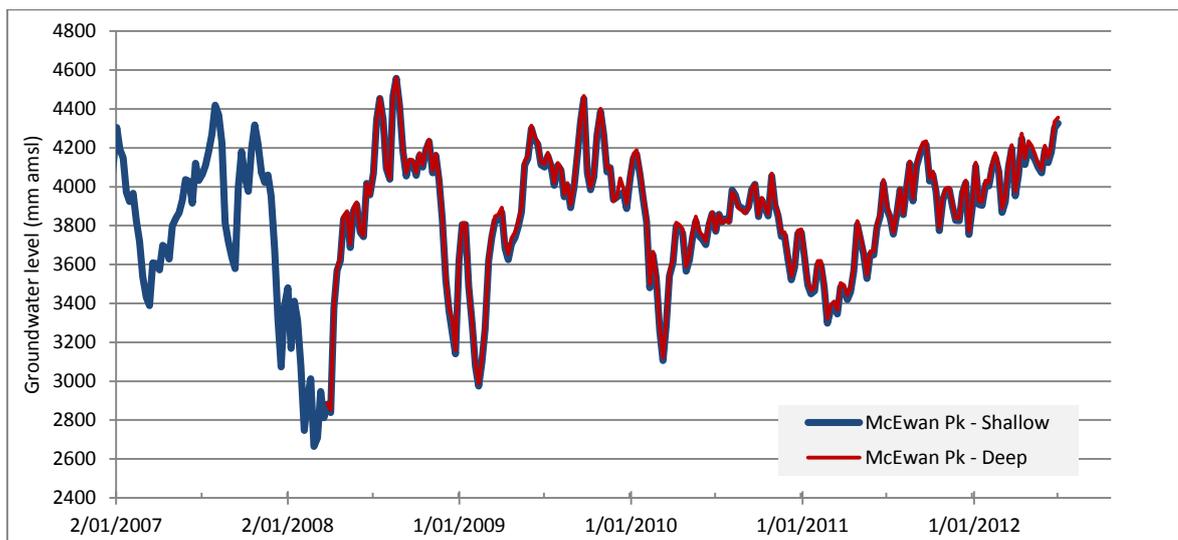
Figure 4.6: Comparison of McEwan Park dual level monitoring records (R27/7153 and R27/0122) for the Upper and Lower Waiwhetu aquifers.

Lower Hutt Aquifer Model Revision (HAM3): Sustainable Management of the Waiwhetu Aquifer

The effects of groundwater abstraction from the bulk water supply wellfield at Waterloo are illustrated in Figure 4.7 which shows wellfield abstraction and Waiwhetu Aquifer levels at McEwan Park on the foreshore during early 2013. There was concern during this time that the first saline intrusion warning level of 2.3m could be triggered. The plot shows the sensitivity of foreshore aquifer levels to abstraction 3km inland at Waterloo and that groundwater levels respond rapidly to adjustments in pumping rate, allowing the foreshore groundwater level to be 'fine-tuned'. Such a response is typical of a highly transmissive confined aquifer.
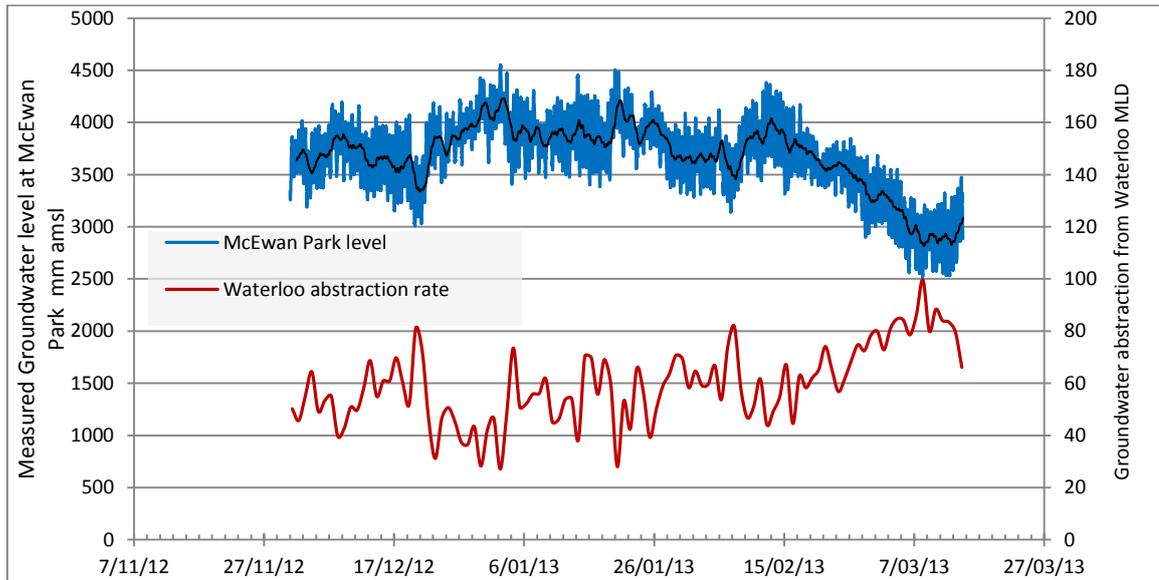
Figure 4.7: Relationship between groundwater abstraction at Waterloo and water level in the Waiwhetu Aquifer at the Petone foreshore (McEwan Park site). Black line is 24-hour mean level at McEwan Park.

Figures 4.7 and 4.8 show that the piezometric levels in the confined Waiwhetu Aquifer (and underlying Moera aquifer) are strongly influenced by tidal cycles, with the effect decreasing with distance from the foreshore. The time lag – or time taken for the piezometric level in the aquifer to peak after high tide –increases with distance from the foreshore. Figure 4.8 shows the tidal variations in groundwater level in the Waiwhetu Aquifer at the foreshore (McEwan Park Shallow well), where a maximum tidal range of about 850mm is evident. Table 4.2 summarises the observed tidal responses at four selected sites in the Waiwhetu Aquifer.
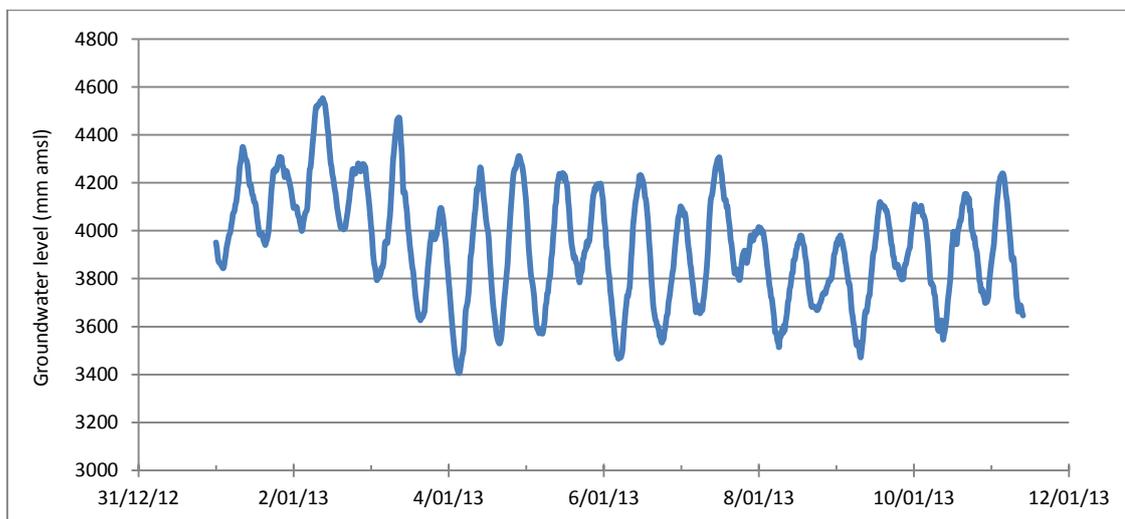
Figure 4.8: Tidally-induced groundwater level fluctuation in the Waiwhetu Aquifer at the Petone foreshore (McEwan Park, Shallow, R27/0122)

Table 4.2: Tidal responses at selected groundwater monitoring sites in the Waiwhetu Aquifer (from WRC, 1995)

Recording site	Distance from foreshore (km)	% of tidal range recorded	Average time lag (mins)
Somes Island	3km offshore	87	0
PCM	0	70	30
HVMTC	1.2	60	45
Hutt Rec	2.2	45	83

4.1.2.3 **Moera gravel aquifer**

Three monitoring bores are located in the main confined part of the Moera Aquifer – IBM1, UWA3 and Marsden Street (Table 4.1 and Figure 4.1). These all intersect the upper freshwater part of the deeper aquifer sequence at just over 100m depth on the western deeper side of the basin (IBM1 and Marsden St), and at about 65m depth in the east (UWA3). Water levels in this aquifer are also tidally influenced showing an efficiency of about 45-50% (WRC, 1995).

Figure 4.9 shows that the Moera Aquifer groundwater levels vary seasonally by up to about 1m. A major influence on levels in this aquifer is abstraction from the overlying Waiwhetu Aquifer. Pumping effects have been documented by WRC (1995) by correlating pumping in the Waiwhetu Aquifer to water levels in the Moera Aquifer. However, pump testing of the Moera gravels in the Marsden Street well (Brown and Jones, 2000) did not result in any measurable response in the overlying Waiwhetu Aquifer – possibly due to the low pumping rate and short duration of the test. Figure 4.9 also illustrates the significant difference in piezometric head between the Waiwhetu Aquifer (IBM2) and the Moera Aquifer indicating that the intervening Wilford Shell Bed is of relatively low permeability and represents an effective aquiclude. There is a head difference of about 1m between the two aquifers. The decline in levels between

about 1994 and 1996 is evident in both aquifers and can be related to higher abstraction from the Waiwhetu Aquifer during this time (see Figure 4.5).
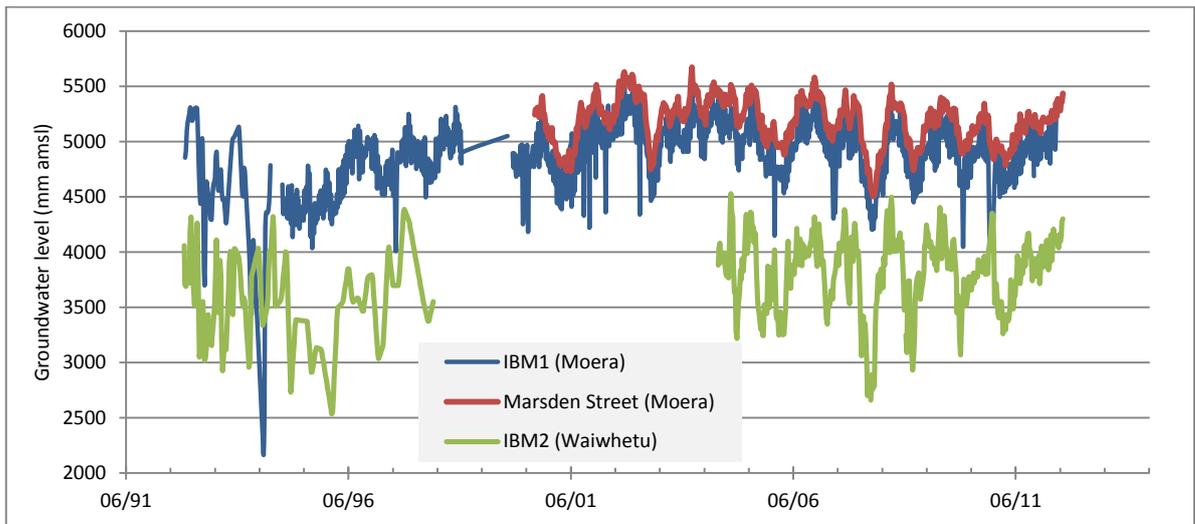
Figure 4.9: Groundwater level monitoring in the Moera Aquifer (IBM1 and Marsden Street) and Waiwhetu Aquifer (IBM2), 1992 to present (7-day means).

4.2   GROUNDWATER FLOW PATTERN

Regional groundwater flow in the Lower Hutt Groundwater Zone occurs down-valley from the unconfined aquifer to the foreshore and continues offshore beneath Wellington Harbour. Figure 4.10 shows groundwater level (water table) contours during winter for the Taita Alluvium based upon the HAM3 simulation since there are very few monitoring sites in the unconfined aquifer from which a water table map can be constructed. The Hutt River recharge zone (upstream of Boulcott) defines a flow net that diverges from the river toward the unconfined aquifer indicating that the river loses flow to the aquifer in this reach. Further downstream, the water table contours begin to converge back towards the river showing that the aquifer discharges into the river down-valley.

Figure 4.11 shows the piezometric contours for the Upper Waiwhetu Aquifer based upon monitoring data and the HAM3 simulation for summer conditions (January 2012). The drawdown associated with the Waterloo Wellfield is evident and the abrupt flattening of the hydraulic gradient downstream of the wellfield is striking, as shown in Figure 4.12.

Figure 4.10: Water table contours for the Taita Alluvium simulated by HAM3 for July 2012 and based on available monitoring data. Contours in metres above mean sea level.
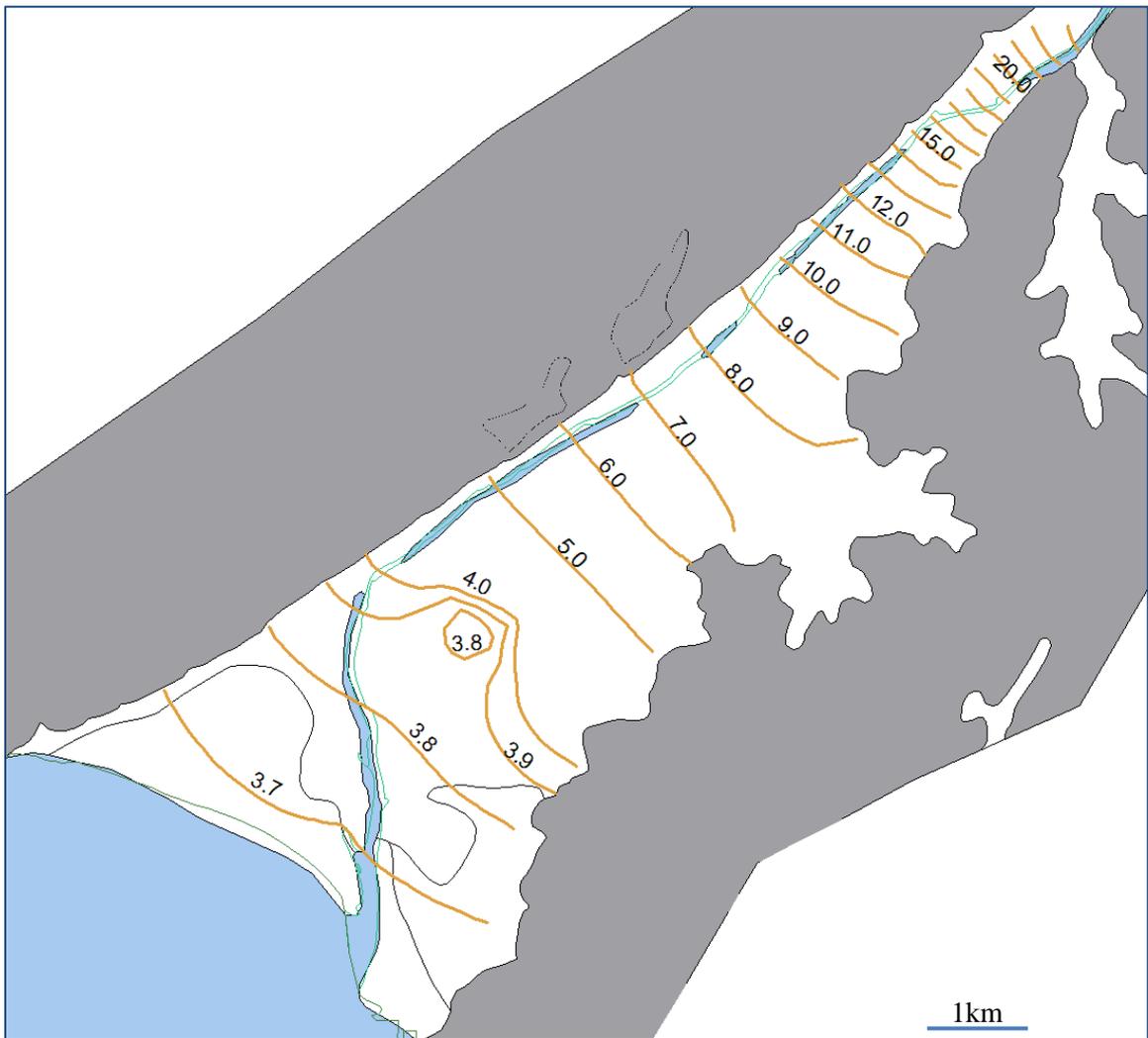
Figure 4.11: Water table contours for the Upper Waiwhetu Aquifer simulated by HAM3 for January 2012 and based on available monitoring data. Contours in metres above mean sea level (note the contour intervals below 4.0m reduce from 1m to 0.1m).
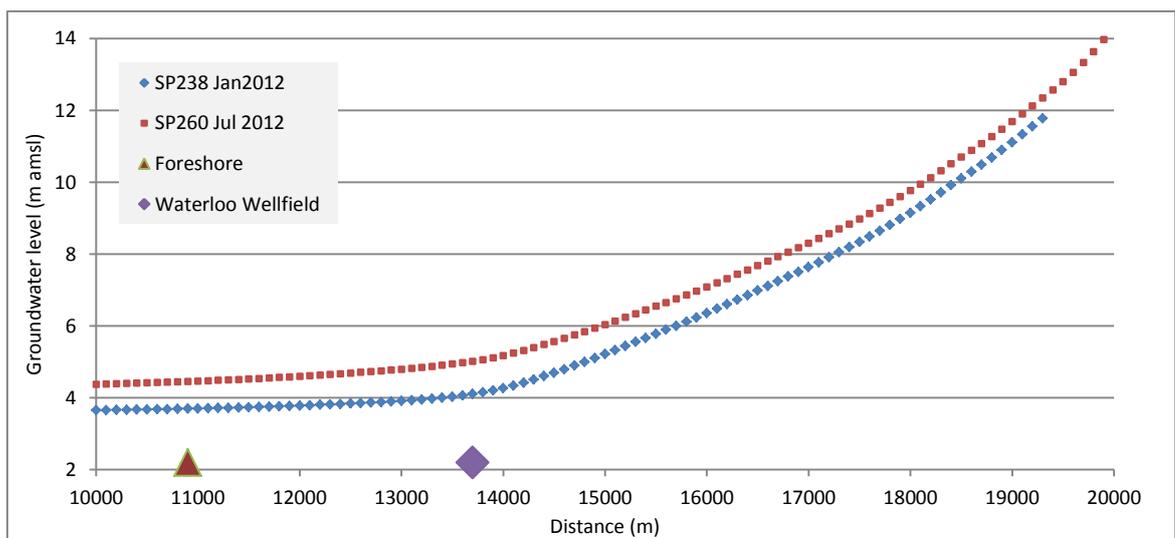
Figure 4.12: Groundwater head profile along the axis of the Lower Hutt valley between Taita Gorge and Petone foreshore for winter and summer conditions.

4.3 HYDRAULIC PROPERTIES

4.3.1 TAITA ALLUVIUM

The Taita Alluvium ranges in thickness from 0 to 16m, thickening towards Taita Gorge. Only one reliable pumping test has been performed in the shallow gravels and therefore the hydraulic properties of the Taita Alluvium are poorly characterised. A large-scale pumping test was carried out in a shallow bore at Avalon Studios (R27/7320) in 1992 and provided a range of transmissivity values of between 2,700 and 52,700 m^2/day, with an average of 4,500 m^2/day (WRC, 1995). This equates to a hydraulic conductivity of around 1,000m/day in the Avalon Studios area, which is probably representative of the more recent Taita Alluvium adjacent to the river where there is a strong connectivity with the river. Further from the river, on older terraces and where the Taita Alluvium merges with the Melling Peat and Petone Marine Beds, the hydraulic conductivity maybe substantially less.

4.3.2 PETONE MARINE BEDS/MELLING PEAT

The confined and artesian conditions encountered in Upper Waiwhetu Aquifer demonstrate that the confining Petone Marine Beds and Melling Peat have a low hydraulic conductivity and are laterally persistent. The beds are predominantly fine-grained silt, sand and coarse sand deposits commonly containing shell and wood fragments or shell beds. Measurements from various construction site investigations provide a horizontal hydraulic conductivity range of $1x10^{-3}$ to $1x10^{-4}$ m/day (WRC, 1995). Vertical hydraulic conductivity is expected to be at least an order of magnitude lower due to the stratified nature of the marine beds and the presence of laterally persistent silt layers.

4.3.3 UPPER WAIWHETU GRAVELS

The Upper Waiwhetu Gravels are characterised as having consistent and exceedingly high transmissivity. They have been extensively tested during resource investigations over the past 80 years or so and WRC (1995) provides a thorough review and re-interpretation of historical testing which is presented in summary form here. A subsequent pumping test was carried out later in 1995 on the Waterloo Wellfield at a rate of 50 ML/day (Butcher, 1996), the results of which are also included here.

The most significant large-scale Waiwhetu Aquifer pumping tests are:

- Wellington Meat Export Company (1933)
- Gear Island (1957 and 1967)
- Hutt Park (1974)
- Gear Island (1991)
- Waterloo (1993)
- Waterloo (1996)

Due to difficulties in the interpretation of the earlier data (Wellington Meat -1933, Gear Island – 1957/67, and Hutt Park -1974), only the latest three tests have been used to derive representative transmissivity and storativity values for the Upper Waiwhetu Aquifer in the Gear Island and Waterloo Wellfield areas.

Each of the tests resulted in the calculation of a wide range of hydraulic property values for each of the monitoring bores. However, given the heterogeneous nature of the

aquifer, the calculation of a transmissivity value for a particular observation bore may not be representative of the aquifer transmissivity at that point. This is because the analytical theory underlying the test interpretation assumes a homogeneous aquifer and radial flow conditions around the pumping bores.

Table 4.3 presents a summary of hydraulic properties for the Upper Waiwhetu Aquifer derived from the three major pumping tests. Geometric mean values for transmissivity and storage coefficient have been calculated for all observation data and for bores in the immediate vicinity of the wellfield. The latter provide an estimate of local hydraulic properties for the aquifer, whilst the mean of all the observation bores provides an estimate of the average regional aquifer properties. More emphasis has been placed on the Waterloo tests since the earlier Gear Island test was of a short duration (24 hours) and at a lower pumping rate.

Table 4.3: Average hydraulic properties for the Upper Waiwhetu Aquifer derived from pumping tests

Pumping Test	Transmissivity m^2/day (geometric mean)	Storage coefficient (geometric mean)
Gear Island 1991 (24 hours at 26.7 ML/day)		
Bores within 500m of pumping	23,400	1×10^{-3}
All observation data	22,000	8×10^{-4}
Waterloo 1993 (40 hours at 35 ML/day)		
Wellfield bores	34,900	9×10^{-4}
All observation data	28,000	7×10^{-4}
Waterloo 1995 (108 hours at 50 ML/day)		
Wellfield bores	38,900	3×10^{-4}
All observation data	27,980	5×10^{-4}

It is evident that the Upper Waiwhetu Gravels exhibit a wide range of hydraulic properties which reflect the rapid fluviatile depositional environment. The pumping test results in Table 4.3 indicate that the mean aquifer transmissivity for the Upper Waiwhetu Aquifer is approximately 28,000 m^2/day, locally increasing to between 35,000 and 40,000 around the Waterloo Wellfield. Assuming an average thickness of 20m for the gravels, this equates to a hydraulic conductivity of approximately 1,400 m/day. The pumping tests indicate a range for the confined aquifer storage coefficient of between 3×10^{-4} and 1×10^{-3}.

4.3.4 LOWER WAIWHETU AQUIFER

Since there have been no pumping tests within the Lower Waiwhetu Aquifer, its hydraulic properties are unknown. However, it has been possible to derive a qualitative assessment of the hydraulic conductivity nature of this aquifer using evidence provided by lithological description and water chemistry. Both suggest that the Lower Waiwhetu Aquifer has a significantly lower groundwater throughflow and correspondingly lower hydraulic conductivity in comparison to the Upper Waiwhetu Aquifer. The Lower Waiwhetu Aquifer has a higher silt and sand content when compared with the Upper Waiwhetu Aquifer, which is suggestive of a lower hydraulic conductivity. In addition, tritium analyses of groundwater from above and below the interstadial aquitard

provides contrasting ages and flow rates for the two aquifers. Groundwater from the Upper Waiwhetu Aquifer is dated at < 2.5 years old, whilst groundwater below the interstadial aquitard has a 45-year mean residence time (Brown and Jones 2000). There is also a small increase in total anions and cations accompanied by a slight increase in conductivity and pH in the Lower Waiwhetu Aquifer.

4.3.5 WILFORD SHELL BEDS

The Wilford Shell Beds represent an aquitard unit comprising silt, clay and sand deposits. The hydraulic conductivity for this unit is regarded to be similar to the Petone Marine Beds/Melling Peat as it shares comparable lithological and depositional characteristics. An average horizontal hydraulic conductivity of between 0.1 and 0.01 m/day has been estimated for the Wilford Shell Beds on the basis of lithology, with the vertical hydraulic conductivity being an order of magnitude lower due to the occurrence of clay and silt layering.

4.3.6 MOERA BASAL GRAVELS

No reliable hydraulic property data were available to characterise the hydraulic properties of the Moera Aquifer until Hughes (WRC, 1998) carried out a free-flowing test on bore UWA3 (WRC 320) at a rate of 16 L/sec. Analysis of the test provided a transmissivity of value of $1,100 – 1,200$ m²/day and a storage coefficient of 2×10^{-4}. More recently, the Marsden Street exploratory bore (R27/6386) was screened in the Moera Aquifer between 106.25 and 115.25 m depth and test pumped over a seven-day period at a mean discharge rate of 39.8 L/sec (Brown and Jones, 2000). Unlike the previous flow test, the pumping test was able to stress the aquifer and provide a more robust determination of the hydraulic properties for the Moera Aquifer. Analysis of the test provided a transmissivity range of 2,100 to 2,600 m²/day, and a confined storage coefficient in the range of 4×10^{-5} to 1×10^{-4}. The hydraulic conductivity of the Moera Gravels can therefore be estimated to be in the range of 150-200m/day if the test bore screen is assumed to be drawing on about a 15m thickness of the gravels.

4.3.7 DEEP STRATA

There is minimal information on which to base an assessment of the hydraulic properties of the deep strata below the Moera Gravels. Short-duration pumping for the purpose of water sampling in borehole R27/6386 from strata below the base of the Moera Gravels has provided data from which an approximate transmissivity can be derived. The highest yielding zone below the Moera Gravels attained a discharge rate of 100 L/min (144 m³/day) and a drawdown of 2.8m after 5 hours pumping. Using the Jacob equation, and by assuming typical confined aquifer variables, the specific capacity for a confined aquifer can be approximated by the following equation (Driscoll,1987):

$$Q/s = T / 2000$$

where:
Q = yield of well, in US gpm; s = drawdown in well, in feet
T = transmissivity, in gpd/ft

Using the recorded specific capacity, an approximate transmissivity for the silty gravels of 70 m^2/day has been derived using the above equation. This is significantly lower than the overlying Moera Gravels.

4.4 GROUNDWATER RECHARGE

4.4.1 RIVER RECHARGE

The Taita Alluvium and the Waiwhetu and Moera aquifers receive recharge sourced from the Hutt River in the upper part of the groundwater catchment where the aquifers become unconfined upstream of Boulcott. The river has a complex recharge-discharge relationship with the shallow unconfined Taita Alluvium aquifer, but generally loses water to underlying aquifers in the area between Taita Gorge and Boulcott/Kennedy Good Bridge. Between Boulcott and the coastline in the area where the Waiwhetu aquifers are confined, the river generally gains groundwater.

A proportion of the river bed losses in the recharge zone remains in the highly permeable Taita Alluvium and flows southwards to the coast, or returns to the river in its lower reaches. The remainder of the loss reaches the deeper aquifers. The Upper Waiwhetu Aquifer receives vertically infiltrating water transmitted through the overlying Taita Alluvium which is in hydraulic continuity with the river bed. Aquifers below the Upper Waiwhetu Aquifer exhibit a relatively small throughflow because of significantly lower hydraulic conductivities (reducing with increasing depth and compaction) and lower hydraulic gradients. The aquifer recharge dynamics and river losses are, however, strongly influenced by the abstraction regime, river conditions and unconfined aquifer levels.

Quantification of river recharge relies upon a limited number of concurrent river flow gaugings, which out of necessity have been carried out mostly under low flow conditions when gaugings are more easily and safely undertaken and when the measurement errors are smaller. The concurrent gaugings carried out between 1969 and 2013 are shown in Figure 4.13. Each shows a similar pattern of flow loss between Taita Gorge and the Kennedy Good Bridge area downstream of which flows either level off or start to increase. At higher river flows there also appears to be an apparent flow gain in the initial 2km or so downstream of Taita Gorge to about Taita Rock, below which flow losses occur (higher measurement errors associated with higher flows may however call this observation into question).
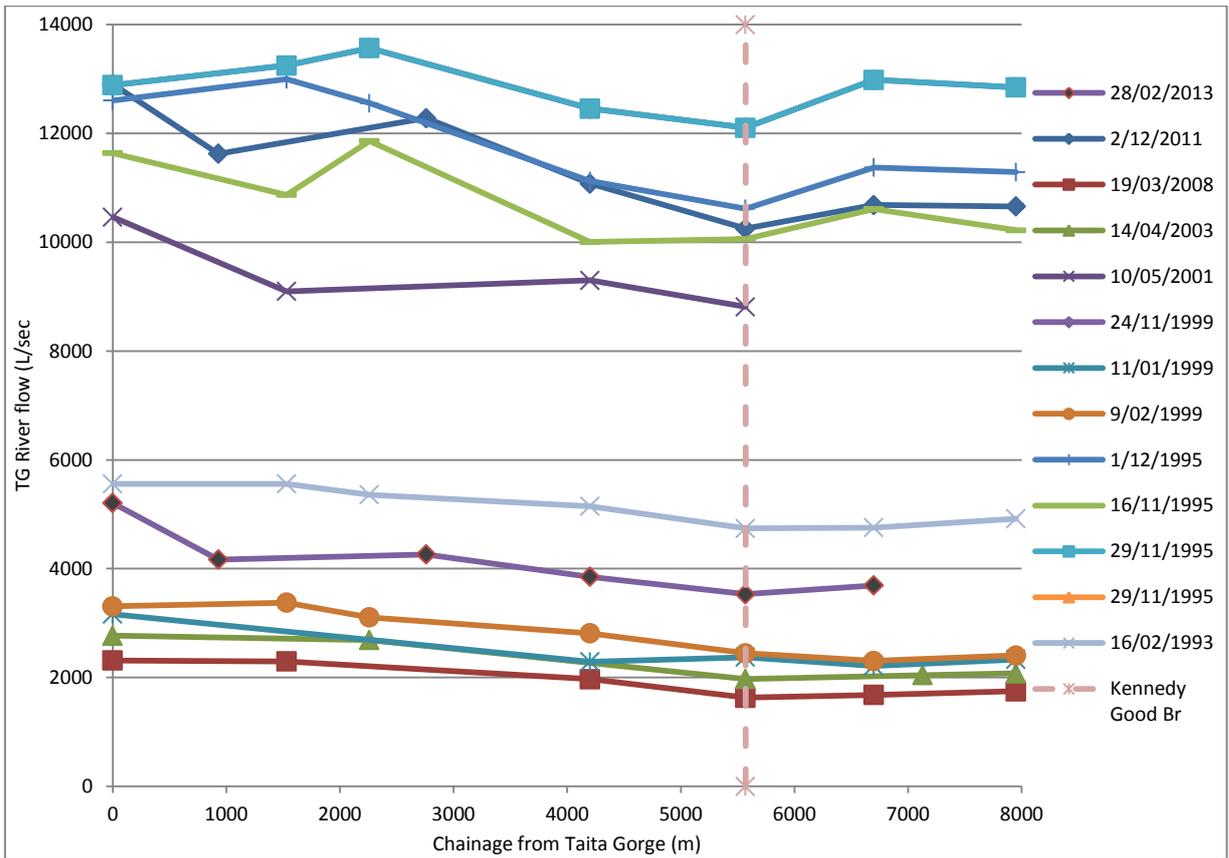
Figure 4.13: Concurrent flow gaugings between Taita Gorge (0m) and Melling Bridge (7950m) showing flow loss above the Kennedy Good Bridge (5570m).

Figure 4.14 shows the concurrent gauging data in the form of a flow loss between Taita Gorge and Kennedy Good Bridge plotted against the river flow at Taita Gorge. The relatively scattered 'trend' indicates that other factors also affect the flow loss in addition to the flow magnitude in the river – these are groundwater abstraction in the confined Waiwhetu Aquifer (drawdowns extend beneath the river in the unconfined aquifer area), and groundwater level in the unconfined aquifer. The plot indicates that under low flow conditions the river loses between about 800 and 1,500 L/sec between Taita Gorge and Kennedy Good Bridge. At higher river flows it should be borne in mind that the flow gaugings have an error of +/- 10% and therefore the gauging error could be a large proportion of the calculated loss. Figure 4.14 should therefore be interpreted with this in mind. For this reason the construction of a relationship between the flow at Taita Gorge and Kennedy Good Bridge based on the concurrent gauging data (such as that presented in WRC, 1995) is not considered meaningful – particularly since the river loss is also influenced by a number of factors and not just river flow.
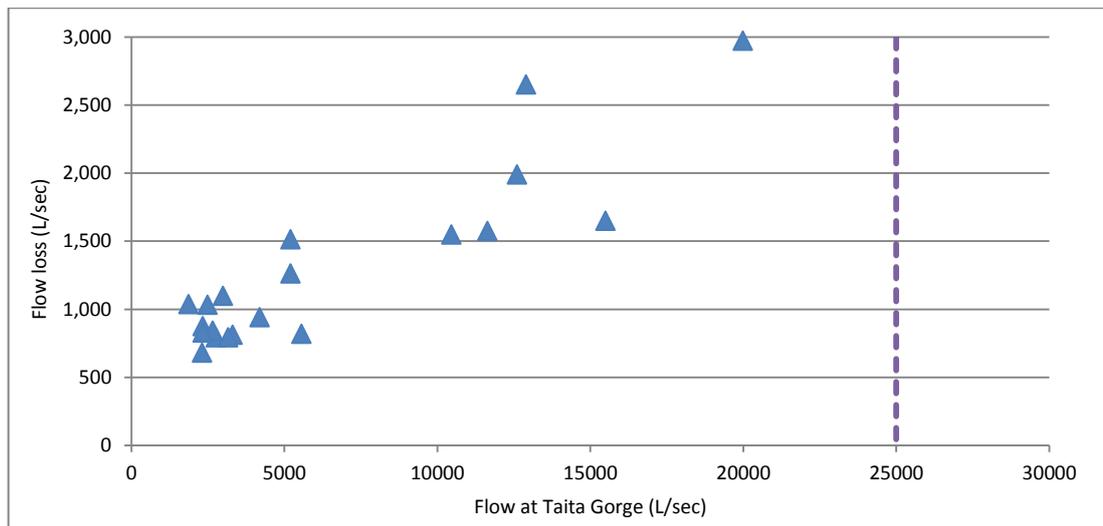
Figure 4.14: Measured flow losses in the Hutt River between Taita Gorge and Boulcott based on concurrent flow gaugings between 1969 and 2012. The mean flow in the river is 25,000 L/sec as shown. Flow gauging error is +/- 10%.

4.4.2 RAINFALL RECHARGE

Infiltration of rainfall is a source of recharge to the Taita Alluvium but is considered to be a relatively minor component of the water balance for the Lower Hutt Groundwater Zone. Sound estimation of the quantity of water migrating through the soil zone to the water table is however regarded to be important in terms of developing the HAM3. A soil moisture balance approach has been used whereby it is assumed that the soil becomes free-draining when the moisture content reaches a threshold value ('field capacity') when excess water then becomes groundwater recharge. The soil moisture balance method described by Rushton et al. (2006) was adopted for this study which introduces an addition concept – that of near-surface soil storage. This recognises that potential evapotranspiration can occur on days following heavy rainfall since, even though the soil profile may be dry at depth, moisture from rainfall can be held near to the soil surface. Actual evapotranspiration is calculated using the readily and total available water (RAW and TAW) based upon soil properties and the effective rooting depth. Runoff was also incorporated in a rudimentary manner using the USDA SCS runoff method (SCS, 1972) which partitions rainfall between through-flow or runoff and the soil moisture store using an SCS number (derived from USDA on the basis of land use, soil properties and slope).

Base data required for the soil moisture balance model are daily climatic data (rainfall and potential evapotranspiration), and soil and runoff properties and distribution (field capacity, wilting point, rooting depth and SCS number) for the main soil groups in the study area.

Daily climate data (rainfall and PET) has been provided by NIWA who have undertaken a spatial interpolation of daily rainfall and potential evapotranspiration (PET) using a spline model (Tait et al. 2006) for the Wellington Region on a 500m grid. The climate modelling was based on all available climate data from both NIWA and Greater Wellington rain gauge and climate sites. Each grid square therefore has a daily interpolated rainfall and potential evapo-transpiration record for the period 1/1/1992 to 1/7/2012. Since there is negligible rainfall gradient across the Lower Hutt Valley, a

single climate square near Avalon (square 80_132) was chosen to represent the valley to provide a daily rainfall and Penman PET record.

On the basis of the NZLRI soils map, four predominant soil types are recognized upon which the soil moisture balance model is based (Figure 4.15).
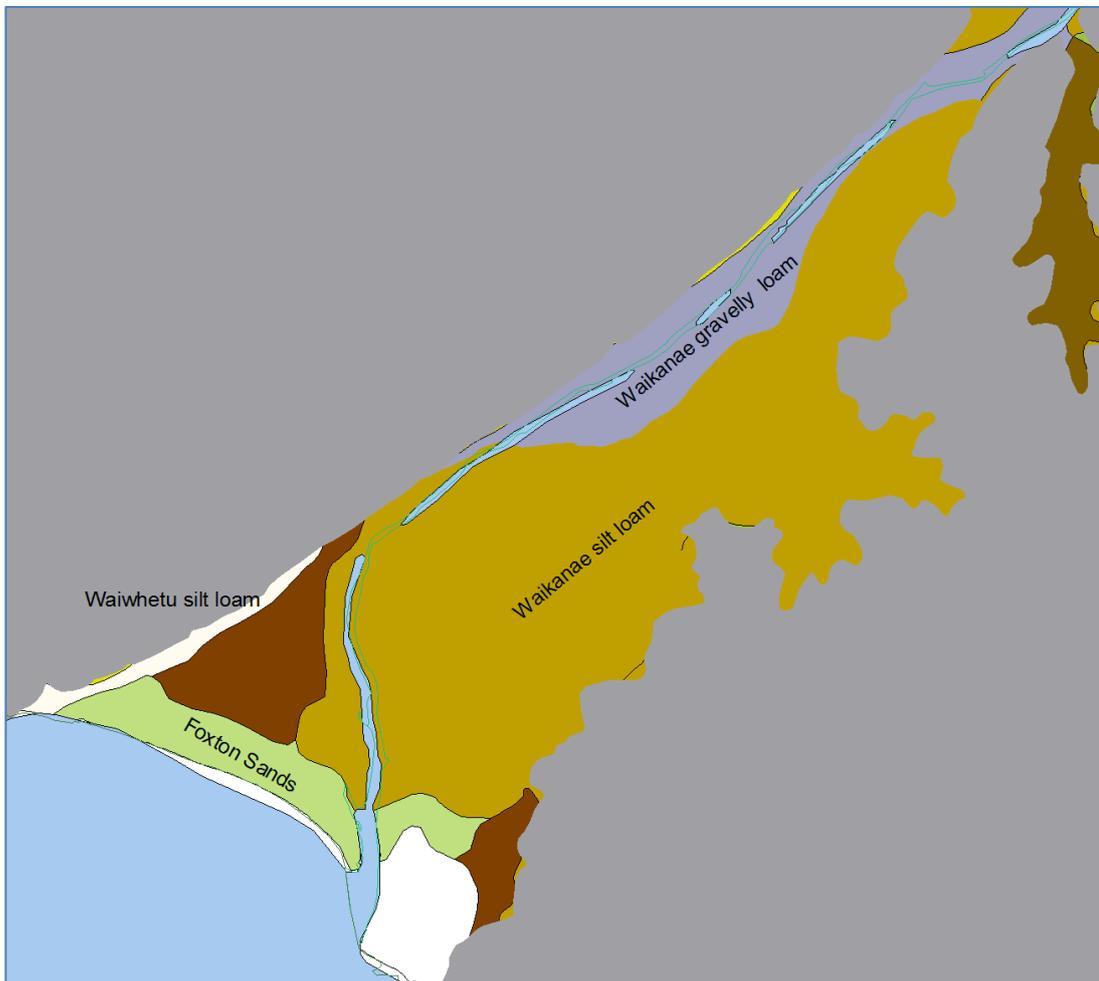
Figure 4.15: Simplified NZLRI soil groups used in the recharge model for the Lower Hutt Groundwater Zone

Table 4.4 contains the soil parameters used as well as a summary of the annual average recharge amounts for each soil type. The table also shows an 'urban factor' which attempts to account for increased rainfall runoff in urban areas – estimated to be between 40-50%. The modelled daily recharge amounts were reduced by this amount. Average annual recharge over the predominant Waikanae gravelly and silt loams is estimated to be around 36-45% of average annual rainfall (1140mm).

Table 4.4: Simplified soil groups used in the recharge model for the LHGZ and modelled rainfall recharge summary

Soil Class	Soil Parameter (mm)					Urban factor	Recharge % of rainfall	Average recharge mm/year
	WP	RAW	AW	FC	SCS No.			
Waikanae gravel loam	40	19	46	86	70	1.0	45	523
Waikanae silt loam	76	27	54	150	82	0.4	36	425
Waiwhetu silt loam	100	66	211	311	90	0.5	17	200
Foxton sands	40	19	46	86	70	0.4	45	523

4.5 GROUNDWATER DISCHARGE

Groundwater returns, through the Taita Alluvium, to the Hutt River downstream of Boulcott and to smaller drainage systems such as the Waiwhetu Stream. There is also a throughflow to the sea along the foreshore. Quantification of groundwater flows into the Hutt River is difficult since the river is tidal up to Ewen Bridge and therefore the interaction between the river and shallow aquifers is likely to be a highly variable and complex one.

The confined Waiwhetu Gravels and deeper aquifers naturally discharge through vertical leakage across overlying aquitards, both onshore and offshore.

4.5.1 SUBMARINE SPRINGS

Discharge from the Upper Waiwhetu Aquifer is also known to occur offshore at discrete points in the form of submarine springs. These are assumed to be discharging from the Waiwhetu Gravels where the artesian pressure has been breached or burst through the Petone Marine Beds aquiclude. The recent high-resolution and high-accuracy MBES bathymetry survey of the harbour floor (NIWA, 2010) is particularly useful for locating spring vents and for relating the vent depths to the estimated top of the Waiwhetu Aquifer beneath the harbour. Harding (2000) investigated a number of submarine springs and was able to conduct some basic flow measurements in some of the active vents. This work should be referred to for detailed descriptions of the springs and their postulated modes of formation (possible methane release and/or seismic decoupling of unconsolidated sediments where they lap on to the basement greywacke bedrock of the Somes Island horst structure). Scouring of the relatively thin Petone Marine Beds, particularly around the Hutt River mouth, may also account for some of the submarine springs.

The enlarged bathymetry contour map shown in Figure 4.16 clearly identifies the location of the spring vents on the harbour floor. There are three main spring clusters:

- Hutt River mouth – at least 6 substantial vents up to 10m deep (below surrounding sea floor) and 100m across. The closest is about 500m from the Petone beach.

- Point Howard wharf area – a cluster with about 2 main vents some 5-6m deep.
- Somes Island – three large vents on the north, south and south-western tips of the island. The south-western vent is over 300m across and 6-7m deep.
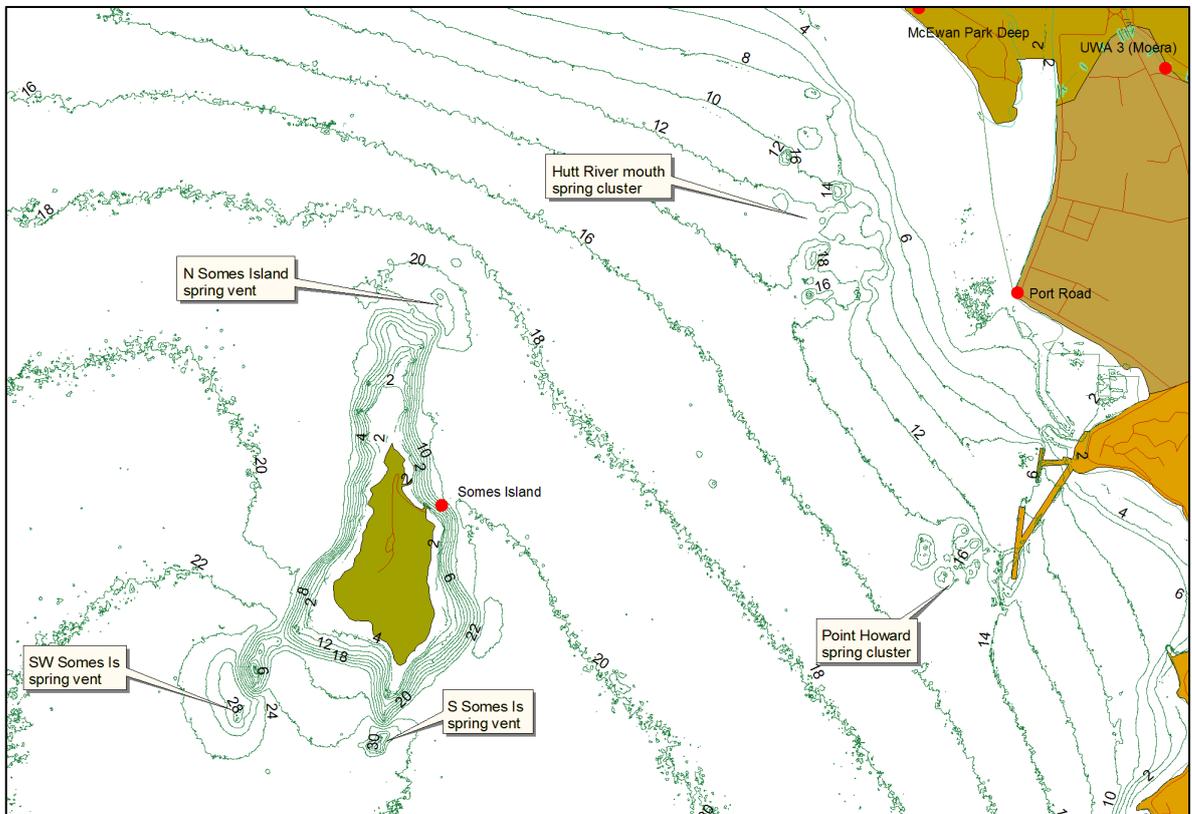
Figure 4.16: Location of submarine spring vents off the Hutt River mouth and around Somes Island based on multi-beam sonar bathymetry survey (NIWA, 2010). Contours are in metres below mean sea level. Red circles are monitoring bores.

Information suggesting that the submarine spring vents relate to groundwater discharge from the Waiwhetu Aquifer is as follows:

- Somes Island: the Waiwhetu Aquifer in bore R27/1170 (shown in Figure 4.16 as 'Somes Island') is recorded at 12.5m below the sea bed (which is at -13.5m, from the bathymetry survey). This places the top of the aquifer at -26m below datum (mean sea level). The spring vent on the northern tip of Somes Island is about 5-6m deep and the base lies at -25m (using bathymetry data) – at about the same level as the top of the Waiwhetu Gravels. Figure 4.17 schematically illustrates the south-western Some Island spring vent.

- Hutt River mouth: the deepest spring pits have a depth of -23m below mean sea level whilst the undisturbed harbour floor sits at about -13m. The vents are therefore substantial features, being up to 10m deep. The top of the Waiwhetu Gravels in this area can be extrapolated from foreshore bore data and are estimated to lie at about -25m.
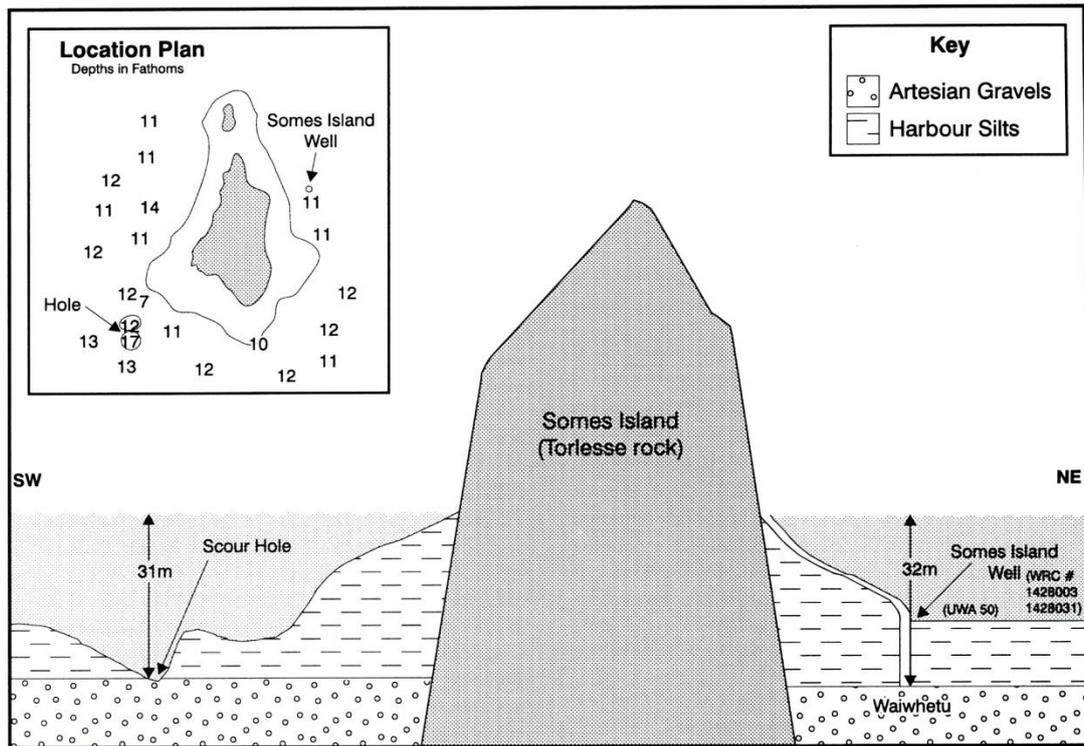
Figure 4.17: Cross-section of the Somes Island area showing the relationship between the Waiwhetu Aquifer and the spring vent (or scour hole) off the south-western tip of the island (from Begg and Mazengarb, 1996).

Harding (2000) evaluated the flows emanating from many of the spring vents and determined that only the ones at the Hutt River mouth, Point Howard wharf and northern end of Somes Island seemed to be weakly active at the time of his inspection. Examination of the large vents on the south-western side of Somes Island did not yield any evidence for active spring flow.

An 'order of magnitude' estimate of submarine spring discharge is necessary for assisting the calibration of the HAM3. Approximation of the discharge from the spring vents has been attempted using Harding's flow meter data – though the tentative nature of such an approximation should be appreciated as there are many uncertainties and only a few of the active vents were surveyed.

For the spring cluster at the Hutt River mouth (Harding's 'Zone 1'), one of the spring vents showed an average current speed of about 0.05m/sec in winter. If the discharge vent is assumed to be $1m^2$ (evidence from Harding suggests that water emanates from a discrete conduit), then the flow equates to about $0.05m^3$/sec or 4 L/sec. If there are three active vents in this cluster then the total mean discharge could be in the order of 12 L/sec or about 1,000 m^3/day (1MLD). There could be a similar discharge from the other active vents and therefore the total spring discharge could be in the order of 1-2 ML/day.

Since the spring vents appear to be a source of artesian discharge from the Upper Waiwhetu Aquifer, their existence, activity and locations are particularly of relevance in terms of assessing saline intrusion risk. The preceding discussion highlights

significant uncertainties and information gaps regarding the nature of the springs and their discharge characteristics.

4.6 RESOURCE UTILISATION

Groundwater usage in the Lower Hutt Groundwater Zone has not changed significantly over the past two decades. Table 4.5 shows the current consented groundwater takes from the groundwater zone total 33.7×10^6 m^3/year – 90% of which is associated with the Greater Wellington Regional Council public water supply take. Figure 4.18 shows the locations of the consented takes including the location of the GWRC public water supply wellfield at Waterloo in Lower Hutt City. Metered annual volumes for the GWRC public water supply are shown in Figure 4.19 which shows that annual GWRC abstraction rarely exceeds 25×10^6 m^3/year .

Table 4.5: Current consented groundwater takes in the Lower Hutt Groundwater Zone

Consent No	Permit Holder	Aquifer	Inst rate L/sec	Daily rate m³/d	Annual rate m³/year
WGN970036	Wellington Regional Council (Utility Services Division)	WG	962.0	83115.0	30,253,860
WGN070193	Unilever NZ Trading Ltd	WG	29.4	2542.9	915,600
WGN120019	Avalon Studios (cooling &reinjection)	TA	28.0	2419.2	880,589
WGN000020	Hutt Valley Health	WG	25.0	2160.0	786,240
WGN080397	Hutt City Council	TA	17.7	1530.0	12,075
WGN120153	Hutt City Council	WG	11.6	1,102	15,000
WGN080402	Boulcott's Farm Heritage Golf Club Inc	WG	20.0	995.0	199,000
WGN070183	Shandon Golf Club	WG	32.0	560.0	63,000
WGN070184	Canterbury Spinners Limited	WG	6.3	542.9	197,601
WGN000020	Hutt Valley Health (emergency)	WG	5.2	450.0	0
WGN080208	Boulcott's Farm Heritage Golf Club Inc	WG	12.0	400.0	80,000
WGN080433	Woolyarns Ltd	TA	8.5	285.7	104,000
WGN070154	NZTS Services Limited	WG	3.3	142.7	51,936
WGN070189	Imperial Tobacco New Zealand	WG	1.1	65.0	23,660
WGN040360	Petone Pure Water Company Ltd	WG	2.0	50.0	18,200
WGN030126	Teri Puketapu	WG	0.5	43.2	15,725
WGN090243	Hutt City Council	WG	1.3	30.0	10,920
WGN090282	Department of Conservation	WG	0.3	24.0	8,736

WG= Waiwhetu Gravels, TA = Taita Alluvium

Figure 4.18: Locations of consented groundwater takes in the Lower Hutt Groundwater Zone with the largest takes labelled. Circle size is proportional to the consented abstraction volume.
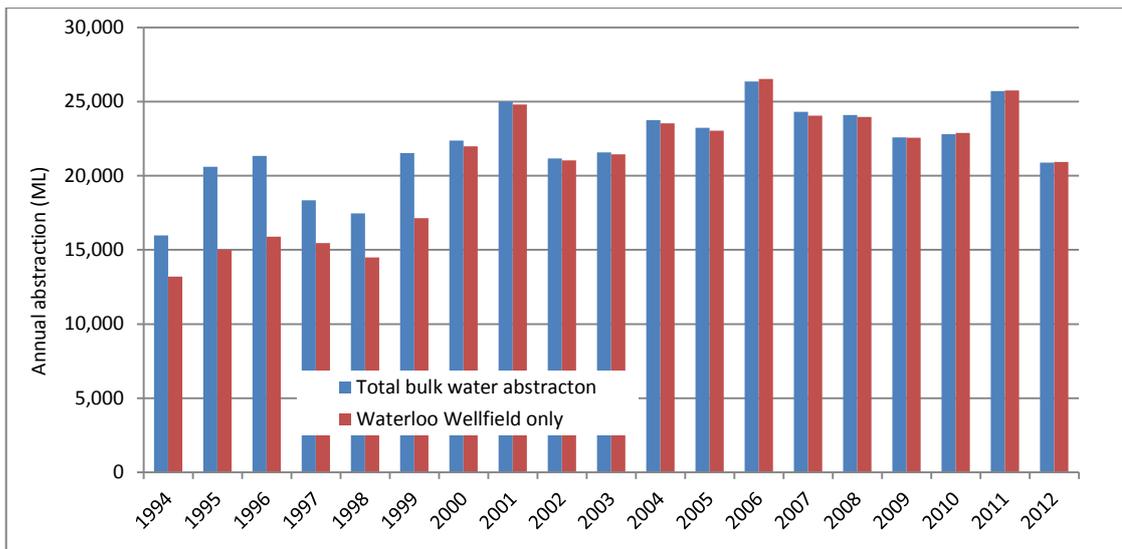
Figure 4.19: Metered GWRC annual bulk water abstraction volumes between 1994 and 2012. The Gear Island wellfield near the foreshore provided some of the supply prior to 2001. The consented annual GWRC abstraction is 30,254ML.

5   CONCEPTUAL MODEL AND WATER BALANCE

The numerical groundwater modelling process draws together large quantities of data from which a conceptual interpretation for a groundwater system is developed. This conceptual framework must be then translated into a quantitative numerical representation. Strong emphasis is therefore placed on producing a sound conceptualisation of the groundwater system as a fundamental basis for numerical analysis.

The purpose, form and significance of a conceptual model is explained in the MDBC modelling guidelines (Middlemis 2001):

- *Development of a valid conceptual model is the most important step in a computer modelling study.*
- *The conceptual model is a simplified representation of the essential features of the physical hydrogeological system and its hydrogeological behaviour, to an adequate degree of detail.*
- *Conceptual models are subject to simplifying assumptions which are required because a complete reconstruction of the field system is not feasible, and because there is rarely sufficient data to completely describe the system in comprehensive detail.*
- *The conceptualisation is developed using the principle of parsimony such that the model is as simple as possible while retaining sufficient complexity to adequately represent the physical elements of the system and to reproduce system behaviour.*

The conceptual hydrogeological model has been tailored to ensure it can adequately address the key issues faced in the management of the groundwater resources in the Lower Hutt Groundwater Zone. Specifically, these are:

- The sustainability of groundwater abstraction from the Waiwhetu Aquifer
- Saline intrusion risk
- The impacts of sea level rise and/or land subsidence
- The potential impacts of seismic rupturing of the overlying aquitards along the Wellington Fault

5.1   CONCEPTUAL HYDROGEOLOGICAL MODEL SUMMARY

Figures 3.1 to 3.3 contain a series of diagrams which describe the conceptual model developed for the Lower Hutt groundwater basin. Section 3.2.4 also describes in detail the geological framework.

The Lower Hutt groundwater basin extends from Taita Gorge to the harbour entrance area. The Wellington Fault has played a major role in the creation of a basin structure within which has accumulated a layered sequence of sediments – including gravel, sand, silt and peat. Groundwater is most abundant within coarse gravel horizons which occur as three distinct and laterally persistent water-bearing layers. The deepest is the Moera Gravel at a depth of between 100 and 160m beneath a silt-rich aquitard (Wilford Shell Beds). Although its upper part contains fresh water, the gravels contain progressively more saline water with depth.

The overlying Waiwhetu Gravels constitute an artesian aquifer which extends down the Hutt Valley and spreads out beneath Wellington Harbour. This aquifer is the principal

water supply aquifer in the Lower Hutt basin, and supplies Wellington with up to 40% of its water. The Waiwhetu Gravels are about 50m thick in total but can be divided into an upper part that is more transmissive and a lower part that is less productive and more matrix-rich. The Upper Waiwhetu gravels lie at 20-30m below the ground surface beneath Lower Hutt and Petone and are confined by a marine aquitard (the Petone Marine Beds) which thickens and becomes more compact offshore and is currently still being deposited in the harbour. The gravels are coarse and well-sorted and they exhibit an exceptionally high transmissivity (20-30,000 m^2/day). The gravels extend offshore at least as far as Somes Island. North of Lower Hutt City, the Waiwhetu Gravels become unconfined and are overlain by (or merge with) the third gravel-rich deposits, called the Taita Alluvium, associated with recent deposition by the Hutt River.

The Lower Hutt aquifer system can essentially be divided into an inland, unconfined aquifer zone covering an area of about 5km^2 and extending from Taita Gorge to the Hutt Golf Course-Boulcott area (between Melling Bridge and Kennedy Good Bridge), and a confined aquifer zone overlain by the Petone Marine Beds and deeper aquitards extending south of the Hutt Golf Course and out into the harbour. The confining layers, particularly the Petone Marine Beds, are anticipated to thicken offshore as they accumulate (and continue to do so) in the subsiding Wellington Harbour Basin. The degree of confinement (or 'leaky-confinement') is therefore regarded to increase offshore as the aquitard thickens and becomes more compact due the overlying weight of sea water. The high pressure head in the Upper Waiwhetu Aquifer recorded at Somes Island (up to 4m above mean sea level and estimated to be 6m higher when abstraction ceases) in the middle of the harbour confirms that the aquifer must remain pressurised under the harbour and therefore does not have a direct connection to the ocean (except via slow vertical leakage and at localised spring vents). The pressure heads in the Waiwhetu Aquifer are highly sensitive to disruptions of the aquitard, as observed historically by dredging operations near the Hutt River mouth which 'punctured' the aquitard and caused significant decline in aquifer level. In this respect, the Waiwhetu Aquifer is regarded to be a relatively unique coastal aquifer due largely to the tectonic context of the harbour.

Recharge occurs principally by infiltration through the bed of the Hutt River between Taita Gorge and Kennedy Good Bridge at an average rate of about 100,000m^3/day (100ML/day). The river recharges the unconfined aquifer along with minor localised rainfall recharge. The down-valley flow is then partitioned into the shallow Taita Alluvium, the confined Waiwhetu Aquifer system and the upper part of the underlying confined Moera Aquifer. Most of the flow from the unconfined aquifer however enters the highly transmissive Waiwhetu Gravels and, to a significant extent, is induced to do so by abstraction drawdowns associated with the Waterloo wellfield. Groundwater abstraction in the Waiwhetu Aquifer (mainly from the Waterloo wellfield) also induces higher losses from the bed of the Hutt River along the recharge reach. Tritium analysis suggests that groundwater takes about three years to flow from the Hutt River recharge zone to the foreshore through the Upper Waiwhetu Aquifer. There is significant upwards diffuse leakage from the confined aquifers across the aquitards into the lower reaches of the Hutt River (below Boulcott) and beneath the harbour. There are also spring vents in the harbour which also appear to relate to discharge from the confined Upper Waiwhetu Aquifer.

5.2 HYDROGEOLOGICAL FRAMEWORK AND WATER BALANCE ESTIMATION

The conceptual model for the Lower Hutt Groundwater Zone is required to describe the 'hydrogeological framework' – the system stresses in terms of inputs, outputs, regional flows, and flows between the various hydrostratigraphic units.

The conceptual components of the regional water balance are as follows:

Inputs: Rainfall recharge

                 Infiltration through the Hutt River bed

                 Valley-side recharge

Outputs: Discharge to Hutt River and other streams or springs

                 Diffuse seepage from confined aquifers to the sea

                 Submarine spring discharges from Waiwhetu Aquifer

                 Groundwater abstraction from bores

It has been possible to calculate an independent 'steady state' or average water balance to supply a basic 'order of magnitude' assessment of the various system inflows and outflows. This provides a valuable check on the numerical model flow balance predictions. Table 5.1 contains the estimated water balance for the Lower Hutt Groundwater Zone.

Table 5.1: Estimated average water balance for the Lower Hutt Groundwater Zone (based on annual average quantities)

	In (m^3/day)	Out (m^3/day)
Rainfall recharge	30,000	
Hutt River flow loss/gw recharge	95,000	
Distributed submarine leakage		15,000
Submarine spring discharge		2,000
Groundwater discharge to Hutt River and streams		44,000
Discharge to Waiwhetu Stream		4,000
Abstraction		60,000
Total (m^3/day)	*125,000*	*125,000*

The sources of the various balance quantities are as follows:

- *Rainfall recharge*: annual mean = 0.4m (see Table 4.4) * area of valley floor ($28.4km^2$)

- *River inflow*: values based on concurrent gaugings – average loss is about 1,100L/sec or 95,000m^3/day (see Section 4.4.1)
- *Distributed submarine leakage:* Assume vertical hydraulic conductivity of 0.001m/d for Petone Marine Beds, a hydraulic gradient of 0.2 (2m of head across 10m thickness of aquitard), and harbour area of 68x10^{6}m^2 = leakage of about 15,000m^3/day.
- *Groundwater discharge to Hutt River and streams*: calculated from balance as an unknown and incorporates leakage from onshore parts of confined aquifers into Taita Alluvium and river.
- *Discharge to Waiwhetu Stream*: gauging data estimate
- *Abstraction*: mean 2,000ML/year or 60,000 m^3/day

The water balance illustrates that groundwater abstraction represents a very significant portion of the water balance and that flows to and from the Hutt River dominate the natural aquifer recharge-discharge dynamics.

6 DEVELOPMENT OF HAM3

6.1 MODEL PURPOSE AND OBJECTIVES

The purpose of the revised Hutt Aquifer Model (HAM3) is to assist the GWRC Water Supply Group optimise the sustainable yield and operational management of the Waiwhetu Aquifer. The model will assist in forecasting the 'state of the aquifer' and will provide information to support planning strategies for responding to climate change and the potential response of the groundwater system to a large-scale seismic event.

Specific objectives or outcomes for the model are as follows:

- Provide an accurate, calibrated simulation of the Lower Hutt groundwater system which can be used to predict or forecast its response to current and potential future stresses.
- Review and make recommendations for the sustainable yield of the Waiwhetu Aquifer.
- Review and make recommendations for a robust saline intrusion risk management framework for the Waiwhetu Aquifer.
- Develop a methodology of forecasting the 'state of the aquifer' and predicting the sustainable yield ahead of summer/stress periods.
- Assess the effects of sea level rise on the Waiwhetu Aquifer and the impact on its sustainable yield.

6.2 MODEL COMPLEXITY AND PREDICTIVE CONFIDENCE LEVEL

With reference to the purpose and objectives of the HAM3, it is necessary to define the required degree of model complexity and level of confidence in its predictive capability. The MDBC (Middlemis 2001) and NZ Ministry for the Environment (NZME 2002) modelling guidelines define model complexity as the degree to which a model application resembles the physical hydrogeological system. A 'complex model' (or 'aquifer simulator') is required for the HAM3 to meet the purpose and objectives of the model. Such a model relies upon the availability of adequate data and a sufficiently detailed conceptual understanding of the groundwater system. It also requires a considerable investment of time, skills and data to develop.

The recently released Australian groundwater modelling guidelines (Barnett et al. 2012) discuss the need to assess the degree of confidence that can be applied to a model's predictions to meet the project objectives. In particular, Guiding Principle 2.3 of the guidelines is a critical consideration in the planning stage of developing a groundwater model:

> *Guiding Principle 2.3: A target model confidence level classification should be agreed and documented at an early stage of the project to help clarify expectations. The classification can be estimated from a semi-quantitative assessment of the available data on which the model is based (both for conceptualisation and calibration), the manner in which the model is calibrated and how the predictions are formulated.*

Factors to be considered in establishing the model confidence level classification (Class 1, Class 2 or Class 3 in order of increasing confidence) include:

- the available data (and the accuracy of that data) for the conceptualisation, design, construction and calibration. Consideration should be given to the spatial and temporal coverage of the available datasets and whether or not these are sufficient to fully characterise the aquifer and the historic groundwater behaviour that may be useful in model calibration;

- the calibration procedures that are undertaken during model development. Factors of importance include the types and quality of data that is incorporated in the calibration, and the level of fidelity with which the model is able to reproduce observations and current conditions. This is important if model predictions are to be run from the present day forward;

- the consistency between the calibration and predictive analysis. Models of high confidence level classification (Class 3 models) should be used for prediction in a manner that is consistent with their calibration. For example, a model that is calibrated in steady state only will likely produce transient predictions of low confidence. Conversely, when a transient calibration is undertaken, the model may be expected to have a high level of confidence when the time frame of the predictive model is of less or similar duration to that of the calibration model;

- the level of stresses applied in predictive models. When a predictive model includes stresses that are well outside the range of stresses included in calibration, the reliability of the predictions will be low and the model confidence level classification will also be low.

The purpose of the HAM3 require that a high confidence level simulation (Class 3) is required. Table 6.1 shows the characteristics and indicators for a 'Class 3' confidence level model from Barnett et al. (2012). The considerable volume of historical monitoring data, the detailed geological understanding of the Lower Hutt Groundwater Zone, and the available data for model conceptualisation, construction and calibration are sufficient to meet the requirements of a Class 3 confidence level model.

Table 6.1: Characteristics and indicators for a Class 3 confidence level model (adapted from Barnett et al., 2012)

Data Requirements	Calibration	Prediction	Key Indicator
Spatial and temporal distribution of groundwater head observations adequately define groundwater behaviour, especially in areas of greatest interest and where outcomes are to be reported.	• Adequate validation is demonstrated.	• Length of predictive model is not excessive compared to length of calibration period.	• Key calibration statistics are acceptable and meet agreed targets.
Spatial distribution of bore logs and associated stratigraphic interpretations clearly define aquifer geometry.	• Scaled RMS error or other calibration statistics are acceptable.	• Temporal discretisation used in the predictive model is consistent with the transient calibration.	• Model predictive time frame is less than 3 times the duration of transient calibration.
Reliable metered groundwater extraction and injection data is available.	• Long-term trends are adequately replicated where these are important.	• Level and type of stresses included in the predictive model are within the range of those used in the transient calibration.	• Stresses are not more than 2 times greater than those included in calibration.
Rainfall and evaporation data is available.	• Seasonal fluctuations are adequately replicated where these are important.		• Temporal discretisation in predictive model is the same as that used in calibration.
Aquifer-testing data to define key parameters.	• Transient calibration is current, i.e. uses recent data.	• Model validation suggests calibration is appropriate for locations and/or times outside the calibration model.	• Mass balance closure error is less than 0.5% of total.
Streamflow and stage measurements are available with reliable baseflow estimates at a number of points.	• Model is calibrated to heads and fluxes.		• Model parameters consistent with conceptualisation.
Reliable land-use and soil-mapping data available.	Observations of the key modelling outcomes dataset is used in calibration.		• Appropriate computational methods used with appropriate spatial discretisation to model the problem.
Good quality and adequate spatial coverage of digital elevation model to define ground surface elevation.			• The model has been reviewed and deemed fit for purpose by an experienced, independent hydrogeologist with modelling experience.

6.3 HAM3 DESIGN

6.3.1 MODEL CODE SELECTION

A number of numerical computer codes can simulate groundwater flow – each have inherent strengths and weaknesses. To deliver the objectives of this study, important considerations when selecting a suitable model code were:

- The requirement to represent a relatively complex, layered groundwater environment and incorporate a degree of local-scale detail in certain areas.
- An ability to accurately simulate the interaction between groundwater and surface water.
- The requirement to interface with the PEST parameter estimation model to enhance calibration robustness and assist in the evaluation of model uncertainty.

The finite difference model code MODFLOW (USGS) was selected because it meets the above criteria and is the most widely accepted and verified code. MODFLOW was used in conjunction with the data processing interface Groundwater Vistas (Environmental Simulations Inc., 2012, version 6).

6.3.2 MODEL GRID AND LAYER STRUCTURE

Definition of the active model domain is based upon the geological analysis and conceptualisation presented in Sections 3-5. The Lower Hutt groundwater system is delineated by the contact between Quaternary basin-fill sediments and greywacke basement outcrop and extends beneath Wellington harbour.

The model domain, shown in Figure 6.1, extends from Taita Gorge to the entrance of Wellington harbour; the active model grid covers a an area 107.5km^2, of which a third (28.4km^2) is onshore.

The grid has been rotated 37° to align it with the principal groundwater flow direction and the north-western fault-bound edge of the basin. The default grid cell size is 100m x 100m which is applied to the entire on-shore portion of the model and is also used offshore as far as the Somes Island area. Further offshore the grid spacing progressively increases to a maximum of 500m.

The model has eight layers to represent the stratified nature of the leaky aquifer system and to adequately simulate vertical head gradients. The relationship between model layers and the hydrostratigraphy is shown in Table 6.1. The Petone Marine Beds are represented by two layers to enable more accurate simulation of vertical flow gradients and leakage across the aquitard. The Waiwhetu Gravels have also been divided into an Upper and Lower member in recognition of their significantly different hydraulic properties.

Table 6.1: HAM3 layer structure and corresponding hydrostratigraphic units

Layer No.	Hydrostratigraphic unit	GNS geol. model unit equivalent
1	Taita Alluvium-Petone Marine Beds. Offshore – ocean/constant head	2
2	Petone Marine Beds aquiclude and Taita Alluvium in unconfined area	2
3	Petone Marine Beds aquiclude and Taita Alluvium in unconfined area	2
4	Upper Waiwhetu Aquifer (confined aquifer-) / semi-confined gravels upstream	3
5	Lower Waiwhetu Gravels (confined aquifer)	3
6	Wilford Shells Beds (aquitard) / Moera Gravels unconfined area	4
7	Moera Gravels	5
8	Older Basal Gravels	6

Figure 6.2 shows three representative cross-sections through the HAM3 – one down-valley near to the north-western margin, and two across the valley at the Petone foreshore and through Somes Island (the locations of the sections are shown in Figure 6.1).
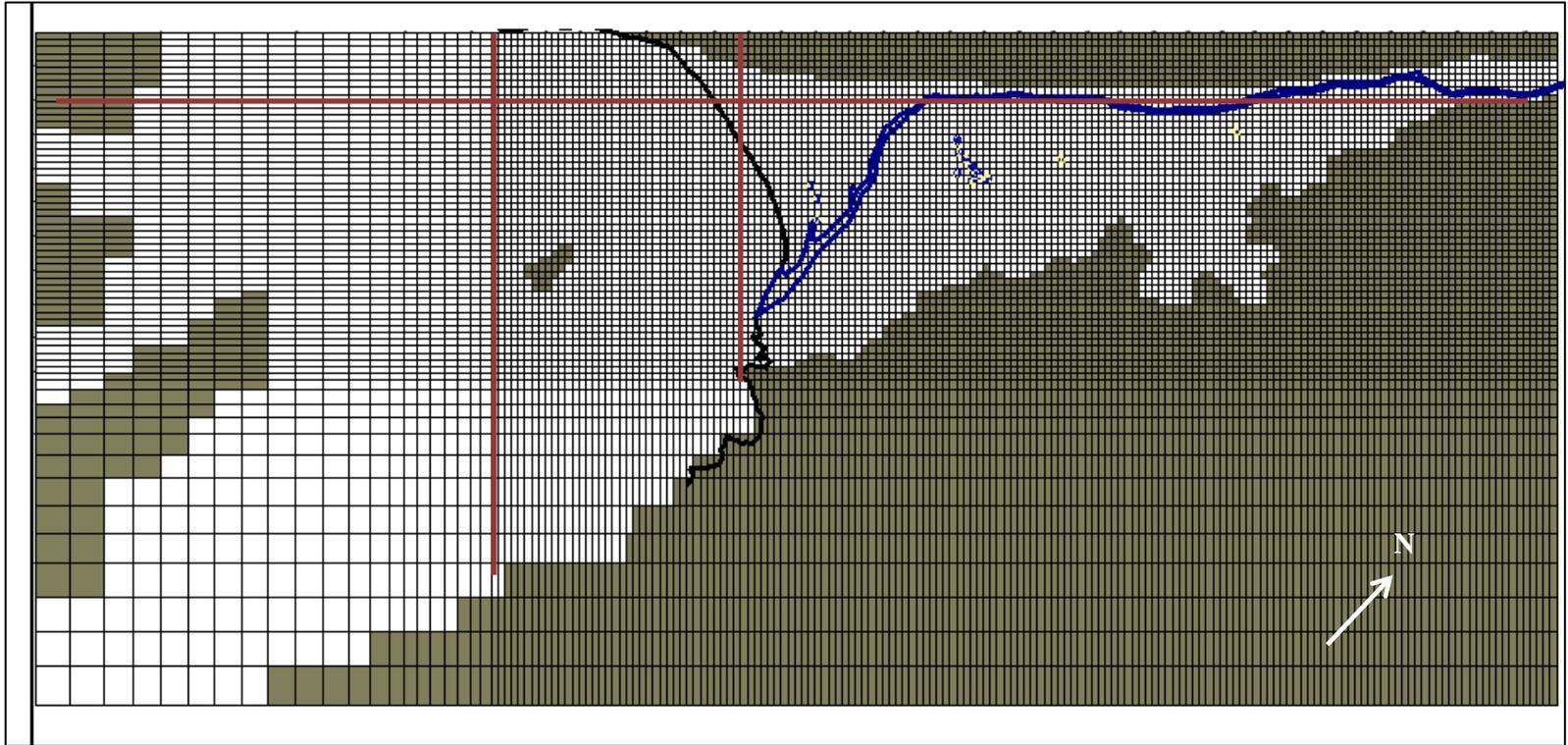
Figure 6.1: HAM3 grid design (showing location of cross-sections)
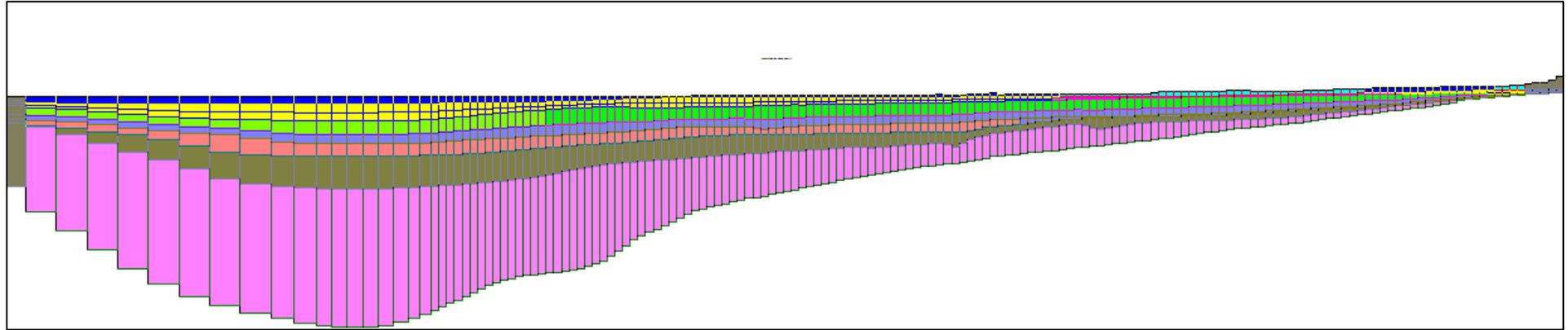
Long cross-section (Row 11) along Hutt River and parallel to the Wellington Fault. Taita Gorge on far right.
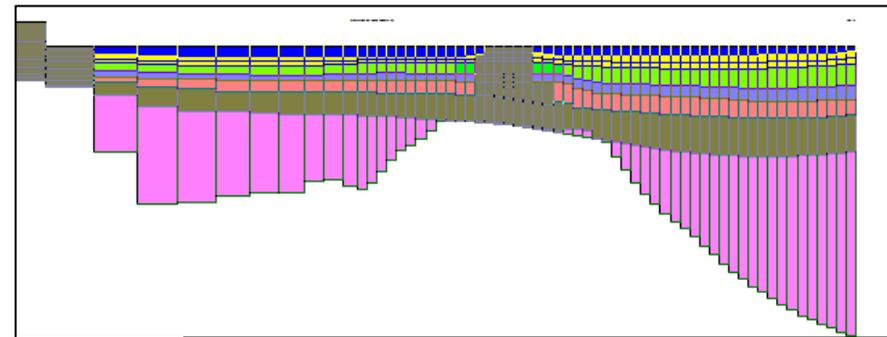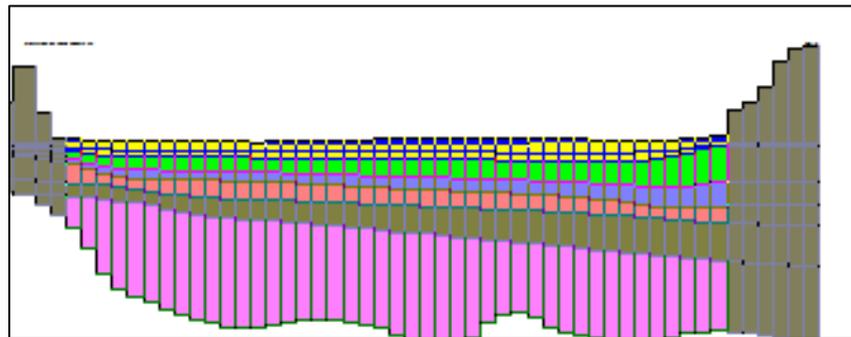
Cross-valley section (Col 65) at Petone foreshore. Wellington Fault on right.   Cross-valley section the Somes Island (Col 30).

Figure 6.2: Cross-sections through the HAM3 showing layer structure (see Figure 6.1 for locations of section lines).

Taita Alluvium = dark blue; Petone Marine Beds – yellow; Upper Waiwhetu Gravels – light green; Lower Waiwhetu Gravels – purple; Wilford Shell Beds – red; Morea Gravels – brown; Basal Gravels – purple.

The principal layer boundaries for the onshore part of the aquifer system were derived directly from the three-dimensional geological model developed by GNS Science for the Lower Hutt Basin (Boon et al., 2010) as described in Section 0. This model has been modified by subdividing two of the GNS geological model units to accommodate the conceptual hydrostratigraphy identified in this study. Unit 2 of the GNS model incorporated the Taita Alluvium, Melling Peat and Petone Marine Beds. However, it is recognised that younger Taita Alluvium overlies a generally mixed, heterogeneous, semi-contemporaneous underlying sequence which is dominated by the low permeability Petone Marine Beds sequence (in the lower part of the valley). This unit was therefore split into two layers using available geological data (principally bore logs) which are distinctive only in the confined aquifer area between around Boulcott and the coastline. GNS Unit 3 (Waiwhetu Gravels) was also subdivided into an Upper and Lower part as described in Section 3.2.2.2 using geological evidence and interpretations carried out during the previous HAM2 model.

Since the GNS geological model only extends as far as the shoreline, the offshore sub-harbour layered aquifer structure was modelled using the seismic reflection geophysical surveying carried out by Wood and Davey (1992). The geophysical data proved useful in defining main reflective horizons such as the top of the last glacial (Q2-4) gravels which, together with near-shore bores drilled around Somes Island, provided information to model the sub-harbour location of the Waiwhetu aquifer. Combined with the NIWA bathymetry survey (Section 2.3), the thickness of the overlying Petone Marine Beds could also be reasonably defined. Offshore modelling of the deeper hydrogeological layers has relied upon the geophysical interpretations of Wood and Davey (1992); the interpretations of the deeper layers inherently have a lower confidence level than the spatial definition of the shallower Waiwhetu Gravels and marine bed.

6.3.3 GROUND AND HARBOUR FLOOR ELEVATION

The ground surface in the HAM3 has been derived from a high-resolution Digital Terrain Model (DTM) for Lower Hutt valley floor collected by GWRC. Processing of the data was undertaken as part of the three-dimensional geological model developed by GNS Science (Boon et al., 2010).

The offshore base of Layer 1 represents the harbour floor in HAM3 with the layer essentially representing the ocean (constant head). The high-accuracy bathymetry survey has been used in the model for simulation of the harbour floor/top of the Petone Marine Beds. The bathymetry data has also been used to accurately locate the submarine spring vents in the model.

6.3.4 INITIAL HEAD CONDITIONS

Preliminary initial head conditions for the transient flow model were derived from the heads generated by a steady state model. However, since the steady state generated head distribution is not consistent with the commencing boundary stresses of the transient model, the first stress period of transient model runs were run at steady state to provide a stable starting head condition.

6.4 Boundary conditions

6.4.1 External model boundary and assumptions

The external model boundaries define the active grid domain and coincide with the contact between basin fill sediments and greywacke bedrock. This also applies to the base of the onshore part of the model on the basis of bore data and geophysical interpretation. Offshore, the basin deepens considerably and although there is little information on the deeper sediment sequence the depth to basement has been based on geophysical interpretation – although the model is not sensitive to the location of this offshore basement since sediments below the Moera Gravels exhibit a low permeability and are known to contain saline groundwater (i.e., there is negligible throughflow).

6.4.2 River boundary

The HAM3 represents the Hutt River using the Modflow RIVER package. The river bed elevation and channel width have been derived from the 1998 cross-section surveys carried out by GWRC (refer to Section 2.1) since bed levels are actively managed to 1998 levels for flood control purposes. The lowest (thalweg) bed elevations were used in the model.

HAM3 relies on the permanent flow gauge at Taita Gorge (TG) for the calculation of downstream river stage. This is achieved through the development of location-specific TG flow / downstream stage relationships using the GWRC MIKE11 surface water flood model (2000). The relationships allow river stage to be calculated at locations downstream of Taita Gorge based upon the measured flow at Taita Gorge. Two of the flow-stage relationships were verified in the field at locations on the river recharge reach above Kennedy Good Bridge. Temporary pressure transducers were installed in the river adjacent to the Mabey Road and Nash Street bankside piezometer clusters (Figure 4.1) for a period of about 1 month. Comparison of the monitored river level data (surveyed to the common valley datum – mean sea level) with the predicted stage heights based on the TG flow record showed close agreement. Therefore, a reasonable degree of confidence can be attributed to the MIKE11 model-derived TG flow- stage relationships for locations downstream of Taita Gorge.

Since the transient HAM3 runs at a 7-day stress period, 7-day mean Taita Gorge flows were calculated and then transformed into a stage height at thirteen locations downstream. Appendix 1 contains the TG flow – stage relationships derived from the Mike 11 model and Figure 6.3 shows the locations of the sites where river stage has been calculated; stages between these locations have been linearly extrapolated in HAM3.
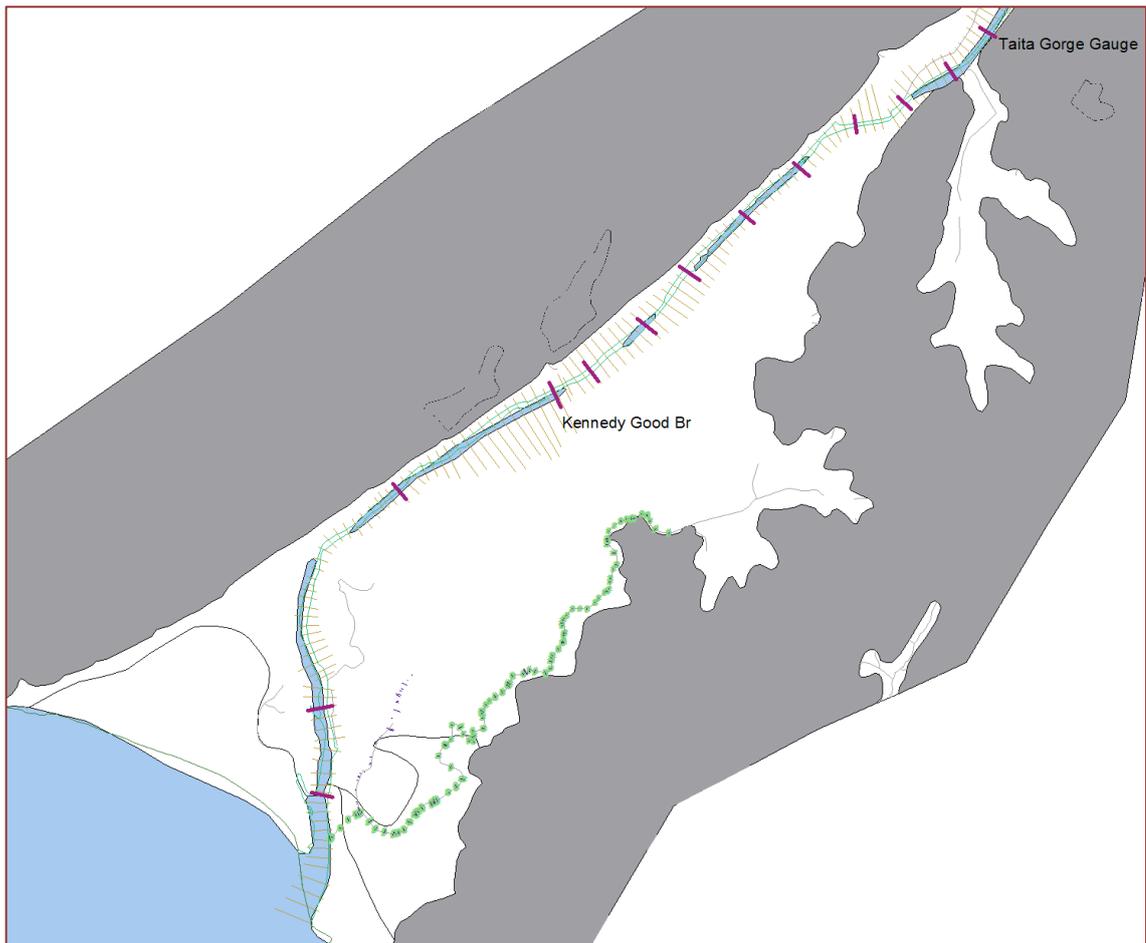
Figure 6.3: Locations of 13 river stage calculation sites using flow monitoring at Taita Gorge. Also shown are GWRC cross-section survey locations on the Hutt River and Waiwhetu Stream.

Streambed conductance is a parameter used by MODFLOW to control the flow of water to and from the underlying aquifer. This parameter is usually derived through trial and error in the calibration process. Bed conductance is calculated using the length of the river in each river cell (L), the width of the river (W) in the cell, the thickness of the river bed (M), and the hydraulic conductivity of the river bed material (K). The stream-bed conductance, C, is described as:

$$C \; = \; K\,L\,W\,/\,M$$

The river width (W) has been derived from GWRC flood protection survey cross-sections. The bed thickness (M) has been held constant for each cell at 1m. The length of the reach (L) coincides approximately with the cell dimension of 100m.

The main 'unknown' term in the conductance equation is the vertical hydraulic conductivity of the channel bed. An approximation of this term has been derived using the groundwater level recorded by the bankside piezometers at Mabey Road and adjacent river level monitoring to derive a vertical hydraulic gradient next to the river. Figure 6.4 shows monitoring data at Mabey Road for the period during which temporary river level recording was undertaken. During this time the river level was approximately 0.5m

above the water table (Mabey 7m and 13m piezometers). The groundwater level was also above the river bed.
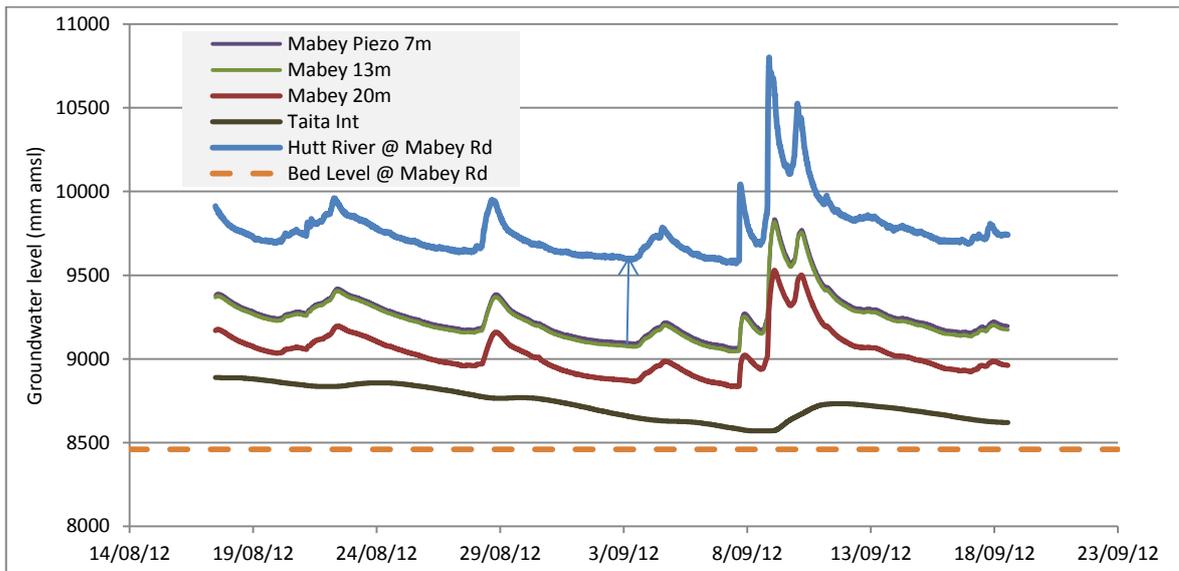
Figure 6.4: Comparison of river stage, bed elevation and adjacent groundwater levels in the bankside Mabey Road piezometer cluster during December, 2012.

Vertical hydraulic conductivity of the river bed can be broadly calculated using the following assumptions:

- That the observed vertical head gradient between the river and aquifer is applicable along the entire 5km reach of river that loses water to the aquifer. This is confirmed using the bankside piezometer cluster at Nash Street located about 1.8km upstream.
- That the loss from the river along the recharge reach is 1000 L/sec (refer to Section 4.4.1).

Vertical hydraulic conductivity (kv) can be calculated using the following equation

$$kv = Q / A\ i$$

where:
Q = river loss (1,000L/sec or 86,400m^3/day)
A = area of losing bed: 5,000m x 50m = 250,000 m^2
i = dh/dz – vertical head gradient between the river and the aquifer: dh (head difference) = 0.5m on 3/9/12. dz (distance between stream bed and piezometer screen top) = 2.8m. So, i = 0.18

therefore: kv = 86,400 / 250,000 * 0.18 = <u>1.9m/d</u>

The above calculation can be used as a guide for the vertical hydraulic conductivity of the river bed, bearing in mind assumptions inherent in the calculation.

Estimated river bed conductance per 100m grid square of river with an average width of 80m is therefore in the order of 16,000 m/day, assuming a bed thickness of 1m.

Rushton (2003) propositions that when the regional water table in the adjacent aquifer intersects the sides of the river channel, the loss is not directly proportional to the bed

conductance. In this instance, the river loss depends principally on the hydraulic gradient between the river and the aquifer, and the hydraulic properties of the adjacent aquifer; the loss from the river increases as the head difference increases. But when the river channel lies above the surrounding water table (i.e., the river becomes 'perched'), the loss from the channel approaches a constant value and becomes directly proportional to the bed conductance term described above.

Therefore, during higher water table conditions (generally over winter), and also when the river levels may be higher, the bed losses would tend to be controlled by the head gradient between the river and aquifer and the hydraulic properties of the unconfined aquifer. It would be expected the head differences between the river and aquifer would be lower in winter and therefore losses would be lower. During low unconfined aquifer level conditions (summer), when the head gradient reaches its maximum, the river bed conductance will become the limiting control on bed losses.

6.4.3 DRAIN BOUNDARIES

The Waiwhetu Stream is known to receive some groundwater discharge, although quantification of the flux is difficult to estimate due to lack of information and tidal influences in the lower reaches. The stream has been represented in the HAM3 using the Modflow Drain package which allows discharge from the aquifer to the stream (but not vice versa). A bed conductance of 0.1m has been applied to the drains in recognition of the low-permeability, silty channel lining. Such a conductance allows a groundwater discharge in the order of that estimated in Section 2.2.

6.4.4 CONSTANT HEAD BOUNDARIES

Wellington Harbour is simulated as a constant head condition which has been assigned to Layer 1 of the HAM3. A constant head of 0.2m amsl has been set since this represents the current mean sea level in Wellington Harbour relative to the Wellington Vertical Datum-1953 (WVD-53). Use of a mean sea level 0.2m from about 1990 therefore appears to be appropriate on the basis of long-term sea level monitoring for Wellington Harbour presented by NIWA (2012).

Since the HAM3 transient model runs at 7-day stress periods it is important to assess whether the constant head condition of 0.2m is appropriate given that the 7-day mean will have two monthly maxima and two minima relating to neaps and springs in the month. Figure 6.5 shows the continuous tidal monitoring in Wellington Harbour for the second half of 2012, over-plotted with the 7-day mean level (normalised to a 0.2m mean sea level). The variation from the overall mean is up to about 0.1m, which has been established (through model sensitivity analysis) to have a negligible effect on groundwater levels beneath the harbour and at the foreshore.
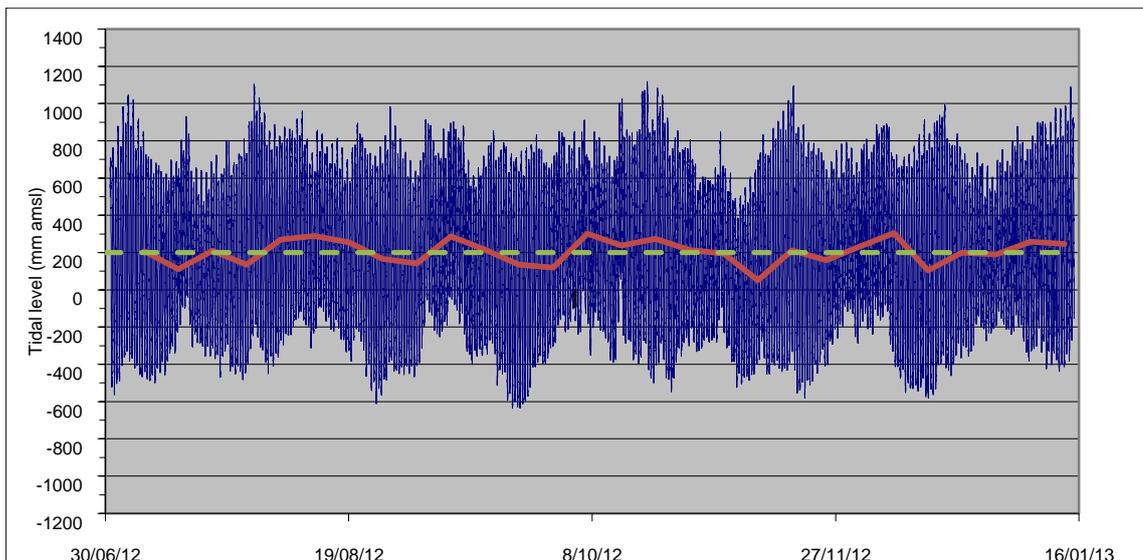
Figure 6.5: Tidal range in Wellington Harbour (Queens Wharf) showing 7-day mean level (red line). Data are normalised to a 0.2m mean sea level (above WVD-53).

The constant head condition provides a 'sink' for diffuse submarine leakage from the offshore confined aquifers and for point source discharges at submarine spring vents.

6.4.5 SUBMARINE SPRING BOUNDARIES

Although not strictly a numerical boundary as such, the submarine spring vents have been represented using a combination of the constant head condition the harbour in conjunction with an adjusted vertical hydraulic conductivity for the Petone Marine Beds (model layers 3 and 4). This set-up in effect mimics a MODFLOW general head boundary condition. Grid cells coinciding with known spring vent locations in layers 2 and 3 were assigned a higher vertical hydraulic conductivity to allow localised discharge from the underlying Waiwhetu Aquifer. The vertical hydraulic conductivity at the spring vent sites was adjusted during the calibration process to provide a total discharge to the harbour of the correct order of magnitude. The simulated springs therefore provide a connection between the aquifer and the harbour, albeit an attenuated/resistive one which is consistent with current understanding of the springs.

6.5 HYDRAULIC PROPERTY ZONES

6.5.1 HYDRAULIC CONDUCTIVITY

Development of the hydraulic property zonation framework for the Lower Hutt groundwater system maintains consistency with the conceptual hydrogeological model presented in Section 5 and the parameter definitions contained Section 0.

Table 6.2 lists the hydraulic conductivity and storage zones used in the HAM3 and the measured or estimated ranges for transmissivity and hydraulic conductivity (from discussion in Section 0). Figure 6.6 shows the hydraulic conductivity zonation for each model layer.

Table 6.2: Hydraulic conductivity and storage zones used in the HAM3 including measured and estimated ranges of transmissivity and horizontal hydraulic conductivity

Hydrostratigraphic unit	Model layer	Hydraulic conductivity zone	Transmissivity m^2/day	Hydraulic conductivity range m/day	Est. mean hydraulic conductivity m/day
Taita Alluvium/Melling Peat/Marine beds	1 – 3	1, 2, 3	3,000-53,000	1,000-5,000 (?)	1,000 (Avalon area)
Petone Marine Beds aquitard	2 – 3	4, 10	-	0.1-0.001	0.001
Upper Waiwhetu Aquifer	3 – 4	3, 11	22,000-39,000	1,000-2,000	1,500
Lower Waiwhetu Gravels	5-6	5	no data	-	500
Wilford Shell Bed	6	6		0.1-0.01 (?)	0.01
Moera Gravels	7	7	1,000-2,600	150-250	200
Basal Gravels	8	8	70-150 (?)	10-30 (?)	20

Due to the highly stratified nature of the sediment sequence and the occurrence of laterally-persistent, silt-rich layers, particularly in the aquitards, vertical hydraulic conductivity (kz) values are assumed to be at least one order of magnitude lower than the horizontal hydraulic conductivity (kh) values listed in Table 6.2.

6.5.2 STORAGE ZONES

Unconfined storage parameter zones are only assigned to layers 1 and 2 since the water table will not drop into deeper layers. Although there is no pump testing information to provide a specific yield for the Taita Alluvium, based on the lithology of the unconfined aquifer, it is estimated that specific yield will range from 0.05 to 0.1.

Various pumping tests in the Upper Waiwhetu Gravels provide a range for the confined storage coefficient (S) of $1 \times 10^{-3} – 3 \times 10^{-4}$. The specific storage (Ss) required by Modflow 2000 will therefore be an order of magnitude lower than this range. Pumping tests in the Moera Gravels provide a slightly lower confined storage coefficient range of $1 \times 10^{-4} – 4 \times 10^{-5}$. Other confined strata are likely to exhibit a similar range in the confined storage parameter.

6.5.3 RECHARGE ZONES

There are four active rainfall recharge zones which reflect the soil groups identified on the valley floor (refer to Section 4.4.2). Each zone has a unique recharge record based upon soil moisture balance calculations. Figure 6.7 shows the recharge zones on Layer 1.
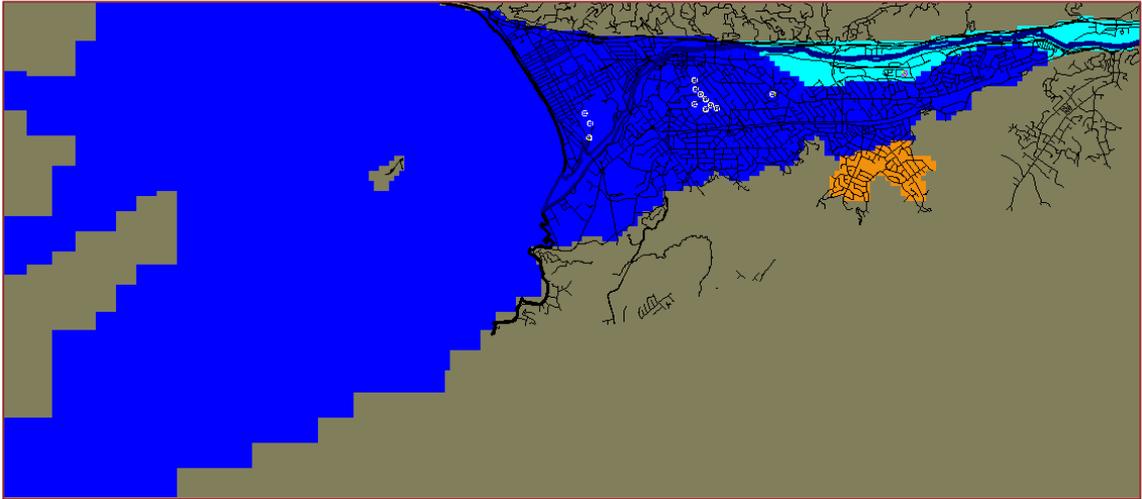
Layer 1: Taita Alluvium. Zone 1 TA (dark blue); Zone 2 recent floodplain (light blue); Zone 10 Melling Peat (orange)
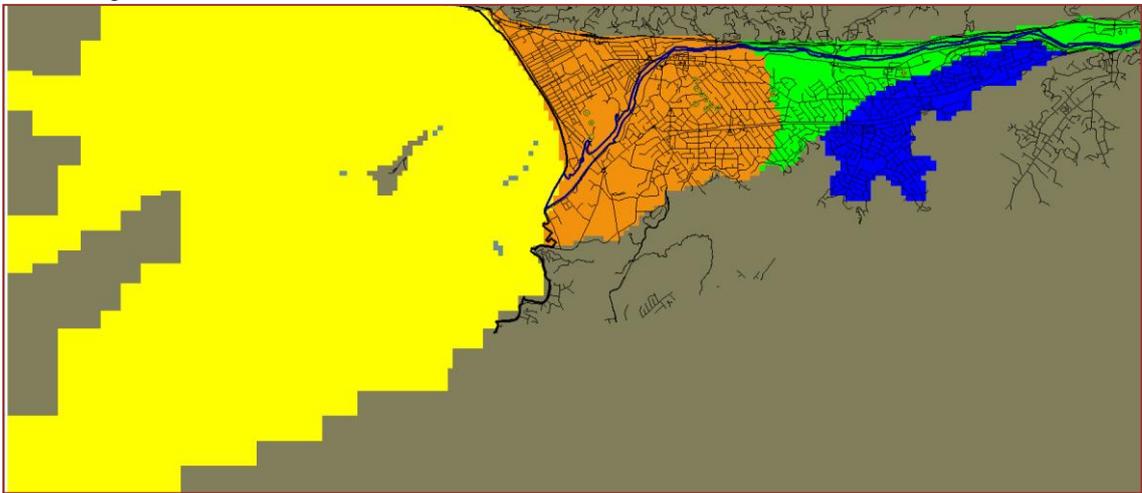
Layers 2 and 3: Petone Marine Beds aquitard and Taita Alluvium. Zone 4 PMB (yellow); Zone 10 PMB (orange); Zone 3 TA (green); Zone 1 TA (dark blue).
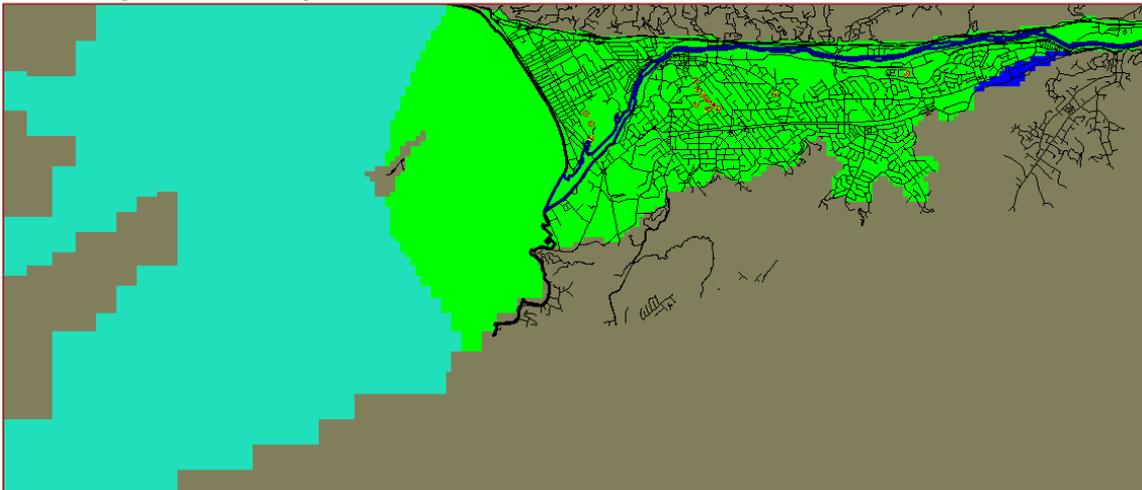
Layer 4: Zones 3 and 11 – Upper Waiwhetu Gravels (UWG). Zone 3 UWG onshore (green); Zone 11 UWG offshore (teal).

Figure 6.6: Hydraulic conductivity zonation in the HAM3.
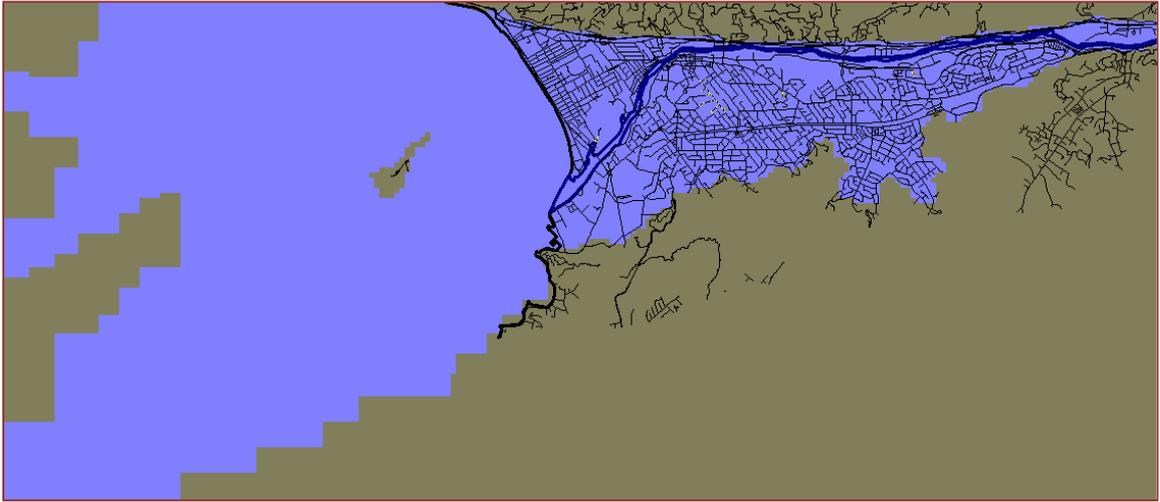
Layer 5: Lower Waiwhetu Gravels (LWG). Zone 5 LWG (purple)
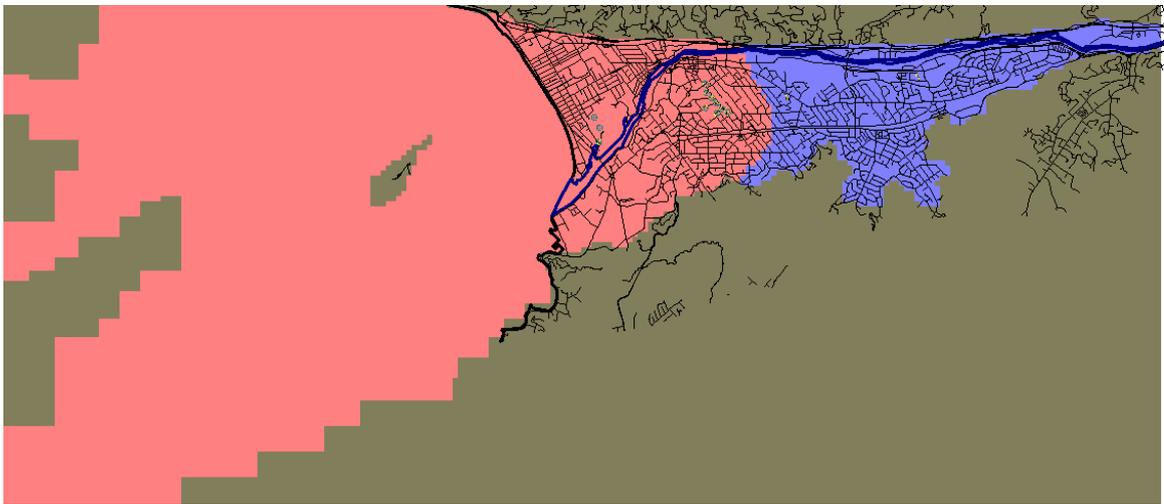
Layer 6: Wilford Shell Beds aquitard and Lower Waiwhetu Gravels. Zone 6 WSB (pink); Zone 5 LWG (purple)
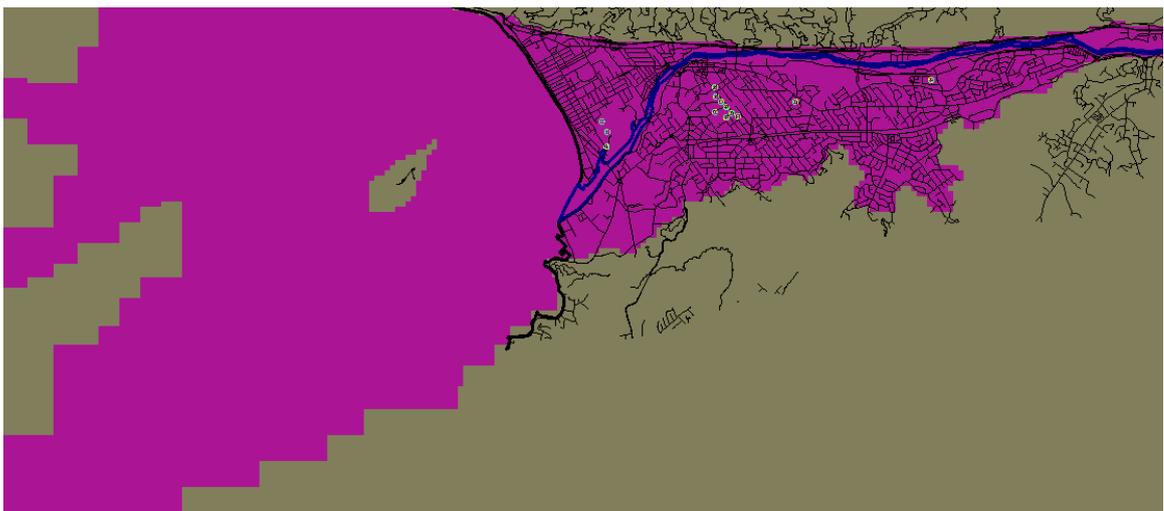
Layer 7: Moera Gravels (MG). Zone 7 MG (pink)

Figure 6.6 (cont): Hydraulic conductivity zonation in the HAM3.
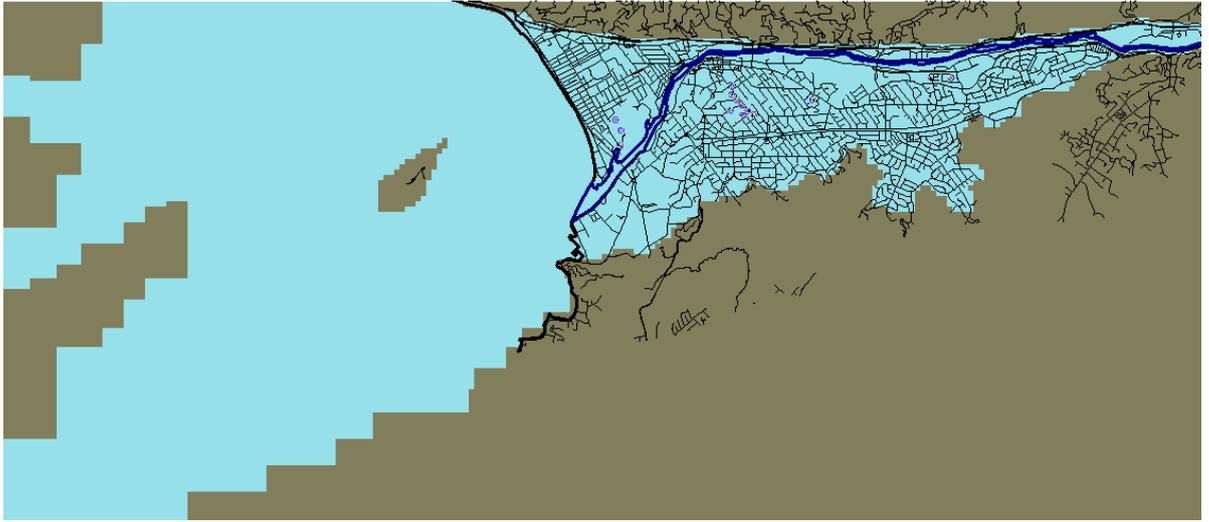
Layer 8: Basal gravels. Zone 8 (blue).

Figure 6.6 (cont): Hydraulic conductivity zonation in the HAM3.
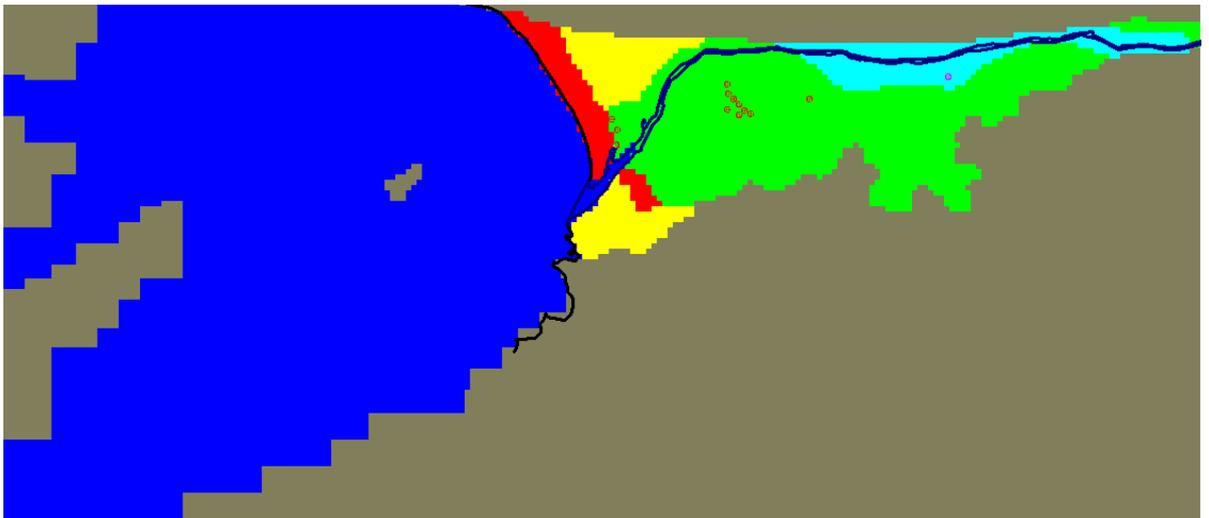
Figure 6.7: Rainfall recharge zonation in Layer 1 reflecting soil types. Zone 1(dark blue = zero); Zone 2 (light blue); Zone 3 (green); Zone 4 (yellow); Zone 5 (red).

7 MODEL CALIBRATION

7.1 CALIBRATION STRATEGY

The HAM3 model is categorised as an 'aquifer simulator' of high complexity (Middlemis 2001) having a Class 3 confidence level (Barnett et al. 2012) to meet its prediction-focused purpose. The calibration methodology has therefore been designed to maximise prediction reliability using the procedure described below.

The model calibration process has entailed the adjustment of independent variables (parameters and fluxes) within realistic limits to produce the best match between simulated and measured data (groundwater levels and water balance components such a spring flows and measured river flow losses/gains). As such, the calibration process is an 'inverse approach' attained through the adjustment of parameters such as hydraulic conductivity, storage coefficient and stream-bed conductance until the solution matches observed data.

Such a calibration process, although necessary, cannot on its own provide a reasonable degree of confidence in the predictive capability of the model. It shows that a model can reproduce system behaviour under a certain set of conditions (Middlemis 2001). Sensitivity analysis must also accompany the calibration process to assess uncertainties inherent in the calibration.

Calibration traditionally involves a manual trial-and-error process of systematic parameter adjustment until a relatively good fit between simulated and observed data is achieved. The manual process is time-consuming and subjective, but nevertheless regarded to be a valuable first step in the model calibration process through which the conceptual model can be tested and the sensitivity of input parameters evaluated and adjusted if necessary. Automated calibration using inverse parameter estimation algorithms (such as PEST) removes some of the subjectivity of the manual trial-and-error process and provides an insight to the 'non-uniqueness' of a model.

Manual calibration under steady state conditions was initially undertaken as a first step to evaluate the conceptual model. This was followed by a manual transient flow calibration phase to obtain a sense of model sensitivity and further test the appropriateness of the conceptual model and boundary conditions and to tune the hydraulic conductivity zonation framework.

Following completion of a manual 'pre-calibration' phase, the automated parameter estimation code PEST (Dougherty, 2008) was utilised to optimise the calibration, perform a sensitivity analysis and provide information on the uniqueness, or robustness, of the calibration. The PEST calibration was performed for a five-year dataset (2007-2012) during which a wide range of system stresses occurred. Finally, a verification run was performed using a 20-year calibration dataset.

7.2 Minimising non-uniqueness

Non-uniqueness is inherent in most complex groundwater flow models and arises because a number of different parameter sets can produce the same model outputs – i.e. multiple calibrations are possible using different combinations of model inputs because certain parameters (such as recharge and transmissivity) are highly correlated. The matching of measured heads alone by a 'calibrated model' does not mean that the hydraulic properties used in the model are correct and that the model can be confidently used for predictive purposes.

The MDBC (Middlemis, 2001) modelling guidelines suggest that the following methods should be conjunctively employed to reduce the non-uniqueness of a model:

a) Calibrate the model using hydraulic conductivity (and other) parameters that are consistent with measured values. The range for various parameters is justifiably restricted.
b) Calibrate the model to a range of hydrogeological conditions (a wide range of climate and induced stresses, such as abstraction).
c) When possible, calibrate the model using measured water balance fluxes (such as spring flows, river losses/gains) as calibration targets.

The three recommendations have been implemented in the HAM3 as described below.

With reference to requirement a), during model calibration, hydraulic conductivity ranges have been guided by pumping test analyses for the main aquifer units which were referenced during the calibration process as constraints.

To address requirement b), the transient model calibration and verification period covers a 20-year period over which both climate stresses and abstraction stresses have experienced a large variation.

In terms of requirement c), Sections 0 and 5 provides an evaluation of the water balance for the Lower Hutt aquifer systems and quantification of components of the balance, such as groundwater-surface water fluxes and spring discharges. This data has been heavily relied upon during the calibration process to ensure that the simulated water balance is consistent with field information.

7.3 Calibration targets and data processing

7.3.1 Head targets

Table 4.1 lists the groundwater level monitoring sites used in the model calibration (see Figure 4.1 for locations). These are distributed across the Lower Hutt Valley and principally located in the Upper Waiwhetu Aquifer, Moera Aquifer and the unconfined aquifer zone. Section 4.1.1 provides further details of the groundwater level monitoring network.

For the transient model calibration process, the continuous groundwater level monitoring data were averaged over 7 days. This has the effect of smoothing out the

tidal variation – which, at the Petone foreshore in the Waiwhetu Aquifer, can be up to about 70% of the tidal range measured in the harbour. However, an averaging over 7 days will still show two monthly maxima and two minima relating to neap and springs, as discussed in Section 6.4.4, resulting in a +/- 0.1m harbour fluctuation in the averaged record (see Figure 6.5). This will equate to a tidal effect in the averaged groundwater level data of up to about 0.07m (assuming a 70% tidal efficiency at the foreshore and a 0.1m monthly variation), reducing inland as the tidal effects diminish. Such an effect is not regarded to significantly impact on the use of the averaged groundwater head data for model calibration.

The Nevis Street (R27/1223) groundwater level monitoring data was not used in the calibration since it is considered to be unreliable (the casing may be damaged).

7.3.2 WATER BALANCE TARGETS

Water balance targets were used alongside head targets during the calibration of the HAM3. These were, in order of priority:

- River flow losses (aquifer recharge) between Taita Gorge and Kennedy Good Bridge were given a high priority in the calibration process. Quantification of the losses is based on the concurrent gauging database (Section 4.4.1)

- Spring discharge into Wellington Harbour (Section 4.5.1) was assigned a relatively low weighting due to the assumptions and uncertainties inherent in quantification of this flux

- Return fluxes to the Hutt River – 'order of magnitude' assessment based on limited available data.

- Discharge to the Waiwhetu Stream – 'order of magnitude' assessment based on limited available data.

7.4 CALIBRATION EVALUATION

Model calibration has been evaluated in both quantitative and qualitative terms.

Quantitative measures include:

- Mathematical and graphical comparison between measured and simulated heads.
- Comparison between simulated and measured water balance components.

The qualitative assessment of the calibration entailed comparing simulated and observed groundwater flow patterns, comparison of model outputs with the conceptualisation of the groundwater system, and evaluation of the patterns of groundwater-surface water interaction with reference to observed patterns.

Calibration acceptance measures used in the HAM3 are summarized in Table 7.1.

Table 7.1: Calibration Acceptance Measures (after Middlemis 2001)

Performance Measure	Criteria	Comments
Water balance: The water balance error term at the end of each model time step is the difference between total modelled inflow and total modelled outflow, including changes in storage, expressed as a percentage of total flux.	A value of less than 1% is a normal guideline for each stress period or for the entire simulation (steady state).	
Iteration residual error: The error term is the maximum change in heads between successive iterations.	Iteration convergence criterion should be set one or two orders of magnitude smaller than the level of accuracy desired in the model head results.	
Qualitative measures: Patterns of observed groundwater flow. Patterns of groundwater-surface water interaction. Patterns of aquifer response to stresses. Distributions of aquifer properties adopted to achieve calibration.	Subjective assessment of the accuracy of fit between modelled and measured groundwater levels, flow patterns, bore hydrographs, and surface water flows. Justification for adopted model aquifer property zonation and ranges of values.	Should take into consideration the adopted conceptual model, particularly relating to surface water interaction, model discretisation effects and interpolation effects.
Quantitative measures: Statistical measures of the differences between modelled and measured head data. Mathematical and graphical comparisons between measured and simulated aquifer heads, and flow system components.	Use residual head statistics. Consistency between modelled head values and observed values. Comparison of simulated and measured components of the water budget, including surface water flows, groundwater abstraction and evapotranspiration rates.	A range of quantitative measures should be carefully selected for use in the calibration procedure. It is expected that any model calibration is unlikely to be good in all areas, but it should be good in critical areas.

7.5 PRELIMINARY STEADY STATE 'CALIBRATION'

It is routine practice to develop a steady state simulation to test the conceptual model, ensure that the parameter zonation framework is appropriate, and check that the model predicts a realistic water balance consistent with the estimated fluxes (discussed in Section 5.2).

When an aquifer is in 'steady state', inputs and outputs (and therefore groundwater heads) are assumed to remain constant. In other words, the groundwater system is in equilibrium. True equilibrium conditions rarely occur in any groundwater system - especially those which are dominated by volatile river-aquifer fluxes and highly variable rainfall recharge processes. Periods when heads and fluxes remain stable over a relatively long period of time, such as late summer or late winter, are the closest that an equilibrium condition is approached.

The results of the steady state calibration run are shown in Figure 7.1 and in Table 7.2. This 'pre-calibration' model was manually fitted to average head and water balance target data. The overall residual mean of the calibration is 0.01 and the scaled RMS is 0.025 – both indicating a very good match between the observed and modelled groundwater heads in all aquifers.

Note the steady state calibration has a different layer structure to the transient calibration because the Petone Marine Beds (layer 2) was later modified and divided into two layers in the subsequent transient simulations. Layer 3 is therefore the Waiwhetu Aquifer in this model version.
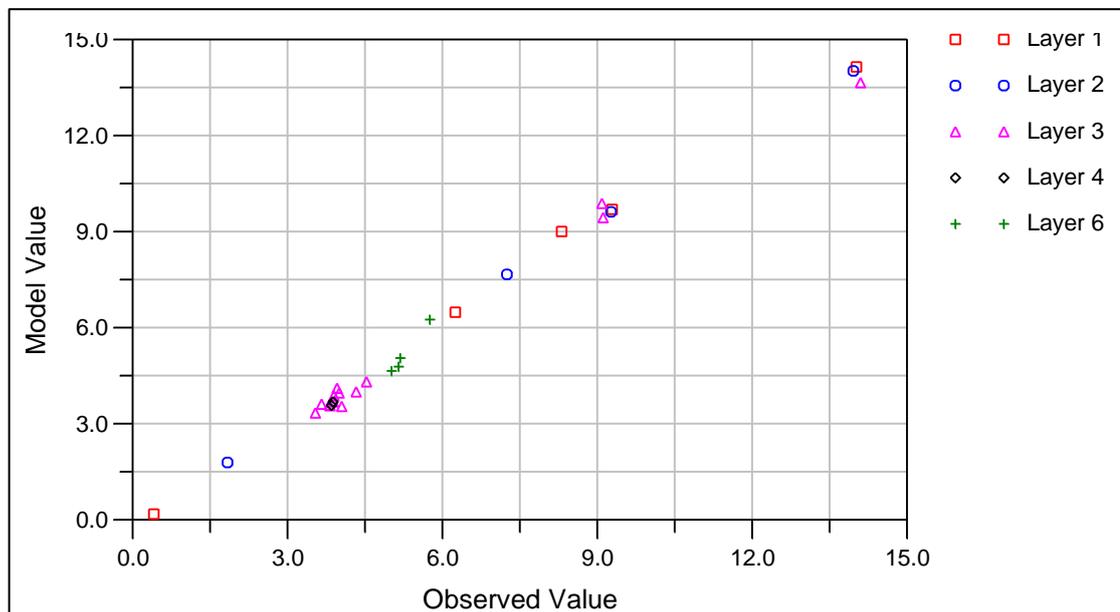

Figure 7.1 : HAM3 steady state model 'calibration' to average head conditions.

Table 7.2: Calibration statistics for steady state model.

Statistical performance measure	Calibration Statistic	Unit
No of observations	29	No.
Absolute residual mean	0.28	L
Min residual	-0.71	L
Max residual	0.51	L
Residual standard deviation	0.025	L
Observed range in head	13.69	L
Mean of residuals	0.01	L
Sum of residual squares	3.31	L^2
Root mean square (RMS) error	0.34	L
Scaled RMS	0.025	%

At a regional scale in a heterogeneous aquifer system, the calibration is regarded as a good initial simulation and provides confidence in the conceptualization of the flow system, and the assumptions that have been adopted.

The steady state mass balance (inflow and outflow rates) is shown in Table 7.3 which also shows the conceptual water balance (discussed in Section 5.2). Inflows are river recharge and rainfall recharge and outflow from the groundwater system is dominated by five processes – discharge back into the rivers, abstraction from wells, discharge to drain cells (Waiwhetu Stream), and discharge to sea into the constant head boundary.

Table 7.3: Steady state mass balance (conceptual water balance in brackets)

	In (m³/day)	Out (m³/day)
Rainfall recharge	16,500 (30,000)	
Hutt River flow loss/gw recharge	106,000 (95,000)	
Distributed submarine leakage		14,000 (15,000)
Submarine spring discharge		2,000 (2,000)
Groundwater discharge to Hutt River and streams		33,000 (44,000)
Discharge to Waiwhetu Stream		3,500 (4,000)
Abstraction		70,000 (60,000)
Totals (m³/day)	*122,500 (125,000)*	*122,500 (125,000)*

Comparison of the steady state model output and the estimated conceptual water balance shows that they are consistent. This result provides confidence in the set-up of the HAM3 and the translation of the conceptualization of the groundwater environment into a numerical representation.

7.6 TRANSIENT CALIBRATION

7.6.1 TRANSIENT CALIBRATION RUN SET-UP

The transient calibration model was set up using 5 years of data for the period 1/7/2007 to 27/6/2012. The relatively short time period was selected to ensure workable model run times for manual and automated calibration activities. The calibration period incorporates a wide range of climatic conditions and therefore represents a window of time in which there was a large range in system stresses.

Following the automated PEST calibration and paramrter optimisation process using the 5-year dataset, a verification run was performed using monitoring data covering the period 1/7/1992 to 1/12/2012 (20 years).

The transient groundwater models were run using a weekly stress period divided into 5 timesteps with a multiplier of 1.2. The 5-year calibration run therefore has 260 stress periods and a run duration of 1,820 days. The first stress period was set to run to steady state to provide a stable starting head condition for the run. The USGS PCG2 (Hill, 1990) solver was employed using a head change criterion of 0.01. The model converges quickly and the 5-year simulation takes about 5 mintues to run.

7.6.2 AUTOMATED CALIBRATION AND PARAMETER OPTIMISATION (PEST)

Calibration of the transient HAM3 model was undertaken using the PEST inverse model (Version 11, Doherty 2008) in parameter estimation mode. The calibration process relied principally on groundwater level observation targets listed in Table 4.1. However, the process was also manually constrained using water balance calibration targets. A weighting of 1 was applied to all groundwater level observation data, except for Taita Intermediate in the unconfined aquifer which was assigned a weighting of 2.

PEST was run for only hydraulic conductivity and storage parameters using the zonal framework described in Section 6.5 (Figures 6.6). Rainfall recharge, being a relatively minor water balance component which has been fairly confidently calculated, was not adjusted during the calibration process (particularly since recharge is also highly correlated with transmissivity). River bed conductance also proved to be relatively insensitive and was therefore not estimated using PEST.

The PEST inverse model was initially run to identify highly correlated parameters and insensitive parameters, which resulted in some parameters being frozen (fixed) prior to proceeding to the automated calibration process. These were generally parameters in zones where there were few or no observations – such as the horizontal hydraulic conductivity of aquitards, unconfined aquifer in the southern part of the valley, and the deep basal gravels.

After initial assessment there remained a total of 15 adjustable parameters and 13 fixed parameters. Table 7.4 lists these zones and the PEST set up configuration for each of them. The minimum and maximum bounds were set using available knowledge or estimated based upon typical ranges for specific lithologies. All adjustable parameters were log-transformed.

Table 7.4: Transient calibration parameter zone PEST set-up. Adjust = PEST adjustable parameter; Fix = frozen insensitive parameter; Kx = horizontal hydraulic conductivity; Ky = vertical hydraulic conductivity; S = specific storage; Sy = specific yield. Kx and Kz values are in m/day.

Type	Use	Name	Zone	Unit/location	Initial/Fixed Value	Minimum	Maximum
S	Adjust	ss1	1	Taita Alluvium	5E-5	1.0E-06	1.0E-04
S	Adjust	ss3	3	Upper Waiwhetu Gravels	5E-5	1.0E-06	1.0E-04
S	Adjust	ss4	4	Moera Gravels/Wilford SB	5E-5	1.0E-06	1.0E-04
S	Adjust	ss6	6	Lower Waiwhetu Gravels	5E-5	1.0E-06	1.0E-04
Sy	Adjust	sy1	1	Taita Alluvium	0.1	5.0E-02	2.0E-01
Kx	Adjust	kx3	3	Upper Waiwhetu Gravels	1200	1000	1400
Kx	Adjust	kx5	5	Lower Waiwhetu Gravels	300	150	500
Kx	Adjust	kx7	7	Moera Gravels	80	50	500
Kz	Adjust	kz2	2	Taita alluvium – recharge zone	1	1.0E-01	50
Kz	Adjust	kz3	3	Upper Waiwhetu Gravels	1	1.0E-03	5
Kz	Adjust	kz4	4	Petone Marine Beds – offshore	0.002	1.0E-04	1.0E-02
Kz	Adjust	kz5	5	Lower Waiwhetu Gravels	0.1	1.0E-02	10
Kz	Adjust	kz6	6	Wilford Shell Beds	0.0005	1.0E-04	1.0E-03
Kz	Adjust	kz7	7	Moera Gravels	0.1	1.0E-02	1
Kz	Adjust	kz10	10	Petone Marine Beds – onshore	0.002	1.0E-04	1.0E-03
S	Fix	ss2	2	Petone Marine Beds on/offshore	5E-5	1.0E-06	1.0E-04
Kx	Fix	Kx1	1	Taita alluvium – main valley	500	-	-
Kx	Fix	Kx2	2	Taita alluvium – recharge zone	100	-	-
Kx	Fix	Kx4	4	Petone Marine Beds – offshore	0.5	-	-
Kx	Fix	Kx6	6	Wilford Shell Beds	5	-	-
Kx	Fix	Kx8	8	Basal gravels	30	-	-
Kx	Fix	Kx10	10	Petone Marine Beds – onshore	0.5	-	-
Kx	Fix	Kx11	11	Upper Waiwhetu Gravels – distal harbour	1000	-	-
Kz	Fix	kz1	1	Taita alluvium – main valley	5	-	-
Kz	Fix	Kz8	8	Basal gravels	1	-	-
Kz	Fix	Kz11	11	Upper Waiwhetu Gravels – distal harbour	0.1	-	-

7.6.3 OBJECTIVE FUNCTION DEFINITION

The objective function is used to describe the match between the simulated groundwater heads and the observation data. Its formulation is therefore critical for automated model calibration and for this model the objective function was formulated as the sum of squares of the residual between target groundwater levels (historic monitoring data) and model-simulated groundwater levels.

7.6.4 TRANSIENT CALIBRATION RESULTS

7.6.4.1 Head calibration

During the PEST calibration the model objective function (phi) reduced relatively quickly after about 5 optimisation runs and stablised at about 120 m^2, at which point the run was terminated. Tables 7.5 and 7.6 present the final PEST optimisation results in the form of quantitative measures to assess the calibration quality – both for the whole model and for individual monitoring sites. The rapid stabilisation of the objective function is in part attributable to reasonable initial parameter estimates derived from the steady state modelling and pre-PEST manual calibration work. Appendix 2 contains the head calibration plots for each of the monitoring sites for the 5-year run.

The model calibration has a high correlation coefficient of 0.998 which is an indication of the overall unweighted goodness of fit between modelled outputs and observations. Ideally, R should be above 0.9.

RMS – root mean square error (or quadratic mean error) for the model is 0.17m but ranges from 0.08 to 0.43 for individual monitoring sites. The scaled RMS error for the model is very low at 0.012 and, together with the other statistics, indicates a very good fit between model and observed heads.

Table 7.5: Summary head calibration statistics for transient model

Number of Targets:	3604
Range in Observed Values:	14.17m
Minimum Residual:	-0.84m
Maximum Residual:	0.75m
Sum of Squared Residuals:	109.7m^2
RMS Error:	0.17m
Residual Mean:	-0.02m
Absolute Residual Mean:	0.13m
Standard Deviation:	0.17m
Scaled Residual Mean:	-0.0015
Scaled Absolute Residual Mean:	0.009
Scaled Standard Deviation:	0.0122
Scaled RMS Error:	0.0123

Table 7.6: Measures of calibration performance for head observation sites – grouped into aquifers. SSR = sum of squared residuals (objective function, or phi). RMS = root mean squared error.

Site Name	Bore ID	No Residuals	Phi (SSR)	RMS error
Upper Waiwhetu Aquifer (confined)				
Bell	R27/1123	17	0.53	0.18
Birch	R27/6097	10	0.23	0.15
Huttrec	R27/61115	255	14.88	0.24
HVMTC	R27/0120	259	8.11	0.18
IBM2	R27/1265	257	8.42	0.18
McEw_Sh	R27/0122	257	7.14	0.17
Mitch_Pk	R27/1116	259	6.58	0.16
Port	R27/1118	17	0.35	0.14
Randw	R27/1122	258	7.58	0.17
Somes	R27/1171	226	10.58	0.22
Tam_Sh	R27/7154	225	5.06	0.15
Lower Waiwhetu Aquifer (confined)				
McEw_Dp	R27/7153	220	5.53	0.16
Tam_Dp	R27/7215	213	5.00	0.15
Taita Alluvium (unconfined)				
TaitaInt	R27/1117	259	6.95	0.16
Gear_UC	BQ32/0041	9	0.06	0.08
Mabey_7	BQ32/0031	16	0.34	0.15
Mabey_13	BQ32/0030	16	0.11	0.08
Mabey_20	BQ32/0020	16	0.11	0.08
Nash_7	BQ32/0029	17	3.15	0.43
Nash_13	BQ32/0028	17	1.10	0.25
Nash_20	BQ32/0023	17	6.68	0.63
Thorny	R27/6982/	10	0.06	0.08
Traf	R27/1121	17	0.44	0.16
Moera Aquifer				
IBM1	R27/0320	255	6.00	0.15
Marsd	R27/6386	260	2.64	0.10
UWA3	R27/1086	222	2.04	0.10

The RMS error column in Table 7.6 shows relative calibration model-to-measure fit for each individual monitoring site. It also shows the proportional contribution to the objective function of the different sites and aquifer groupings. The residuals associated with monitoring sites in the Upper Waiwhetu Aquifer contribute to more than half of the objective function of the model purely because there are some 2,040 residuals in this group (57% of the total residuals). The RMS errors of residuals in the Upper and Lower Waiwhetu aquifers and the Moera Aquifer are generally less than 0.2m indicating a good model-to-measurement groundwater head calibration fit. The Taita Alluvium aquifer contains some monitoring sites with a higher RMS

error – these tend to be the bankside piezometers at Nash St. Possible reasons for the poorer calibration at this site are significant localised layering in the unconfined aquifer and large changes in head over small vertical distances; the more generalised model layer structure is unable to simulate such local heterogeneity.

Weighted calibration residuals are expected to be random, normally distributed and independent to ensure there are no systemic issues with the calibration – the test for this is through the use of probability plots. If the residuals are independent and normally distributed they should fall on an approximately straight line, as shown by the HAM3 calibration residuals in Figure 7.2.

Figure 7.3 shows a cumulative sum of squares residual plot for the HAM3 calibration which shows that the influences on the objective function are relatively evenly distributed and that phi is not dominated by a single or a few observations.
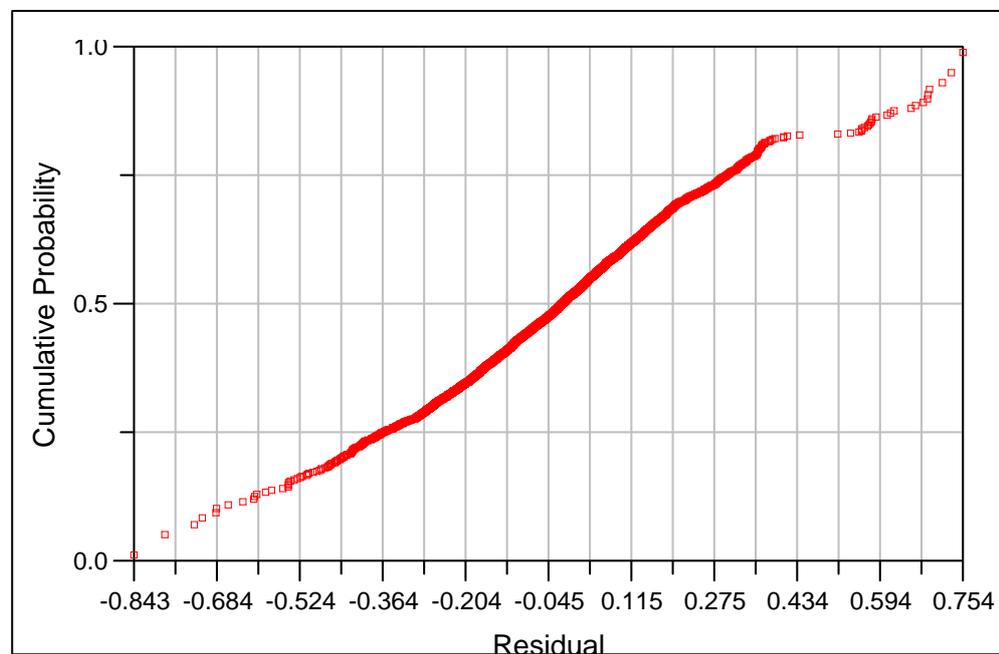
Figure 7.2: Residual probability plot. Ideally, the plot should be close to a straight line, indicating a normal distribution.
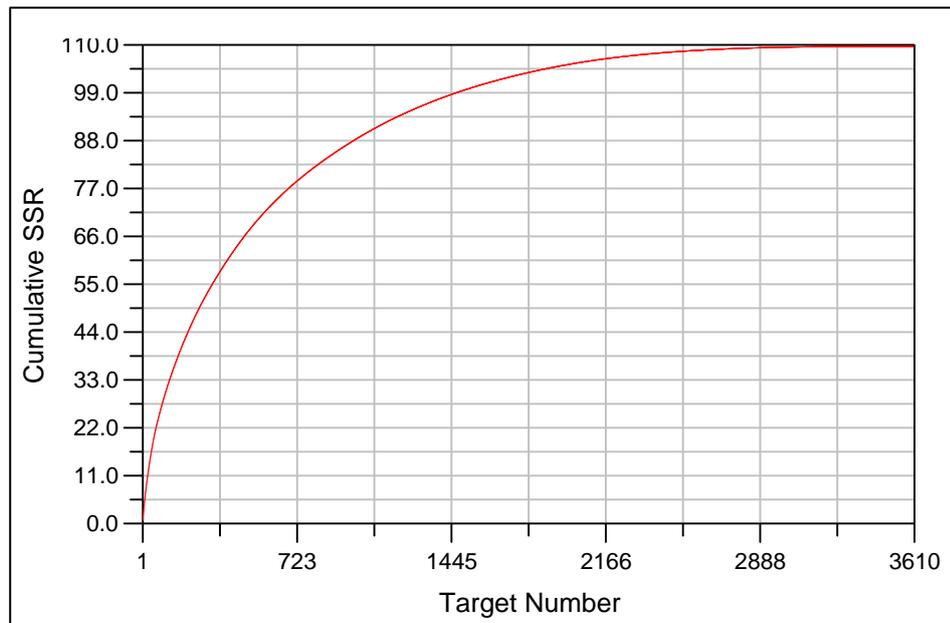
Figure 7.3: Cumulative sum of squares head residuals plot for HAM3 transient calibration showing that the influences on the objective function in PEST are relatively evenly distributed.

7.6.4.2   **Water balance calibration**

Simulated water balance components from the calibrated HAM3 are provided in Appendix 3 and constitute an important component of the model calibration process. Reference was made to measured and estimated water balance fluxes during the calibration process, and qualitative weighting assigned on the basis of the reliability of flux data.

Figure A3.1 shows the simulated rainfall recharge over the 5-year calibration period based upon the soil moisture balance methodology described in Section 4.4.2. The highly seasonal nature of rainfall recharge is apparent, with generally no recharge occurring during the summer months due to the high soil moisture deficit. The modelled daily mean recharge is about 17ML/day ($6.2 \times 10^6 \text{m}^3$/year) but the average during the winter months is around 30-40ML/day.

Figure A3.2 shows the simulated abstraction rate which is dominated by the Waterloo Wellfield. Abstraction during the calibration period has remained relatively constant at between 50 and 80 ML/day.

Accurate simulation of groundwater recharge from the Hutt River in the reach between Taita Gorge and Kennedy Good Bridge is important for building confidence in the predictive capability of the model since this is the main recharge source to the confined aquifers. Close attention was therefore given to ensuring that the simulated river loss along this reach is consistent with measured flow losses (Section 4.4.1). Figure A3.3 shows the simulated river loss and gain above and below Kennedy Good Bridge respectively. The modelled flow losses lie within the observed/measured flow loss range, averaging 102ML/day (1,180 L/sec), although they do not show the same variability as the measured losses (which have a

relatively higher gauging error at higher flows). Figure 7.4 shows the simulated and measured river flow loss from the recharge reach as a function of flow in the river (at Taita Gorge). It is interesting to observe that the model does not show a correlation between river flow (or stage) and flow loss to groundwater. It is suggested that this is because the main control on flow loss is the vertical gradient between the river stage and adjacent water table in the unconfined aquifer (as well as pumping rate from the Waiwhetu Aquifer). When river levels are higher over a period of time (such as during the winter), groundwater levels are also likely to be higher and therefore losses from the river will be less. Figures 7.5 and 7.6 illustrate this relationship using simulated river flow losses and measured groundwater levels at the Taita Intermediate monitoring site. The exception to this relationship is when there is a short-duration high flow event in the summer when the water table is also low, in which case river losses may be higher than normal. Since the model simulation averages aquifer and river flow conditions over 7 days, such events would not tend to be apparent in the model output. This could explain why the model does not simulate the higher measured losses. However, the higher error associated with measurements made at higher river flows (see discussion in Section 4.4.1) is of a magnitude approaching the actual loss and means that a lower degree of confidence should be assigned to them. For these reasons, the model-simulated losses are considered to be a reasonably good representation of measured river flow losses between Taita Gorge and Kennedy Good Bridge.
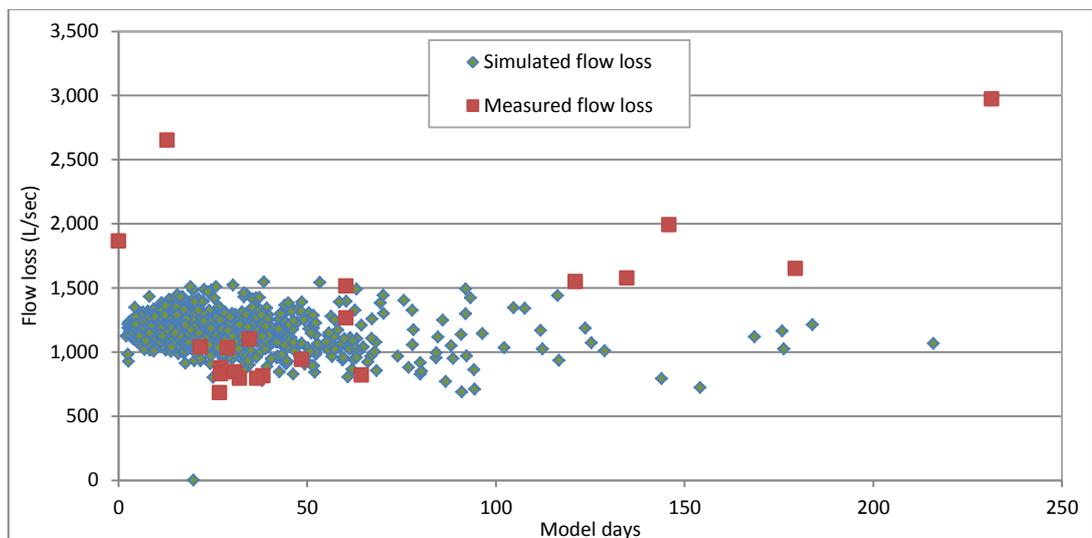
Figure 7.4: Simulated and observed flow losses from the Hutt River between Taita Gorge and Kennedy Good Bridge plotted against flow in the Hutt River measured at Taita Gorge.
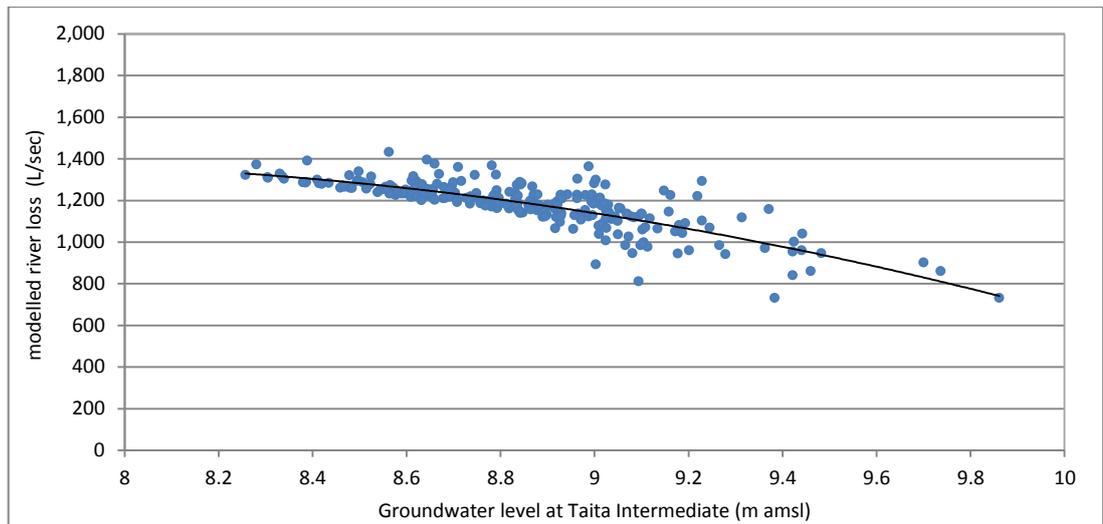
Figure 7.5: Simulated flow losses from the Hutt River between Taita Gorge and Kennedy Good Bridge plotted against groundwater level at the Taita Intermediate monitoring site.
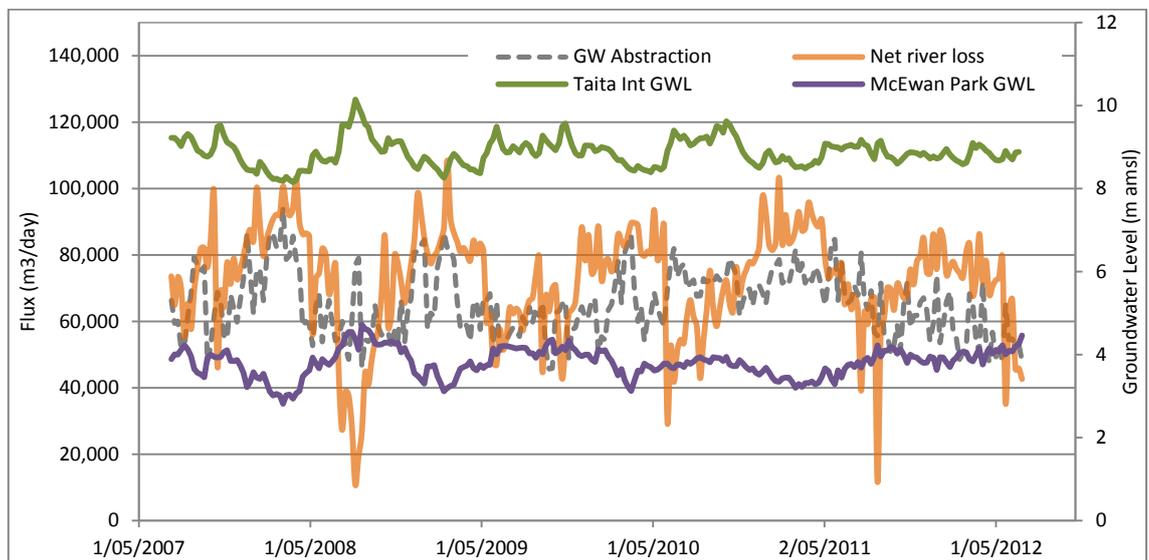
Figure 7.6: Plot showing relationship between simulated losses from the Hutt River between Taita Gorge and Kennedy Good Bridge and groundwater levels. When groundwater levels are higher, the river losses drop. The total groundwater abstraction rate (also plotted) influences river flow losses by inducing recharge through the river bed.

Figure A3.4 shows the modelled return flow from the Taita Alluvium back into the Hutt River downstream of Kennedy Good Bridge. This component of the water balance is difficult to measure in the field because of the tidal nature of the river up to about Ewen Bridge. The model predicts a river flow gain averaging about 30 ML/day over the year, but ranging between about 20ML/day in the summer and rising to about 40ML/day or above during winter. This range is consistent with the conceptual water balance (Section 5.2).

Groundwater discharge into the Waiwhetu Stream on the valley floor is another component of the water balance which has not been 'field-verified', but is estimated to be in the order of 3-4,000m^3/day, or about 30-50L/sec (Section 2.2). Figure A3.5 shows the simulated discharge in the drain cells which represent the stream; the simulated discharge falls within the estimated range.

The offshore discharge – both as diffuse leakage though the Petone Marine Bed aquitard and via discrete springs on the harbour floor is shown in Figure A3.6. The constant head boundary condition representing the harbour creates a hydraulic gradient across the aquitard between the confined Waiwhetu Aquifer and the sea. The simulated discharge varies seasonally and ranges from about 13ML/day in summer to over 20 ML/day in winter. The daily mean offshore discharge is 16.5ML/day.

In terms of submarine spring discharge, the aquitard vertical hydraulic conductivity was increased over the spring vent sites and the leakage rate at the vents was 'calibrated' to the estimated discharge (discussed in Section 4.5.1) of 1-2 ML/day. Figure A3.7 shows a simulated, seasonally-variable submarine discharge of between about 1.5 and 2ML/day, which is consistent with the conceptualisation. It is important to note that foreshore water levels in the Waiwhetu Aquifer are sensitive to the springs' discharge rate since they are effectively an abstraction – with the closet spring vents being only about 500m offshore at the Hutt River mouth.

7.6.5 CALIBRATED PARAMETER VALUES

Table 7.7 contains the calibrated values for both the PEST-optimised and fixed parameters. The table also contains, for comparison, the measured or estimated parameter value ranges from pumping tests or other information, showing that the calibrated values fall within these ranges.

**Table 7.7: Calibrated parameter values for hydrostratigraphic units in the HAM3.
Adjust = optimised adjustable parameters; fix = fixed parameters not optimised using
PEST.**

Type	Use	Param Name	Zone	Unit/location	Initial/ Fixed Value	Optimised value	Measured or estimated range
Storage properties (Ss and Sy)							
S	Adjust	ss1	1	Taita Alluvium	5E-5	8.0E-5	
S	Fix	ss2	2	Petone Marine Beds on/offshore	5E-5	3.2E-05	
S	Adjust	ss3	3	Upper Waiwhetu Gravels	5E-5	3.2E-5	1E-4 – 3E-5
S	Adjust	ss4	4	Moera Gravels/Wilford SB	5E-5	4.4E-5	4E-5 – 1E-5
S	Adjust	ss6	6	Lower Waiwhetu Gravels	5E-5	6E-5	
Sy	Adjust	sy1	1	Taita Alluvium	0.1	0.074	
Hydraulic conductivity (m/day)							
Kx	Fix	kx1	1	Taita alluvium – main valley	500	292	100-5,000?
Kz	Fix	kz1	1	Taita alluvium – main valley	5	0.1	
Kx	Fix	kx2	2	Taita alluvium – recharge zone	100	1000	100-5,000?
Kz	Adjust	kz2	2	Taita alluvium – recharge zone	1	0.22	
Kx	Adjust	kx3	3	Upper Waiwhetu Gravels	1200	1400	1,000-2,000
Kz	Adjust	kz3	3	Upper Waiwhetu Gravels	1	0.11	
Kx	Fix	Kx4	4	Petone Marine Beds – offshore	0.5	0.63	0.1-0.001?
Kz	Adjust	kz4	4	Petone Marine Beds – offshore	0.002	0.0005	
Kx	Adjust	kx5	5	Lower Waiwhetu Gravels	300	336	500?
Kz	Adjust	kz5	5	Lower Waiwhetu Gravels	0.1	10	
Kx	Fix	Kx6	6	Wilford Shell Beds	5	6.36	0.1-0.01?
Kz	Adjust	kz6	6	Wilford Shell Beds	0.0005	0.00018	
Kx	Adjust	kx7	7	Moera Gravels	80	200	150-250
Kz	Adjust	kz7	7	Moera Gravels	0.1	0.96	
Kx	Fix	Kx8	8	Basal gravels	30	30	120-30?
Kz	Fix	Kz8	8	Basal gravels	1	1	
Kx	Fix	Kx10	10	Petone Marine Beds – onshore	0.5	0.57	0.1-0.001?
Kz	Adjust	kz10	10	Petone Marine Beds – onshore	0.002	0.004	
Kx	Fix	Kx11	11	Upper Waiwhetu Gravels – distal harbour	1000	1000	?
Kz	Fix	Kz11	11	Upper Waiwhetu Gravels – distal harbour	0.1	1	

7.6.6 PARAMETER SENSITIVITY

PEST calculates the composite sensitivities following the calculation of the Jacobian matrix for each iteration. The relative sensitivity (obtained by multiplying the composite value by the magnitude of the log value of the parameter) assists in comparing the effects of different parameters of different magnitude on the calibration process.

The relative sensitivities have been plotted in Figure 7.7 to identify those parameters that most affect the calibration and to identify any parameters that may degrade the performance of the parameter estimation process (i.e., very insensitive parameters due to high degrees of correlation and/or an absence of observation data within some parameter zones). The less sensitive parameters were frozen after initial evaluation of the PEST run leaving 15 adjustable parameters to be optimised by PEST (see Table 7.4 for the list of final adjustable parameters).
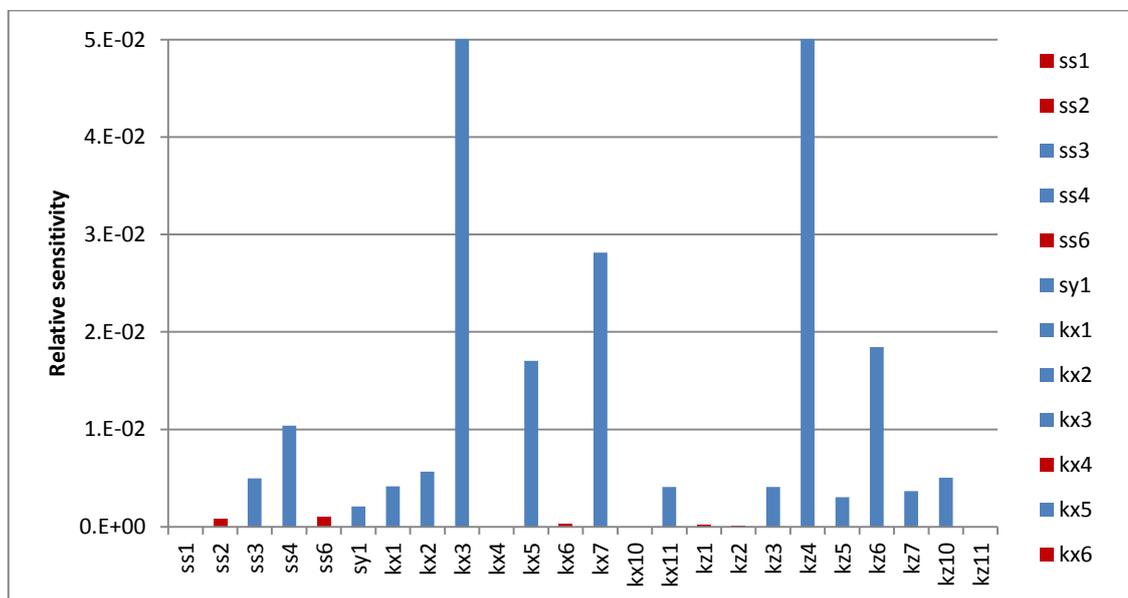

Figure 7.7: Parameter relative sensitivities derived from an initial PEST run. The least sensitive parameters (in red) were fixed prior to completing the optimisation process on the remaining 15. The most sensitive parameters are kx3 (Upper Waiwhetu gravels, horizontal hydraulic conductivity), kx4 (offshore Petone Marine Beds, vertical hydraulic conductivity) and kx7 (Moera gravels, horizontal hydraulic conductivity).

Figure 7.7 shows that the five most sensitive parameters in the HAM3 are:

- kx3: Upper Waiwhetu gravels (horizontal hydraulic conductivity)
- kz4: Petone Marine Beds offshore aquitard (vertical hydraulic conductivity)
- kx7: Moera gravels (horizontal hydraulic conductivity)
- kz6: Wilford Shell Beds aquitard (vertical hydraulic conductivity)
- kx5: Lower Waiwhetu gravels (horizontal hydraulic conductivity)

A more 'traditional' sensitivity analysis has also been undertaken on all model parameters including river bed conductivity and the harbour constant head condition. This was undertaken by adjusting each of the model parameters by a factor

(generally between 0.25 and 2) and recording the effect on the model calibration using the sum of squared residuals error. A graphical representation of the sensitivity analysis for hydraulic conductivity is shown in Figure 7.8 and is consistent with the relative sensitivities calculated by PEST.
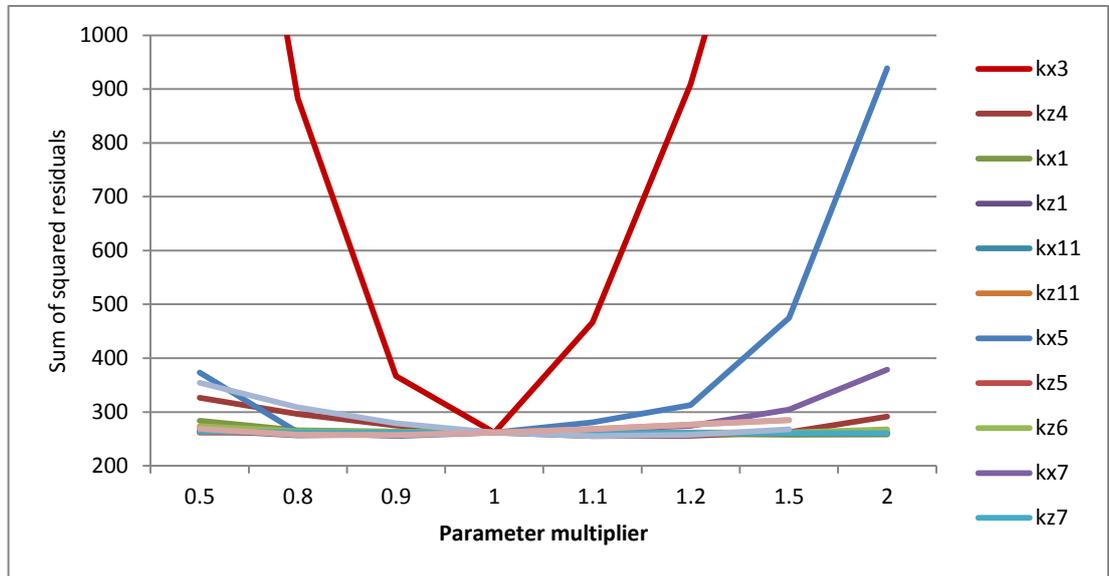
Figure 7.8: Manual sensitivity analysis (hydraulic conductivity) showing model calibration at parameter multiplier = 1 where the sum of squared residuals is minimised. The most sensitive parameters are kx3, kx5 and kx7.

Figure 7.9 shows sensitivity analyses for the harbour constant head values and river bed conductance. Small changes in the harbour level don't seem to affect the model, but once levels increase by a factor of about 1.5 (equivalent to a sea level rise of 0.1m above current levels), impacts on the system begin to become evident. In terms of river bed conductance, a reduction in magnitude by a factor of 0.75 seems to cause a radical increase in SSR at a critical point, although increases in bed conductance appear to have little effect on the model calibration.
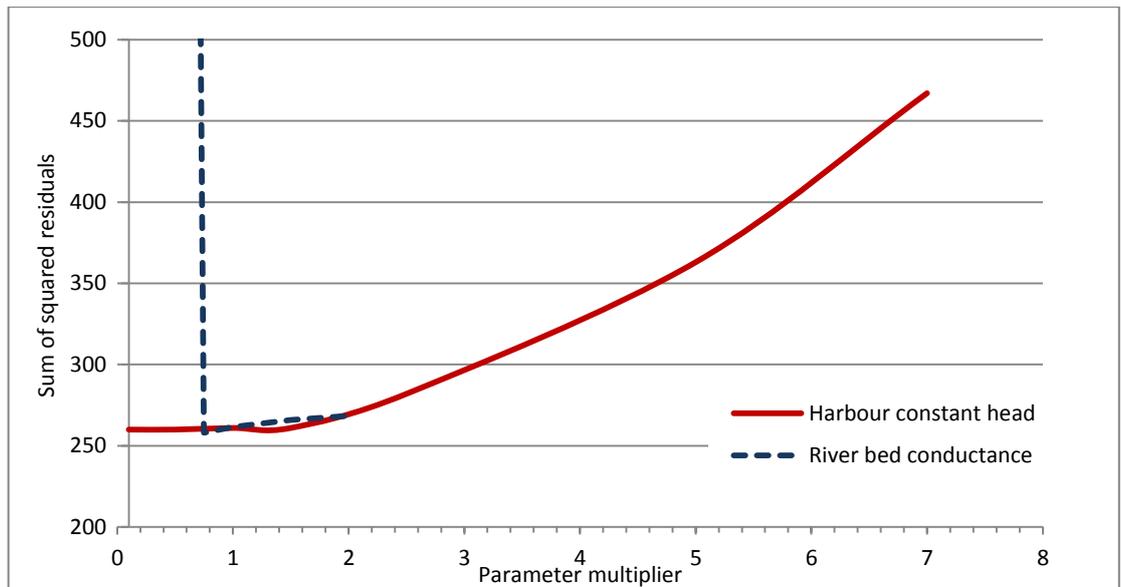
Figure 7.9: Sensitivity analysis for river bed conductance and harbour constant head level.

7.7 VERIFICATION RUN

The purpose of a model verification run is to provide a check on the ability of the calibrated model to replicate historical aquifer conditions and stresses using information which was not included in the calibration process. Prior to the start of the calibration run (1/7/2007) a reliable and extensive groundwater head monitoring dataset is available for the 15-year period 1/7/1992 to 1/7/2007. This dataset has been used to verify the HAM3. The verification run required sourcing additional historical groundwater abstraction data from municipal supply wells and private industrial users. Climate data to extend the rainfall recharge record, and river flow data from Taita Gorge, were derived from GWRC databases.

The Hutt River bed level experiences cycles of degradation and aggradation along different reaches at different times, which is reflected by the long-term record at the Taita Intermediate monitoring site (Figure 4.2). There is insufficient information to incorporate such changes in the model and the bed level is fixed throughout the verification run (to 1998 levels). The effects of bed level changes on the verification simulation appear to be most relevant to the unconfined aquifer and are discussed below.

Groundwater abstraction was very different in the early 1990's – industrial use was significantly higher in the foreshore area. There was also a relatively large abstraction (5-6 ML/day) by the Lower Hutt City Council at Buick Street on the foreshore which was decommissioned in 1999. Some abstraction was also occurring at the Gear Island Wellfield by GWRC up until 1999 (see Figure 4.5). Pumping records are available for some of these abstractions and have been incorporated into the HAM3 verification run. Estimates have been made based on permitted abstraction rates for many of the industrial users.

The output plots for the 20-year verification run are contained in Appendix 4. The verification model run was continued to 1/7/2012 and therefore incorporates the 5-year calibration period at the end. The head output plots (Figures A4.1 to A4.9) show a close match between observed heads and simulated heads in all aquifer units. Longer-term trends are also matched – for instance in the Waiwhetu Gravels during the 1990's. However, during the first few years of the verification run there is a slightly larger mis-match, which is probably due to uncertainties in the simulation of abstractions from the Waiwhetu Aquifer.

The Taita Intermediate site (Figure A4.8) shows a 'hump' in the observed data between about 2003 and 2006 which can be explained in terms of changes in Hutt River bed level (Section 4.1.2). Since the model does not incorporate bed level changes the simulated groundwater level at this site does not replicate the trend. The model-to-measurement fit on either side of the 2003-6 anomaly is, however, very good. It is also interesting to note that monitoring data at downstream monitoring sites in the Waiwhetu Aquifer does not pick up this anomaly and therefore does not appear to be sensitive to small changes in the unconfined aquifer level due to river bed level changes.

Overall, the verification run provides assurance that the HAM3 is capable of simulating a wide range of stress conditions and thus provides confidence in its predictive ability.

7.8 HAM3 CALIBRATION REVIEW

HAM3 has been calibrated to groundwater level and mass balance observations for the period 1997 – 2012 and verified for the preceding 15-year period 1992-2007.

The calibration has been evaluated in both qualitative and quantitative terms by comparing the simulation results with field measurements. Simulated mass balances and groundwater heads exhibit a good visual and statistical fit to observed data.

The calibration has been qualitatively assessed by comparing simulated and observed groundwater flow patterns to ensure that the model outputs are consistent with the conceptualisation of the groundwater system. The observed pattern of groundwater-surface water interaction is also replicated by the model. The appropriateness of the conceptual hydrogeological model at a regional scale is validated through the calibration.

The importance of accurately incorporating surface water – aquifer fluxes (loss through the bed of the Hutt River) in the calibration process is paramount to achieving the desired level of confidence in the predicative capability of the model, since this is the principal recharge source. Calibration of the model to observed and estimated water balance water fluxes provides a validation of the simulated spatial and temporal recharge dynamics.

Model non-uniqueness has been minimised by following the MDBC modelling guidelines (Middlemis 2001). In particular, this has entailed calibration using ranges for hydraulic conductivity (and other parameters) which are consistent with

measured data, calibrating the model to a wide range of climatic and abstraction stresses, and calibrating to measured water balance fluxes (such as spring flows, river losses/gains).

Automated calibration using the inverse estimation algorithm PEST has removed some of the subjectivity of manual calibration and has provided an insight into the non-uniqueness of the model. The relative sensitivities of parameters have helped identify parameters which have been accurately estimated.

Confidence can be placed in the calibration robustness for the principal aquifers in the catchment – the unconfined Taita Alluvium and the confined Waiwhetu Gravels and Moera Gravels.

7.8.1 MODEL PURPOSE

The purpose of the HAM3 is to predict or forecast the response of the Lower Hutt groundwater system to current and potential future stresses. In particular, the model is required to facilitate sustainable management of the Waiwhetu Aquifer and to evaluate risks associated with saline intrusion, sea level rise and seismic activity. For these purposes a complex 'aquifer simulator' (Middlemis, 2001) high confidence level simulation (Class 3; Barnett et al., 2012) is required. The characteristics and indicators of the calibration of a high confidence level (see also Table 6.1) are as follows:

- Adequate validation is demonstrated.
- Scaled RMS error or other calibration statistics are acceptable.
- Mass balance closure error is less than 0.5% of total.
- Model parameters are consistent with conceptualisation
- Long-term trends are adequately replicated where these are important.
- Seasonal fluctuations are adequately replicated where these are important.
- Transient calibration is current, i.e., uses recent data.
- Model is calibrated to heads and fluxes.
- Appropriate computational methods are used with appropriate spatial discretisation to model the problem.

The preceding discussions demonstrate that the above conditions (in addition to other indicators and conditions contained in Table 6.1) have been met in the calibration of the HAM3. It can therefore be considered to be a Class 3 high confidence level model. However, it is recommended that the model be reviewed and deemed fit for purpose by an experienced, independent hydrogeologist with modelling experience.

7.8.2 MODEL LIMITATIONS AND ASSUMPTIONS

Limitations associated with the HAM3 calibration are:

Uncertainties around offshore aquifer characteristics and discharge: The greater proportion of the Lower Hutt Groundwater zone lies beneath Wellington Harbour. Although the model calibration is relatively insensitive to the modelled offshore

geometry of the Waiwhetu gravels and the other formations, it is very sensitive to the location and rates of discharge through the Petone Marine Beds. The HAM3 has been set up to release water both as diffuse seepage across the marine aquitard and via discreet springs – identified on the basis of high-accuracy harbour bathymetry surveying and from historical data. The total amount of offshore discharge from the system is relatively well constrained by the overall system water balance – there is good information on aquifer recharge and onshore discharge (including abstraction). However, the rate that water is released from the submarine springs has been constrained by relatively sparse information – albeit that the order-of-magnitude flow rates are probably correct. Because the springs close to the Petone foreshore have a big impact on foreshore groundwater levels, the calibration should be verified or improved using additional submarine spring monitoring data if they become available in the future.

Geological complexity along the Wellington Fault: The geological sequence is known to have been severely disrupted adjacent to the active Wellington Fault. Since the complexity of the immediate area adjacent to the fault has not been characterised, the model assumes that the stratigraphic sequence continues across the fault. This is only really relevant in the foreshore area near to the western valley edge where the fault moves away from the greywacke valley walls. Therefore, in this area the model may not reflect the complex geology and may impact on the accuracy of the HAM3 around the fault should recognised when, for example, the model is used to explore rupturing of the Petone Marine Beds aquitard along the fault. This limitation is not considered to affect model accuracy in the main valley area.

Surface water flow gaugings: gauged river flow losses between Taita Gorge and Kennedy Good Bridge are necessarily undertaken during low and stable river flows. Bed losses at higher flows have a low reliability since the gauging errors (usually in the order of +/- 10%) are large in relation to the actual bed losses. Concurrent gaugings undertaken at higher flows therefore have a large scatter associated with them. The behaviour of the model in terms of bed losses is therefore difficult to verify at higher river flows.

Hutt River bed variability and stage simulation: the Hutt River bed is highly mobile and experiences complex patterns of natural bed movement. It is also affected by gravel extraction activities. The evolution of the river bed during the model calibration has not been taken into consideration since there is not enough information to do so. However, the verification of the HAM3 indicated that the confined aquifers are relatively insensitive to small bed level variations.

The HAM3 also relies upon the external calcuation of river stage in each river boundary cell using the monitoring flow record at Taita Gorge. This has been achieved using flow and stage relationships derived from a surface water model (MIKE11) developed in 2000 by GWRC. The MIKE11 model is calibrated to high flow conditions and its accuracy in predicting river stage at various points along the river may be less accurate at low flows – although the accuracy of the model at low

flows has been tested using short-term stage monitoring and shown to be satisfactory.

Waiwhetu Stream discharge: Little is known about the interaction between the Waiwhetu Stream and shallow groundwater on the valley floor. Estimates of stream flow losses have been made for the model calibration. However, this limitation has a negligible impact the calibration of the confined aquifers in the HAM3.

Despite the model limitations and assumptions, the calibration outputs provide confidence that the HAM3 model provides a good representation of the Lower Hutt Groundwater Zone.

8 MANAGEMENT OF THE WAIWHETU AQUIFER

The purpose of the HAM3 project is to provide an analysis tool to assist the management of the Lower Hutt groundwater resource. In particular, the model, in addition to other information, is required to address the following needs:

- Assessment and review of the sustainable yield of the Waiwhetu Artesian Aquifer with particular focus on managing saline intrusion risk.

- Development of tools to optimise the use of the resource, and forecast aquifer yield during summer stress periods.

The Waiwhetu Aquifer is currently managed on the basis of saline intrusion risk and the estimated maximum sustainable yield of the Lower Hutt aquifers is based upon managing this risk.

A second sustainability criterion is the induced loss from the Hutt River as a result of groundwater abstraction in the Waiwhetu Aquifer. This has not historically been taken into consideration by GWRC when determining water allocation in the Lower Hutt Valley. However, it is recommended that the induced losses from the river, quantified using the HAM3, should be taken into consideration in the new GWRC conjunctive (surface water – groundwater) water management framework.

8.1 IMPACTS OF CURRENT AND HISTORICAL ABSTRACTION

Development of the Waiwhetu Aquifer commenced over a century ago, but the past 50 years have seen a progressive increase in abstraction. It is estimated that as a result, the natural aquifer throughflow at the coast has reduced by between 80 and 90%. The remaining throughflow to the harbour area therefore represents less than 20% of the natural outflow and the hydraulic gradient downstream of the wellfield and offshore is consequently very shallow. This is reflected by age dating of groundwater in the Waiwhetu Aquifer at the foreshore of about 45 years (Morgenstern, 2007; possibly from a water sample taken from the slower-moving lower Waiwhetu Aquifer), compared to an approximate 2 year age at the Waterloo wellfield.

To provide a baseline for sustainable yield evaluation, the HAM3 model has been used to characterise the response of the Lower Hutt groundwater system to current and historical abstraction in terms of the effects on groundwater heads and the aquifer water balance. This has entailed the comparison of two model scenarios:

- Scenario 1: the 5-year calibration run, which includes groundwater abstractions;
- Scenario 2 (baseline run): the same as Scenario 1 except all GWRC pumping is turned off.

Subtraction of the two sets of modelled heads enables the characterisation of aquifer drawdown under different pumping and climatic conditions. Figure 8.1 provides a snapshot of aquifer drawdown in April 2009 for the Upper Waiwhetu Aquifer, when abstraction from the wellfield was about 60ML/day. It is evident that abstraction

from Waterloo results in significant drawdown across the entire groundwater system – the drawdown around the production wells in the middle of the valley is clearly visible. There is a marked flattening of the hydraulic gradient downstream of the wellfield in response to the reduction of the aquifer throughflow caused by the abstraction. The drawdown extends under the whole of Wellington Harbour where it exceeds 2m – reflecting the low aquifer storage, high transmissivity, reduction in throughflow, and the 'semi-blind' nature of the sub-harbour aquifer (i.e. it does not have an open connection with the ocean, except very locally at submarine spring sites). A steep drawdown gradient extends upstream of the wellfield beneath the Hutt River, inducing recharge through the river bed.
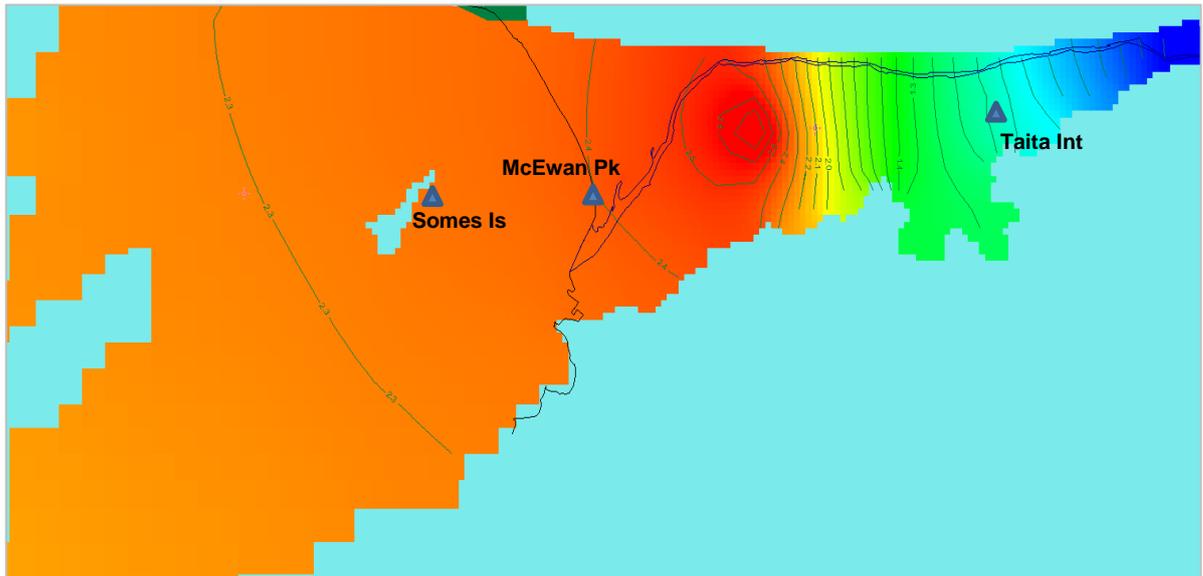
Figure 8.1: Simulated drawdown in the Upper Waiwhetu Aquifer (April, 2009). Waterloo Wellfield pumping rate is 60 ML/D. Note offshore drawdown exceeds 2m beneath the whole of Wellington Harbour.

Figure 8.2 shows the simulated drawdown at three critical monitoring sites – Taita Intermediate in the unconfined (recharge) zone, McEwan Park (on the Petone foreshore, Upper Waiwhetu Aquifer), and at Somes Island (Upper Waiwhetu Aquifer). The locations of these sites are shown on Figure 8.1. The aquifer drawdown at the foreshore and offshore ranges between about 2m and 3m and is clearly correlated to the pumping rate from the Waterloo Wellfield. Drawdown in the unconfined aquifer at Taita Intermediate is consistently around 1m.
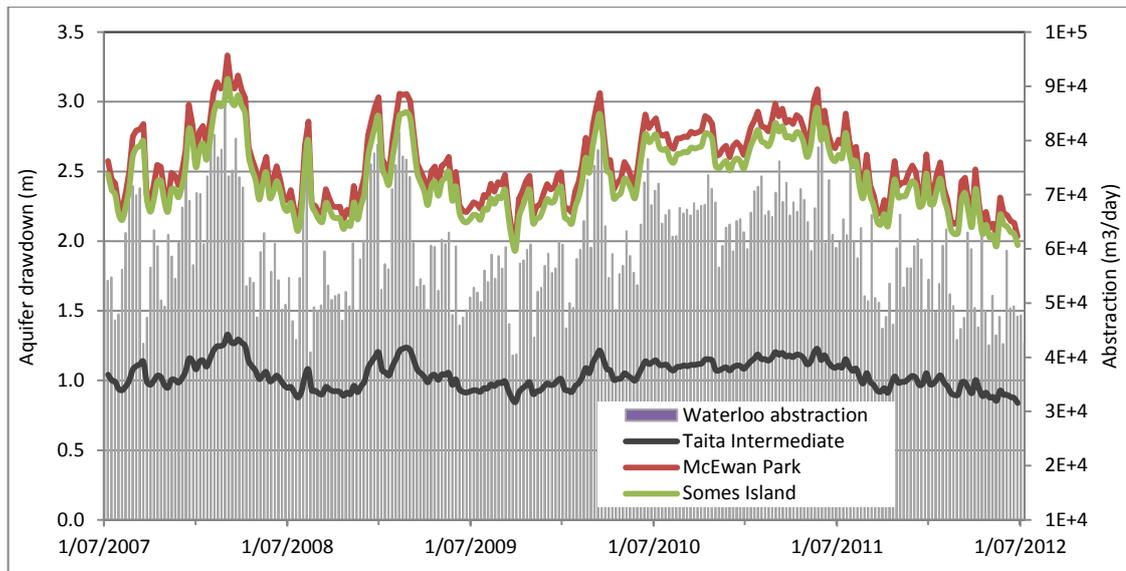
Figure 8.2: Simulated drawdowns at Taita Intermediate, McEwan Park (foreshore) and Somes Island from the HAM3 calibration run.

Figure 8.3A shows the simulated effects of abstraction on river loss – the additional induced recharge from the river caused by the drawdown associated with pumping from the Waterloo Wellfield. Modelled induced recharge ranges from 25,000 to 40,000m³/day (25-40MLD) which equates to about 45% of the total measured river losses of between 60 and 100 ML/day (Figure 7.6).

Figure 8.3B shows the same data over a short period of time between December 2008 and March 2009 to demonstrate the rapid response in river recharge to changes in pumping rate. This is also consistent with the minimal time lag observed between abstraction at Waterloo and response in foreshore groundwater levels as illustrated by Figure 8.17 – aquifer levels (and connected surface water systems) are very sensitive to abstraction and small variation in abstraction rate..

Figure 8.4 shows an apparent linear relationship between Waterloo abstraction and induced river recharge. The correlation equation for the relationship (in m³/day) is:

$$\text{Induced river loss} = 0.2498 * \text{pumping rate (Waterloo)} + 15{,}978$$

Induced recharge constitutes about 40-60% of the pumping rate – the proportion being higher at lower pumping rates possibly because proportionally more water is drawn from storage at higher pumping rates.
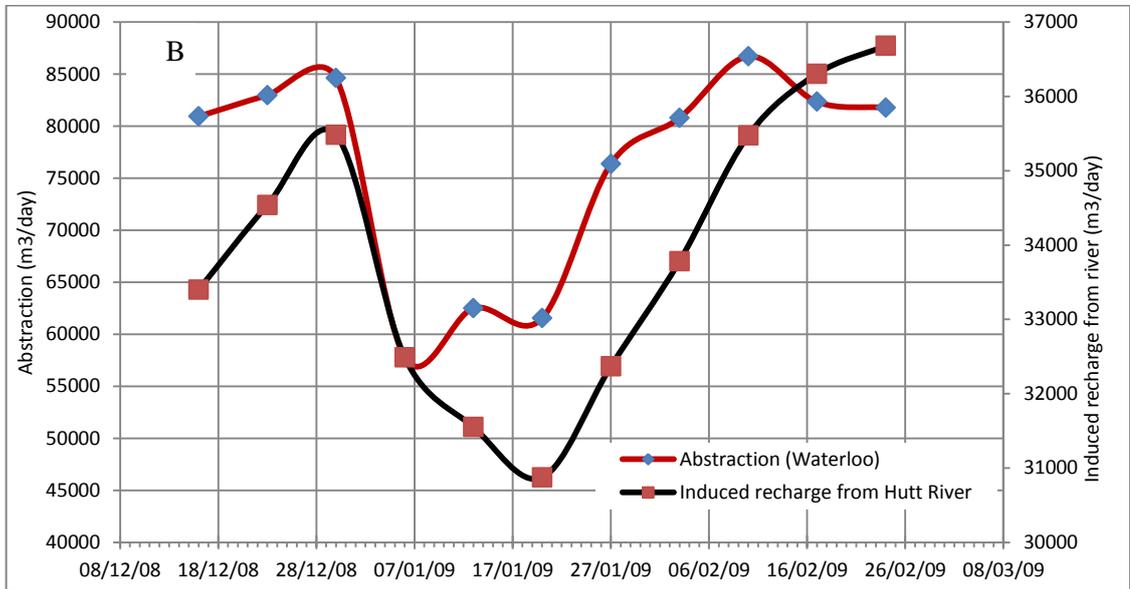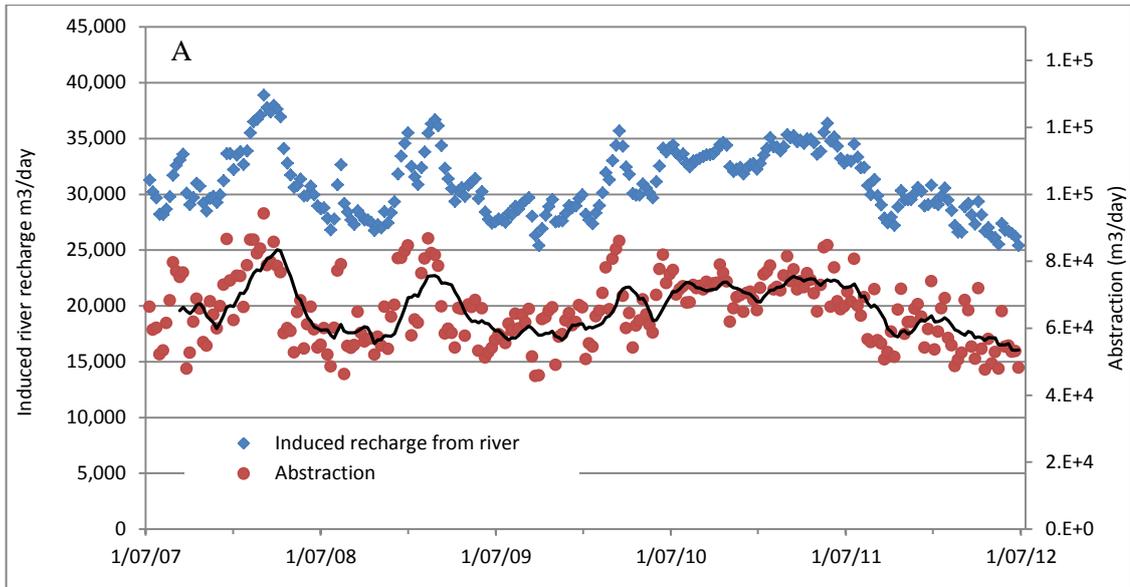
Figure 8.3: A: Relationship between abstraction and induced recharge from the Hutt River (derived from subtracting the pumping HAM3 scenario from the non-pumping scenario) for the period 2007-2012   B: Detailed relationship between pumping rate and induced recharge between December 2008 and March 2009 show minimal time lag between changes in pumping rate and induced recharge.
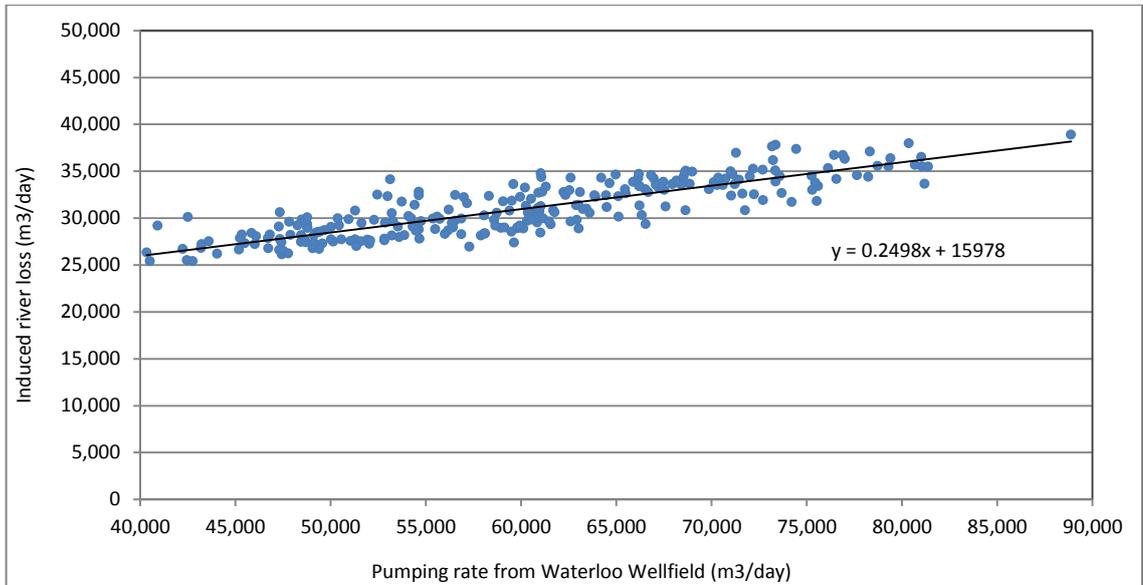
Figure 8.4: Relationship between abstraction from the Waterloo Wellfield and induced recharge from the Hutt River.

With regards the impact of (Waterloo) abstraction on the submarine spring discharge from the Waiwhetu Aquifer, Figure 8.5 shows spring flow is estimated to decrease by 50-70% when abstraction is occurring.
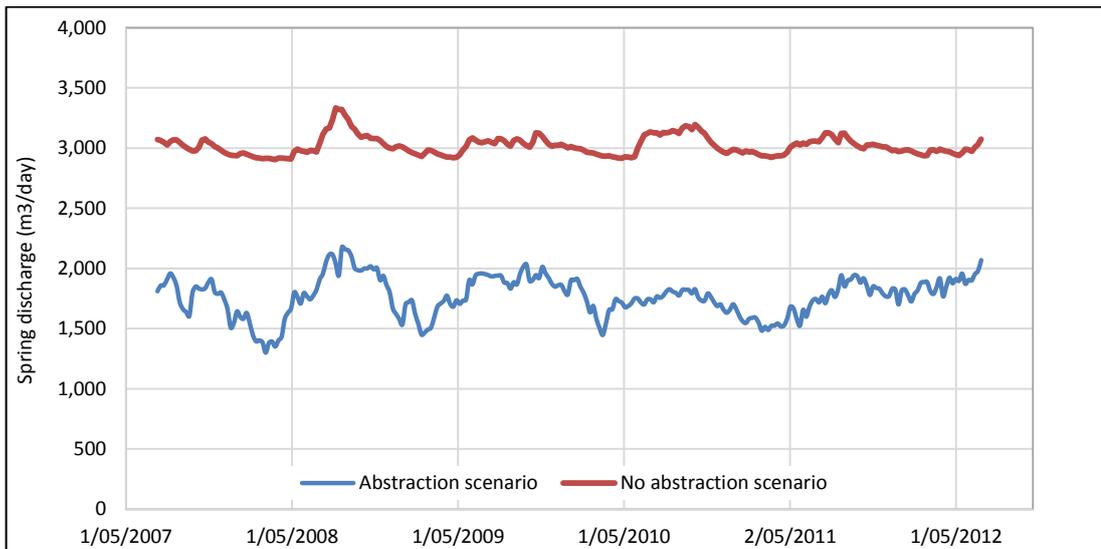
Figure 8.5: Simulated total discharge from submarine spring into Wellington Harbour during abstraction and when no abstraction is occurring. Note the flows cannot be verified independently and are estimates derived from the HAM3 model.

8.2 SALINE INTRUSION RISK EVALUATION AND MANAGEMENT

Being a critical water source for Wellington and a vulnerable coastal aquifer, the principal criterion for the management of the Waiwhetu Aquifer is saline intrusion risk. The calculated sustainable yield of the Lower Hutt aquifers centres on minimising this risk. GWRC currently manage the Waiwhetu Aquifer by maintaining a minimum groundwater level at the coast which theoretically prevents the movement of saltwater inland and towards the Waterloo wellfield.

A review of the saline intrusion risk in the Waiwhetu Aquifer, commencing with a conceptual and theoretical assessment of potential mechanisms of saltwater intrusion, has been undertaken. An understanding of the atypical offshore hydrogeological environment (described in Chapters 4 and 5) is critical to this process. A revised saline intrusion risk management framework is then presented based upon the review.

8.2.1 POTENTIAL SALTWATER INTRUSION MECHANISMS

Ingress of saltwater into the Waiwhetu Aquifer could conceptually occur via two processes:

- the inland migration of a postulated offshore saline water interface; and/or
- the backflow of harbour waters at submarine discharge sites close to the foreshore.

The first mechanism assumes that saline water is already present in the Waiwhetu Aquifer at some distance offshore, inferring that there must be a direct distal connection between the aquifer and the ocean. There is, however, no evidence for this and the conceptualisation of the offshore aquifer system (i.e. the aquifer has no open connection to the sea) renders it an unlikely scenario – which nevertheless needs to be considered in the absence of direct information to the contrary. Model scenarios have been undertaken using the HAM3 to explore a possible distal direct contact between the Waiwhetu Aquifer and the sea bed. These unequivocally show that the sub-harbour aquifer could not remain pressurised if this were the case, and both the Somes Island and foreshore groundwater levels could not be calibrated.

The risk of saline intrusion backflow through the spring vents is considered a more likely scenario given that the spring vents apparently provide the only (attenuated) hydraulic connection between the Waiwhetu gravels and the sea. Such connections occur very locally through partially closed vents in the silt-dominated Petone Marine Beds aquitard. Individual vents only appear to be a few square meters in area at most (Harding, 2000). Furthermore, the spring outflow needs to overcome a vertical hydraulic conductivity resistance – the connection is not an uninhibited open one. Again, this conclusion has been reached using the HAM3 which has shown that a foreshore/Somes Island head and spring flow calibration can only be achieved if the vertical hydraulic conductivity at the spring vent sites introduce a vertical resistance to outflow.

8.2.2 CRITICAL AQUIFER STATES

A set of critical states associated with heightened risk were identified by Phreatos (2001) from which minimum foreshore groundwater pressures in the Waiwhetu Aquifer were determined. These critical states are:

1. Reversal of offshore groundwater gradients and cessation of aquifer throughflow at the coast;
2. Cessation of submarine spring discharge and equalisation groundwater pressures with the harbour pressure at submarine spring vents; and
3. Foreshore groundwater levels drop below the Ghyben-Herzberg saline intrusion prevention level.

The assessment of the critical states resulted in a staged set of management triggers for groundwater levels in the upper part of the Waiwhetu aquifer (expressed as 24-hour means).

Warning level:	2.5m amsl
Critical level:	2.3m amsl
Minimum allowable foreshore level:	2.0m amsl

In 2008, additional saline intrusion monitoring sites were constructed on the foreshore at McEwan Park and Tamatoa (see Figure 4.1 for their locations). Separate monitoring wells were screened in the upper and lower Waiwhetu gravels and these continuously monitor both groundwater level and electrical conductivity. However, none of these sites have been incorporated into the day-to-day management of the aquifer.

8.2.3 REVIEW OF SALINE INTRUSION CRITICAL AQUIFER CONDITIONS

A review of the critical saline intrusion states has been undertaken using updated hydrogeological and monitoring information in addition to outputs from the HAM3.

8.2.3.1 Critical condition 1: Reversal of offshore groundwater gradients and cessation of aquifer throughflow at the coast

Since the sub-harbour Waiwhetu Aquifer is pressurised and appears to have no direct offshore 'constant head' ocean connection, abstraction from the Waterloo wellfield draws down groundwater pressures in excess of 2m beneath the harbour (Figure 8.1). In doing so, the flow gradients and associated aquifer throughflow have become very small. Monitoring data for the period following the migration of abstraction from the coast to the Waterloo wellfield (i.e. post 2000) show that abstraction from the wellfield has not caused a reversal of the offshore flow gradients, or drawn water from the sub-harbour aquifer.

Prior to the commissioning of the GWRC Waterloo wellfield in 1999, pumping from the foreshore area (at Gear Island and Buick Street) resulted in drawdowns which extended offshore and sourced some water from the near shore submarine aquifer. However, it is unlikely that the sub-harbour flow reversal would have extended very far from the foreshore. Prior to 1978, foreshore groundwater levels at McEwan Park dropped to between 1.5 and 2m during the summer months, and apparent offshore flow gradient reversals were observed diurnally during March 1973 at the end of a long dry period.

The point at which the offshore gradient between McEwan Park and Somes Island would reverse and result in a saline intrusion risk was previously calculated to be 1.4m at the foreshore using data collected during 1973 (Donaldson and Campbell, 1977). This minimum level was adopted until 2001 when it was realised that, because McEwan Park lies very close to the Gear Island pumping wells (and within their cone of depression), use of the 1973 McEwan Park level data to calculate the head gradient between the foreshore and Somes Island is problematic (Phreatos, 2001). The calculated minimum foreshore level (when the offshore hydraulic gradient was assumed to be zero) was too low due to the effects of Gear Island drawdown. A groundwater divide caused by the pumping at Gear Island would occur between the foreshore and Somes Island and flow would have been drawn back from beneath the harbour to the pumping wells. Depending on how far offshore the reverse gradient extended, and whether it was as far as the Hutt mouth submarine springs, the historic risk of saline intrusion was probably significant. It is ultimately important to appreciate that historical groundwater level monitoring data collected during the period when foreshore abstraction was occurring should not be relied upon to predict the saline intrusion risk for the current inland abstraction regime from Waterloo.

Periodic utilisation of the offshore aquifer may therefore be possible as demonstrated by the historic foreshore pumping. However, caution must be exercised to ensure that the risk of saline intrusion is confidently managed – the heightened risk of saline intrusion when the offshore flow gradient in the aquifer

begins to extensively flatten and reverse (and offshore throughflow ceases) can be identified and managed through vigilant monitoring.

Post-foreshore pumping groundwater level monitoring data and simulated outputs from the HAM3 have been used to identify when critical hydraulic gradient conditions occur in the Waiwhetu Aquifer. Interpretation of the gradient downstream of Waterloo first requires an understanding of the drawdown effects associated with wellfield abstraction. Figure 8.1 illustrated that the Waterloo abstraction causes a considerable flattening of the hydraulic gradient downstream of the wellfield, and that there is also a cone of depression around the pumping centre. This means that there is a groundwater divide (or 'stagnation point') between the Waterloo Wellfield and the foreshore – to the north of the divide groundwater flows to the pumping bores whilst to the south the flow direction is offshore (albeit at a very shallow gradient). It is apparent from modelling a range of abstraction rates and aquifer recharge states that the divide extends no further than about 1.5km towards the coast in the vicinity of the Randwick and HVMTC monitoring sites. Figure 8.6 illustrates this using the HAM3-simulated hydraulic gradient in the Waiwhetu Aquifer along model row 21, which passes through the wellfield and extends offshore past Somes Island to the model boundary (see Figure 8.7 for the location of model row 21).Two scenarios are shown in Figure 8.6 demonstrating an offshore flow gradient and groundwater divide at a pumping rate of 80ML/day, and a reversal of the offshore gradient at a significantly higher pumping rate of 130ML/day. Under the current Waterloo pumping regime, which peaks at about 80-90ML/day, a groundwater divide, or stagnation point, occurs about 1.5km downstream of the wellfield whilst a positive offshore flow gradient is maintained. The foreshore groundwater level for this particular scenario is about 2m amsl.
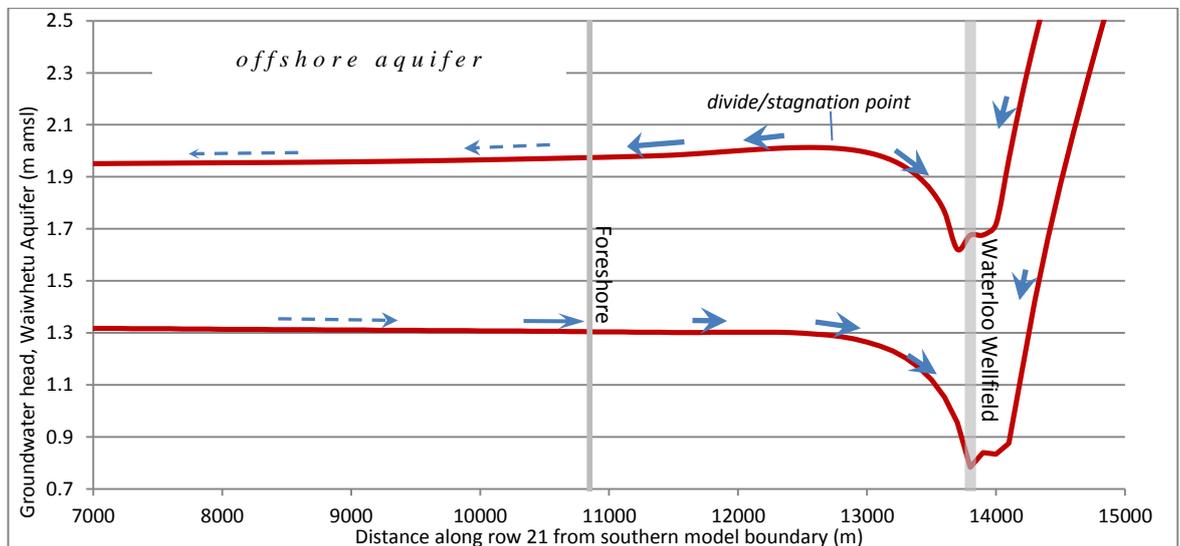
Figure 8.6: Modelled offshore and onshore hydraulic gradients in the Waiwhetu Aquifer along a section line (model row 21) perpendicular to the shoreline and intersecting the Waterloo Wellfield at an abstraction rate of 80ML/day (top plot) and 130 MLD (lower plot).

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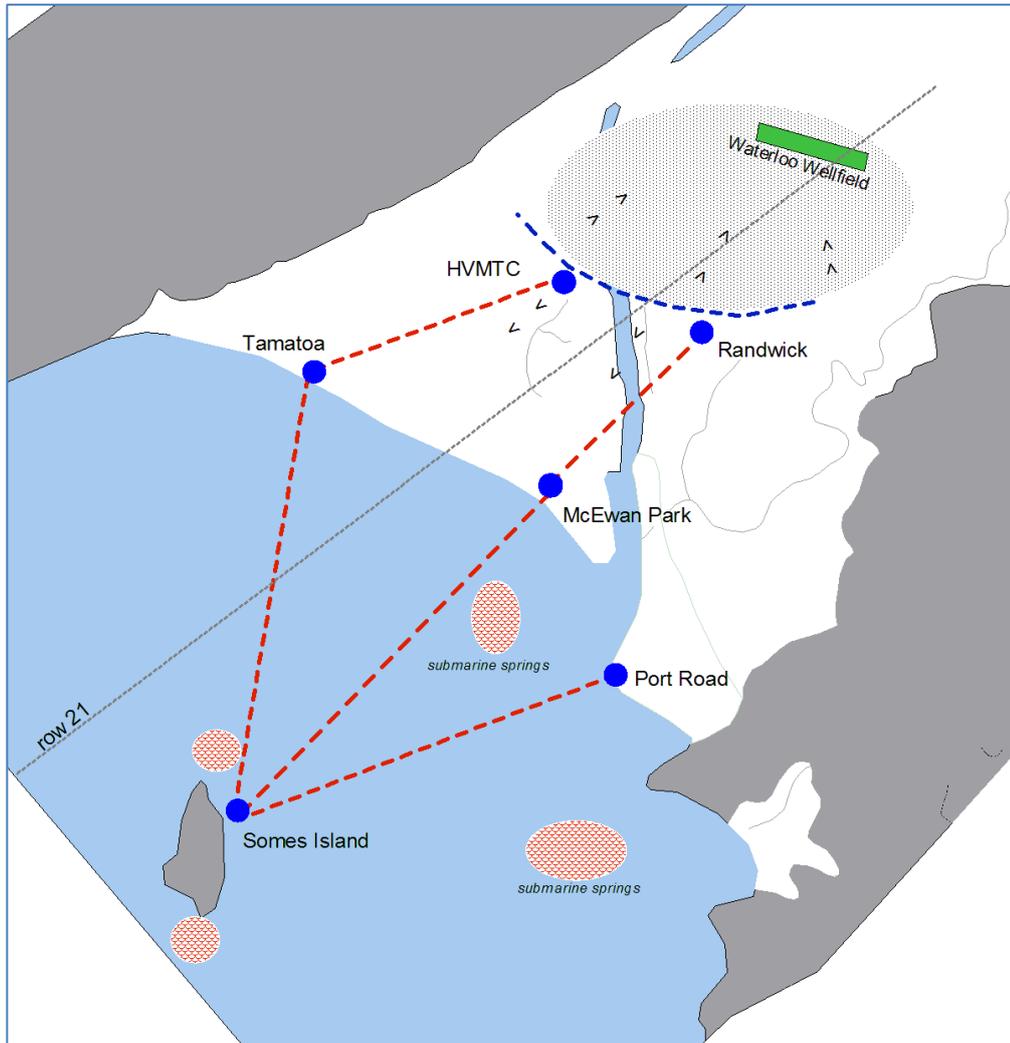
Figure 8.7: Indicative extent of Waterloo Wellfield cone of depression based on HAM3 (stippled zone). The groundwater divide is shown by the blue dashed line – the location is dependent on the pumping rate and recharge zone aquifer levels. Also shown are groundwater monitoring sites and hydraulic gradient calculation lines in the Upper Waiwhetu Aquifer (red dashed lines). The location of model row 21, used to construct Figure 8.6, is also shown.

Prediction of groundwater throughflow cessation and an associated reversal of offshore hydraulic gradient will occur when the groundwater divide south of the Waterloo wellfield drops below both the foreshore and offshore (Somes Island) groundwater levels as shown in Figure 8.6 (130 ML/day scenario). A critical 'elevated risk' reverse flow gradient will then exist between the Waterloo pumping wells and the sub-harbour aquifer.

The occurrence of this condition has been investigated using groundwater flow gradients based on historical monitoring data in order to:

- measure the offshore flow gradient between the foreshore groundwater levels and Somes Island level; and
- measure the gradient between the foreshore and the Waterloo wellfield using carefully selected monitoring sites.

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Offshore flow gradient

Figure 8.8 is based upon measured weekly average groundwater gradients between Somes Island and three foreshore sites – McEwan Park (shallow), Tamatoa (shallow) and Port Road (see Figure 8.7 for locations). The plot shows the head difference between each foreshore site and Somes Island – a positive number therefore indicates a positive offshore gradient. At a head difference value of zero the gradient is flat, becoming reversed as the line drops into the negative domain of the plot (below the green line). For each of the three gradient analyses, the foreshore record was plotted against the Somes Island record to obtain a linear regression relationship between them. These relationships are:

- Somes Island gw level = 0.884 * McEwan Park gw level + 0.22
- Somes Island gw level = 0.93 * Tamatoa gw level + 0.12
- Somes Island gw level = 0.959 * Port Road gw level + 0.08

The difference between each of the foreshore levels and the calculated Somes Island level (using the above equations) was then used to produce Figure 8.8.
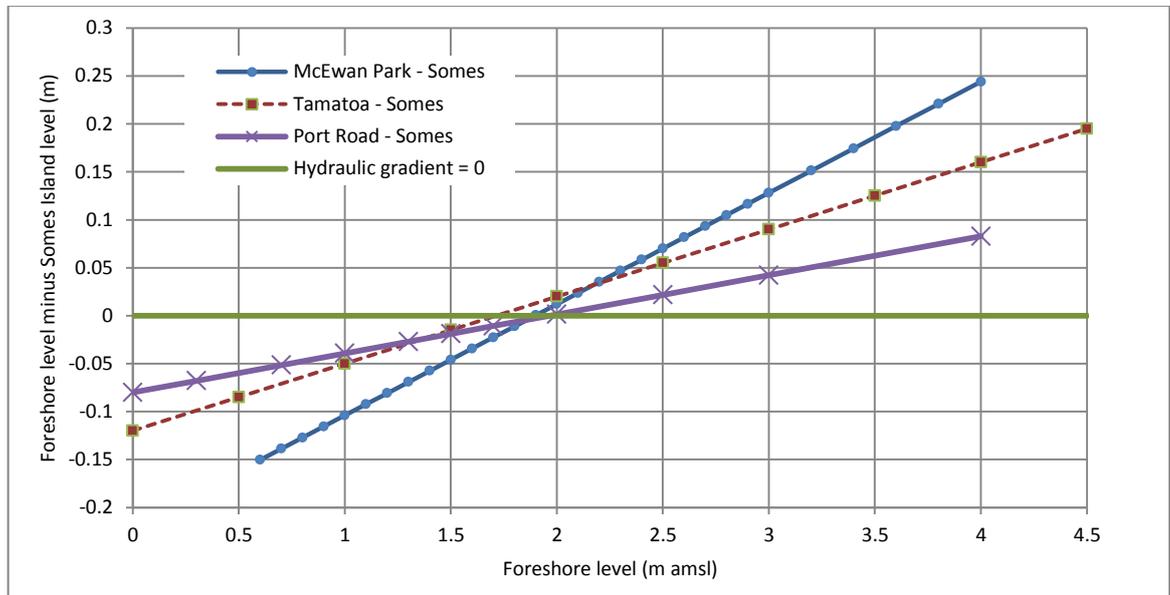
Figure 8.8: Analysis of hydraulic gradients in the Waiwhetu Aquifer between the Petone foreshore (Tamatoa, McEwan Park and Port Road) and Somes Island to determine when the offshore hydraulic gradient in the aquifer reverses (i.e. drops below the zero gradient line). The plot is based upon 7-day mean levels and utilised monitoring data as well as simulated data from the HAM3 (Port Road only). The green line shows that the gradient is zero between about 1.7 and 2m amsl.

Figure 8.8 shows that the Tamatoa-Somes and Port Road-Somes gradients are shallower than the McEwan Park/Port Road -Somes gradient. This is because the projected gradients between these sites are not perpendicular to groundwater flow equipotential lines (see Figure 4.11). It is apparent from Figure 8.8 that the flow gradient between the foreshore and Somes Island becomes zero when the foreshore level is between about 1.7 and 2m amsl.

To complement the hydraulic gradient analysis, outputs from the HAM3 have been used to show when throughflow in the Waiwhetu Aquifer at the coastline ceases (i.e. when the hydraulic gradient approaches zero). Figure 8.9 shows the modelled relationship between throughflow at the coastline and the McEwan Park groundwater level. Extrapolation of the trend indicates that throughflow ceases when the foreshore level is around 2-2.5m amsl.
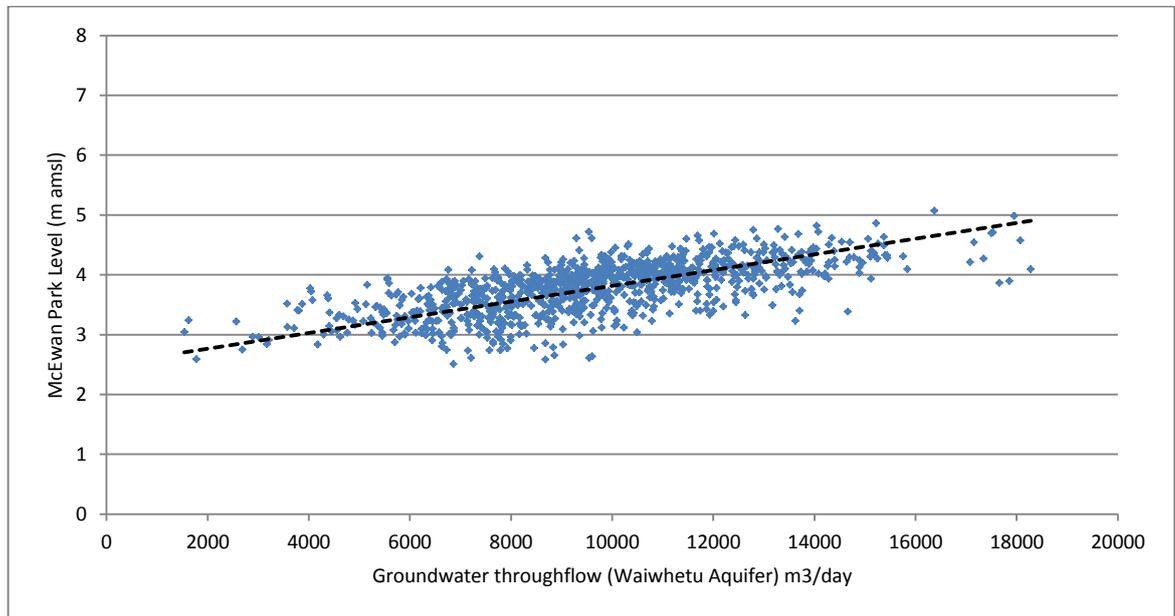
Figure 8.9: Output from HAM3 showing the relationship between aquifer throughflow in Upper Waiwhetu Aquifer and foreshore groundwater level at McEwan Park. The plot indicates that throughflow ceases when the foreshore level is about 2-2.5m amsl. Based on 7-day mean flows.

Onshore flow gradients

Groundwater level monitoring sites in closer proximity to the Waterloo wellfield (Randwick, HVMTC and Bell Park; Figure 8.7) experience a more dynamic and amplified response to pumping rate variations from the wellfield compared to the foreshore sites. Also, the Waterloo cone of depression may occasionally migrate past these sites and therefore a gradient calculated between them and the foreshore could be misleading since a groundwater divide will exist between them (as illustrated in Figure 8.6). It is not possible to produce a simple linear relationship between a gradient between one of these sites and the foreshore level such as those presented in Figure 8.8 for offshore gradients. However, it is useful to plot the differential head between the foreshore and inland monitoring sites to show when an apparent reverse gradient occurs.

Figure 8.10 contains a plot of the head difference between Randwick and McEwan Park showing that there has been a positive head difference over the past few years of about 50-100mm. These two sites are about 1,500m apart and therefore the hydraulic gradient in the Waiwhetu Aquifer below the wellfield is extremely low at about $3-7 \times 10^{-5}$. For comparison, the McEwan Park-Somes Island head difference is also shown in Figure 8.10 showing a much larger head differential because of the

greater distance between these sites (3,200m) even though the head gradient is comparable to the onshore gradient.

The drop in the Randwick-McEwan Park gradient from about 2005 seems to relate to increased annual abstraction from the Waterloo Wellfield (see Figure 4.19). The Randwick-McEwan Park gradient occasionally approaches zero when the wellfield abstraction rate (as a 7-day mean) approaches 100 ML/day. However, a positive gradient is maintained offshore (between McEwan Park – Somes Island) indicating that the aquifer does not enter a critical saline intrusion risk condition even though the apparent onshore gradient might reverse as the Waterloo cone of depression expands at higher pumping rates.
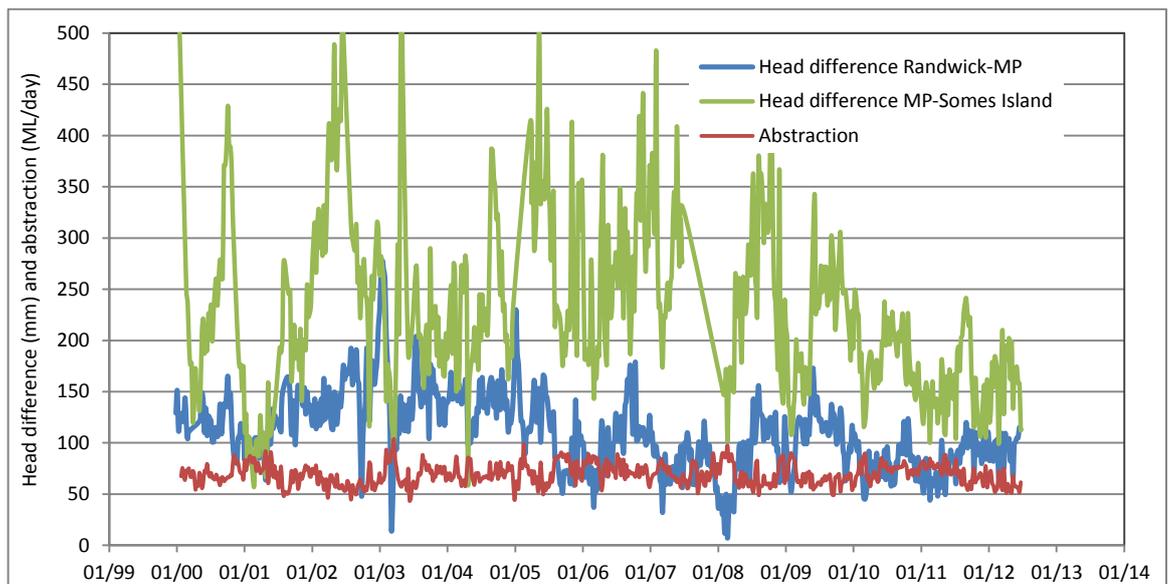
Figure 8.10: Head differential plots for Randwick – McEwan Park (MP) and MP – Somes Island groundwater level monitoring sites (heads and abstraction are plotted as 7-day means).

Figure 8.11 illustrates the hydraulic gradients between HVMTC – Tamatoa, and Tamatoa – Somes Island. Over the past few years (from about 2010), the onshore level difference between Tamatoa and HVMTC is about the same as that measured between Randwick and McEwan Park (Figure 8.10) of about 50-100mm. However, during 2009 and 2010 the head gradient between HVMTC and Tamatoa apparently reversed during periods when the pumping rate was higher. The reversal is not however reflected in the offshore gradient between Tamatoa and Somes Island which remain strongly positive – the groundwater level at Tamatoa has also always remained relatively high and above 3.0m amsl during the reversals. These observations suggest that the drawdown associated with high pumping rates from Waterloo (>90 ML/d) extends preferentially towards HVMTC, but does not reach the coast – the groundwater divide seems to migrate past HVMTC and a continual reversed gradient between the coast and HVMTC may not occur.

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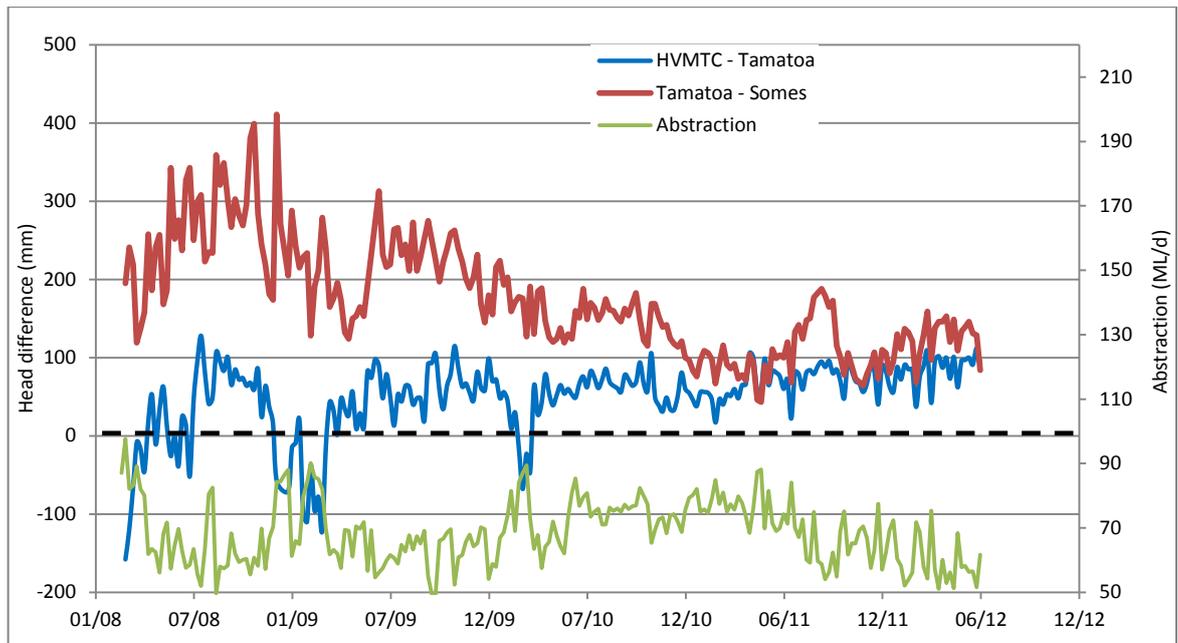
Figure 8.11: Head differential plots for HVMTC – Tamatoa and Tamatoa – Somes Island groundwater level monitoring sites.

Monitoring of offshore and selected onshore hydraulic gradients can therefore provide warning of an elevated saline intrusion risk in the Waiwhetu aquifer. In particular, the offshore hydraulic gradient in the Waiwhetu Aquifer shows when flow in the sub-harbour aquifer is being drawn back onshore and towards the wellfield. The onshore gradients can also provide advance warning of the onset of such conditions.

8.2.3.2   Critical condition 2: cessation of submarine spring discharge

When the offshore piezometric level in the Upper Waiwhetu Aquifer reaches a critical level beneath the submarine spring vents, diffusion and backflow of saltwater through the spring conduit and into the aquifer could occur. Because some of the spring vents are relatively close to the foreshore (the closest is only 600m from McEwan Park), the risk of this saline intrusion mechanism is regarded to be important.

A critical condition at the spring sites occurs when the ocean pressure at the sea floor equals or exceeds the freshwater pressure in the underlying aquifer. Submarine springs will cease to flow when the aquifer pressure equalises with the sea water pressure at the base of the spring vent depression. The piezometric pressure in the aquifer under this critical condition was originally evaluated by Donaldson and Campbell (1977) using the Darcy flow equation, taking into account the density difference between sea water and freshwater, as:

$$Q = R \ (h - \rho_s \ g \ d_t)$$

where:

Q = spring flow

R = the leak parameter incorporating the size of the leak and the resistance (kA)

h = head in the Waiwhetu Aquifer at the spring site (L, amsl)

ρ_s = density of sea water (ML^{-3}) = 1.025 tonnes/m^3

ρ_f = density of freshwater = 1.0 tonnes/m^3

g = acceleration due to gravity

d_t = total depth of sea water column above the spring vent (L)

According to this relationship, higher freshwater outflows will occur in shallower waters and, conversely, salt water inflow would occur preferentially at the deeper leak sites. Using the above equation, flow from the submarine springs will cease when:

$$h = \rho_s \, g \, d_t$$

$$= \rho_f \, g \, \text{x} 1.025 d_t$$

Reducing ρ_f g to 1, and referencing h to the mean sea level datum:

$$h = (1.025 \text{ x } d_t) - d_{msl}$$

where:

d_{msl} = depth of sea water column above spring vent from a mean sea level datum (note d_{msl} can be different to d_t as discussed below).

This is recognised as a post-critical situation as salt water could diffuse into the aquifer upon equalisation of the aquifer and harbour floor pressures, thus inducing saltwater flow into the aquifer.

Based upon the high resolution bathymetric survey discussed in Section 2.3, the maximum depth of the submarine spring vents (d_{msl}) occurring between the foreshore and Somes Island is 30m below mean sea level (the spring off the southern end of Somes Island is the deepest). Figure 8.12 shows the locations and depths of the spring vents based on the bathymetry survey.
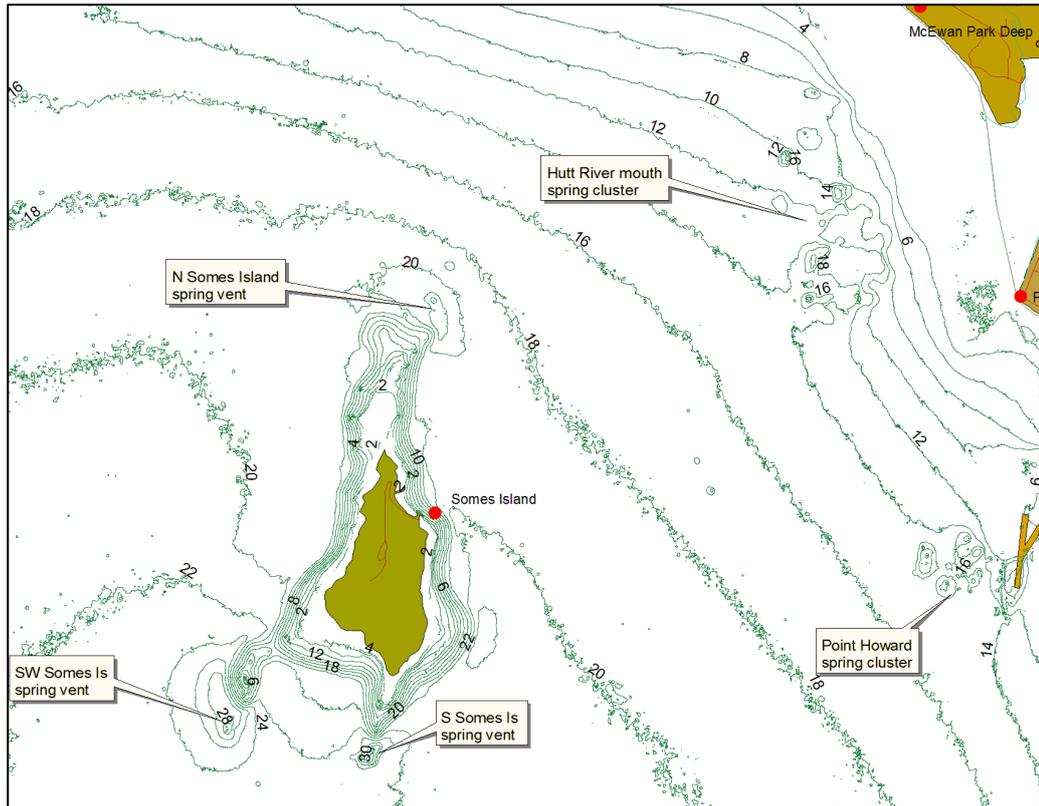
Figure 8.12: Submarine spring vent locations off the Petone foreshore as potential saline intrusion risks to the Waiwhetu aquifer. Depths are in meters below mean sea level.

If a tidal range of about 0.8m above mean sea level and a 0.2m sea level rise (see Section 6.4.4) are taken into account, the adjusted seawater column depth above the deepest spring vent base (d_t) is 31m. The critical head (for the deepest spring vent) in the underlying aquifer (h) therefore becomes:

$$h = (1.025 \times 31) - 30 = \textbf{1.8m above mean sea level}$$

Figure 8.13 schematically shows the components of the calculation and the different terms.

To be useful for saline intrusion risk management, it is important to be able to relate the calculated critical head condition in the Waiwhetu Aquifer beneath the spring vent to an equivalent level at the Petone foreshore. When the springs are flowing, extrapolation of the foreshore groundwater head to submarine spring vents using the offshore hydraulic gradient is problematic. This is because the piezometric heads around the springs in the harbour floor are likely to be depressed, much in the same way as a cone of depression associated with an abstraction bore. However, when flow from the springs has ceased, or becomes very low, there will be negligible drawdown around them and an extrapolation of the head in the Waiwhetu Aquifer beneath the spring and the foreshore becomes feasible. Using a conservative hydraulic gradient between McEwan Park and Somes Island of 5×10^{-5} (based on calculations in Section 8.2.3.1), a groundwater level in the Waiwhetu Aquifer at

McEwan Park/foreshore equivalent to 1.8m beneath a spring vent at a distance of 4,000m offshore (the down-gradient distance to deepest Somes Island springs) is 0.2m higher. Therefore, a critical condition for the deepest spring off Somes Island occurs when the level at McEwan Park/foreshore is about 2.0m amsl (1.8m + 0.2m). This level should theoretically ensure that all of the harbour floor springs do not experience a back-flow of sea water.
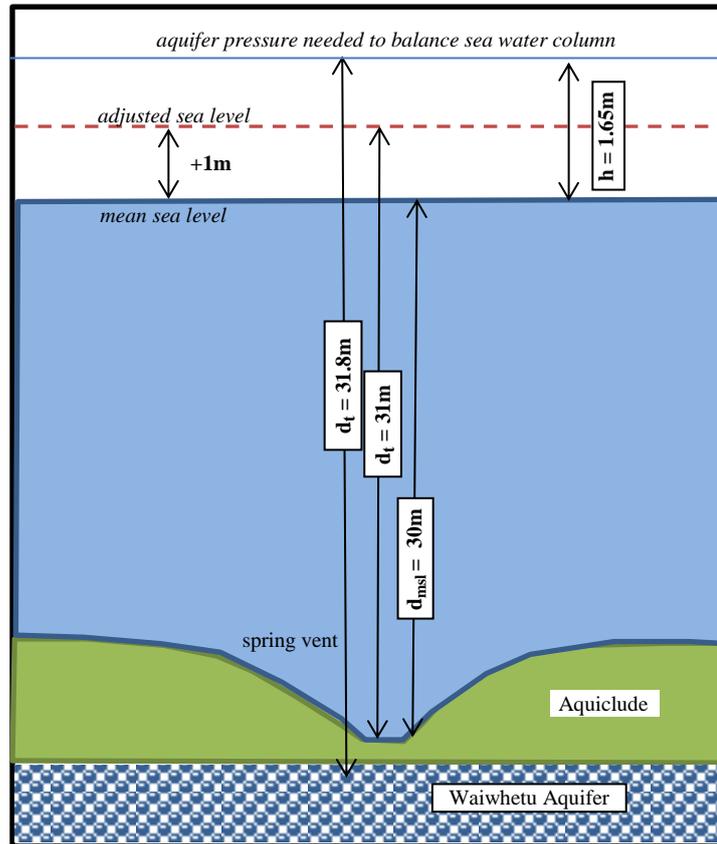
Figure 8.13: Diagrammatic representation of critical aquifer pressure calculation beneath the deepest submarine spring off Somes Island (30m depth).

If only the closer and shallower Hutt River mouth spring vents are considered – since they represent more of an immediate saltwater intrusion risk – the critical level is less. The deepest of the Hutt mouth spring cluster is 25m and about1,500m from the foreshore. The critical aquifer level (h) at the foreshore is therefore:

$$d_t = 25 + 1 = 26m$$

$$d_{msl} = 25m$$

$$h = (1.025 \times 26) - 25 = \mathbf{1.65m}$$

The equivalent foreshore critical level is 1,500m x hydraulic gradient of 5×10^{-5} = 0.08m higher = 1.73m amsl.

Monitoring of submarine spring flows from a vent off the Hutt River mouth by Harding (2000) showed that the springs seem to stop flowing when the McEwan Park aquifer level reached about 2.2m amsl as shown in Figure 8.14. This assessment is based on a very limited current meter dataset from a single vent, and assumes a linear extrapolation of the dataset. Coupled with the difficulties in obtaining reliable flow monitoring data on the sea floor, the data and the projected trend (Figure 8.14) should be treated with due caution. But should the assumptions and data be accepted, the derived level of 2.2m for the cessation of Hutt River mouth springs is higher than the above calculated critical level of 1.7m. A plausible explanation for this could be that spring discharge from the underlying Waiwhetu Aquifer needs to overcome a vertical hydraulic conductivity impedance through the Petone Marine beds. Therefore spring flow would be expected to cease under a higher aquifer pressure than the calculated backflow critical pressure.
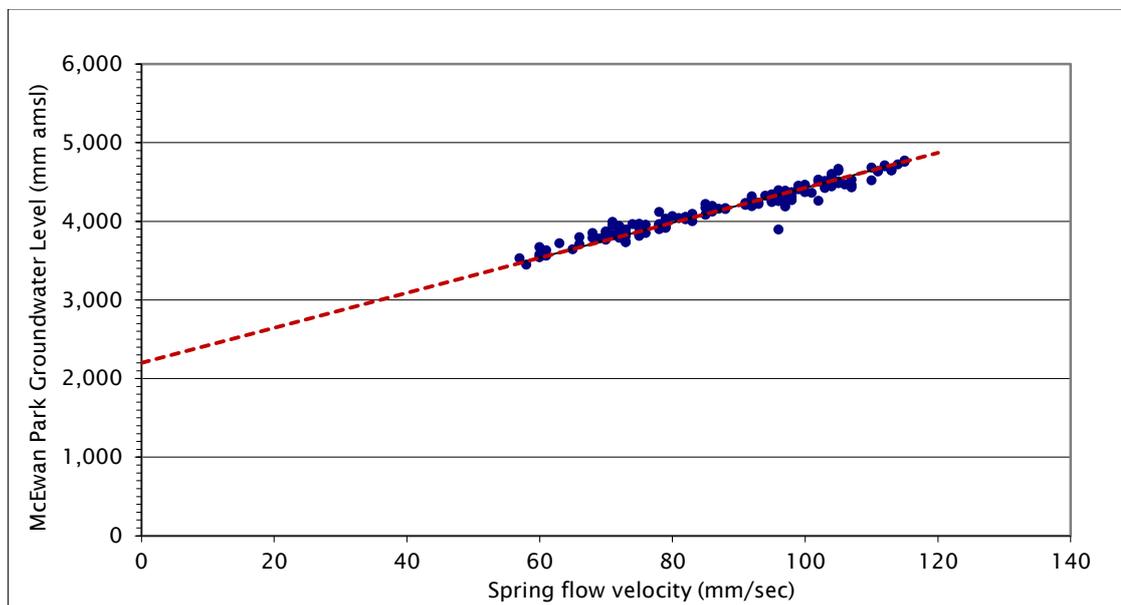
Figure 8.14: Measured submarine spring flow from a vent near the Hutt River mouth in relation to groundwater level at McEwan Park on the Petone foreshore (data from Harding 2000). A linear extrapolation of the trend indicated that spring flow will cease when the McEwan Park level reached 2.2m amsl. Data are plotted using a 12 hour time lag between spring velocity measurement and McEwan Park level.

8.2.3.3 Critical condition 3: Foreshore levels drop below theoretical saline intrusion prevention minimum levels

The onshore migration of saline water can be theoretically prevented by ensuring the foreshore groundwater levels in the Waiwhetu Aquifer do not fall below the Ghyben-Herzberg minimum level.

The Ghyben-Herzberg equation applies to hydrostatic conditions (i.e. there is no flow in the aquifer) – which can be considered appropriate for the Upper Waiwhetu Aquifer at the Petone foreshore since throughflow will be very small when foreshore groundwater level drops below about 3m amsl (see Figure 8.9). The equation is

based on a simple hydrostatic relationship between the density differences of sea water and freshwater:

$$z = (\rho_f / \rho_s - \rho_f) h_f$$

where:

z = the depth below sea level of the freshwater interface;

h_f = the height of the freshwater column above sea level that maintains a balance with the saltwater interface

ρ_f = density of freshwater

ρ_s = density of sea water

The relationship demonstrates that sea water occurs at depths below sea level equivalent to approximately 40 times the height of freshwater above sea level when typical values for ρ_f of 1.0 tonne/m^3 and for ρ_s of 1.025 tonnes/m^3 are used:

$$z = 40 \, h_f$$

Acknowledging the assumptions of the Ghyben-Herzberg relation, it provides a simple and conservative guideline (PDP, 2011) to calculate groundwater pressures above which no sea water intrusion problems should occur. In this sense, it can be used to derive a conservative foreshore groundwater pressure minima in the Waiwhetu Aquifer to ensure that saltwater intrusion cannot occur. It can also be used to trigger a requirement for more rigorous monitoring.

Calculation of a minimum foreshore groundwater level in the Waiwhetu Aquifer relies upon an accurate knowledge of the base elevation parallel to the Petone foreshore of both the lower and upper units of the Waiwhetu Aquifer. This information has been derived from the geological model described in Section 0 from which the HAM3 has been constructed. A high degree of confidence can be invested in the geological model at the foreshore due to the large number of bore logs in this area.

Figure 8.15 shows the modelled base elevations of the Upper and Lower Waiwhetu aquifers along the foreshore. The highly transmissive Upper Waiwhetu Aquifer has a HAM3 calibrated hydraulic conductivity of 1,400m/day. The Lower Waiwhetu Aquifer is considerably less permeable (HAM3 hydraulic conductivity of 336 m/day) but in hydraulic connection with the Upper Waiwhetu – there is a negligible head difference between these units.

If the Ghyben-Herzberg equation is used to calculate a minimum level to prevent saline water migrating to the deepest part of the Upper Waiwhetu Aquifer of -60m (Figure 8.15), a minimum level of 1.5m amsl should be maintained, or 1.7m if the current sea level of +0.2m is taken into account (see Section 6.4.4).

Protection of the Lower Waiwhetu Aquifer from saline intrusion would require a minimum groundwater pressure at the foreshore of about 2.2m amsl (2m + 0.2m sea level rise) if the deepest part is taken to be -80m. At 2.0m amsl the offshore flow

gradient (and aquifer throughflow) is predicted to be more or less zero (Figure 8.8) and therefore the Ghyben-Herzberg hydrostatic assumption becomes valid.
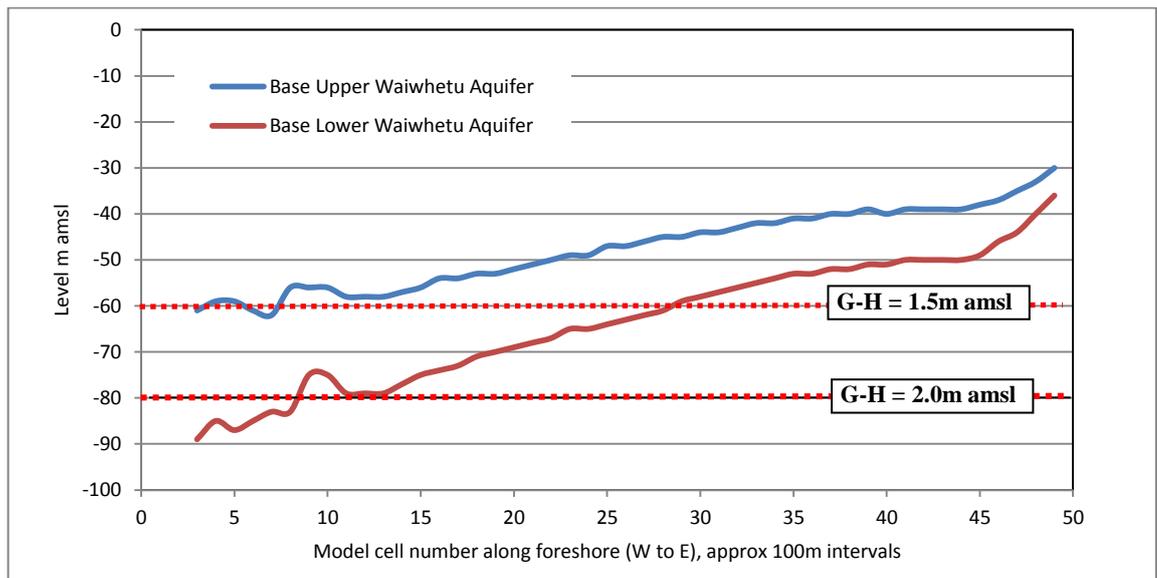
Figure 8.15: Modelled base of Upper and Lower Waiwhetu aquifers along a section line parallel to the Petone foreshore. Ghyben-Herzberg (G-H) levels to prevent saline intrusion are shown for both horizons.

8.2.3.4 **Other analytical and numerical methods to manage seawater intrusion risk**

Unlike the hydrostatic Ghyben-Herzberg equation, the Glover analytical solution for predicting the location of the saline-fresh interface takes into account aquifer throughflow which tends to push the interface offshore. This would normally be more appropriate since most coastal aquifer systems experience some throughflow. However, in the case of Waiwhetu Artesian Aquifer, the very low hydraulic gradients show that there is very little throughflow at the foreshore. The Glover equation is also more relevant for unconfined aquifers with a permeable hydraulic connection to the sea (PDP, 2011) and therefore its application within the Lower Hutt hydrogeological context is not recommended.

Another analytical method for estimating critical well discharge in a coastal aquifer was developed by Strack (1976). The method calculates a critical abstraction rate which, if exceeded, allows an unstable condition to develop whereby the toe of a freshwater saline water interface could pass through a stagnation point (groundwater divide) thereby allowing sea water will migrate to the well. This is a relatively complex analytical solution which assumes idealised hydrogeological conditions and the existence of a saline interface offshore. One of the critical parameters required by the method is a fixed throughflow per unit width of aquifer (q). The Waiwhetu Aquifer has a complex interaction with the Hutt River and 40-60% of the Waterloo abstraction is induced river recharge the rate of which is proportional to abstraction rate and also dependent upon unconfined aquifer levels. Therefore, the assumption of a fixed throughflow is an unrealistic simplification. Combined with the probable absence of a saline-freshwater interface beneath the harbour, the use of multiple

pumping wells (8) at Waterloo, and the very small coastal throughflows, the Strack method is not considered a suitable tool for assessing the critical yield of the Waterloo wellfield.

The use of a variable density solute transport model such as SEAWAT in conjunction with the HAM3 MODFLOW simulation has also been considered. However the difficulty in accurately characterising model inputs, uncertainties regarding offshore aquifer properties, and the assumptions required to simulate the harbour springs does not offer significant benefits over simple analytical calculation.

8.2.3.5 Summary of critical foreshore critical levels and recommendations

A summary of the critical foreshore groundwater levels for the management of saline intrusion risk in the Waiwhetu Aquifer is provided in Table 8.1 which also shows the current saline intrusion management levels for the McEwan Park monitoring bore.

Table 8.1: Summary of critical saline intrusion foreshore levels for the Upper Waiwhetu Aquifer showing current management levels. Yellow shaded area represents current requirement for intensification of monitoring (warning level) and active management of abstraction (critical level). Ghyben-Herzberg levels in brackets do not take into account the current mean sea level (+0.2m). All other levels implicitly incorporate the current sea level.

McEwan Park / Petone Foreshore Levels in Upper Waiwhetu Aquifer

current management levels

2.6		
warning level **2.5**		
2.4		
critical level **2.3**		
	2.2m	? ? Near-shore submarine springs cease flowing ?
2.2	**2.2m (2.0)**	Ghyben-Herzberg minimum level for base of **Lower Waiwhetu Aquifer**
2.1	**2.0-2.5 m**	Cessation of throughflow at coast (HAM3)
current min level **2.0**	**2.0m**	Calculated critical aquifer pressure beneath Somes Island springs
	1.7-2.0m	Flattening of offshore hydraulic gradient
1.9		
1.8		
	1.73m	Calculated critical aquifer pressure beneath Hutt River mouth springs
1.7	**1.7m (1.5)**	Ghyben-Herzberg minimum level for base of **Upper Waiwhetu Aquifer**
1.6		
1.5		
1.4	*1.4m*	*Pre-2001 minimum level (Donaldson and Campbell, 1978)*
1.3		
m amsl		

Lower Hutt Aquifer Model Revision (HAM3): Sustainable Management of the Waiwhetu Aquifer
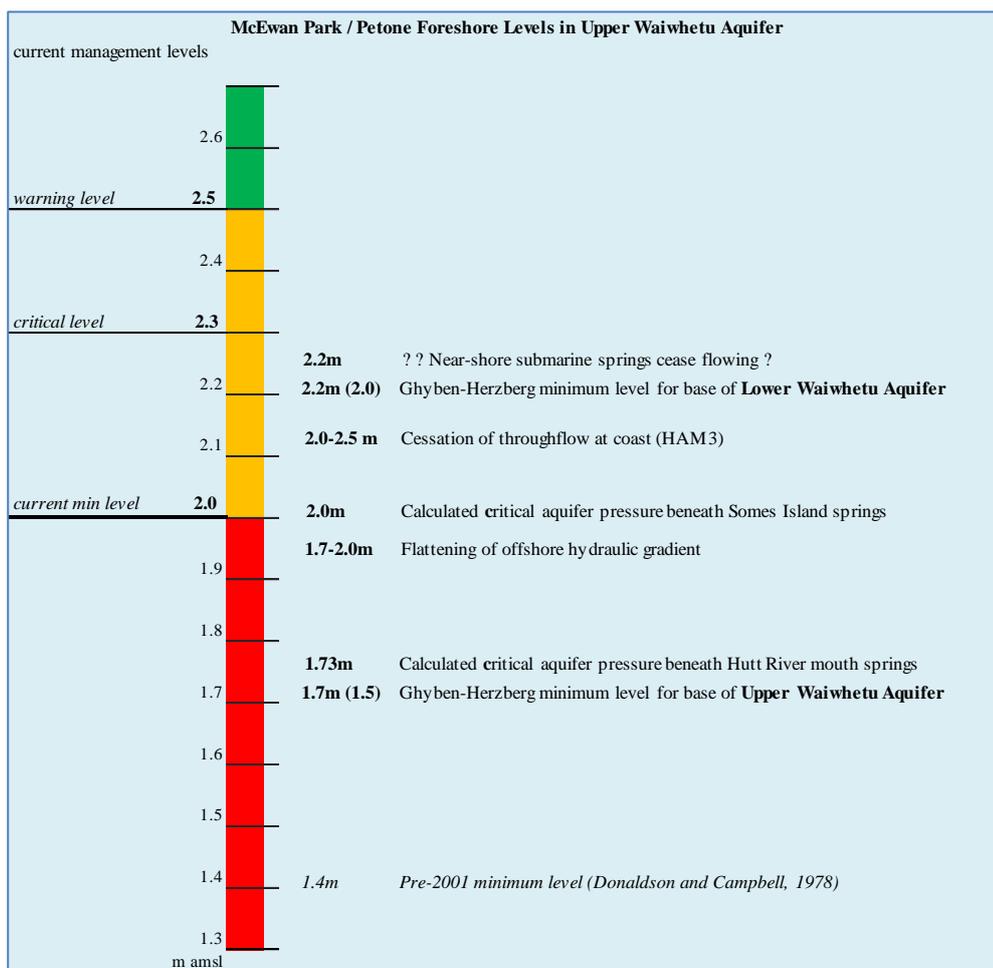
Table 8.1 shows that there is an encouraging consistency between the different methods used to assess saline intrusion risk and calculate minimum foreshore levels. It also shows that the current critical and minimum levels are largely appropriate.

The current minimum foreshore level for the Upper Waiwhetu Aquifer is 2.0m (calculated as a 24 hour mean). This level would theoretically prevent backflow into any of the sub-harbour spring vents and ensure that saline water could not migrate into the base of the highly transmissive Upper Waiwhetu Aquifer. Foreshore groundwater levels above the Ghyben Herzberg minimum level (1.7m amsl) would be maintained and an offshore reversal in the hydraulic gradient avoided. The Upper Waiwhetu Aquifer is more vulnerable due to its potentially rapid flow velocities and its local connection to the ocean at the spring sites. Therefore, the appropriateness of the conservative minimum foreshore level of 2.0m amsl (as a 24 hour mean) can be justified.

Given that the tidal efficiency of the Waiwhetu Aquifer at the foreshore is about 70% (see Table 4.2), a 24-hour mean foreshore level of 2.0m amsl would allow the instantaneous aquifer level to drop by about 70% of the low tidal range. This equates to about 0.3m since the average low tide is about 0.4m below mean sea level. The instantaneous level could therefore drop to about 1.7m amsl which is still sufficient to prevent sea water intrusion into the base of the Upper Waiwhetu Aquifer and prevent backflow at the Hutt River mouth springs (Table 8.1). The absolute low tide minimum level is about -0.8m which means that the foreshore level would intermittently drop to 1.5m. The very short duration of low tidal levels and time lags in the groundwater system relative to sea level are not regarded to pose a saline risk and the 24-hour mean level is regarded to be appropriate.

Table 8.1 also shows that the warning levels of 2.3m and 2.5m to trigger more vigilant observation of aquifer levels and water quality is appropriate. Monitoring recommendations are provided in the next section.

8.2.4 RECOMMENDATIONS FOR SALINE INTRUSION RISK MANAGEMENT AND MONITORING

A saline intrusion risk management framework has been developed which relies both upon theoretical groundwater level/gradient thresholds (as described in Section 8.2.3), and upon a direct detection of water quality changes. The latter is considered particularly important since the Upper Waiwhetu Aquifer potentially has a 'fast response' characteristic due to its exceptionally transmissive, confined nature and the presence of discreet saline intrusion access sites through near-shore submarine spring vents. In this context, a robust monitoring approach capable of rapidly detecting water quality, aquifer levels and flow gradients is therefore essential.

The fast response characteristic of the Upper Waiwhetu Aquifer also means that there is a negligible time lag between changes in pumping rate and the groundwater level response at the foreshore. Therefore changes in pumping rate can be confidently assumed to have an almost instantaneous effect on foreshore pressures in the Waiwhetu Aquifer.
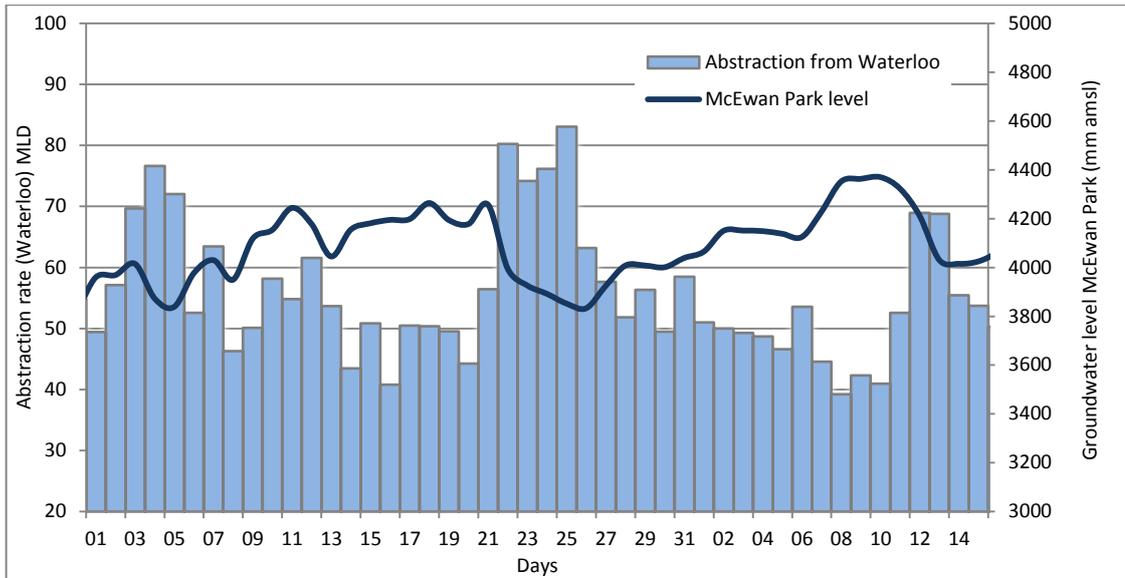
Figure 8.16: Plot illustrating the lack of a significant time lag between changes in pumping rate at the Waterloo Wellfield and aquifer level response at the Petone Foreshore (McEwan Park).
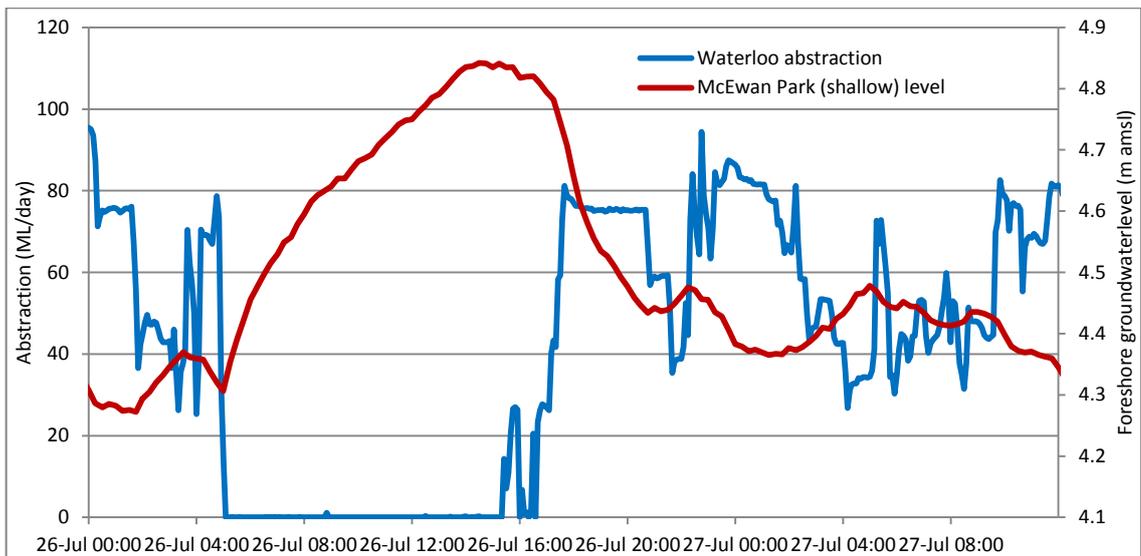

Figure 8.17: Plot pumping rate at the Waterloo Wellfield and aquifer level at the Petone Foreshore (McEwan Park) during a period in July 2012 (when the wellfield was turned off) demonstrating minimal time lags in the Waiwhetu Aquifer. Level data have been corrected for tidal and barometric effects.

The existing network of dedicated sentinel water level and water quality monitoring sites is generally considered adequate. Recommendations are made for the improvement, adaptation or replacement of some sites and the inclusion of a new site. The new foreshore sentinel multi-level constructed in 2008 at Tamatoa and McEwan Park each have a deep well screened in the Lower Waiwhetu Aquifer, and a shallow well screened in the Upper Waiwhetu Aquifer (see also Section 4.1.2.2). The dual level monitoring provides early warning of water quality changes (electrical conductivity) in both the upper and lower parts of the Waiwhetu gravels.

Unfortunately, continuous electrical conductivity (EC) monitoring has not been used in the management of saline intrusion risk and is not incorporated into the resource consent conditions relating to the Waterloo abstraction. The reasons for this and proposed improvements to the EC monitoring network are discussed below.

Figure 8.18 shows the components of a revised saline intrusion monitoring strategy, the elements of which are described in subsequent sections.
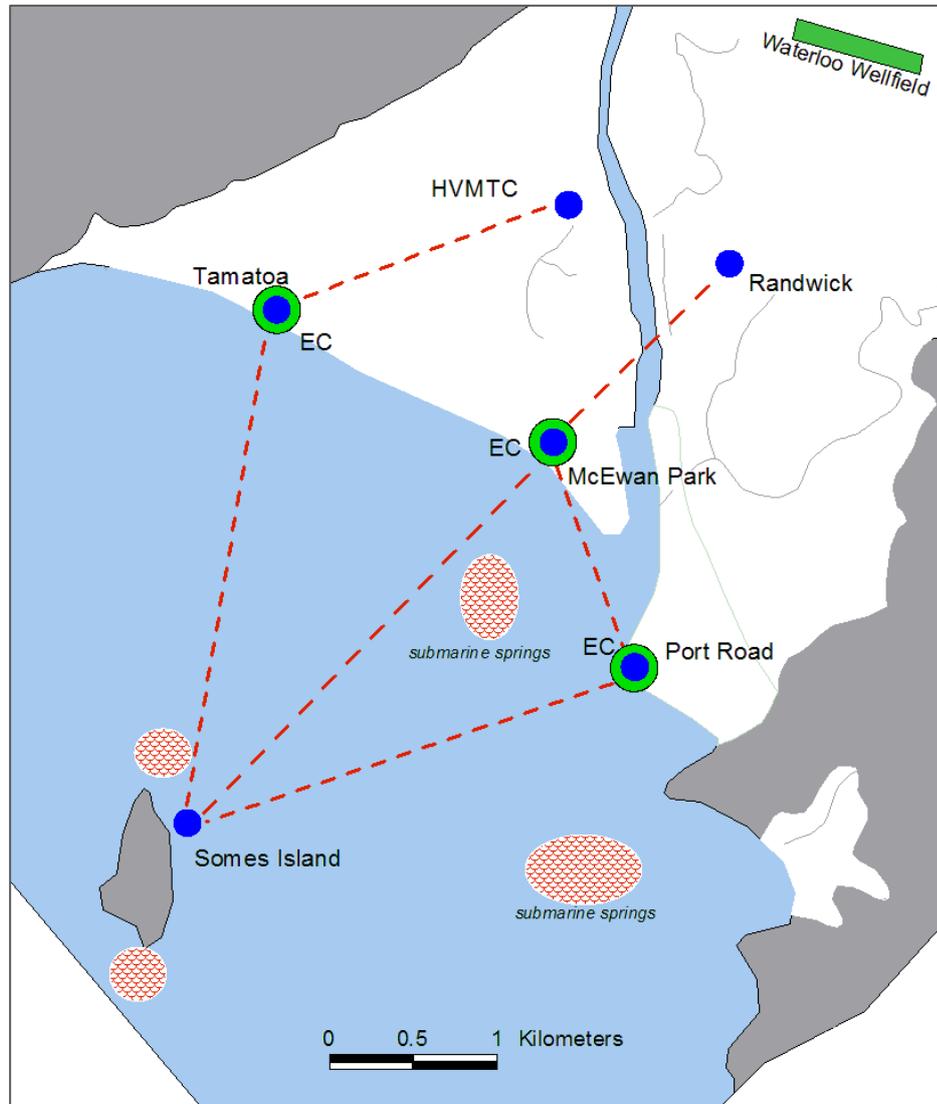
Figure 8.18: Components of a revised saline intrusion monitoring system for the Waiwhetu Aquifer, Lower Hutt. Blue circles are continuous groundwater level monitoring bores, green circles are bores equipped with continuous electrical conductivity probes, dashed red line are monitored hydraulic gradients.

8.2.4.1   **Groundwater level risk thresholds**

Summarising the outcomes of the critical aquifer level analyses (Section 8.2.3), the following three saline intrusion risk management thresholds for the Upper Waiwhetu Aquifer are recommended:

> **Review Level: 2.5m amsl (24-hour mean)**
>
> **Alert Level: 2.3m amsl (24-hour mean)**
>
> **Minimum Level: 2.0m amsl (24-hour mean)**

These are consistent with the three current management levels (2.5, 2.3 and 2.0m). However, it is recommended that the Review and Alert levels provide a more structured function of stepping up from an increased state of awareness at 2.5m, to an intensification of monitoring at 2.3m.

The 24-hour mean minimum level of 2.0m indicates that the aquifer is approaching an elevated saline intrusion risk state when offshore gradients may begin to reverse.

The 2.3m Alert Level signifies the onset of a low but rising saline intrusion risk as the offshore hydraulic gradient approaches a critical state. The need to implement a more intensive water quality monitoring regime when the Alert Level is reached is therefore recommended – a tiered investigation and aquifer manage response is detailed below. The foreshore water level should be allowed to drop to this level without prior permission. Under the current resource consent, permission is required to proceed below a critical level of 2.3m, but there is no formalised aquifer management or monitoring protocol in place within GWRC should this trigger be activated. It is recommended that a formal process be adopted when the Alert Level is triggered and that this be incorporated into the conditions of consent. This would avoid delays and confusion around management actions when the foreshore levels indicate a low risk of saline intrusion between 2.3 and 2.0m amsl. Resource managers at GWRC should be involved and consulted during this process.

The Ghyben-Herzberg minimum level for the Lower Waiwhetu Aquifer occurs at 2.2m amsl, but this is not regarded to be a critical level since the lower and deeper part of this unit has a low hydraulic conductivity – the proposed minimum level of 2.0m will protect all but the deeper western part of this unit. It should also be borne in mind that the Ghyben-Herzberg level is a conservative approximation for short term water level declines and the 2.3m Alert Level monitoring response provides an appropriate heightened alertness to changes in aquifer water quality.

Currently, the level recorded in the McEwan Park (shallow) monitoring bore (R27/0122) is relied upon solely for the management of the Waiwhetu Aquifer. Management levels are set for this site in the resource consent conditions for the abstraction from Waterloo wellfield (consent number WGN970036). Wellfield abstraction is generally conservatively managed so that the level remains above the present warning level (2.5m amsl). It is recommended however that both the McEwan Park and Tamatoa (shallow) foreshore sites be used to provide a more robust aquifer monitoring system. The McEwan Park site should however remain as

a principal trigger site as it lies in the middle of the valley where groundwater flows may be higher than towards the edges.

McEwan Park (shallow) – bore condition

There are concerns around the long term viability of the original McEwan Park (shallow bore; R27/0122) which seems to be in poor condition. When it is flushed for water quality sampling, the water rapidly turns a red colour and is sediment-laden. Together with the presence of red slime on monitoring equipment, indicates the probable presence of iron bacteria (which has recently affected some of the Waterloo production wells). The bore was originally constructed without a screen and protrudes only into the very top of the Upper Waiwhetu Aquifer (it was cased and left open at the base). In 2001 the casing was perforated between 28.4 and 29.6m depth to improve the flow of groundwater through the bore for electrical conductivity monitoring purposes. It is recommended that a camera survey be undertaken on this bore, and that it be rehabilitated or replaced with a new structure if required. It is preferable that this bore is replaced and properly screened in the lower part of the Upper Waiwhetu Aquifer to improve its early warning ability to detect saline intrusion.

8.2.4.2 Hydraulic gradients

In addition to monitoring the water levels at McEwan Park (shallow) and Tamatoa (shallow), the following onshore and offshore gradients (differential levels) should be observed by plotting the 24-hour moving average difference between the following pairs of sites (shown in Figure 8.19):

Offshore
- McEwan Park– Somes Island
- McEwan Park – Port Road (projected)
- Tamatoa Shallow – Somes Island
- Port Road – Somes Island

Onshore
- Randwick – McEwan Park
- HVMTC – Tamatoa

The Port Road monitoring site has been added to the coastal sentinel bore network as it occupies a strategic position on the eastern side of the valley and is also further down the hydraulic gradient in the Waiwhetu Aquifer from McEwan Park or Tamatoa by about 800-900m (see Figure 4.11). It is likely that the groundwater level at Port Road will be similar to that beneath the Hutt mouth submarine springs because it lies along the strike of the groundwater flow contours and is aligned with the springs. This site can therefore be used to observe the near-shore hydraulic gradient using McEwan Park thereby reducing reliance on the Somes Island monitoring bore for offshore gradient analysis.
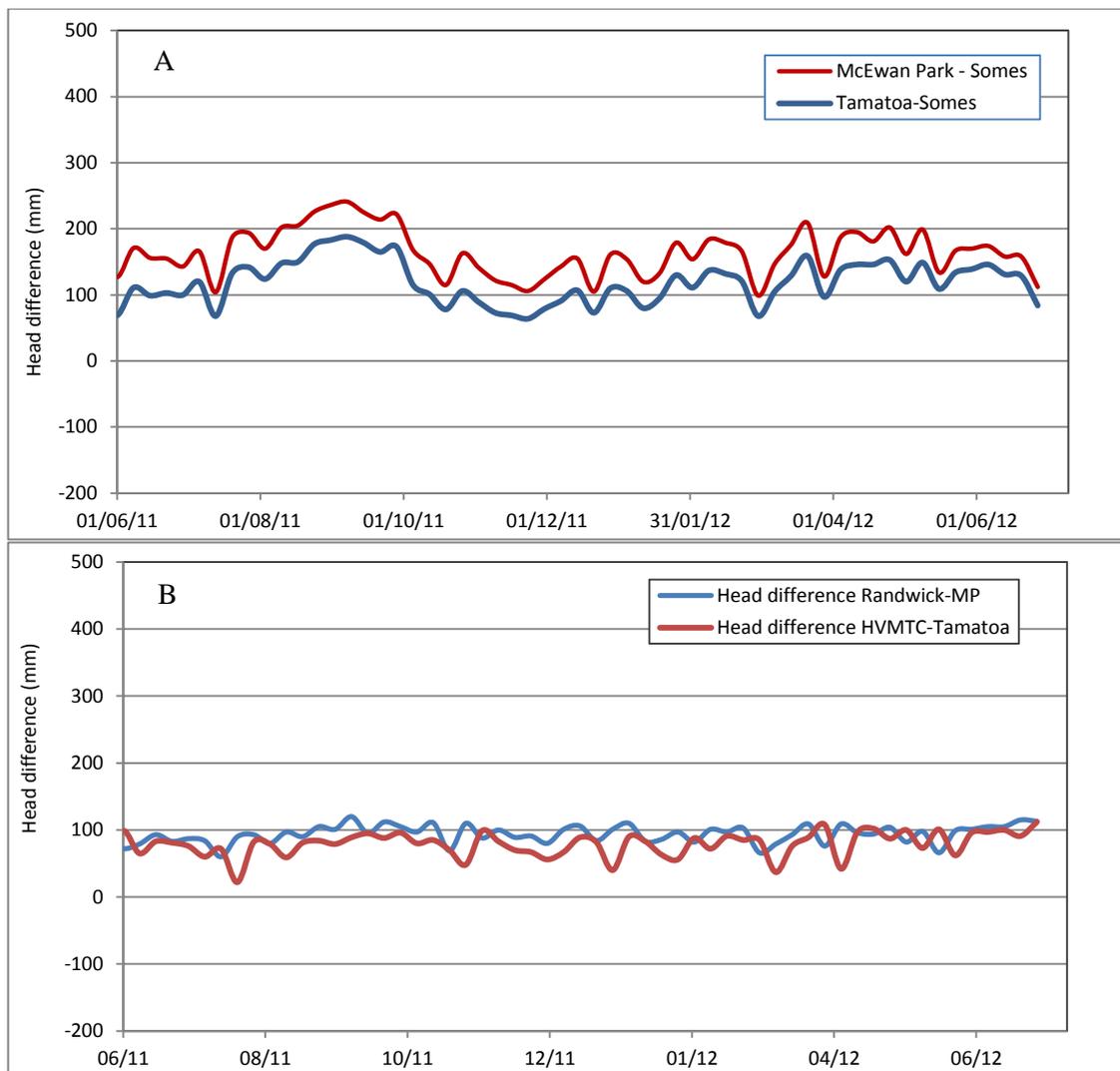
Figure 8.19: Offshore (A) and onshore (B) groundwater head differential plots recommended for alert condition saline intrusion monitoring. Note Port Road gradients are not shown as insufficient reliable data currently exist.

It is possible for the onshore gradients to reverse safely (Figure 8.19B) as long as the offshore gradients (Figure 8.19A) remain positive. The reversal of both onshore gradients (Randwick-MP and HVMTC-Tamatoa) should however trigger an alert condition in the aquifer in addition to the foreshore water level trigger of 2.3m. The onshore gradient between Randwick and McEwan Park is a more reliable indicator (as discussed previously) and could be used to trigger more vigilant quality monitoring at the foreshore should it reverse.

Should one or more of the offshore gradients reverse, the aquifer is probably entering a state of elevated saline intrusion risk. It is likely that this would only happen when the foreshore level drops below 2.0m (the minimum level) according to the analyses presented in Figure 8.8. Observation of flow gradients becomes particularly important below the 2.3m Alert Level.

Port Road – bore condition

The Port Road monitoring bore (R27/1118) was decommissioned in 1997 but was reactivated for a short period in 2012 to provide additional HAM3 calibration data. The GWRC Wells database indicates that when a camera survey was carried out on this bore in 2000, gravel was encountered at 9m depth (it was originally drilled to 28.7m). The bore was probably constructed in the same manner as McEwan Park as an open-bottomed steel tube with no screen. Gravel has subsequently migrated upwards probably due to the tidal rise and fall in level. The bore therefore needs to be replaced, particularly if EC monitoring is to be carried out at this site.

8.2.4.3 Water quality monitoring

The continuous monitoring of electrical conductivity (EC) at sentinel foreshore wells provides a good direct indicator of changes in water quality which may reflect the onset of saline intrusion. There is a close relationship between EC and chloride which is the major anionic indicator of sea water presence in the aquifer. However, elevated EC levels may not necessarily indicate saline intrusion as other factors may influence groundwater quality. EC trends and thresholds should therefore be used to trigger the need for a more comprehensive chemical analysis such as those recommended in the New Zealand Guidelines for the monitoring and management of sea water intrusion risks on groundwater (PDP, 2011).

Continuous EC monitoring has been taking place at the multilevel Tamatoa and McEwan Park sentinel wells since 2009. They are set-up to record EC and temperature (which is used to compensate the EC measurements) at 15 minute intervals, and are connected to the GWRC telemetry system. In addition to these sites, it is also recommended that the Port Road site be equipped with EC monitoring equipment in the Upper Waiwhetu Aquifer only (in a replacement bore).

Figure 8.20 shows the record for each EC monitoring bore. It is apparent that the EC (and temperature) probes in all but the Tamatoa shallow bore have experienced problems since their installation. As a result the historical data is largely regarded to be unreliable. The faulty instruments have recently been replaced – the last six months of the McEwan Park records shows a stable trend for the deep and shallow bores.

The Tamatoa shallow record shows a very consistent EC record of about 125-135 µS/cm which is consistent with the recent McEwan Park shallow, Upper Waiwhetu measurements (Oct 2013 onwards). The most recent EC data for the Lower Waiwhetu Aquifer at McEwan Park shows a relatively stable but higher level which sits at about 200-210 µS/cm. It appears that the equivalent Tamatoa deep site is continuing to experience problems.
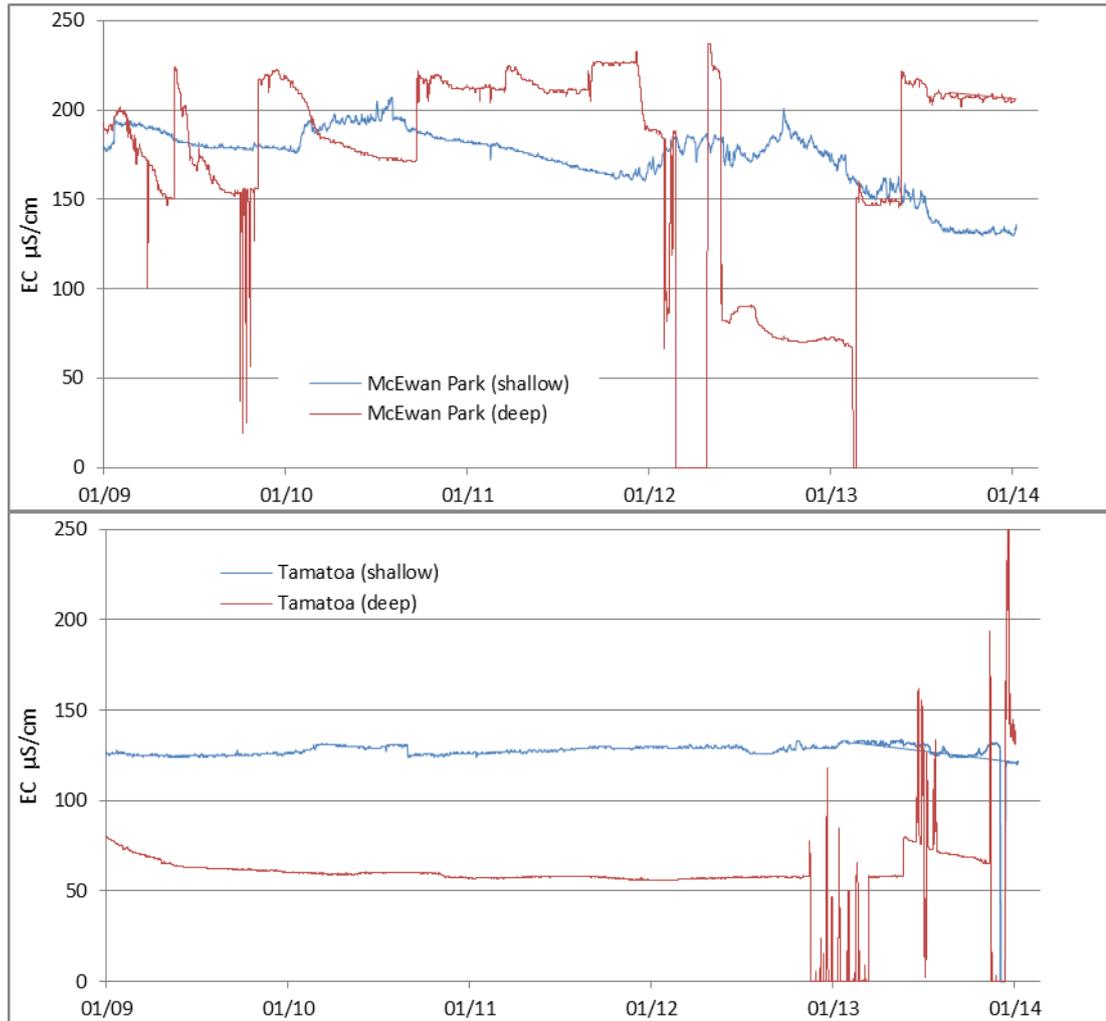
Figure 8.20: Electrical conductivity monitoring in Tamatoa and McEwan Park foreshore sentinel wells, 2009 to present. The data show that EC monitoring has been unreliable prior to recent replacement of probes.

Based on the reliable EC monitoring to date, the following EC trigger levels are proposed to indicate the onset of significant water quality changes in the Lower and Upper Waiwhetu Aquifers:

EC = 150 µS/cm – Upper Waiwhetu Aquifer
EC = 250 µS/cm – Lower Waiwhetu Aquifer

Five EC monitoring sites should form part of the revised water quality monitoring network:

McEwan Park (shallow)
McEwan Park (deep)
Tamatoa (shallow)
Tamatoa (deep)
Port Road (new)

Should the threshold EC triggers be breached in one or more monitoring bore, the following two-tiered response is recommended:

Tier 1 *(initial) response- within 24 hours:*

- Review all monitoring data (including water levels and gradients);
- As a precautionary measure the pumping rate should be reduced; and
- All monitoring wells equipped with EC probes should be flushed (at least 2 bore volumes by free-flowing) and the EC readings then checked against an independent portable meter.

Tier 2 *response – within 48 hours:*

- Should the rise in EC be confirmed in the field, additional water quality sampling and chemical laboratory analysis from samples taken from all water quality sites must be carried out;
- Should additional water quality data confirm the likelihood of saline intrusion, the pumping rate from the Waterloo wellfield should be immediately reduced incrementally until an improvement in water quality is observed.
- Resource managers at GWRC should be informed and involved in the assessment of the monitoring data.

Both Tier 1 and Tier 2 responses should be carried out within 24-48 hours of detecting elevated EC levels. EC trends may also provide advance warning that a trigger may be breached and the response can therefore be anticipated.

Alert Level water quality monitoring (<2.3m)
Alert Level water quality monitoring is triggered when aquifer levels reach or drop below 2.3m amsl (24-hour mean). When this occurs, the Tier 1 response methodology should be implemented on a weekly basis (i.e. the EC trigger does not need to be breached to initiate a Tier 1 response, it is triggered in this case by the Alert foreshore level). The breaching of the EC trigger levels should initiate a Tier 2 response.

General downhole EC instrument maintenance and calibration
Due to the historical problems experienced with EC monitoring as illustrated in Figure 8.17, it is recommended that the five EC monitoring site are checked and calibrated annually. Ideally, this should be scheduled immediately prior to the summer (November-December). At this time, the bores should also be flushed thoroughly by free-flowing or pumping. It is also recommended that the EC sentinel bores be properly developed by an approved contractor at least every five years.

8.2.4.4   **8.2Summary of proposed saline intrusion monitoring and risk management**

Table 8.2 summarises the recommendations for the revision of the saline intrusion risk management framework for the Waiwhetu Aquifer. The table is divided into three saline intrusion risk categories – '*none*', '*low to increasing*' and '*elevated*'. These categories are based primarily upon foreshore level thresholds, but also incorporate hydraulic gradients (onshore and offshore) and water quality (EC) thresholds. Monitoring and abstraction management responses relevant to each risk category are also shown. The requirement to instigate a structured tiered water quality investigation in response to the breaching of EC thresholds, and/or when the foreshore levels drop below 2.3m amsl, and/or when all onshore gradients reverse is an important new component to the aquifer management framework.

Table 8.2: Saline intrusion risk management framework and risk categories for the Waiwhetu Aquifer, Lower Hutt. The underlined indicators are the default triggers for identifying saline intrusion risk. Additional indicators are also important alternative or additional risk category trigger.

SI Risk	Indicators	Response(s)
None	**STANDBY LEVEL: 2.5m** McEwan Park or Tamatoa <2.5m (24 hr) and: All offshore gradients positive Randwick-MP onshore gradient positive and: EC < 150 µS/cm Upper Waiwhetu EC < 250 µS/cm Lower Waiwhetu	Wellfield operators on standby to actively manage foreshore levels through abstraction rate adjustment; Employ yield prediction tool (HADC).
Low to Increasing	**ALERT LEVEL: 2.3m** McEwan Park or Tamatoa < 2.3m (24 hr) and/or: Both onshore gradients negative or positive All offshore gradients positive and: EC < 150 µS/cm Upper Waiwhetu EC < 250 µS/cm Lower Waiwhetu	Instigate Alert Level water quality monitoring and perform weekly (Tier 1 protocol). Wellfield operators required to actively manage foreshore levels through abstraction rate adjustment. Employ yield prediction tool (HADC).
Elevated	**MINIMUM LEVEL: 2.0m** McEwan Park or Tamatoa < 2.0m (24hr) and/or: One or more offshore gradients negative and/or: EC > 150 µS/cm Upper Waiwhetu EC > 250 µS/cm Lower Waiwhetu (or consistently rising EC trends)	Reduce pumping rate to maintain minimum foreshore level above 2.0m or until water quality improves. Instigate water quality investigation response (Tier 1 and, if necessary, Tier 2).

8.2.4.5 Implementation of the saline intrusion risk management framework

Physical works

The preceding sections have made several recommendations regarding the requirement to undertake works to establish the saline intrusion monitoring system. In summary, these are:

- Replacement/cleaning of the current McEwan Park monitoring well (shallow, R27/0122).
- Replacement of the Port Road monitoring wells (Upper Waiwhetu Aquifer) and installation of continuous water level and EC/temperature instrumentation.
- Flushing/development of remaining Tamatoa and McEwan Park EC monitoring sites.
- Inspection and calibration of EC probes at all EC monitoring sites on an annual basis, accompanied by thorough flushing of the bores.
- 5-yearly cleaning/development of all monitoring sites.

SI framework implementation

Since the revised framework retains the current three foreshore groundwater level triggers, it would be possible to implement the framework and incorporate the additional components prior to a revision of the consent conditions. The new framework essentially 'tightens up' the existing monitoring system which relies on a single foreshore level, and stages the monitoring response in a structured way.

Due to the more complex nature of the new framework, which incorporates a number of saline intrusion indicators, it will be necessary to develop a 'live' display screen which is linked to the GWRC telemetry (SCADA) systems. This screen should clearly display the current saline intrusion risk status and all three monitoring components – water levels, hydraulic gradients and EC levels – in addition to the Waterloo abstraction rates. Additional information such as the aquifer level in the unconfined aquifer at Taita Intermediate and the flow in the Hutt River should also be included to assist in active abstraction management (Section 8.3; a link to the 'HADC' spreadsheet should also be considered). Relevant personnel should automatically be informed via email of any changes in saline intrusion risk status and the triggering of threshold levels.

8.3 AQUIFER YIELD EVALUATION AND MANAGEMENT

Previous investigations have assessed the yield of the Waiwhetu Aquifer using a modelling approach to identify a maximum pumping rate that could be sustained whilst managing the risk of saline intrusion by means of a minimum foreshore groundwater level. This quantity has then been adopted in GWRC resource management policy and applied to resource consent conditions. Whilst this approach is valid, it is considered overly simplistic as it provides only a maximum aquifer yield under a 'worst-case' aquifer stress condition. Under normal climatic and aquifer state conditions, such an approach unnecessarily inhibits the use of the

resource as it may be possible to abstract significantly more from the aquifer under the same saline intrusion risk management constraints.

The maximum yield of the aquifer is highly dependent upon aquifer storage/head conditions – particularly in the unconfined part of the aquifer – and recharge potential from the Hutt River. A somewhat different approach to the yield management of the Waiwhetu Aquifer is therefore advocated, one which is based upon an dynamic evaluation of aquifer storage and recharge state using a simple calculation tool based upon the HAM3. This tool – the Hutt Aquifer Drawdown Calculator, or HADC – is described in detailed below.

To provide a grounding for the exploration of a new more dynamic approach to resource management, the HAM3 has first been used to verify the 'traditional' fixed maximum yield.

8.3.1 VERIFYING MAXIMUM FIXED SUSTAINABLE AQUIFER YIELD USING HAM3

A fixed maximum aquifer sustainable yield for the Waiwhetu Aquifer has been assessed using the verification version of the HAM3 model (see section 7.7). This simulation incorporates the 20-year period 1992-2012 during which a wide range of actual river and climatic conditions were experienced. Three synthetic Waterloo pumping rate scenarios have been examined:

- Abstraction scenario 1: constant pumping from the Waterloo Wellfield at 90 ML/day; and
- Abstraction scenario 2: constant pumping from the Waterloo Wellfield at 100 ML/day; and
- Abstraction Scenario 3: Seasonal pumping of 90 ML/day for five months between December and April (inclusive); for the remaining seven months of the year the abstraction rate was reduced to 60 ML/day.

Private abstraction wells were also operational during the scenario model runs pumping at a constant 5.5 ML/day (the estimated abstraction rate).

Figure 8.21 shows the model outputs in terms of groundwater level at McEwan Park on the foreshore for the three abstraction scenarios. It can be seen that all scenarios are 'sustainable' in that the conservative alert foreshore level of 2.3m is not breached by scenarios 1 and 3 which peak at 90 ML/day. Scenario 2, which examines a constant Waterloo pumping rate of 100 ML/day and total aquifer yield of 105.5 ML/day, also remains largely within the 2.0m minimum level threshold but that the foreshore level drops slightly below 2m amsl twice during the 20 year simulation.
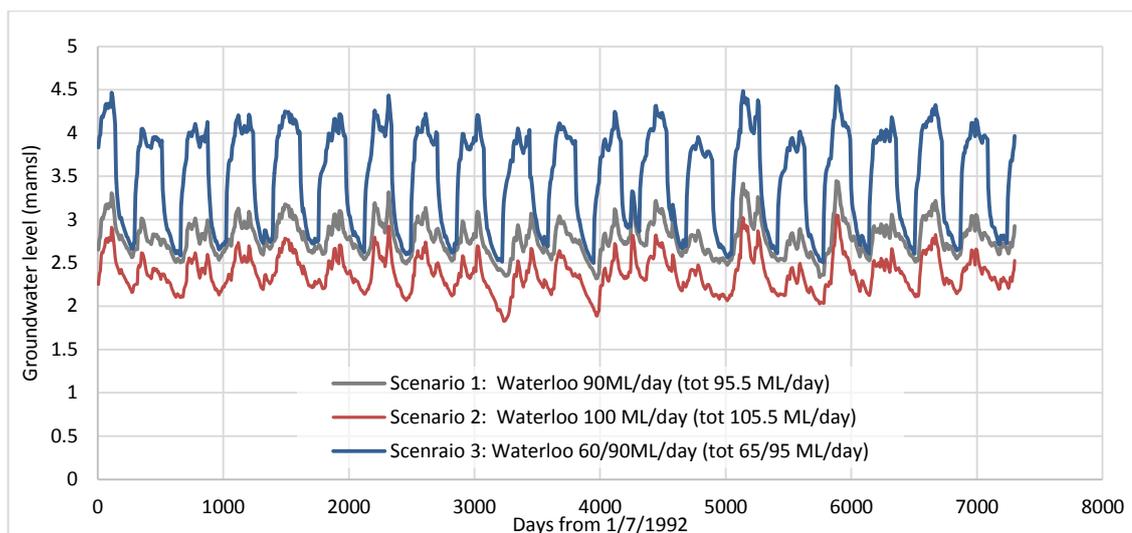
Figure 8.21: Modelled and observed McEwan Park (foreshore) groundwater levels under three abstraction scenarios from the Waterloo Wellfield: Scenario 1 – constant abstraction at 90 ML/day; Scenario 2 – constant abstraction at 100 ML/day Scenario 3 – abstraction at 90 ML/day between December and April (5 months), and 60MLD for the remainder of the year. This simulation runs from 1/7/1992 to 1/7/2012 and uses actual river and rainfall inputs for this period (7-day means). The pumping scenarios also incorporate an additional 5.5ML/day from other users of the resource.

The HAM3 sustainable yield verification run therefore confirms that if a minimum foreshore groundwater level of 2.0m is to be maintained, that a maximum yield from the Waiwhetu Aquifer should be slightly less than the Scenario 2 total rate (105.5 ML/day) at about 100ML/day to avoid triggering a minimum foreshore level of 2.0m. This would mean that the potential long- term (mean) abstraction from the Waterloo Wellfield would be about 95ML/day.

The HAM3 outputs also show that a short term maximum abstraction rate from the Waiwhetu Aquifer in excess of 100 ML/day is attainable when aquifer conditions permit. Although during stress periods, the maximum aquifer yield will drop to about 100 ML/day to maintain a minimum foreshore level of 2.0m (including other resource users). Further assessment of a variable maximum yield is provided in Section 8.3.5.

8.3.2 ACTIVE AQUIFER YIELD MANAGEMENT

The foreshore head in the Waiwhetu Aquifer is not only affected by the pumping rate at the Waterloo wellfield, but also by the state of the Hutt River (recharge potential) and the associated groundwater level in the unconfined aquifer (storage potential). The sustainable yield[2] is therefore not static and dependent upon the recharge and storage 'state' of the unconfined aquifer. This means that the imposition of a fixed abstraction limit on the aquifer will restrict use of the resource

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[2] 'sustainable yield' in terms of managing the risk of saline intrusion using a minimum level in the Waiwhetu Aquifer at the Petone foreshore

when recharge and storage conditions safely allow a greater quantity to be abstracted.

Because a number of factors need to be considered when assessing the maximum aquifer yield (restrained by a particular minimum foreshore level), tools such as the HAM3 are required so that a number of interacting influences on the groundwater system – such as storage and recharge states – can be accounted for. Assuming that the Waiwhetu Aquifer is to be managed 'actively' on a day to day basis, use of the HAM3 is impractical due to the highly specialised technical skills and time resources required to operate it. As a practical alternative, a simplified spreadsheet modelling tool (called the Hutt Aquifer Drawdown Calculator, or 'HADC') has been developed using critical relationships derived from the HAM3 to assist in the operational management of abstraction from the Waterloo wellfield with respect to saline intrusion minimum foreshore aquifer levels. It should be appreciated that the HADC tool is reliable only for the short-term prediction of yield from the Waterloo Wellfield (1-2 months) - the HAM3 should be relied upon for the assessment of longer term sustainability.

8.3.3   THE HUTT AQUIFER DRAWDOWN CALCULATOR (HADC)

The HADC (excel) spreadsheet tool estimates the maximum aquifer yield and predicts aquifer yield during forecast dry periods when the river and unconfined aquifer levels are in recession, or when a recession/stress period is anticipated. The spreadsheet calculations rely on a recharge and storage indicator (groundwater level) in the unconfined aquifer, and the anticipated behaviour of this indicator during prolonged dry periods. It also relies upon HAM3-derived abstraction-drawdown relationships between different points in the aquifer.

Abstraction from the Waiwhetu Aquifer is sustained by its connection to the Hutt River which provides both natural recharge and pumping-induced recharge via leakage through the river bed between Kennedy Good Bridge and Taita Gorge. The state of the Hutt River (stage) also controls the groundwater level in the unconfined aquifer as shown in Figure 4.3. The Taita Intermediate groundwater level monitoring site is located about 800m from the river and, although not subject to the same volatility as the river stage, responds to both short and long-term trends in river stage.

The groundwater level at Taita Intermediate is therefore an indicator of aquifer recharge and storage state and can be used to assess the yield potential of the Waiwhetu Aquifer.

If the Taita Intermediate level is to be used to assess the aquifer yield, and since the maximum yield is restrained by the foreshore groundwater levels, in the first instance the head relationship between Taita Intermediate and McEwan Park is needed. This relationship cannot be derived directly from the monitoring record for these two sites because both are strongly influenced by abstraction drawdowns. Therefore, the HAM3 has been used to 'normalise' the heads for abstraction. This has been done by running the HAM3 with all abstraction turned off in order to simulate natural head conditions. The resulting head relationship between McEwan

Park and Taita Intermediate can then be calculated as shown in Figure 8.22 from which the following linear correlation has been derived :

McEwan Pk normalised level = 0.669 * Taita Int normalised level – 0.366 (1)
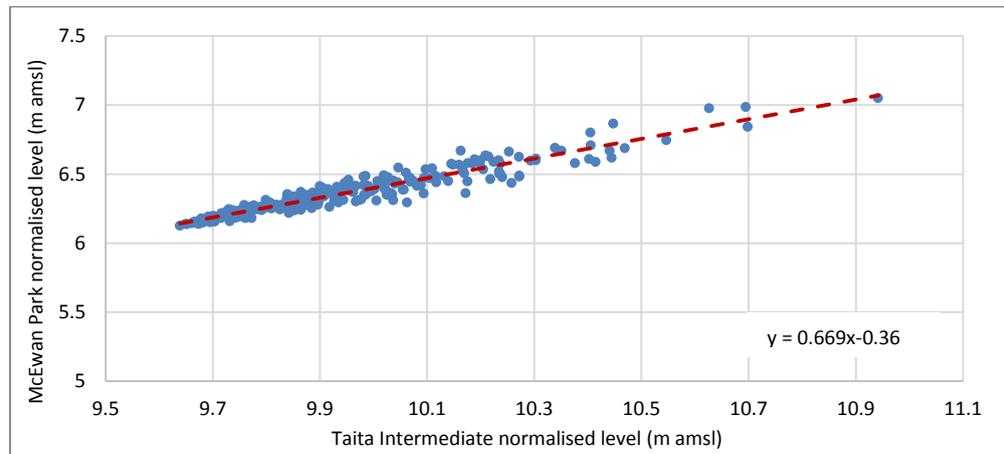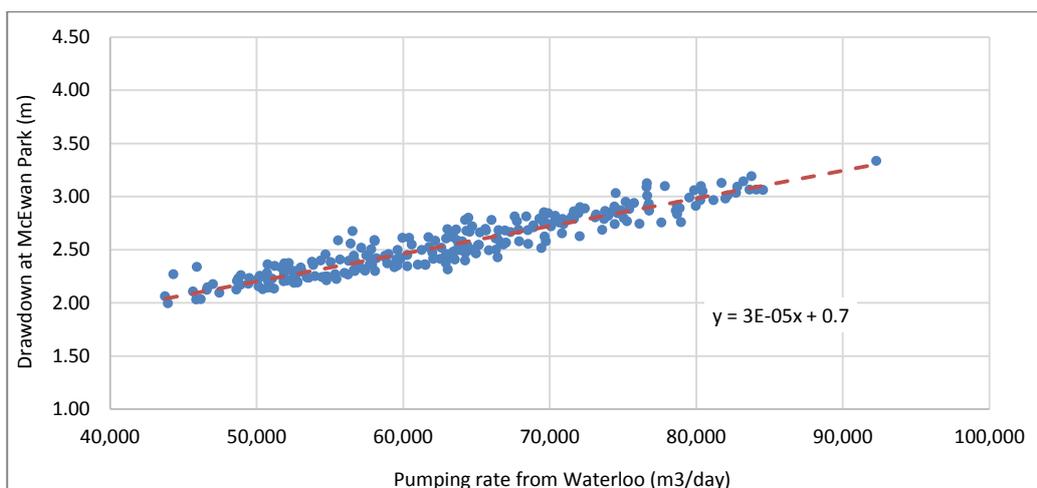

Figure 8.22: Simulated relationship between groundwater levels at Taita Intermediate and McEwan Park normalised for pumping. Outputs from HAM3 calibration run with GWRC abstraction turned off.

A second step is to characterise the drawdown response to abstraction from the Waterloo wellfield on groundwater heads at McEwan Park and at Taita Intermediate. This is done by comparing the HAM3 calibration head outputs from a no abstraction simulation to the abstraction simulation. The relationship between pumping rate and drawdown at the foreshore is shown in Figure 8.23 from which the follow correlation has been derived:

Drawdown at McEwan Park = 3 x10^{-5} * pumping rate + 0.7 (2)

The foreshore groundwater levels at McEwan Park (Figure 8.22) are highly responsive to changes in abstraction rate and the drawdown varies between about 2 and 3m.

Figure 8.23: Simulated relationship between abstraction at Waterloo and drawdown at McEwan Park.

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Figure 8.24 shows the relationship between drawdown at Taita Intermediate and the pumping rate. In contrast to the foreshore response, the drawdown at Taita Intermediate is relatively insensitive to variation in abstraction probably due to the higher storage coefficient in the unconfined aquifer and greater distance from the wellfield. Drawdown generally varies between 0.8 and 1.3m.

The figure shows a scatter plot with a red dashed trend line. The equation displayed is:

$$y = 1E\text{-}5x + 0.444$$

The y-axis is labeled "Drawdown at Taita Intermediate" ranging from 0.00 to 1.40. The x-axis is labeled "Pumping rate from Waterloo (m3/day)" ranging from 40,000 to 100,000.
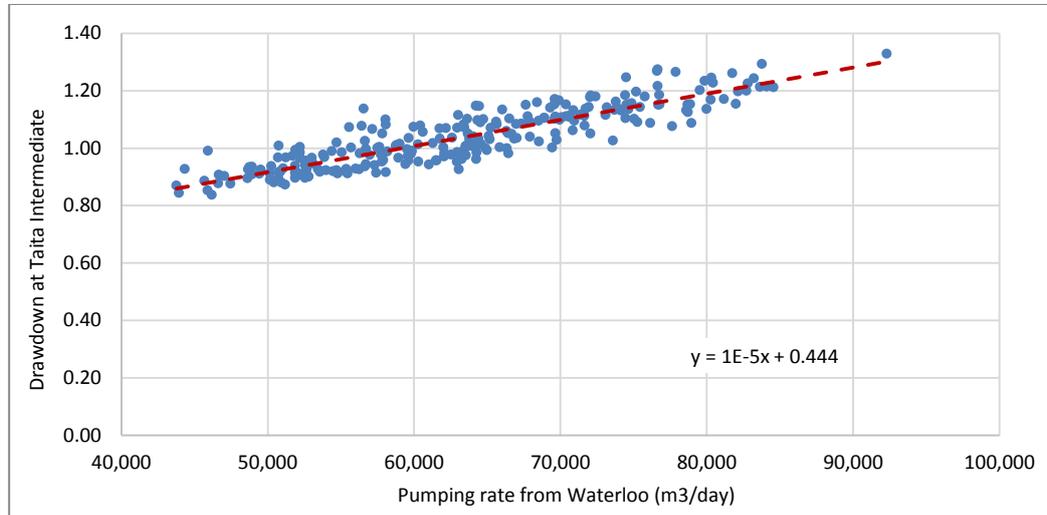
Figure 8.24: Simulated relationship between abstraction at Waterloo and drawdown at Taita Intermediate illustrating the relative insensitivity of the unconfined aquifer level to abstraction rate due to the strong buffering by the Hutt River.

The drawdown at Taita Intermediate can be calculated using Figure 8.24 which provides the following linear correlation has been derived:

Drawdown at Taita Intermediate = 1 x10^{-5} * pumping rate + 0.444 (3)

The three correlations represented by Equations 1-3 can be used to calculate the drawdown at McEwan Park under any specified pumping rate and groundwater level at Taita Intermediate. To do this, the effects of pumping are first removed from the Taita Intermediate level using Equation 3. The non-pumping head at McEwan Park can then be calculated using Equation 1, which then allows Equation 2 to be used to calculate the pumped drawdown at McEwan Park.

The HADC excel spreadsheet performs the following sequence of operations for each time step:

step 1: Input 1 – Taita Intermediate groundwater level – this can be an historical monitoring record, or a calculated exponential recession of the aquifer level during a dry period from a specified starting head (see discussion below on recession calculation).

step 2: Input 2 – the daily abstraction rate for the Waterloo Wellfield (this is averaged over the preceding 4 days in the spreadsheet to account for system time lags between pumping and the response at Taita Intermediate).

step 3: Calculate the drawdown at Taita Intermediate using equation 3.

step 4: Calculate the pumping-normalised level at Taita Intermediate (step 1 + step 3).

step 5: Calculate the pumping-normalised level at McEwan Park using equation 1.

step 6: Calculate the drawdown at McEwan Park using equation 2.

step 7: Calculate the pumping-influenced level at McEwan Park (step 5 – step 6).

Figure 8.25 shows the output from the spread sheet calculation for the 5-year HAM3 model calibration run period (July 2007 to July 2012). The inputs to the spread sheet are the observed Taita Intermediate groundwater level and pumping rate at the Waterloo Wellfield. Figure 8.25 also displays the calculated head from the HAM3 and the observed levels from monitoring data showing that the HADC spread sheet model is capable of accurately predicting the groundwater level in the Waiwhetu Aquifer at the foreshore.
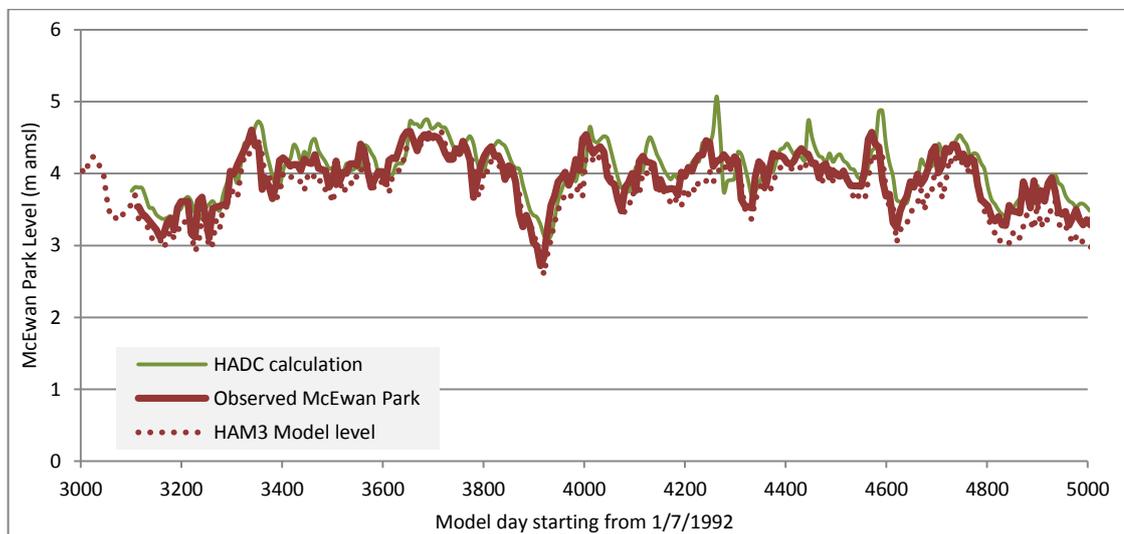
Figure 8.25: Comparison of head outputs for McEwan Park from the Hutt Aquifer Drawdown Calculator (HADC) spread sheet with HAM3 predictions and observed data.

8.3.4 Optimising and forecasting aquifer yield using the HADC

The Hutt Aquifer drawdown calculator (HADC) provides a useful and adaptable tool for forecasting and optimising the yield of the aquifer based upon the state of the unconfined aquifer (and implicitly, the Hutt River) and using a specified foreshore minimum groundwater level.

The HADC model has the following modes:

- Forecast, or prediction, mode
- Yield optimisation mode

Forecast mode calculates the daily mean foreshore groundwater level when a constant or variable pumping schedule for the Waterloo wellfield is input. The yield

optimisation mode calculates the maximum sustainable yield from the Waterloo wellfield based upon an available drawdown at the coast by specifying a minimum foreshore groundwater level.

Both modes rely on an estimation of the groundwater level recession rate at Taita Intermediate from a specified starting level. Alternatively, a known or assumed groundwater level record for Taita Intermediate can be input. However, the principal benefit of the HADC lies in its ability to forecast the sustainable wellfield yield when the aquifer system becomes stressed and is in recession – i.e. during an anticipated dry period when the river remains at low flow and the unconfined aquifer storage slowly drains.

The HADC calculates the recession of the unconfined aquifer which is based upon the examination of groundwater level monitoring data at Taita Intermediate (TI). Representative aquifer recession level data at Taita Intermediate associated with summer dry periods are shown in Figure 8.26. An exponential decay equation has been fitted to the observed recessions (shown by the black solid lines in Figure 8.26) – the equation takes the form:

TI level (t) = C - A * (1-exp^{-kt})

where: A = amplitude or range of the recession, which is variable depending on the starting TI head (C). The linear equation for calculating A (derived from examining a number of curves with different starting heads) is 0.87*C-7.

C = offset from zero, or initial TI head

k = a constant representing the half-life of the curve, derived by trial and error during curve fitting = 0.025

The recession analyses has been undertaken using TI monitoring data which is influenced by pumping – there being no opportunity to undertake a recession analysis in the absence of abstraction effects. The modelled recessions therefore represent a pumping-influenced drainage of the unconfined aquifer. The exponential decay equation therefore implicitly assumes that the pumping effects are more or less consistent for each recession curve. Since all of the observed recession curves relate to the past 6-7 years, the summer pumping rates are comparable and Figure 8.26 shows that the modelled recessions approximate the observed data relatively well over a range of TI starting conditions. After the HADC has calculated the TI level recession using the above equation, it will normalise it for pumping drawdown as part of its calculation procedure.
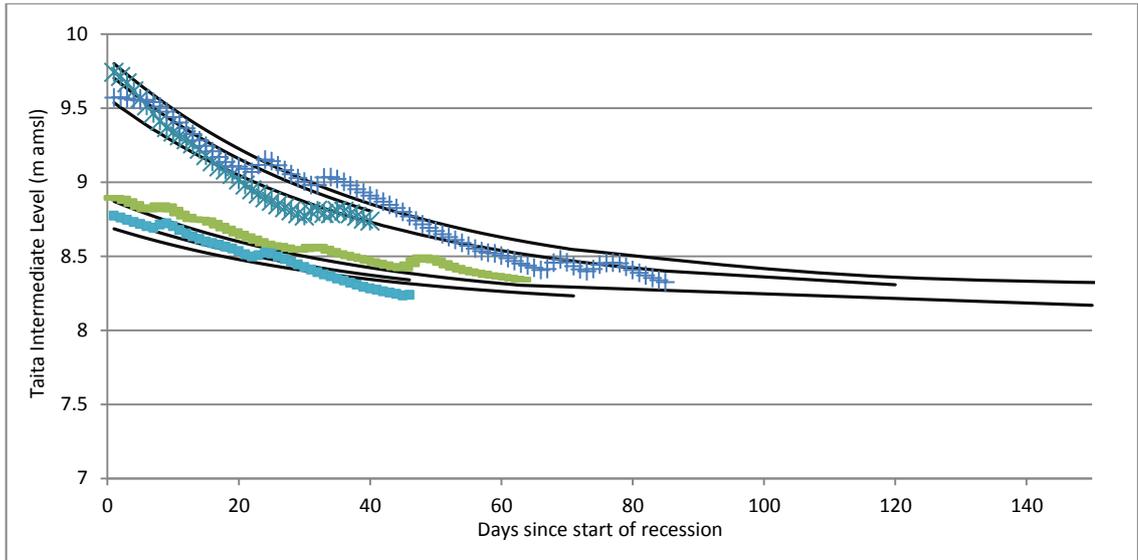
Figure 8.26: Measured summer groundwater level recession rates in the Taita Intermediate monitoring well for the past 6 years (symbols), and modelled exponential decay curves (black solid lines). Notes the monitored levels are affected by small variations in pumping rate.

Figures 8.27 and 8.28 show the HADC input screen and output plots respectively. Input requirements are the starting head at Taita Intermediate (Box A), initial pumping rate associated with the starting head (Box B), and an option in Box C to specify either a constant pumping rate, a specific pumping schedule (pasted into column O), or a flag to calculate the maximum pumping rate required to maintain a specified foreshore level (Box D).

	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1		HADC		Version 4 23/01/2014													
4	Box A	Taita Intermediate starting level:		8.80	m (amsl)	note the calculation is sensitive to the starting level and starting pumping rate (Box B)							Box D	Minimm level McEwan Park			
5	Box B	Pumping rate at starting TI level:		85,000	m3/day	nominally 60-70MLD, preferably use average pumping rate over preceeding 24 hours								2.50	m (amsl)		
7	Box C	Constant Waterloo pumping rate		-	m3/day	enter either a constant pumping rate, or '0' for max calculated rate, or '1' for the variable daily pumping schedule specified in Col Q											

Time (days)	Pumping (Waterloo)	4 d Av pumping rate	Taita Int recessed (pumping) level	drop in TI level	Change in pumping effect on TI level	TI level adjusted to aq recession and pumping rate	calc Taita Int drawdown	normalised aquifer level at TI (no abstraction)	normalised aquifer level at McEwan Park (no abstraction)	Calculated drawdown at McEwan Park	calc level at McEwan Park	Available aquifer drawdown at McEwan Park	Calculated max pumping rate at Waterloo		Optional pumping schedule m3/d Enter '1' in Box C to activate
	m3/day				m	m amsl	m	m amsl		m	m		m3/day		
1	85000	85000	8.800	0.00	0.000000	8.8000	1.29	10.09	6.59	3.25	3.34	4.09	113082		
2	113082	99041	8.768	0.032	-0.140412	8.6276	1.43	10.06	6.57	3.67	2.90	4.07	112368		0
3	112368	103484	8.753	0.015	-0.044424	8.5678	1.48	10.05	6.56	3.80	2.76	4.06	112025		0
4	112025	105619	8.738	0.015	-0.021352	8.5314	1.50	10.03	6.55	3.87	2.68	4.05	111689		0
5	111689	112291	8.723	0.015	-0.066723	8.4500	1.57	10.02	6.54	4.07	2.47	4.04	111362		0
6	111362	111861	8.709	0.014	0.004300	8.4400	1.56	10.00	6.53	4.06	2.48	4.03	111043		0
7	111043	111530	8.695	0.014	0.003313	8.4294	1.56	9.99	6.52	4.05	2.48	4.02	110732		0
8	110732	111207	8.681	0.014	0.003231	8.4190	1.56	9.98	6.51	4.04	2.48	4.01	110429		0
9	110429	110891	8.668	0.013	0.003151	8.4089	1.55	9.96	6.50	4.03	2.48	4.00	110133		0
10	110133	110584	8.655	0.013	0.003074	8.3991	1.55	9.95	6.50	4.02	2.48	4.00	109844		0
11	109844	110284	8.642	0.013	0.002998	8.3894	1.55	9.94	6.49	4.01	2.48	3.99	109563		0
12	109563	109992	8.630	0.012	0.002924	8.3801	1.54	9.92	6.48	4.00	2.48	3.98	109288		0
13	109288	109707	8.618	0.012	0.002852	8.3709	1.54	9.91	6.47	3.99	2.48	3.97	109020		0
14	109020	109429	8.606	0.012	0.002781	8.3620	1.54	9.90	6.46	3.98	2.48	3.96	108759		0
15	108759	109157	8.595	0.011	0.002712	8.3533	1.54	9.89	6.46	3.97	2.48	3.96	108504		0
16	108504	108893	8.584	0.011	0.002645	8.3448	1.53	9.88	6.45	3.97	2.48	3.95	108256		0
17	108256	108635	8.573	0.011	0.002580	8.3365	1.53	9.87	6.44	3.96	2.48	3.94	108014		0
18	108014	108383	8.562	0.011	0.002516	8.3285	1.53	9.86	6.43	3.95	2.48	3.93	107777		0

Figure 8.27: Screen shot of the predictive version of HADC (Hutt Aquifer Drawdown Calculator) spreadsheet model to forecast foreshore levels in the Waiwhetu Aquifer under a specified pumping regime (col O or Box C) and starting head in the unconfined aquifer at Taita Intermediate (Box A). Col E calculates the TI recessed level using an exponential decay equation. The calculated maximum pumping rate (col O) uses the specified minimum foreshore level to calculate the pumping rate which will maintain that level (Box D).
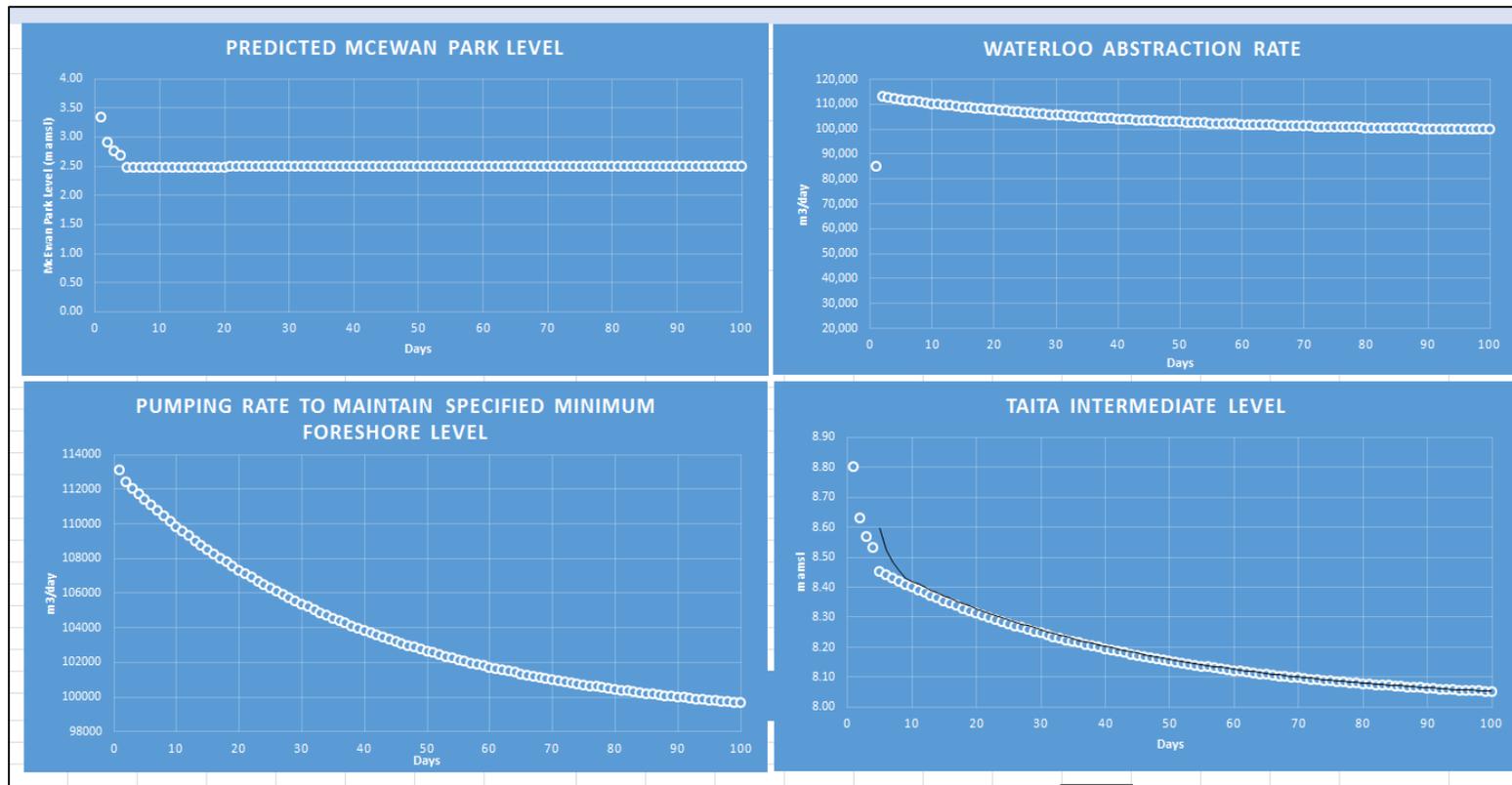
Figure 8.28: Screen shot of HADC plots showing predicted foreshore groundwater level (McEwan Park), wellfield abstraction rates (optimised), and calculated Taita Intermediate groundwater level.

The HADC prediction calculations have been verified by comparing them to groundwater observation data obtained during a prolonged 33 day dry period between 11/2/13 and 15/3/13. The Hutt River remained very low over this time, and the unconfined aquifer level receded to 8.15m at Taita Intermediate – the historic minimum level (1968-2013) being 8.13m. During this period, the Waterloo Wellfield was being pumped at a variable rate, but generally increasing from about 60 ML/day to 80-90 ML/day. The observed starting head of 8.67m at Taita Intermediate was input to the HADC spreadsheet together with the recorded daily pumping rate from the Waterloo Wellfield. Since the actual levels at McEwan Park and Taita Intermediate were measured it is possible to verify the HADC-calculated values. Figures 8.29 and 8.30 show the results which indicate that the McEwan Park and Taita Intermediate level calculated by the HADC closely match the observation data.
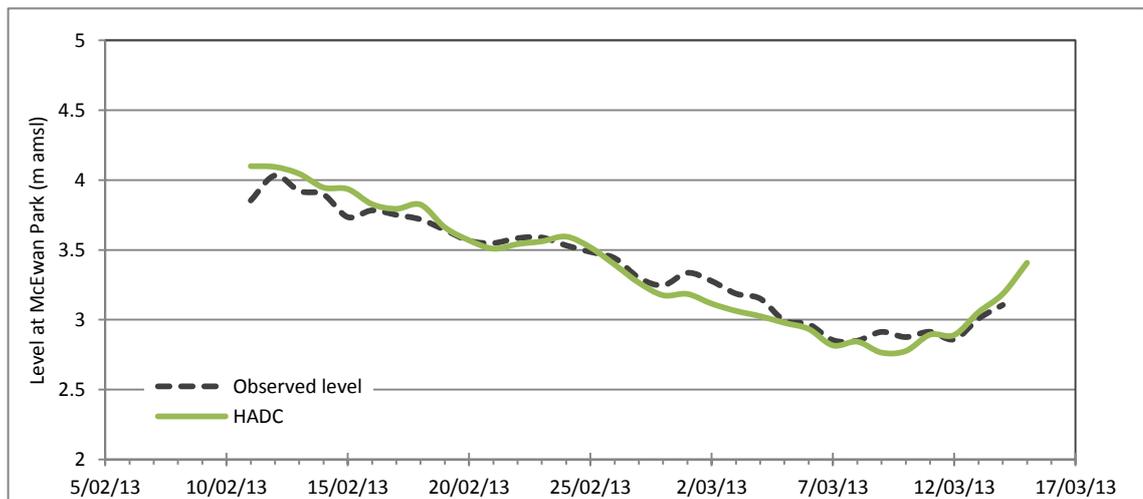
Figure 8.29: Comparison of observed head at McEwan Park and calculated head using the HADC spreadsheet for the 2013 drought period.
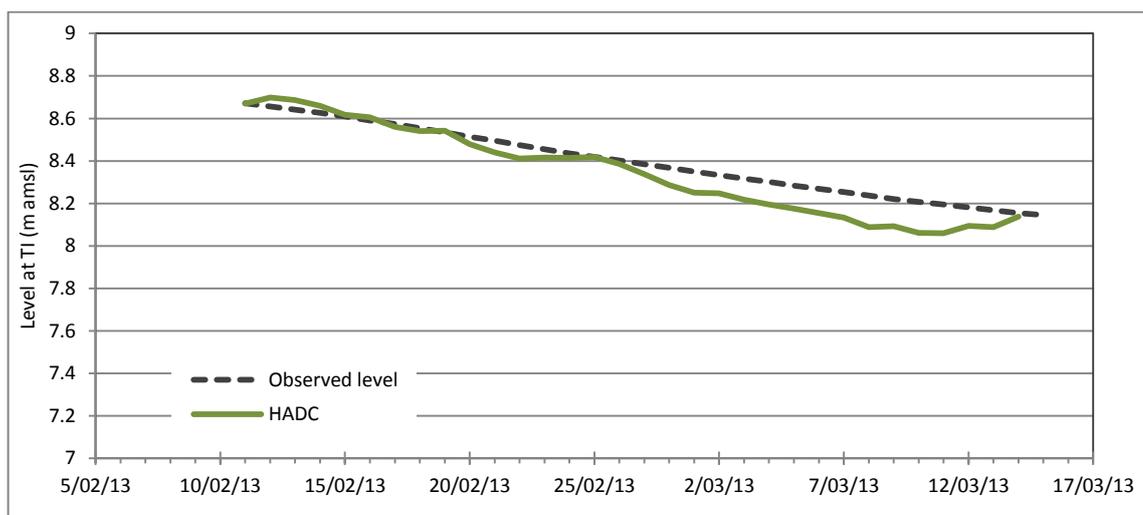
Figure 8.30: Comparison of observed head at Taita Intermediate and calculated head using the HADC spreadsheet for the 2013 drought period.

The yield optimisation mode of the HADC spread sheet calculates the sustainable pumping rate from the Waiwhetu Aquifer whilst maintaining a specified saline intrusion risk management groundwater level at the foreshore. To do this the HADC calculates the available drawdown at the foreshore using the pumping-normalised head at McEwan Park and a specified minimum foreshore level. The pumping rate can then be calculated using the inverse of Equation 2 to provide the pumping rate for a specified available drawdown. This relationship is:

$$max\ pumping\ rate = 33,333*available\ drawdown - 23,333 \qquad (4)$$

8.3.5   WAIWHETU AQUIFER SUSTAINABLE YIELD ASSESSMENT

8.3.5.1   **Long-term mean aquifer yield**

Section 8.3.1 showed that, though running HAM3 abstraction scenarios, the long-term mean yield for the Waiwhetu Aquifer is about 100 ML/day, or 36,500 ML/year. However, this is not the maximum aquifer yield at any point in time, but the maximum rate that would prevent the foreshore level dropping below the 2.0m saline intrusion level during an extreme drought period. During all other times, when the aquifer storage and recharge conditions are not stressed, significantly higher yields can be maintained within the same foreshore level constraints. The HAM3-derived mean daily yield of 100ML can be used for allocation policy and expressed as a 12-month moving mean and also expressed as an annual volume (36,500 ML). However, greater volumes can be safely taken from the aquifer contingent upon aquifer storage and recharge conditions. The HADC tool has been used to help assess the short-term maximum aquifer yield under a range of aquifer conditions as described below.

8.3.5.2   **Maximum short-term aquifer yields**

The HADC tool has been used to assist with assessing the maximum sustainable yield a for the Waiwhetu Aquifer based upon the storage and recharge state of the resource. The groundwater level in the unconfined aquifer at the Taita Intermediate monitoring site is used an indicator of the transient storage and recharge condition. It should be emphasised that the HADC tool is suitable only for the calculation of short-term sustainable aquifer yield, whilst the HAM3 is more reliable for the prediction aquifer sustainability over longer time periods.

Figure 8.31 shows HADC output curves expressing the relationship between pumping rate at the Waterloo wellfield and the Taita Intermediate groundwater level when a minimum foreshore levels of 2.3m (Alert Level) and 2.0m (Minimum Level) are specified. In other words, the pumping rates necessary to hold the foreshore groundwater level at 2.3m and 2.0m amsl are shown by the curves. A 'background' resource use of 5.5ML/day is also built into this analysis. The plot has been produced using actual Taita Intermediate level and Waterloo Wellfield pumping rate data for the period 2007-2012, from which the maximum wellfield yield has been calculated using the HADC spreadsheet.
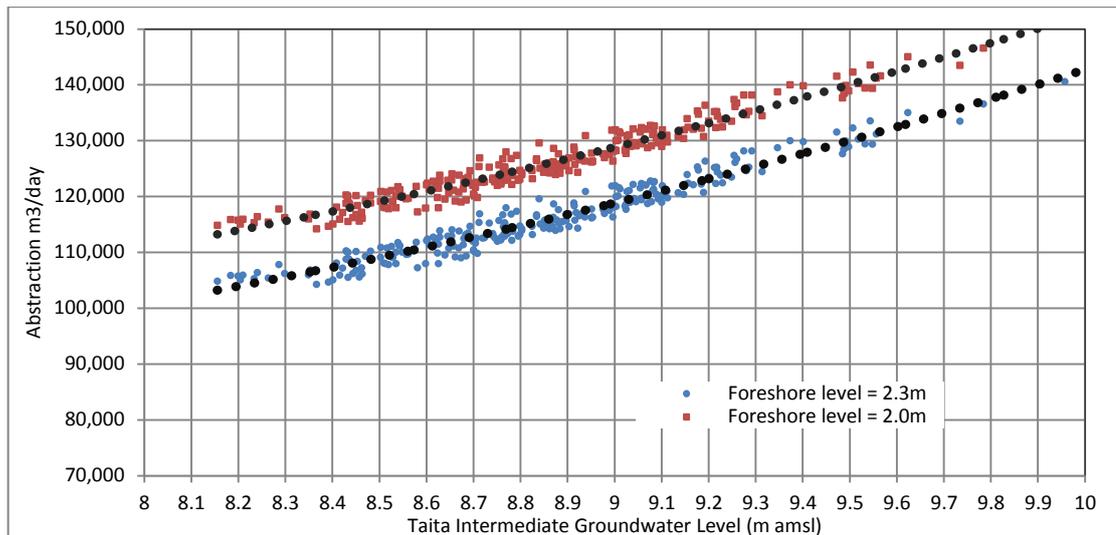
Figure 8.31: HADC-simulated relationship between aquifer level at Taita Intermediate and the pumping rate at the Waterloo wellfield required to maintain a foreshore aquifer levels at McEwan Park of 2.0m and 2.3m amsl. The maximum yield when Taita Intermediate reaches just below its historic minimum of 8.0m is about 110 ML/day when the foreshore level is 2.0m. At higher TI levels the yield can be significantly more. The curves incorporate a 'background' resource use of about 5.5 ML/day.

Figure 8.31 demonstrates the use of the Taita Intermediate groundwater level to estimate the short-term maximum sustainable wellfield yield for a specific minimum foreshore groundwater level. The yield decreases as the unconfined aquifer level recedes. It should be noted that the Taita Intermediate level has not historically dropped below 8.1m (monitoring at this site commended in 1969). Therefore, the maximum sustainable yield under a prolonged dry period should relate to a conservative Taita Intermediate level of about 8m.

The maximum yield for the Waterloo wellfield is about 110 ML/day for a foreshore minimum level of 2.0m and a Taita Intermediate level of 8.0m. This is higher than the maximum wellfield yield derived from the HAM3 (Section 8.3.1 and Figure 8.21) of about 95ML/day (total aquifer yield of a100 ML/day including other users) because the HAM3 scenarios assume a constant abstraction rate over a long period of time and take into account extreme dry (stress) periods, whilst the HADC is a short-term aquifer yield prediction tool.

The HADC curves (Figure 8.31) show that as the unconfined aquifer level rises in response to recharge, the transient sustainable yield can rise substantially above the long term mean aquifer yield to over 140 ML/day. The potential short-term maximum aquifer yields relating to a 2.0m minimum foreshore level and the unconfined aquifer levels at Taita Intermediate are shown the Table 8.3 based on Figure 8.31. Four Taita Intermediate groundwater level bands have been used: 8-8.4m, 8.4-9m, 9-9.5m and >9.5m. A maximum yield has then been assigned to each band based upon the minimum Taita Intermediate level within each. To add a degree of conservatism, the background resource use (5.5 ML/day) has not been added to these figures.

The associated Hutt River depletion (induced recharge) quantity is also as shown for reference purposes. This was calculated using the following equation based on the HAM3 (see discussion in Section 8.1):

Induced river loss = 0.2498 * pumping rate (Waterloo) + 15,978 (m^3/day)

Table 8.3: Guidelines for potential sustainable yield from the Waiwhetu Aquifer based upon groundwater level in the unconfined aquifer at Taita Intermediate and a minimum foreshore level of 2.0m amsl (saline intrusion 'Minimum Level'). The calculated induced recharge from the Hutt River for the maximum aquifer yield is also shown.

Taita Intermediate level (24 hour mean level a msl)	Waiwhetu Aquifer Maximum yield ML/day	Induced recharge from the Hutt River (L/sec)
8-8.4m	110	500
<9m >8.4m	120	530
<9.5m >9m	130	560
>9.5m	140	590

Table 8.3 and Figure 8.31 show the potential maximum yield from the aquifer based on the HADC tool, and show that a maximum yield of more than 140ML/day can be sustained when aquifer conditions permit. In practice, however, the yield from the aquifer will be governed by saline intrusion constraints which will over-ride the rates shown in Table 8.3.

The long-term mean annual allocation from the Waiwhetu Aquifer for resource management policy should however be based on the HAM3 simulations (Section 8.3.5.1). This is because the HAM3 can more reliably predict the sustainable aquifer yield over longer durations and under a range of climatic stresses, unlike the HADC tool which is suited to shorter duration yield assessment.

8.3.5.3   **GWRC consented abstraction and river depletion effects**

The current GWRC Regional Freshwater Plan limits the annual abstraction from the Waiwhetu Aquifer and shallow unconfined Taita Alluvium at 33,000 ML/year. GWRC public water supply abstraction is consented to take 30,254 ML/year. The Regional Freshwater Plan does not specify daily maximum abstraction rates, although the resource consent conditions for the Waterloo wellfield (WGN970036) stipulate a maximum daily abstraction rate of 115 ML/day, and a moving daily mean rate of 83.115 ML/day calculated over a 12 month period. Based on the HAM3 and HADC re-assessment of aquifer yields presented above, there is clearly scope to increase both the mean and maximum abstraction rates if required by GWRC.

The predicted induced loss from the Hutt River (Table 8.3) caused by pumping at Waterloo should be taken into consideration, or 'reserved', by GWRC when assessing the available core allocation from the river. A recent core river allocation assessment of 1,925 L/sec has been made by GWRC for the 'Lower Reach' of the Hutt River (Birchville to the Hutt mouth), 50% of which has been allocated. Therefore, the additional 'take' of 500-600 L/sec between Taita Gorge and Boulcott to sustain pumping from the Waiwhetu Aquifer can be accommodated.

8.4 ASSESSMENT OF AQUIFER STORAGE 'BANKING' TO MEET DEMAND DURING STRESS PERIODS

A management option which GWRC has considered is the preservation, or 'banking', of aquifer storage during spring or early summer in order to allow the wellfield yield to be sustained or increased through high demand periods later in the summer. The HAM3 model has been used to evaluate the feasibility and benefits of storage banking by running four 100-day pumping scenarios (from the Waterloo wellfield):

- Scenario 1: no abstraction for days 0 – 30, then days 30-100 at 80 MLD
- Scenario 2: pumping 40 MLD for days 0-30, then days 30 – 100 at 80 MLD
- Scenario 3: constant abstraction at 80 MLD for 100 days
- Scenario 4: as Scenario 2, but the aquifer has only 30 days to recover prior to stepping to 80MLD at 30 days.

The model was run for 100 days at 1-day stress periods with starting heads for each scenario being derived from the output of the first stress period (which was run to steady state). The abstraction starting condition for Scenario 4 was 80MLD and the aquifer was allowed to recover for 30 days when the pumping rate was reduced to 40 MLD. The Hutt River was held at a constant stage equivalent to the mean annual low flow (at 3.5 cumecs) for the full duration of all scenarios.

Since the Waiwhetu Aquifer is managed to saline intrusion triggers at the foreshore, the scenarios have been assessed using the simulated heads at the foreshore as shown in Figure 8.32. There is clearly a lag in the aquifer drawdown when abstraction at Waterloo is increased at 30 days to 80 MLD (for scenarios 1 and 2). The higher heads prior to the increased demand represent the 'banked' storage which, when abstraction is increased to 80 MLD, is depleted over a period of 20-30 days for scenarios 1 and 2. However, these scenarios assume a fully-recovered aquifer prior to increasing abstraction at 30 days. Scenario 4 may be a more realistic assessment whereby the aquifer has only 30 days to recover prior to the step up in abstraction at 30 days. In this instance the banked storage benefit lasts only about 10-15 days.

Figure 8.32 therefore suggests that, if a prolonged dry period is anticipated, reducing pumping in the preceding weeks to bank aquifer storage has only a limited benefit in helping to sustain a higher future abstraction rate. Figure 8.33 shows the aquifer recovery curve at the foreshore (simulated using the HAM3) indicating that the aquifer will recover by about 80% within 30 days, and by about 65% over two weeks in response to a reduction in pumping rate.
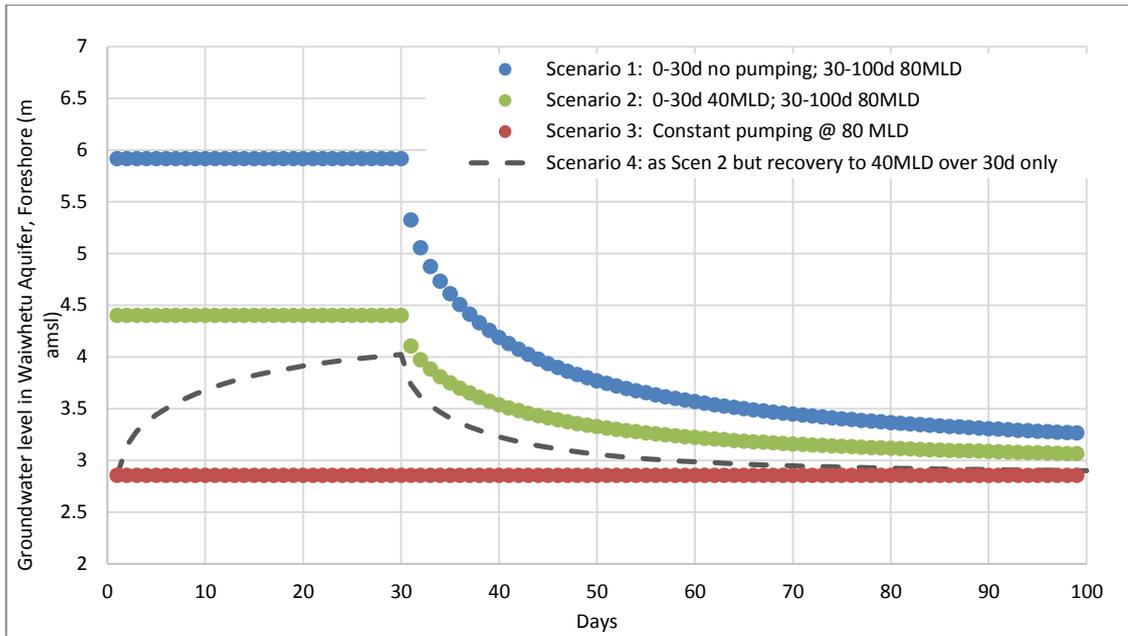
Figure 8.32: Modelled aquifer drawdown in the Upper Waiwhetu aquifer at the Petone foreshore for different pumping regimes. There is a 20-30 day lag before maximum foreshore drawdowns are approached when pumping at the waterloo wellfield is increased to 80 ML/day at day 30. However, scenario 4 probably represents a more realistic assessment showing there is only about 10 days' benefit to storage banking.
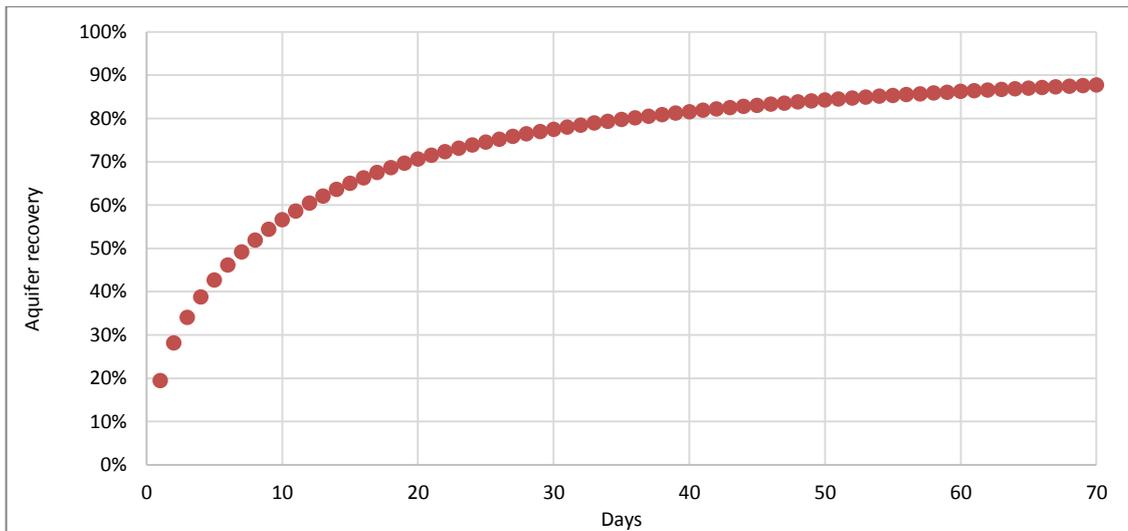
Figure 8.33: Modelled aquifer recovery curve – the Petone foreshore (McEwan Park) in the Upper Waiwhetu Aquifer following a reduction in pumping at the Waterloo Wellfield. Based on steady state pumping prior to recovery.

9 SEA LEVEL RISE/LAND SUBSIDENCE IMPACT ASSESSMENT

A synthesis of sea level variability and trends in Wellington Harbour has been produced by NIWA (2012). This study shows that current mean sea level in the harbour is 0.2m above Wellington Vertical Datum (WVD-53), which represents the average sea level rise over the past 100 years (approximately 2mm per year). Tectonic subsidence is also a feature of the Wellington area which effectively compounds the effect of sea level rise. Relative sea level is currently tracking towards a 0.8m rise by the 2090's, or 1m by 2115. Taking into account both sea level rise and current land subsidence rates, the NIWA report recommends that vulnerability studies that underpin strategic adaptation planning processes should adopt a sea level rise estimate of between 0.5m (low scenario) and 2m (high++ scenario). The 'high scenario' of 1.5m is adopted here as a basis for assessing the vulnerability of the Waiwhetu Aquifer to sea level rise/land subsidence using the HAM3 model.

It should be noted that the extension of the Waiwhetu Aquifer beneath the harbour does not have a direct connection with the ocean and is regarded to be 'blind' – discharge occurs through widespread leakage across the overlying Petone Marine Bed aquiclude, and via very localised spring vents where the high aquifer pressures have periodically burst through the aquitard. The rationale and evidence behind this conceptualisation is detailed in earlier sections of this report. Various offshore aquifer configurations have been tested using the HAM3 model, including scenarios whereby the aquifer has a direct ocean connection. These show that it is not possible to calibrate the model and simulate foreshore and offshore heads in the Waiwhetu Aquifer if it has an open connection to the sea at any distance offshore. The sub-harbour pressure head in the aquifer measured at Somes Island is between 3 and 4m above mean sea level under pumping conditions, and is estimated to have been about 2m higher prior to abstraction (section 8.1). This shows that the Waiwhetu Aquifer beneath the harbour does not equilibrate to sea level.

Conceptually, therefore, the Lower Hutt groundwater system is somewhat different to many coastal aquifers which have a direct connection to the ocean at some distance offshore. As a consequence, the investigation of sea water intrusion and the effects of sea level rise on the groundwater resources in the Lower Hutt valley requires careful consideration of the hydrogeological context and a more complex relationship between the harbour levels and an underlying pressurised aquifer. The sub-harbour Petone Marine Bed aquitard separates the aquifer from the ocean (it allows leakage outflow and limited outflow at discreet spring sites), and represents a key boundary condition in the model. Since aquifers are not rigid bodies, but are elastically compressible, the total stress loading on the aquifer in response to a sea level rise then becomes an important consideration. Within this context, a sea level rise would not simply be expected to result in a rise of equal magnitude in the underlying (leaky) confined aquifer.

9.1 COMPARISON OF AQUIFER HEAD CHANGES DUE TO SEA
LEVEL AND TIDAL LOADING EFFECTS – THEORETICAL DISCUSSION

The head pressures in the offshore and near-shore confined Waiwhetu Aquifer respond according to the temporality of loading stresses imposed by sea level fluctuations. This has important implications when attempting to understand the behaviour of the submarine confined Waiwhetu aquifer subjected to a sea level rise scenario. A discussion on the conceptual and theoretical behaviour of the aquifer, under both transient and 'steady state' loading stresses, is provided in this section.

The total stress (σ_T) acting downward on the offshore Waiwhetu Aquifer is imposed by the weight of the overlying seawater column and by the aquitard materials (and also by atmospheric pressure). The stress is borne in part by the matrix of the aquifer and in part by the pressure (p) of water in the aquifer pores. The portion of the total stress not borne by the fluid is called the effective stress (σ_e) and the two are related by the following equation (Freeze and Cherry, 1979):

$$\sigma_T = \sigma_e + p$$

Most transient groundwater flow problems assume that the weight of the rock and water overlying a confined aquifer remains constant through time. As such (in terms of changes), $\delta\sigma_T = 0$ and

$$\delta\sigma_e = -\delta p$$

However, under daily tidal fluctuations, the total stress will change as the weight of water on top of the aquitard increases and decreases. Under a sea level rise scenario the total stress will also increase gradually over a long period of time.

During the tidal cycle, the total stress applied to the top of the aquitard on the harbour floor is constantly changing, rising and falling with the tide. The piezometric level in the underlying confined Waiwhetu gravels responds immediately to changes in sea level in the order of 80-90% of the tidal range (see section 4.1.2.1) due to changes in the total stress on the aquifer. The load is largely borne by the pore water and is realised as a change in pressure (δp).

A simple analogy for the tidal loading process on the submarine confined Waiwhetu Aquifer is described by Domenico and Schwartz (1990) and involves a spring, a watertight piston, and a cylinder. Figure 9.1a shows a spring under load (σ_T) with a characteristic length (z). If the spring and piston are placed in a watertight cylinder, the spring supports the load σ_T and the water is under the pressure of its own weight as shown by the manometer tube in Figure 9.1b. If an additional load ($\Delta\sigma_T$) is placed on the system as shown in Figure 9.1c (analogous to a tidal rise), because water cannot escape from the cylinder (or only a very restricted amount can escape through a very small opening, i.e. submarine spring vents), the spring cannot compress and the additional load must be borne by the water. This is shown by the manometer tube showing the fluid pressure in excess of the hydrostatic pressure. In the context of the submarine confined Waiwhetu Aquifer, Figure 9.1c conceptually explains what happens to the aquifer fluid pressure when the tidal loading increases

(even though fluid can in reality escape laterally inland or through springs, the effects of the rapidly changing load will dominate; vertical leakage being minimal over such a short duration). This model really only holds validity for transient, short-duration stress fluctuations.
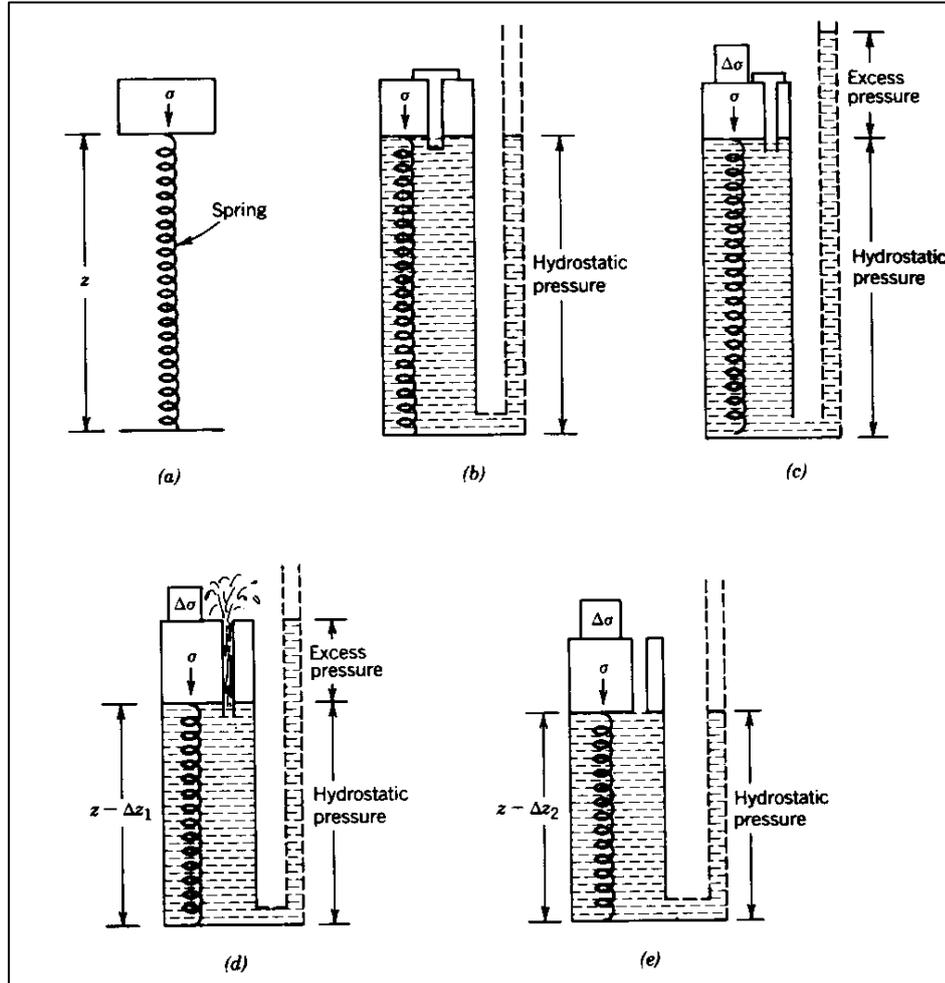
Figure 9.1: Piston and spring analogy showing the transfer of support for the added load from water pressure to the spring (or from water pressure to the aquifer matrix). From Domenico and Schwartz (1990).

In contrast to the diurnal effects on total stress associated with the tidal cycle, under a sea level rise scenario, the change in total stress will increase gradually over a long period of time and be maintained. It is assumed that as the sea level rises, the effects of the increased loading caused by the weight of the sea water column would have time to dissipate by diffusion of the pore fluids (for example via leakage through the aquitard and through localised submarine spring discharge). The pore water pressure is then transmitted to the aquifer skeleton resulting in an increase in the effective stress ($\delta\sigma_e$) and compression of the aquifer. In other words, loading that was originally supported by the water (such as during a tidal rise) is transmitted to the aquifer granular skeleton and the effect on the pore water pressure dissipates. A new head equilibrium would be established in the aquifer, controlled by changes in the aquifer flow and recharge-discharge dynamics in response to the change in sea level.

This process is also conceptually illustrated by the piston and cylinder analogy in Figure 9.1d. Conservation laws of fluid mass state that no change in fluid pressure can occur except by loss (or gain) of water; the sealed cylinder will maintain its pressure indefinitely (Domenico and Schwartz, op cit). If some water is allowed to escape (i.e., through aquifer leakage across the aquitard or through submarine springs) the pressure of water is lowered and the spring compresses in response to the additional load it must support. Hence there is a transfer of stress from the fluid to the spring (c.f. to the aquifer matrix). When the excess pressure is completely dissipated, hydrostatic conditions prevail again and the stress transfer is complete (Figure 9.1e). The difference between Figures 9.1c and 9.1e is essentially the difference between the piezometric head rise due to a transient high tidal loading and a 'steady state' sea level rise, which allows a drained condition to develop.

In summary, a sea level rise scenario would not be expected to result in the same magnitude of change in piezometric head in the Waiwhetu Aquifer as the tidal rise does. The fluid pressure effects of increased in total stress associated with sea level rise dissipates over time and is known as a 'drained' boundary condition (Domenico and Schwartz, 1990).

9.2 Limitations and suitability of HAM3 in assessing sea LEVEL RISE IMPACTS

Groundwater flow models assume that total stress imposed on aquifers remains constant with time and are unable to account for transient changes in pore pressure due to changes in total stress imposed by the tide or other influences (Reeves et al., 2000; CSIRO, 2011; Wang et al., 2011). Hence, the HAM3 could not be expected to simulate the effects of the 'undrained' transient loading stresses associated with the tidal cycle on groundwater heads in the offshore confined Waiwhetu Aquifer.

However, the model can simulate the effects of a 'drained' boundary condition, whereby excess loading stresses (caused by sea level rise) have equilibrated in the confined aquifer system and where hydrostatic conditions in relation to the increased loading prevail. This is because of the long timeframe and assumed 'steady state' loading associated with a sea level rise scenario. Therefore, the HAM3 model is considered an appropriate tool to investigate long-term changes in sea level.

9.3 SIMULATION OF SEA LEVEL RISE WITH HAM3

Having established that the HAM3 can provide valid predictions regarding the potential effects of sea level rise (or land subsidence) on the Lower Hutt groundwater system, a set of scenarios have been simulated to evaluate the impact of sea level rise on resource availability.

Sea level is represented in the HAM3 by a constant head condition assigned to the offshore part of Layer 1. The constant head is also adjusted by a factor of 1.025 to compensate for the density of sea water to provide an equivalent freshwater head.

Three scenarios have been run:

1) baseline current sea level of 0.2m;

2) sea level of 0.97m (rise of 0.75m) ;

3) sea level of 1.74m (rise of 1.5m).

The two sea level rise scenarios of 0.75 and 1.5m are aligned with the projected levels discussed in Section 8.3.5 and would progressively develop over a period of time. The scenarios assume equilibrated constant levels and therefore represent two snapshots in time.

The models are based on the 5-year calibration run with the same set up and abstraction rates (1997-2012) as documented in Section 7. This is the 'baseline run' which incorporates the current sea level of 0.2m, against which the two sea level rise scenarios are compared.

Since the model uses a 7-day stress period, the sea level heads are held constant throughout the simulations. The initial stress period was run to a steady state condition to provide stable starting heads. This also means that the aquifer system has effectively attained 'equilibrium' with the raised sea levels.

Scenario outputs are provided in the form of heads in the Upper Waiwhetu Aquifer (confined area) and Taita Alluvium (unconfined area) for a line of monitoring sites starting at Somes Island then moving onshore to McEwan Park and Randwick Reserve, and ending at Taita Intermediate in the unconfined aquifer zone. Figures 9.2 and 9.3 show the head outputs for the three scenarios for McEwan Park and Taita Intermediate, respectively. Figure 9.4 shows the head profile up the valley from Somes Island to Taita Gorge.
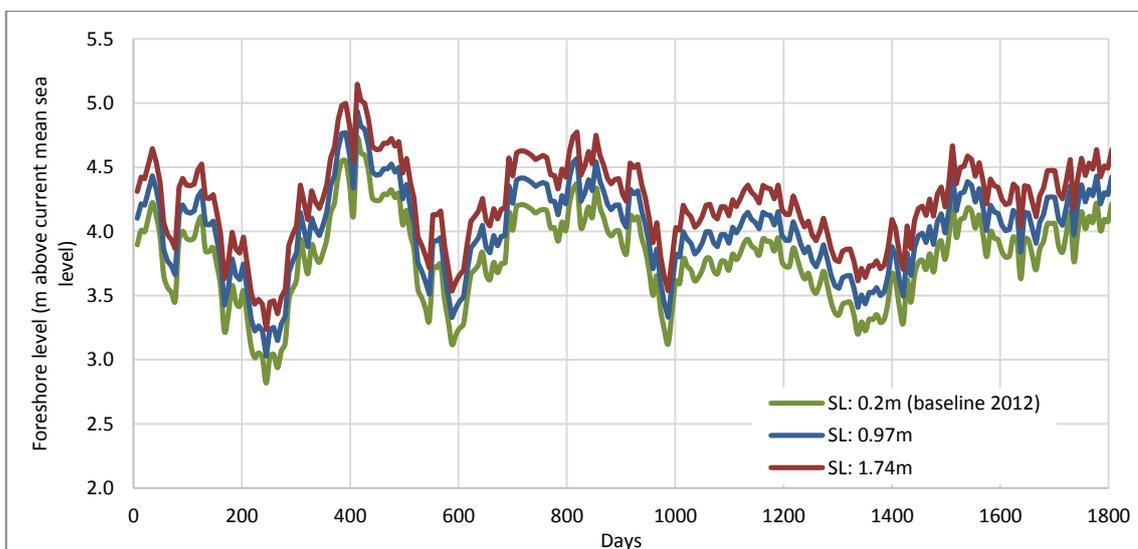
Figure 9.2: Modelled foreshore water levels in the Upper Waiwhetu Aquifer at McEwan Park for different fixed sea levels using the 5-year calibration model (1997-2012).
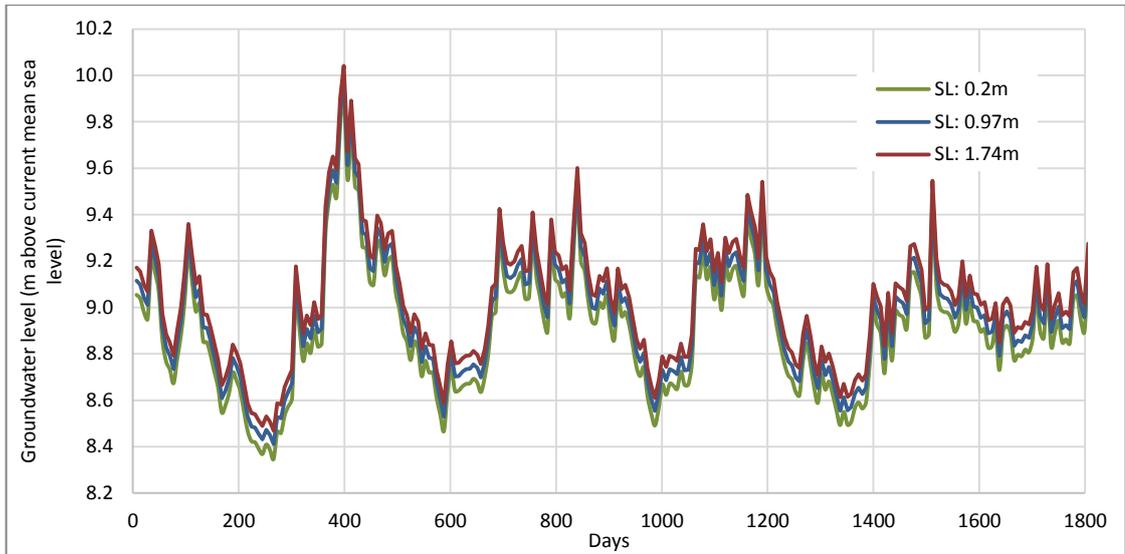
Figure 9.3: Modelled foreshore water levels in the Taita Alluvium at Taita Intermediate for different fixed sea levels using the 5-year calibration model (1997-2012).
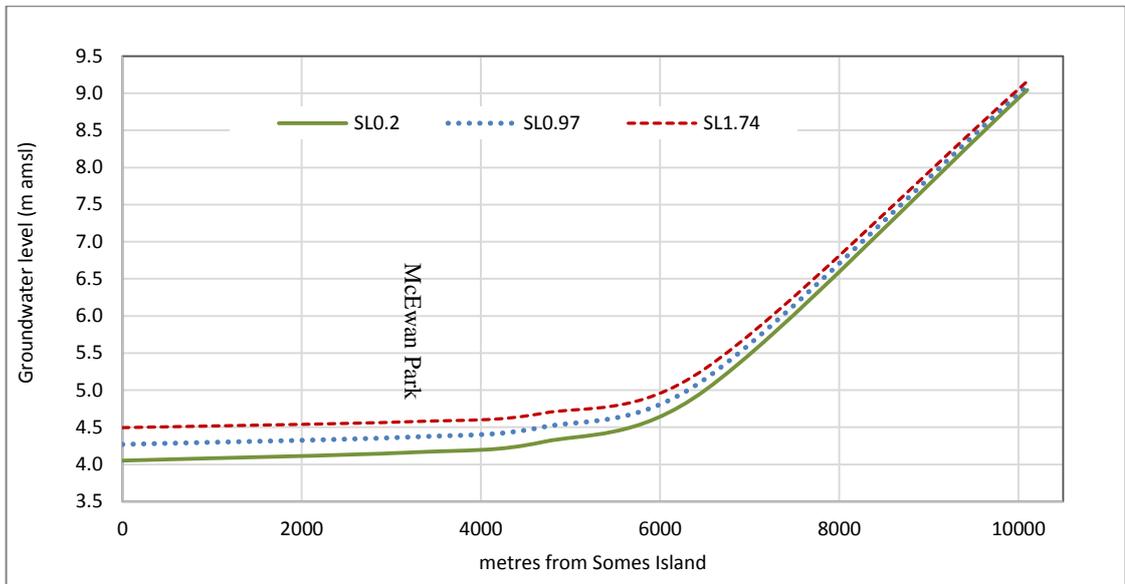
Figure 9.4: Modelled groundwater levels in the confined Upper Waiwhetu Aquifer along the axis of the Lower Hutt valley from Somes Island to Taita Intermediate for different sea level scenarios. Groundwater levels are affected by pumping at Waterloo (at approximately 6000m)

Figure 9.5 shows the simulated change in the heads in the unconfined Taita Alluvium at Gear Island close to the foreshore. Because this aquifer is in direct connection with the ocean, the levels closely reflect the raised sea levels.
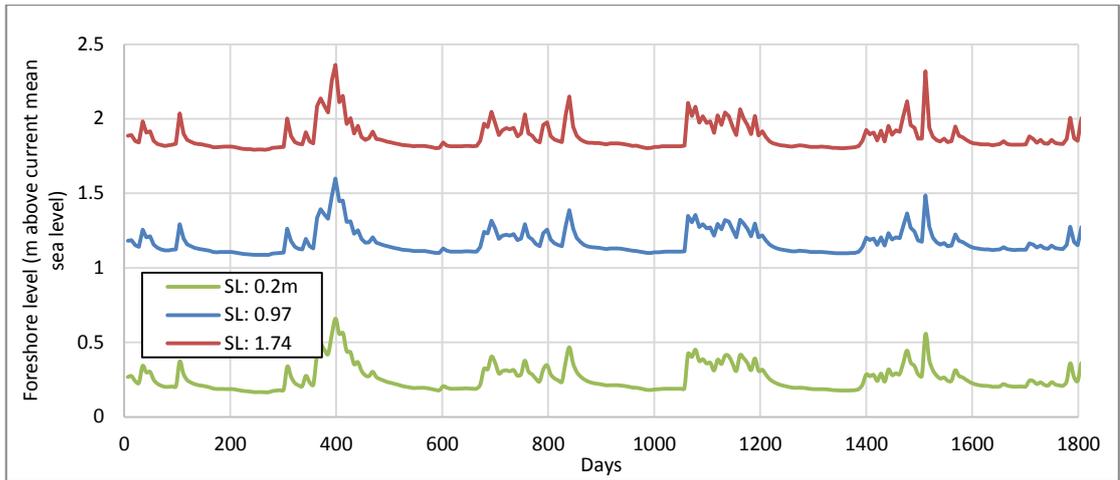
Figure 9.5: Modelled foreshore water levels in the Taita Alluvium at Gear Island near the foreshore for different fixed sea levels using the 5-year calibration model (1997-2012).

It is evident from the scenario outputs that the simulated rise in head in the confined Waiwhetu Aquifer is not equivalent in magnitude to the sea level rise – this would be expected only if the aquifer had a direct open connection to the ocean. The reason for this is discussed in Section 9.2. Table 9.1 shows the magnitude of the coastal 'lifting' of the heads in the Waiwhetu Aquifer under the two sea level rise scenarios, both of which show a rise of just under one third (27%) of the sea level rise magnitude.

The simulated rise in sub-harbour and coastal aquifer heads caused by a change in ocean level can be explained by changes in the aquifer water balance. When sea level is raised, the vertical head gradient between the Waiwhetu Aquifer and the sea reduces (because the aquifer head is higher than sea level). This results in a reduction in offshore discharge from the Waiwhetu Aquifer across the Petone Marine Beds aquitard and from submarine springs as shown in Figure 9.6. Under a 1.5m sea level rise scenario (adjusted sea level of 1.74m) the reduction in discharge is about 5,000m^3/day, which results in an increased head in the aquifer.
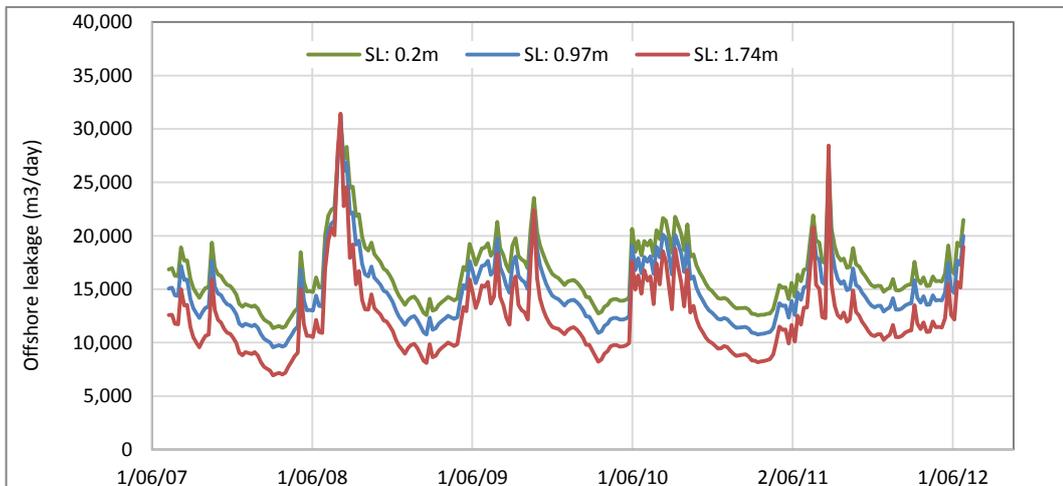
Figure 9.6: Reduction in offshore leakage from the Waiwhetu Aquifer resulting from sea level rise.

The reduction in aquifer discharge is accompanied by a reduction in aquifer recharge through the bed of the Hutt River in the unconfined aquifer zone. This is because the unconfined aquifer level experiences a small increase as a result of sea level rise and therefore the vertical head gradient beneath the river is also reduced. Figure 9.7 shows that the HAM3-predicted reduction in recharge from the Hutt River under a 1.5m sea level rise scenario ranges from about 1,500 to 3,000m³/day – or about 2% of the total recharge amount.
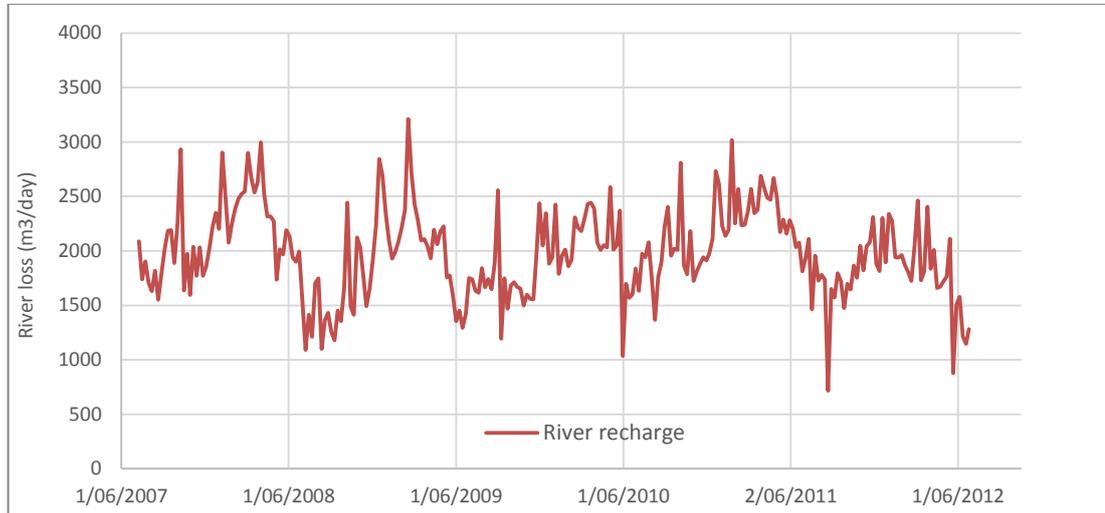
Figure 9.7: Reduction in recharge from the Hutt River as a result of a sea level rise of 1.5m. The simulated quantities equate to about a 2% reduction in total recharge.

Table 9.1: Adjusted sea levels used for HAM3 scenarios, modelled aquifer level lift at foreshore (Waiwhetu gravels), and unconfined aquifer at Taita Intermediate at a seasonal minimum of 8m amsl. Adjusted foreshore minimum saline intrusion levels taking into account sea level rise and aquifer lift. Sustainable aquifer yields are calculated using the HADC spreadsheet. *Datum is mean current sea level (msl) – WVD-53+0.2m.

Sea level rise (m) above datum*	Adjusted sea level (m)	Coastal aquifer level lift (m)	Taita Int aquifer level lift (m)	Equivalent 2.3m foreshore Alert level m amsl	Equivalent 2.0m foreshore Min level m amsl	Sustainable aquifer yield 2.3/2.0 min levels ML/day
0	0.0	0	0	2.3	2.0	100/110
0.75	0.77	0.2	0.05	2.87	2.57	83/93
1.5	1.54	0.4	0.1	3.44	3.14	66/76

Sustainable yields for different equivalent foreshore levels have been calculated using the HADC spreadsheet described in Section 8.3.5, which relates the Taita Intermediate groundwater level to drawdown at the foreshore at different abstraction rates from the Waterloo Wellfield. The sustainable yield is referenced to the saline intrusion foreshore threshold levels of 2.0m and 2.3m. To maintain consistency with the criteria used to set these levels (Section 8.2.3.5), they have been adjusted to the new raised 'mean sea level' and for the 'lifting' of the levels in the Waiwhetu Aquifer at the coast as follows:

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- For a sea level rise of 1.5m for example, the adjusted sea level is 1.54m: current base level of 1.5m * 1.025 (adjustment for the density of saltwater)

- If the minimum foreshore level is 2.3m above the *new* sea level, then the adjusted level is 2.3m + 1.54m – 0.4m (the coastal aquifer lift) = 3.44m.

The derived minimum level (i.e., 3.44m for a 1.5m rise and 2.3m foreshore level) is then used to calculate the maximum pumping rate needed to maintain 3.44m at the foreshore, using the calculation methodology and plots described in Section 8.3.5 (which relate unconfined aquifer levels to coastal drawdown under different pumping rates).

The calculations shown in Table 9.1 are graphically presented in Figure 9.9 which illustrates the predicted decline in yield from the Waiwhetu Aquifer resulting from sea level rise. If the minimum foreshore level of 2.0m is used, the yield from the Waiwhetu Aquifer is predicted to drop from 110 to 93 ML/day for a 0.75m sea level rise, and down to 76ML/day for a 1.5m rise. This equates to a 15% reduction in yield availability for a 0.75m sea level rise, and a 31% reduction for a 1.5m sea level rise. It should also be noted that the HADC tool will over-predict the long-term sustainable aquifer yield when compared to the HAM3(see discussion in Section 8.3.5), so under a minimum foreshore groundwater level of 2.0m, the current sustainable yield is predicted to be 100 ML/day (as opposed the to the HADC-predicted 110 ML/day as shown in Table 9.1 and Figure 9.9). However, the predicted rate of yield decline due to sea level rise would not change from that showing the Figure 9.9..

It should also be borne in mind that other factors associated with sea level rise and climate change, such as a modified hydrological regime in the Hutt River and changes in rainfall recharge, are not considered in this evaluation.
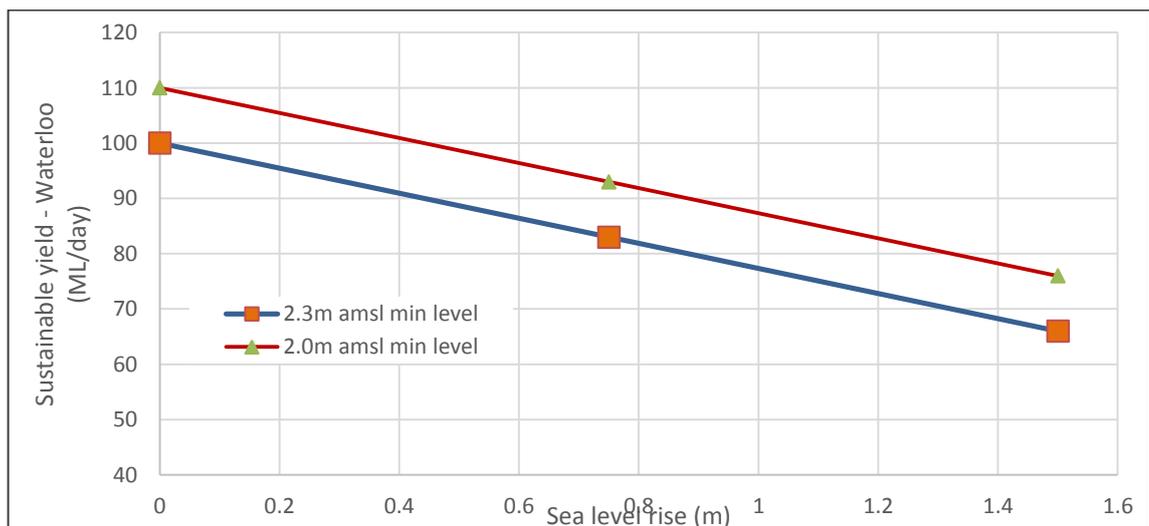
Figure 9.9: Calculated relationship between the yield of the Waiwhetu Aquifer (abstraction from the Waterloo Wellfield) and sea level rise based on saline intrusion minimum levels at the Petone foreshore of 2.0m and 2.53 – adjusted to sea level rise and normalised to coastal 'lifting' of aquifer levels. The plot is based on yield calculations using the HADC spreadsheet.

10 STATE OF AQUIFER MONITORING AND REPORTING

GWRC require a means of assessing and reporting the 'state of the aquifer' in simplistic terms both for operational management of the water supply and for communicating with the wider community.

Two 'indicators' are recommended which provide information on the resource stress state and yield availability:

- Groundwater level in the Upper Waiwhetu Aquifer at Petone foreshore (McEwan Park): saline intrusion minimum level triggers indicate when the resource is becoming stressed and when pumping rates need to be regulated to maintain minimum levels (see Table 8.2).

- The unconfined aquifer levels provide information on both the storage state of the aquifer and river recharge conditions, which in turn influence foreshore levels and the sustainable aquifer yield.

10.1 WAIWHETU AQUIFER GROUNDWATER LEVEL (MCEWAN PARK)

The means by which the foreshore aquifer level at McEwan Park data could be portrayed to show the current state of aquifer in the context of historical data is by an envelope plot.

An envelope plot shows monthly maxima, minima, and lines indicating one standard deviation from the mean, derived from the historical monitoring record. This has been carried out using the McEwan Park monitoring data for the period 1/1/1999 to 20/5/2013. Earlier monitoring data was omitted from the analysis since they are strongly influenced by pumping near the foreshore, particularly from Gear Island (see Figure 4.5).

By plotting smoothed 24-hour mean monitoring data it is very easy to see where the foreshore level is sitting in relation to the historical record. Smoothing can use a 24-hour moving average.

Figure 10.1 shows an example envelope plot for McEwan Park using monitoring data for 2012 and 2013 which is plotted as a 24-hour mean smoothed mean. For the first half of the 2012 year the aquifer levels were well above mean and the sharp drop commencing in early August relates to an increase in pumping rate from Waterloo. Similarly, the dip in level in the 2013 data relate to an increase in abstraction rate during a drought period.
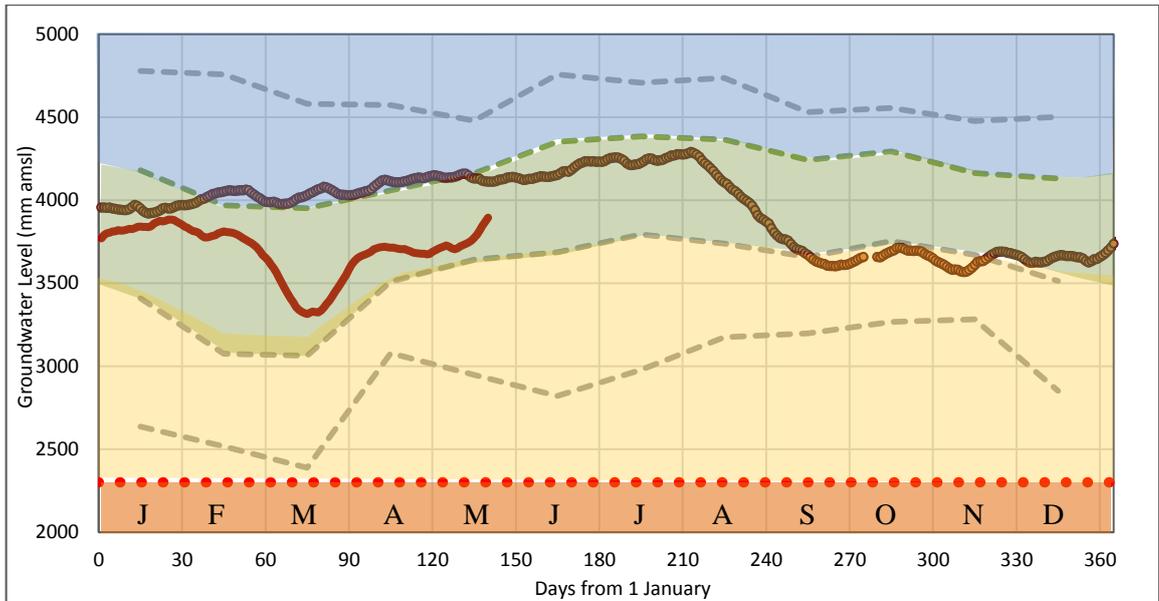
Figure 10.1: Example envelope plot for McEwan Park showing smoothed 24-hour mean groundwater level monitoring data for 2012 (thick orange line) and for the first half of 2013 (thick red line). The plot shows monthly maxima (top dashed line) and minima (bottom dashed line) as well as one standard deviation either side of the monthly mean (dashed grey lines). The saline intrusion alert level of 2.3m is shown by the red dotted line. The colour shadings refer to aquifer status levels (blue = high; green = normal; yellow = low; orange = very low).

Figure 10.1 demonstrates that although the envelope plot is useful in terms of graphically depicting the state of the aquifer, the methodology has limitations because levels at the foreshore are highly sensitive to the pumping regime at the Waterloo Wellfield. The historic pumping style, and hence the maxima, minima and mean levels shown in the envelope plot, may be very different to current or future operational needs. Hence the statistical bounds shown on the plot need to be updated regularly.

Since the Waiwhetu Aquifer is managed to saline intrusion triggers (Section 00), these are the critical control levels for the operation of the Waterloo abstraction, regardless of the historical level envelopes. It is therefore necessary to incorporate the 'Alert' sea water intrusion level in the envelope plot, below which abstractions need to be regulated and monitoring intensified (see Table 8.2). Therefore, as the level starts to approach 2.3m there is an anticipated need to regulate abstraction. It should be noted that the foreshore levels are highly sensitive to abstraction and respond almost immediately to changes in pumping rate so that it becomes relatively 'easy' to fine-tune the foreshore level.

It also follows that because the foreshore levels are highly sensitive to the pumping rate at Waterloo, the use of smoothed 24-hour means rather than a longer-term mean is recommended.

Terminology for reporting on the state of the aquifer using foreshore levels should be framed in terms of the aquifer level but also be referenced to saline intrusion risk

since the aquifer is managed according to this risk. Five aquifer status categories for the Waiwhetu Aquifer at the Petone foreshore are shown in Table 10.1.

Table 10.1: Recommended aquifer status categories relating to Waiwhetu Aquifer groundwater level at the Petone Foreshore (McEwan Park monitoring well). Monitoring levels are assumed to represent smoothed 24-hour means.

Aquifer level status	Saline Intrusion Risk	Definition	Actions
High	Zero	Level falls above one standard deviation above the long-term mean	None
Normal	Zero	Level falls one standard deviation either side of the long-term mean	None
Low	Low	Level falls below one standard deviation below the long-term mean but is great than 2.3m	None -
Very Low	Low to increasing	Level drops below 2.3m (Alert Level)	Increased monitoring, pumping regulation (see Table 8.2)
Critical	Elevated	Level drops below 2.0m (Minimum Level)	Pumping restrictions necessary

10.2 Unconfined aquifer level (Taita Intermediate)

The level of the unconfined aquifer provides information on the status of aquifer storage and indicates the recharge/stage condition of the Hutt River and dictates the sustainable aquifer yield. Section 8.3.3 discusses the merit of using the Taita Intermediate groundwater level as a critical recharge and storage indicator for the groundwater system and as a measure of the yield potential of the Waiwhetu Aquifer.

It therefore makes sense to use the state of the unconfined aquifer as a 'state of the aquifer' indicator, in addition to the foreshore water level (which is controlled by the unconfined aquifer condition).

An envelope plot similar to that produced for the McEwan Park groundwater level is shown for the Taita Intermediate monitoring site in Figure 10.2. The plot has been produced using the full monitoring dataset (1968 to present) and therefore incorporates the effects of changes in river bed level (refer to Figure 4.2 and Section 4.1.2.1). Since levels at Taita Intermediate have not historically dropped below 8.1m, a level of 8m has been selected to signify unusually low level which would potentially impact on the sustainable yield of the resource (see Section 8.3.1).
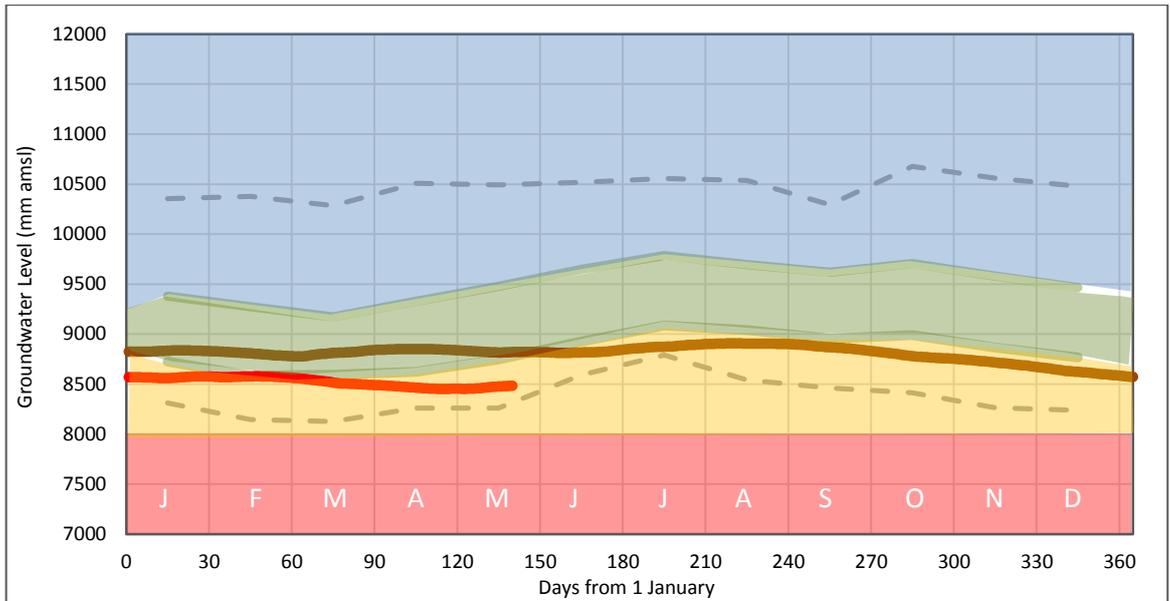
Figure 10.2: Example envelope plot for Taita Intermediate showing smoothed groundwater level monitoring data for 2012 (thick brown line) and for the first half of 2013 (thick red line). The plot shows monthly maxima (top dashed line) and minima (bottom dashed line) as well as one standard deviation either side of the monthly mean (green lines and shading).

Figure 4.2 shows that the groundwater level is currently in the 'low' phase, possibly due to shifts in the bed elevation of the Hutt River. This is reflected in Figure 10.2, which shows that the 2012 and 2013 levels are relatively low when compared to the historic behaviour of aquifer levels.

Four reporting levels could be used to describe the Taita Intermediate level as shown in Table 10.2.

Table 10.2: Recommended aquifer recharge status categories relating to unconfined aquifer level at the Taita Intermediate monitoring well.

Aquifer recharge status	Definition
High	Level is one standard deviation above the long-term mean
Normal	Level falls one standard deviation either side of the long-term mean
Low	Level drops below one standard deviation from the mean and is above 8m
Very low	24 hour mean level drops below 8m

11 Summary and Recommendations

HAM3 summary

The purpose of developing the Hutt Aquifer Model 3 (HAM3) has been to facilitate the sustainable management of the Lower Hutt groundwater system. In particular, the model is required to evaluate risks associated with saline intrusion, evaluate the sustainable yield from the principal Waiwhetu Aquifer and assess the potential impacts of sea level rise. For these purposes a 'high confidence level' aquifer simulator is required.

HAM3 has been calibrated to groundwater level and mass balance observations for the period 1997 – 2012, and verified for the preceding 15-year period 1992-2007. The calibration has been evaluated in both qualitative and quantitative terms by comparing the simulation results with field measurements. Simulated mass balances and groundwater heads exhibit a good visual and statistical fit to observed data.

Model non-uniqueness has been minimised by using ranges for hydraulic conductivity (and other parameters) which are consistent with measured data, calibrating the model to a wide range of climatic and abstraction stresses, and calibrating to measured water balance fluxes (such as spring flows, river losses/gains). Automated calibration using the inverse estimation algorithm PEST has removed some of the subjectivity of manual calibration and has provided an insight into the non-uniqueness of the model.

Confidence can be placed in the calibration robustness for the principal aquifers in the catchment – the unconfined Taita Alluvium and the confined Waiwhetu Gravels and Moera Gravels. HAM3 can therefore be considered to be a high-confidence level model. The model has undergone technical peer review and endorsed as such.

Effects of current and historical groundwater abstraction

The HAM3 has been used to show that the current GWRC abstraction from the Waterloo wellfield results in significant drawdown (2m+) across the onshore and offshore (sub-harbour) Waiwhetu Aquifer downstream of the wellfield. The wellfield drawdown also induces an additional recharge (in addition to the recharge that occurs naturally) from the Hutt River of between 25 and 40ML/day – around 45% of the total river losses of 60-100 ML/day. A relationship between pumping-induced river loss and abstraction at Waterloo is provided to assist in evaluating the effects of groundwater abstraction on the river. Such effects are not currently considered in the management of either the groundwater resource or the Hutt River. Abstraction also causes an estimated 50-70% reduction in submarine discharge from the Waiwhetu Aquifer.

SUSTAINABLE MANAGEMENT OF THE WAIWHETU AQUIFER

The sustainable management of the Waiwhetu Aquifer is primarily focussed upon managing the saline intrusion risk at the Petone foreshore. Critical saline intrusion risk levels in the aquifer at the foreshore in effect define the 'sustainable yield' of the Waiwhetu Aquifer. A revised and expanded saline intrusion risk management framework provides a higher degree of protection and confidence particularly during periods of high water demand and stressed aquifer conditions. Aquifer yield has additionally been assessed using the HAM3 (and a derived calculation tool) under a range of aquifer conditions storage/recharge conditions, and constrained by a minimum saline intrusion foreshore level. The sustainable management of the Waiwhetu Aquifer also takes into consideration the effects of groundwater abstraction on the Hutt River (induced flow loss).

RECOMMENDED REVISED SALINE INTRUSION RISK MANAGEMENT FRAMEWORK

The saline intrusion risk management approach incorporates a set of water level, hydraulic gradient and water quality thresholds within a monitoring framework.

The existing network of dedicated sentinel water level and water quality (electrical conductivity) monitoring sites is generally considered adequate. Despite the existence of this network, under current policy the Waiwhetu Aquifer is managed solely on the level measured in the McEwan Park foreshore monitoring bore (which is in poor condition). Recommendations are made for the improvement, adaptation or replacement of some sites and the inclusion of a new site (Port Road).

The following three saline intrusion groundwater level thresholds for the Upper Waiwhetu Aquifer are recommended:

> Review Level: 2.5m amsl (24-hour mean)
> Alert Level: 2.3m amsl (24-hour mean)
> Minimum Level: 2.0m amsl (24-hour mean)

These are consistent with the three current management levels (2.5, 2.3 and 2.0m). However, it is recommended that the Review and Alert levels provide a more structured framework for stepping up from an increased state of awareness at 2.5m, to an intensification of monitoring at 2.3m. The 2.3m Alert Level signifies the onset of a low but rising saline intrusion risk as the offshore hydraulic gradient approaches a critical state. A two-tiered water quality monitoring response when the Alert Level is triggered is proposed.

Continuous monitoring of electrical conductivity (EC) at sentinel foreshore wells provides a good direct indicator of changes in water quality which may reflect the onset of saline intrusion. In addition to the two existing continuous dual-level EC monitoring sites at the Tamatoa and McEwan Park sentinel wells, development of a third foreshore site at Port Road is recommended (bringing the number of EC monitoring sites to five). Due to the historical problems experienced with EC monitoring, they have not been relied upon to date for saline intrusion monitoring - regular maintenance and calibration of the down hole instruments is therefore

recommended. The following EC trigger levels are proposed to indicate the onset of significant water quality changes in the Lower and Upper Waiwhetu Aquifers:

EC = 150 µS/cm – Upper Waiwhetu Aquifer
EC = 250 µS/cm – Lower Waiwhetu Aquifer

The table below summarises the recommendations for the revision of the saline intrusion risk management framework for the Waiwhetu Aquifer. The table is divided into three saline intrusion risk categories – '*none*', '*low to increasing*' and '*elevated*'. These categories are based primarily upon foreshore level thresholds, but also incorporate hydraulic gradients (onshore and offshore) and water quality (EC) thresholds. Monitoring and abstraction management responses relevant to each risk category are also shown. The requirement to instigate a structured tiered water quality investigation in response to the breaching of EC thresholds, and/or when the foreshore levels drop below 2.3m amsl, and/or when all onshore gradients reverse is an important new component to the aquifer management framework.

Saline intrusion risk management framework and risk categories for the Waiwhetu Aquifer, Lower Hutt.

SI Risk	Indicators	Response(s)
None	**STANDBY LEVEL: 2.5m** McEwan Park or Tamatoa <2.5m (24 hr) and: All offshore gradients positive Randwick-MP onshore gradient positive and: EC < 150 µS/cm Upper Waiwhetu EC < 250 µS/cm Lower Waiwhetu	Wellfield operators on standby to actively manage foreshore levels through abstraction rate adjustment; Employ yield prediction tool (HADC).
Low to Increasing	**ALERT LEVEL: 2.3m** McEwan Park or Tamatoa < 2.3m (24 hr) and/or: Both onshore gradients negative or positive All offshore gradients positive and: EC < 150 µS/cm Upper Waiwhetu EC < 250 µS/cm Lower Waiwhetu	Instigate Alert Level water quality monitoring and perform weekly (Tier 1 protocol). Wellfield operators required to actively manage foreshore levels through abstraction rate adjustment. Employ yield prediction tool (HADC).
Elevated	**MINIMUM LEVEL: 2.0m** McEwan Park and/or Tamatoa < 2.0m (24hr) and/or: One or more offshore gradients negative and/or: EC > 150 µS/cm Upper Waiwhetu EC > 250 µS/cm Lower Waiwhetu (or consistently rising EC trends)	Reduce pumping rate to maintain minimum foreshore level above 2.0m, or until water quality improves. Instigate water quality investigation response (Tier 1 and, if necessary, Tier 2).

Summary of saline intrusion monitoring recommendations:

- **Sentinel groundwater level sites (continuous):**

  McEwan Park (Upper and Lower Waiwhetu)
  Tamatoa (Upper and Lower Waiwhetu)
  Port Road (Upper Waiwhetu)

- **EC monitoring sites (continuous):**

  McEwan Park (Upper and Lower Waiwhetu)
  Tamatoa (Upper and Lower Waiwhetu)
  Port Road (Upper Waiwhetu)

- **Hydraulic gradient monitoring sites:**

  Offshore
  McEwan Park– Somes Island
  McEwan Park – Port Road
  Tamatoa Shallow – Somes Island
  Port Road – Somes Island
  Onshore
  Randwick – McEwan Park
  HVMTC – Tamatoa

- **Response water quality monitoring:**

  Upon breaching EC, gradient or level thresholds, the following two-tiered response is recommended:

  Tier 1 *response - within 24 hours or weekly when Alert level triggered:*
  - Review all monitoring data;
  - All monitoring wells equipped with EC probes should be flushed (at least 2 bore volumes by free-flowing) and the EC readings then checked against an independent portable meter.

  Tier 2 *response – within 48 hours:*
  - Should the rise in EC be confirmed in Tier 1, additional water quality sampling and chemical laboratory analysis from samples taken from all water quality sites must be carried out;
  - Should additional water quality data confirm the likelihood of saline intrusion, the pumping rate from the Waterloo wellfield should be incrementally reduced if it has not already been, until an improvement in water quality or stabilisation of EC trend is observed.
  - Resource managers at GWRC should be informed and involved in the assessment of the monitoring data.

Recommended physical works required to implement saline intrusion risk management framework:

- Replacement or rehabilitation of the current McEwan Park monitoring well (shallow, R27/0122).
- Replacement of the Port Road monitoring wells (Upper Waiwhetu Aquifer) and installation of continuous water level and EC/temperature instrumentation.
- Flushing/development of remaining Tamatoa and McEwan Park EC monitoring sites. Treatment for iron biofouling.
- Inspection and calibration of EC probes at all EC monitoring sites on an annual basis, accompanied by thorough flushing of the bores.
- Scheduled 5-yearly maintenance, bore cleaning/development

Recommendations for implementation of the framework:

The complex nature of the new framework required the development of a 'live' display screen which is linked to the GWRC telemetry systems. This screen should clearly display the current saline intrusion risk status and all three monitoring components – water levels, hydraulic gradients and EC levels – in addition to the Waterloo abstraction rates. Additional information such as the aquifer level in the unconfined aquifer at Taita Intermediate and the flow in the Hutt River should also be included to assist in active abstraction management.

SUSTAINABLE YIELD RECOMMENDATIONS – WAIWHETU AQUIFER

The sustainable yield of the Waiwhetu Aquifer is dependent upon aquifer storage/head conditions – particularly in the unconfined part of the aquifer – and the recharge potential from the Hutt River. A somewhat different approach to the yield management of the Waiwhetu Aquifer is therefore advocated, one which is based upon an dynamic evaluation of aquifer storage and recharge state using a level indicator in the unconfined aquifer at the Taita Intermediate monitoring site. The unconfined aquifer level influences the foreshore groundwater level in the Waiwhetu Aquifer and simple level relationships have been derived between the two 'ends' of the aquifer and the drawdown experienced by them due to pumping at the Waterloo wellfield using the HAM3. These relationships have been incorporated into a simple yield spreadsheet tool – the Hutt Aquifer Drawdown Calculator (or HADC) which can be used to calculate the maximum aquifer yield based on a Taita Intermediate level and a minimum foreshore level. The tool is intended for the short-term (1-2 months) prediction of wellfield yield based upon the unconfined aquifer condition (storage/recharge state). Comparison of the HADC-predicted and observed foreshore and unconfined aquifer levels during the 2013 February-March drought period shows close agreement.

The groundwater level range at Taita Intermediate has been used to calculate the potential yield from the Waiwhetu Aquifer under a range of groundwater levels in the unconfined aquifer (Taita Intermediate well). These are shown in the table below, together with the predicted induced recharge effect on the Hutt River.

Guidelines for the potential maximum sustainable yields from the Waiwhetu Aquifer based upon groundwater level in the unconfined aquifer at Taita Intermediate and a minimum foreshore level of 2.0m amsl.

Taita Intermediate level (24 hour mean level a msl)	Waiwhetu Aquifer Maximum yield ML/day	Induced recharge from the Hutt River (L/sec)
8-8.4m	110	500
<9m >8.4m	120	530
<9.5m >9m	130	560
>9.5m	140	590

This assessment shows that a maximum yield of up to 140ML/day can be sustained when aquifer conditions permit. In practice, however, the yield from the aquifer will be governed by saline intrusion foreshore level constraints which will over-ride allocation quantities.

A long-term mean annual allocation from the Waiwhetu Aquifer for resource management policy should be based on the HAM3 simulations which more reliably predicts the sustainable aquifer yield over longer durations and under a range of climatic stresses. The HAM3 indicates that the long- term mean yield for the Waihwetu Aquifer is about 100 ML/day, or 36,500 ML/year (the current GWRC Regional Freshwater Plan allocation is 33,000 ML). This allocation will prevent the foreshore water level dropping below the saline intrusion minimum level of 2m under an extreme drought condition, but will under-utilise the resource when aquifer conditions allow greater quantities to be abstracted as shown in the table above. It is therefore recommended that the maximum daily abstraction should be 140ML/day.

Based on the HAM3 re-assessment of aquifer yield, there is clearly scope to increase both the mean and maximum consented abstraction rates if required by GWRC for bulk water supply.

The induced loss from the Hutt River caused by pumping at Waterloo should be taken into consideration, or 'reserved', by GWRC when assessing the available core allocation from the river. A recent river allocation assessment of 1,925 L/sec has been made by GWRC for the 'Lower Reach' of the Hutt River (Birchville to the Hutt mouth), 65% of which has been allocated. Therefore, the additional 'take' of 500-600 L/sec between Taita Gorge and Boulcott to sustain pumping from the Waiwhetu Aquifer can be accommodated in the river allocation framework.

Operational yield management and forecasting tool

The Hutt Aquifer drawdown calculator (HADC) has been developed as a simple, short-term yield prediction tool to assist in the operational management of the Waiwhetu Aquifer. HADC is a user friendly proxy for the HAM3 and is able to forecast and optimise (over a short-term) the yield of the aquifer based upon the state (level) of the unconfined aquifer (and implicitly, the Hutt River) and a specified foreshore minimum groundwater level. The principal benefit of the HADC lies in its ability to forecast the sustainable wellfield yield when the aquifer system becomes stressed and is in recession – i.e. during an anticipated dry period when the

river remains at low flow and the unconfined aquifer storage slowly drains. The HADC calculates the recession of the unconfined aquifer using an exponential decay equation based upon observed groundwater recession trends. Using this level, it then calculates the sustainable pumping rate from the Waiwhetu Aquifer whilst maintaining a specified saline intrusion risk groundwater level at the foreshore. Because the foreshore groundwater level in the Waiwhetu Aquifer responds very quickly to changes in the pumping rate at Waterloo, the HADC can be used to help 'steer' the foreshore level so that minimum levels are not breached.

STORAGE 'BANKING' ASSESSMENT

A management option that GWRC has considered is the preservation, or 'banking', of aquifer storage during spring or early summer in order to sustain a higher aquifer yield for an anticipated (forecast) drought period. The HAM3 model has been used to evaluate the feasibility and benefits of storage banking and shows that a 30-day banking period returns a storage benefit for only about 10-20 days.

IMPACT OF SEA LEVEL RISE ON WAIWHETU AQUIFER YIELD

The HAM3 has been used to assess the effects of a sea level rise of up to 1.5m above the current sea level on the yield of the Waiwhetu Aquifer. Such a rise is expected to occur over the next century or more. Aquifer levels at the foreshore are predicted to rise, or 'lift', about 30% of the total sea level rise magnitude (i.e. about 0.4m for a 1.5m rise) due to the confined and pressurised nature of the offshore aquifer. The Waiwhetu Aquifer is relatively unique in this regard – unlike the majority of coastal aquifers, there is no open connection to the ocean, a context which requires special consideration when evaluating the effects of sea level rise. The loading stresses on the aquifer resulting from sea level rise have been carefully considered in this assessment.

The HAM3 predicts that the sustainable yield from the Waiwhetu Aquifer (under seasonally stressed hydrogeological conditions) will decline as sea level rises. If the minimum foreshore level of 2.0m is implemented, the yield from the Waiwhetu Aquifer is predicted to drop from 110 to 93 ML/day for a 0.75m sea level rise, and then to 76ML/day for a 1.5m rise. This equates to an 15% reduction in yield for a 0.75m sea level rise, and a 31% reduction for a 1.5m sea level rise.

RECOMMENDATIONS FOR STATE OF AQUIFER REPORTING

GWRC require a means of assessing and reporting the 'state of the aquifer' in simplistic terms, both to assist in the operational management of the water supply and for communicating the 'health' of the aquifer with the wider community. Two indicators are recommended which provide information on the resource stress state and yield availability – the Waiwhetu Aquifer water level at Petone foreshore (McEwan Park), and the unconfined aquifer level (at Taita Intermediate). Each depicts a different aspect of the aquifer: McEwan Park shows the saline intrusion risk status, whilst Taita Intermediate shows the recharge/storage status. Smoothed 24-hour mean monitoring data for these sites can be portrayed on an envelope plot which shows monthly maxima and minima, with lines indicating one standard deviation from the mean derived from the historical monitoring record. The method

provides a good visual way to put the current levels into the context of the historical record. Four coloured status levels are proposed for each site.

RECOMMENDATIONS FOR FURTHER HYDROGEOLOGICAL RESEARCH

Three related recommendations are suggested regarding further work:

- Formal predictive uncertainty analysis could usefully be performed on the HAM3 to assess the uncertainty associated with key predictions which underpin the groundwater management proposals, in particular, the sea level rise assessment presented in this study. Uncertainty analysis measures the reliability of a parameter estimate or a prediction made by the model and can be expressed by assigning credible confidence limits. This work is particularly relevant in the context of sea level rise and its impacts on resource availability. Model uncertainty analysis is a relatively new area of research and represents a significant step up in terms of technical expertise, and requires a specialist modeller.

- The offshore submarine spring discharges from the Waiwhetu Aquifer represent an important information gap since the rate of water released strongly impacts the artesian pressure at the foreshore. The springs also represent potential saline intrusion sites – the closest being located only 500m from the shoreline. Tentative information from a previous study of the springs has been used to assist the calibration of the HAM3 and aquifer heads tend to restrain the amount of water released from the springs in the model. However, more detailed characterisation of the springs in terms of locating active vents, their flow characteristics and water quality is recommended.

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Appendix 1

Taita Gorge flow – river stage relationships

River stage levels at chosen cross sections related to Taita Gorge flows
Based on Mike 11
outputs (GWRC 2000)

Cross section>	Taita (1230)	1220	1170	1130	1110	1050	1030	1000	980	950	910	880	850	830	810	790	770	760	720	690	640
Flow	37088	37182	37688	38090	38292	38924	39142	39475	39705	40053	40516	40853	41171	41383	41598	41811	42029	42139	42568	42885	43337
(cumecs)	Stage>																				
20	25.31	25.04	23.67	22.85	22.29	19.74	18.5	17.93	17.2	16.16	14.69	13.8	13.07	11.9	10.96	10.56	9.99	9.73	8.68	7.74	6.68
40	25.52	25.25	23.9	23.06	22.5	19.92	18.83	18.13	17.4	16.36	14.94	14.02	13.24	12.12	11.25	10.86	10.26	9.98	8.94	8.02	6.94
70	25.78	25.5	24.18	23.32	22.73	20.14	19.23	18.36	17.66	16.61	15.21	14.26	13.42	12.38	11.54	11.16	10.56	10.25	9.2	8.2	7.22
100	25.99	25.72	24.41	23.5	22.89	20.31	19.49	18.55	17.87	16.81	15.39	14.43	13.55	12.54	11.78	11.39	10.79	10.47	9.38	8.36	7.37
150	26.31	26.04	24.73	23.76	23.11	20.57	19.83	18.83	18.16	17.06	15.64	14.67	13.75	12.78	12.08	11.65	11.09	10.77	9.63	8.6	7.58
200	26.58	26.31	25	23.97	23.3	20.79	20.12	19.06	18.4	17.29	15.86	14.88	13.92	13	12.33	11.87	11.32	10.98	9.81	8.8	7.75
250	26.83	26.57	25.24	24.16	23.48	20.99	20.34	19.27	18.62	17.47	16.05	15.06	14.08	13.19	12.55	12.06	11.49	11.15	9.97	9	7.9
300	27.06	26.8	25.46	24.34	23.66	21.17	20.56	19.46	18.8	17.65	16.23	15.23	14.23	13.37	12.73	12.22	11.64	11.3	10.12	9.17	8.05

Section Equation relating TG flow to stage
SL

1170 $y = 4E\text{-}08x^3 - 3E\text{-}05x^2 + 0.0125x + 23.441$

1110 $y = -3E\text{-}10x^4 + 3E\text{-}07x^3 - 8E\text{-}05x^2 + 0.0142x + 22.039$

1050 $y = -2E\text{-}10x^4 + 1E\text{-}07x^3 - 5E\text{-}05x^2 + 0.0111x + 19.537$

980 $y = -2E\text{-}10x^4 + 1E\text{-}07x^3 - 5E\text{-}05x^2 + 0.0128x + 16.962$

910 $y = -4E\text{-}10x^4 + 3E\text{-}07x^3 - 1E\text{-}04x^2 + 0.017x + 14.0$

830 $y = -4E\text{-}10x^4 + 3E\text{-}07x^3 - 9E\text{-}05x^2 + 0.0155x + 11.625$

760 $y = -1E\text{-}10x^4 + 1E\text{-}07x^3 - 6E\text{-}05x^2 + 0.0146x + 9.1662$

690 $y = -6E\text{-}10x^4 + 4E\text{-}07x^3 - 0.0001x^2 + 0.0164x + 7.4731$

640 $y = -5E\text{-}10x^4 + 4E\text{-}07x^3 - 0.0001x^2 + 0.0189x + 6.3505$

Appendix 2

HAM3 Head calibration plots

Fig A2.1: Nash-7
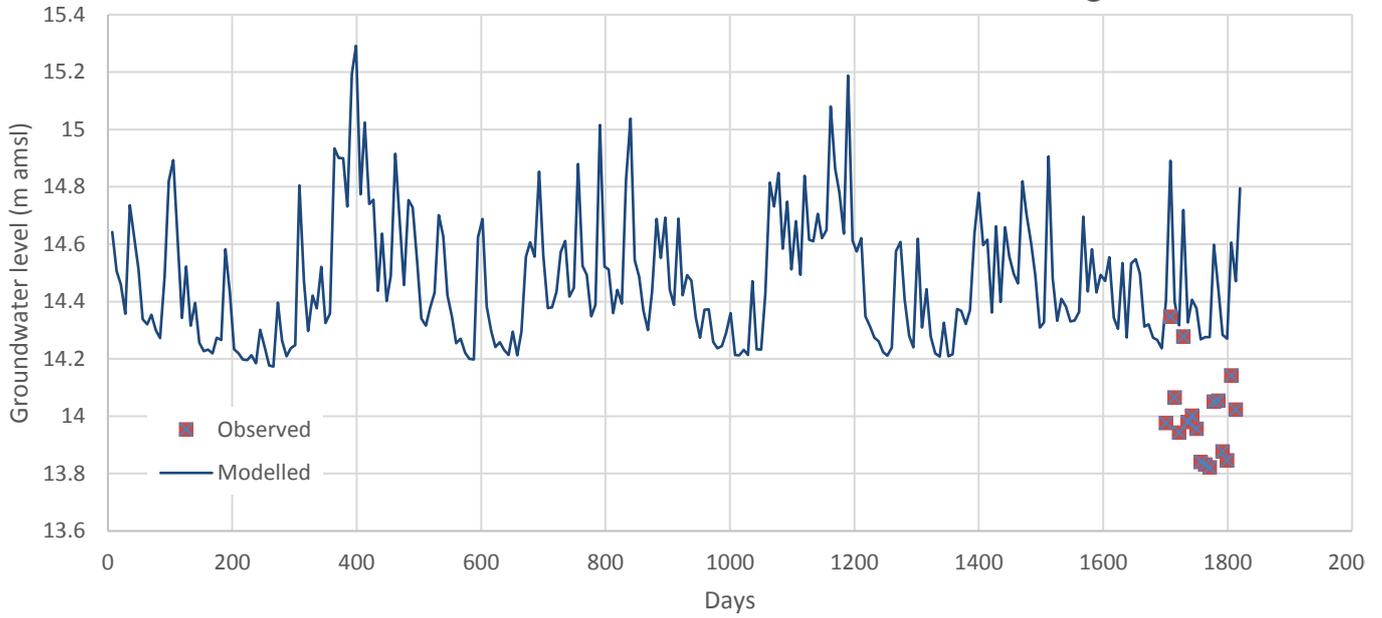
Fig A2.2: Nash-13
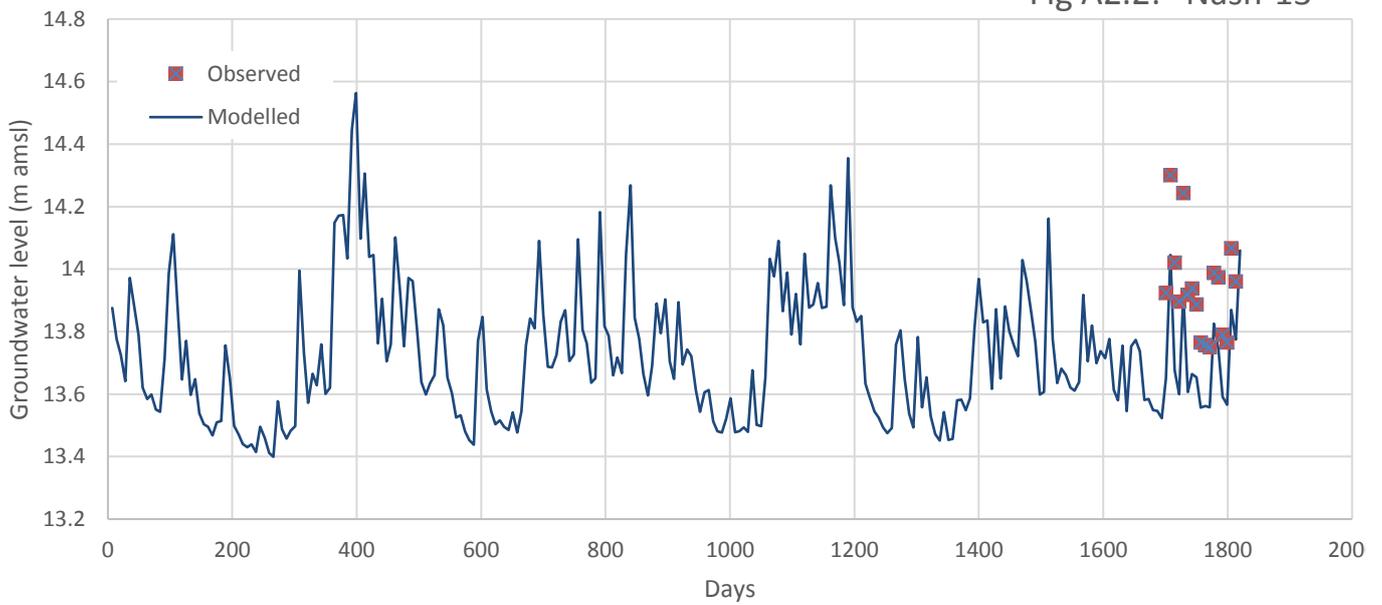
Fig A2.3: Nash-20
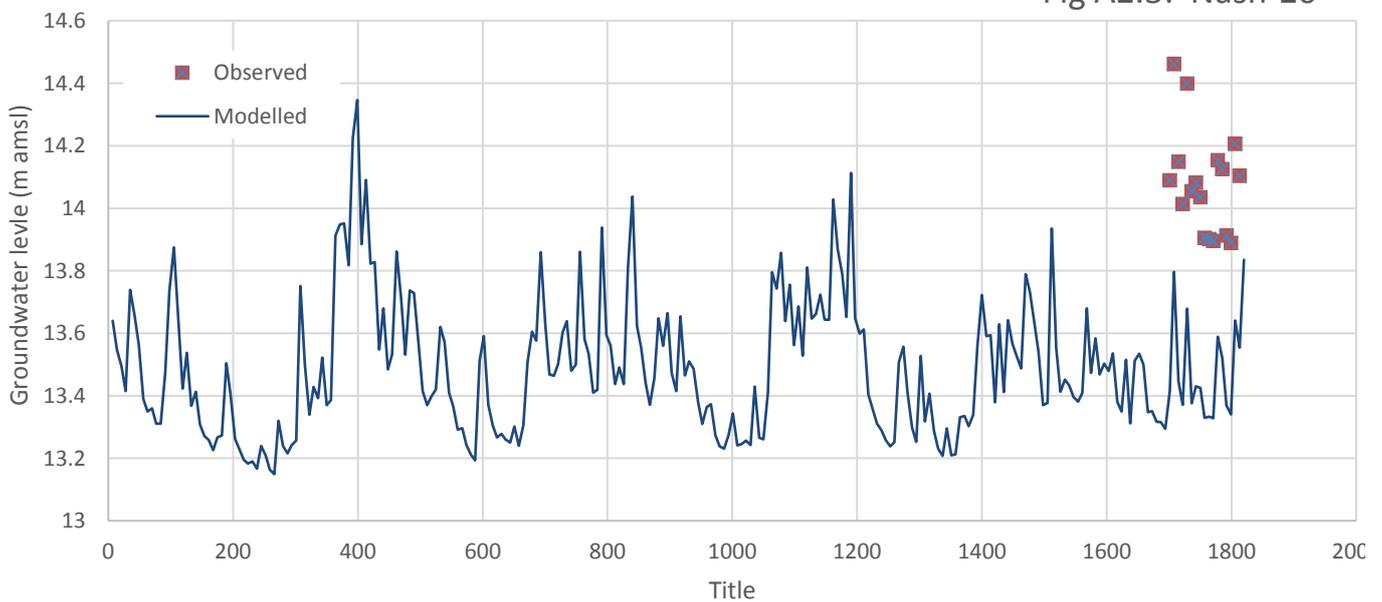
Fig A2.4: Mabey-7 (L1)
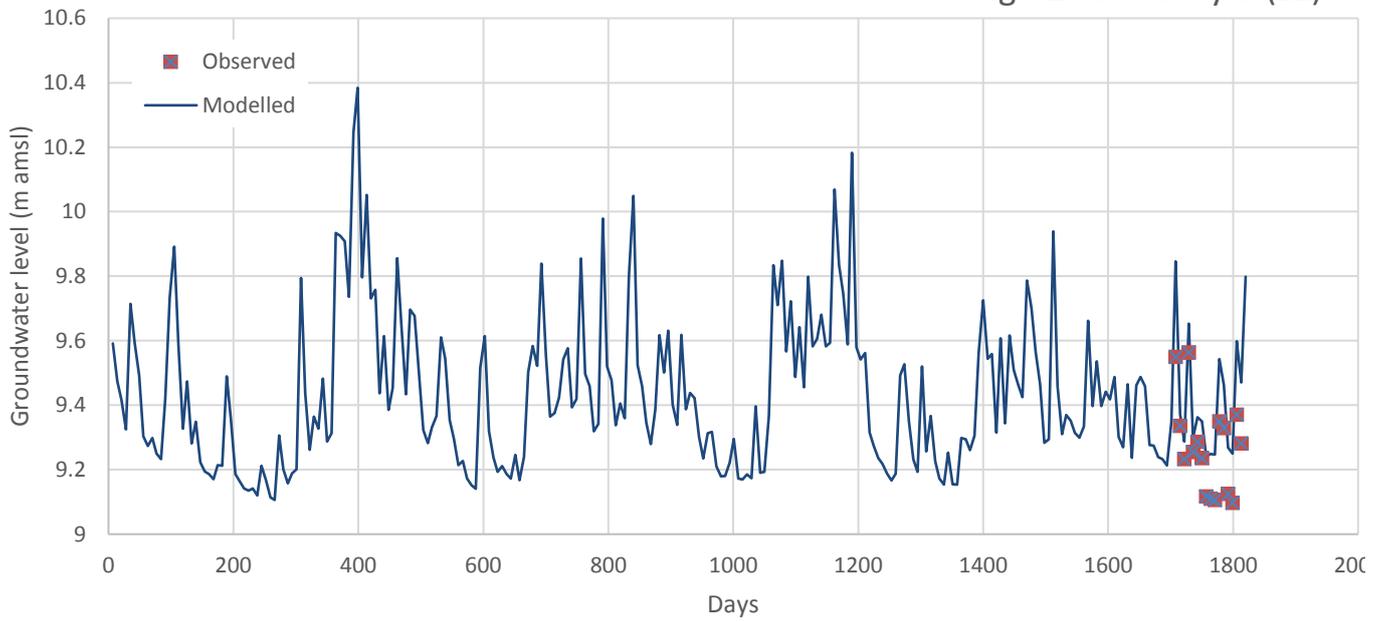
Fig A2.5: Mabey-12 (L2)
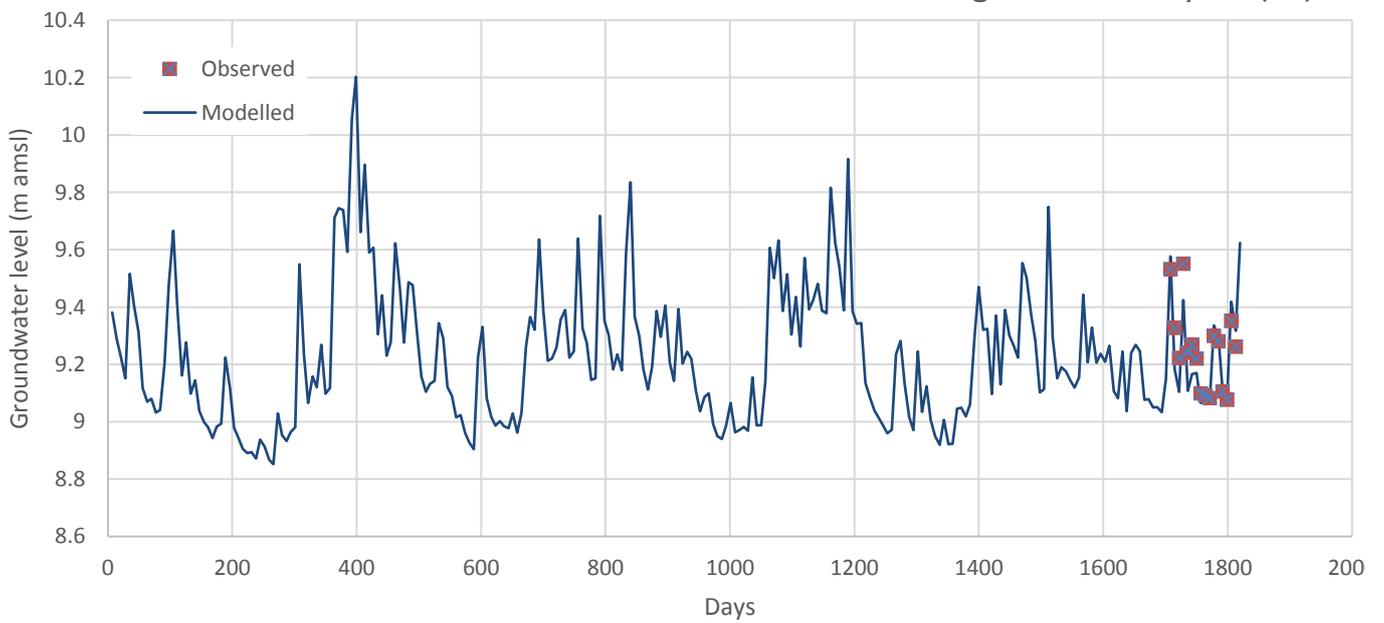
Fig A2.6: Mabey-20 (L3)
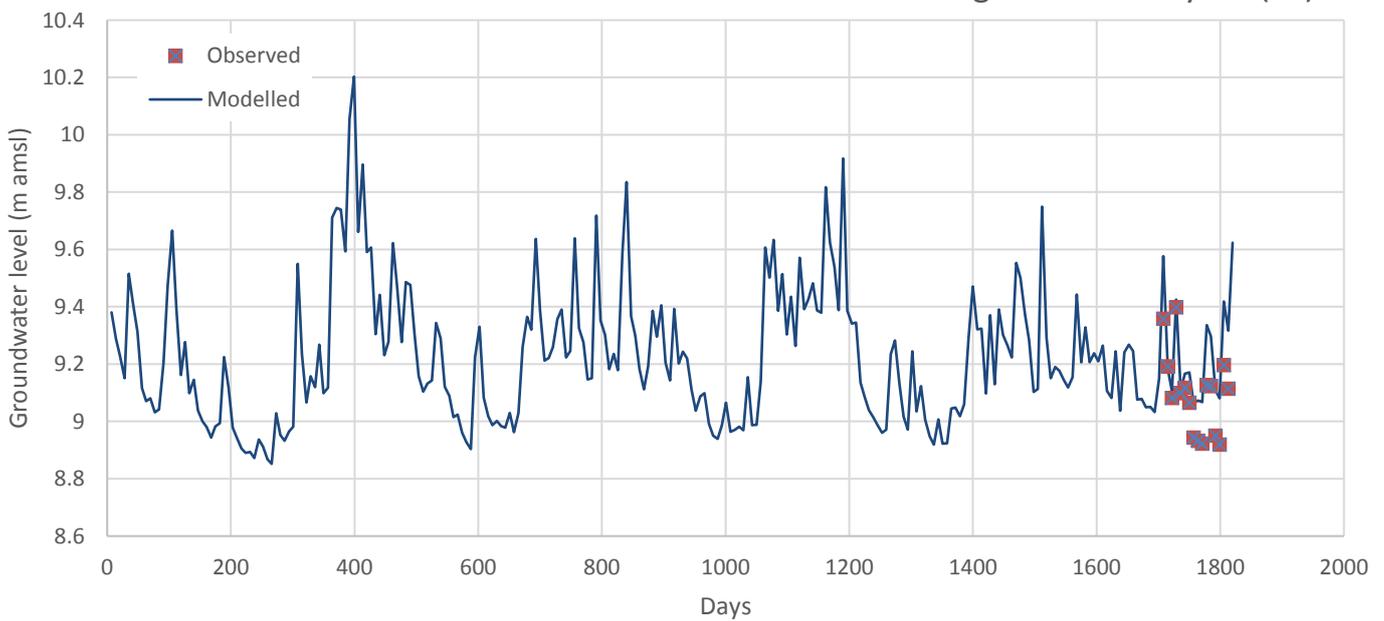
Fig A2.7: Thorneycroft (L1)
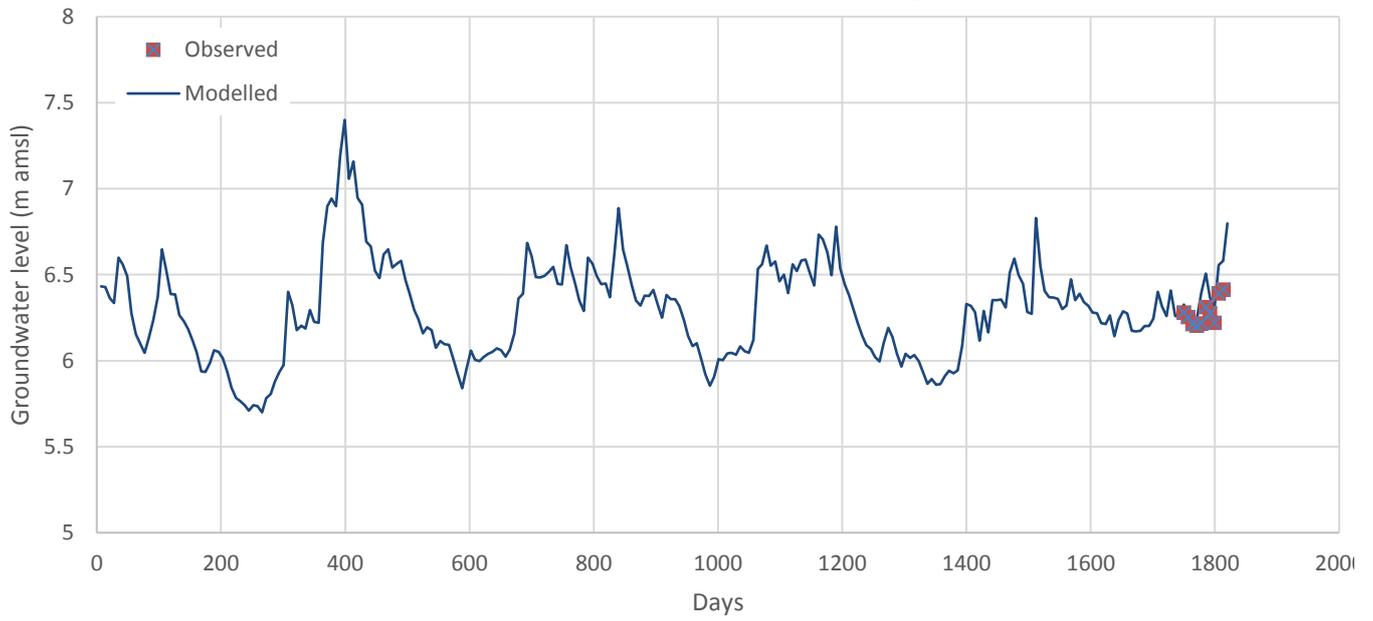
Fig A2.8: Gear Is - Unconfined (L1)
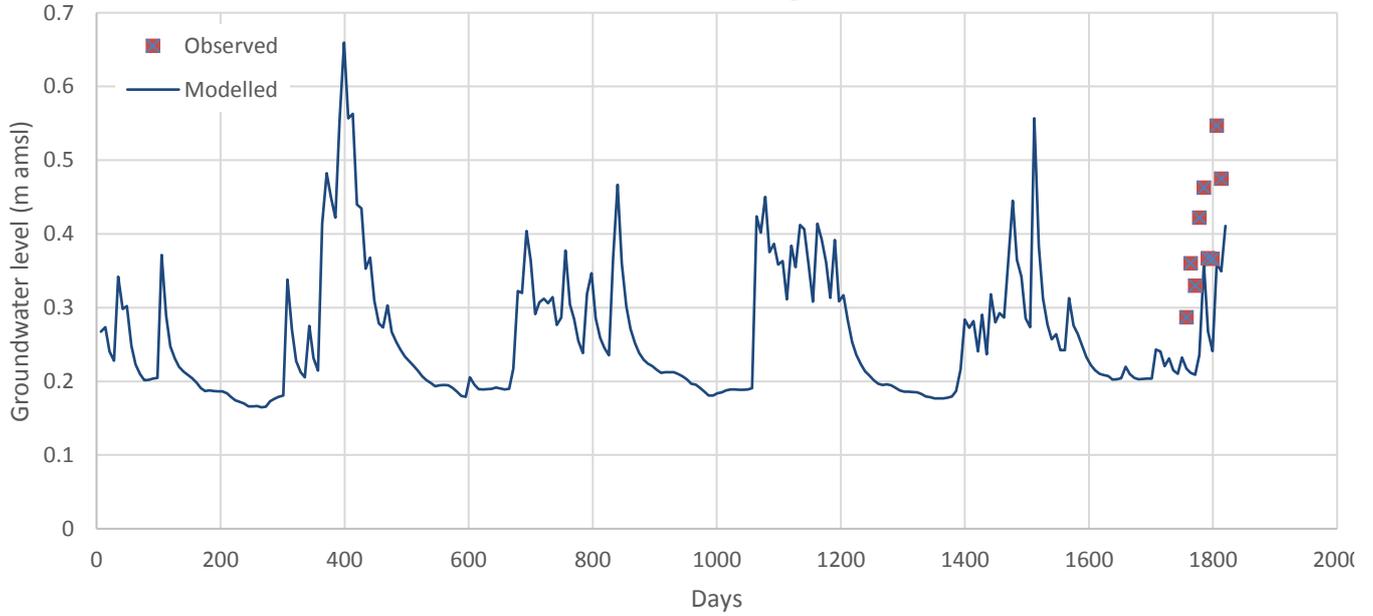
Fig A2.9: Taita Intermediate (L4)
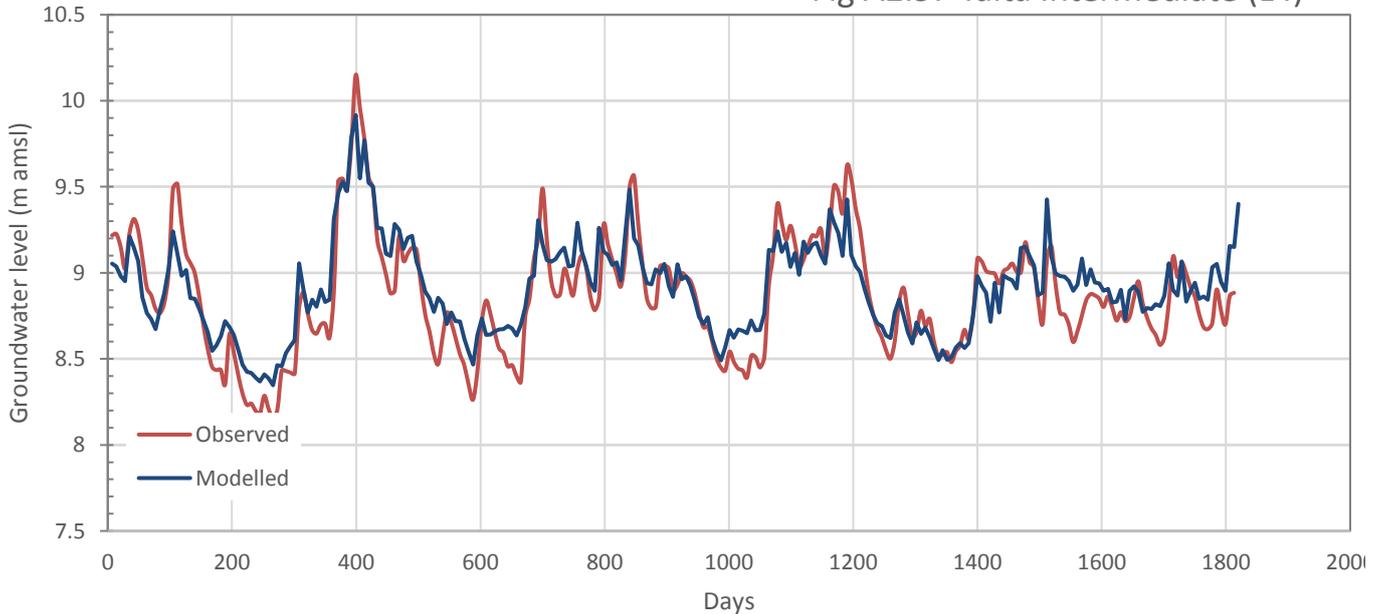
Fig A2.10: Birchville (L4)
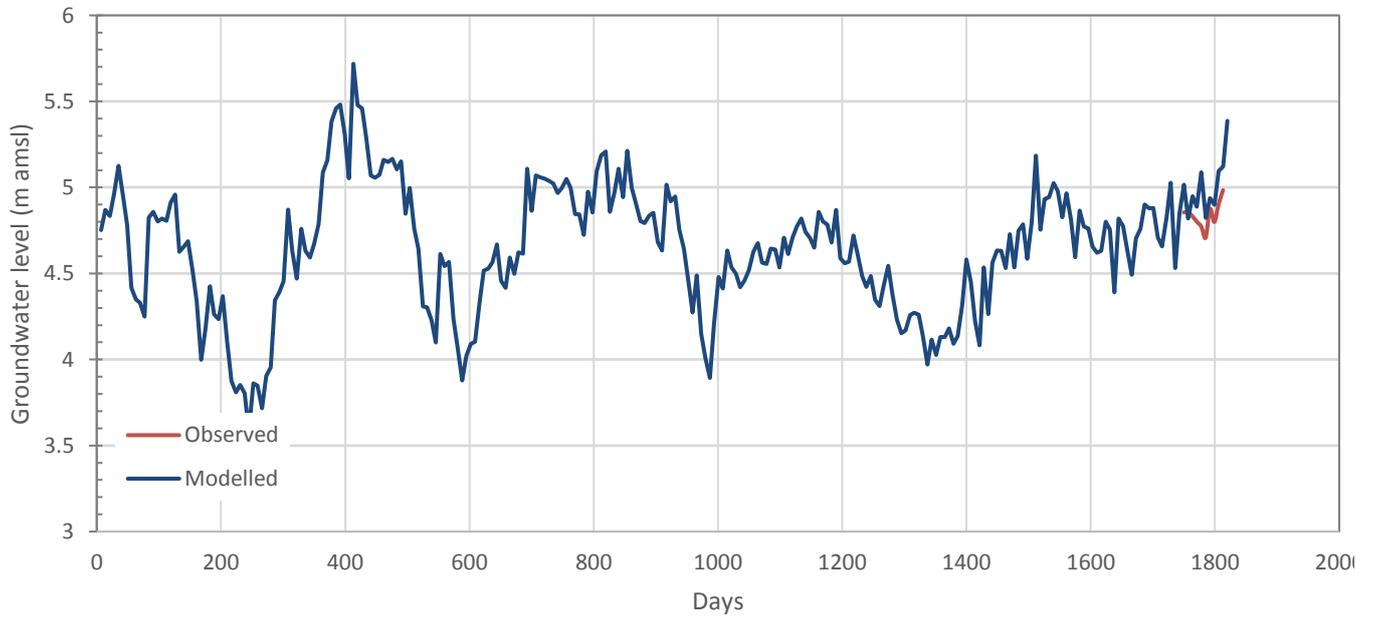
Fig A2.11: Trafalgar (L4)
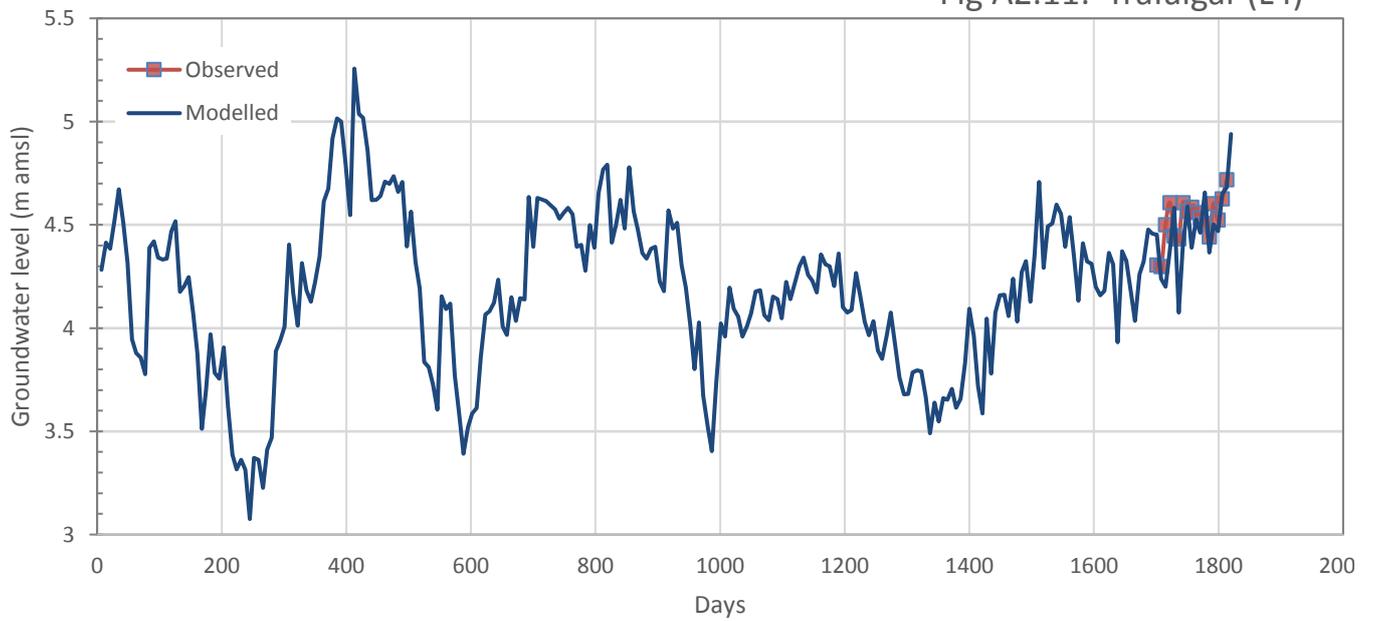
Fig A2.12: Bell (L4)
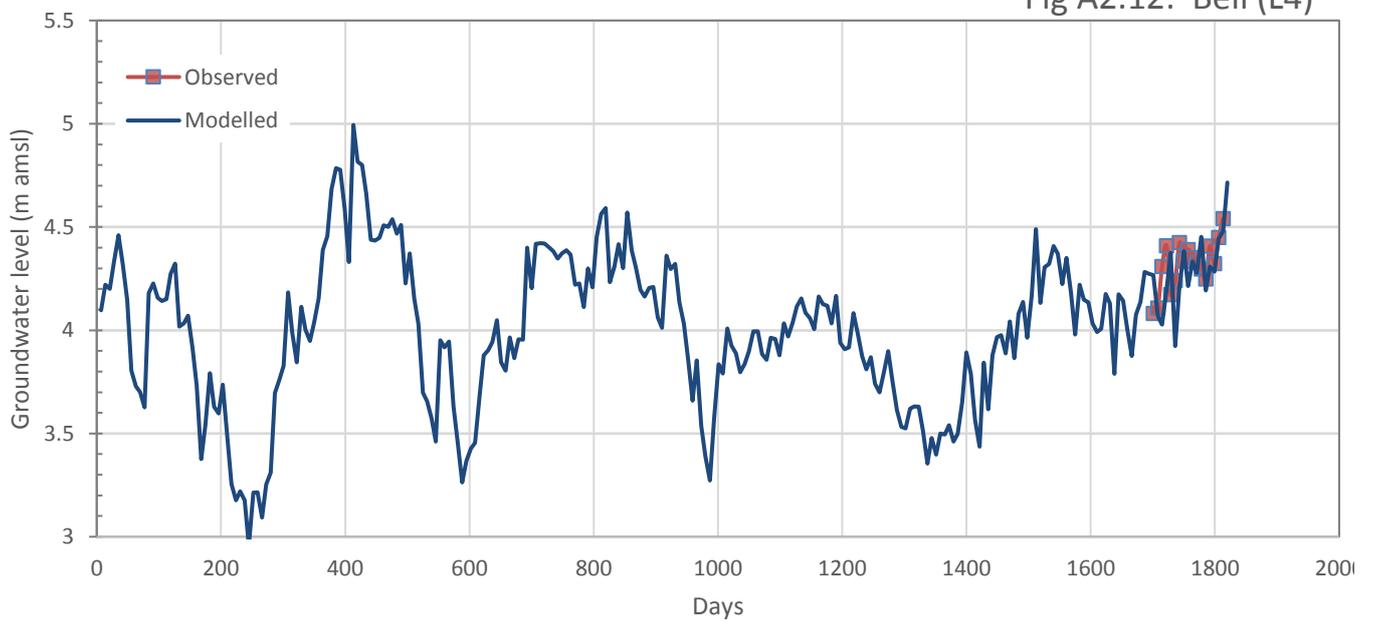
Fig A2.13: Randwick (L4)
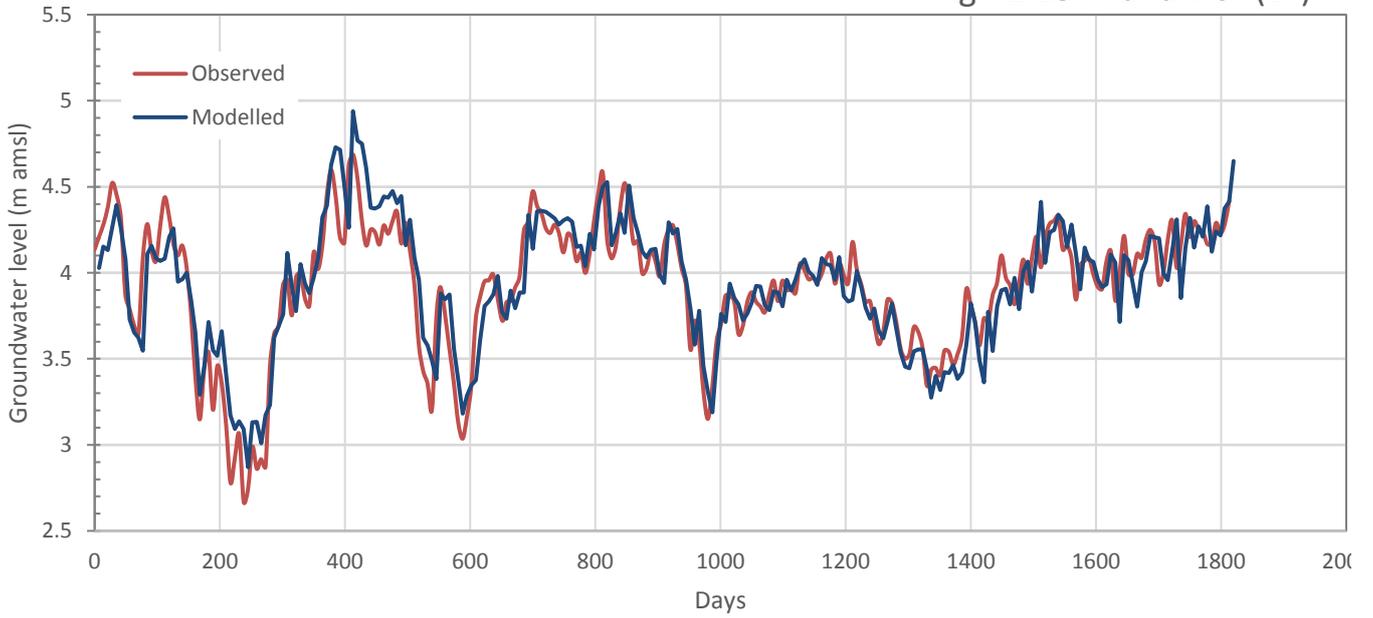
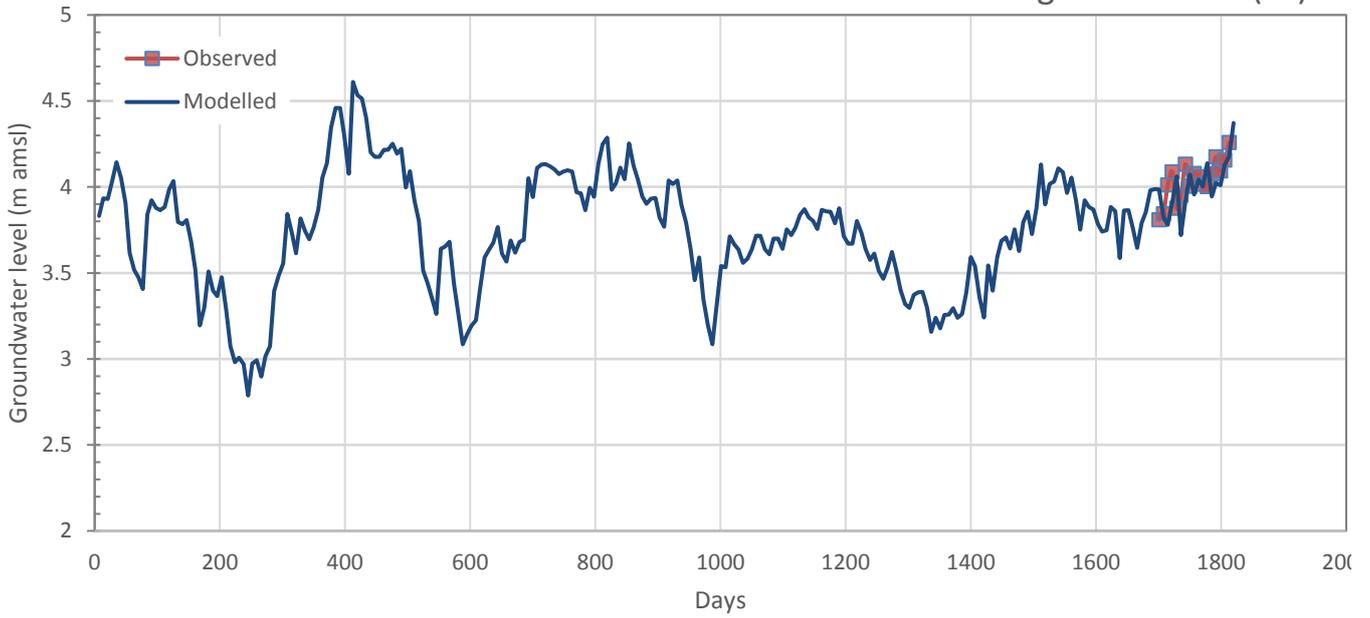Fig A2.14: Huttrec (L4)
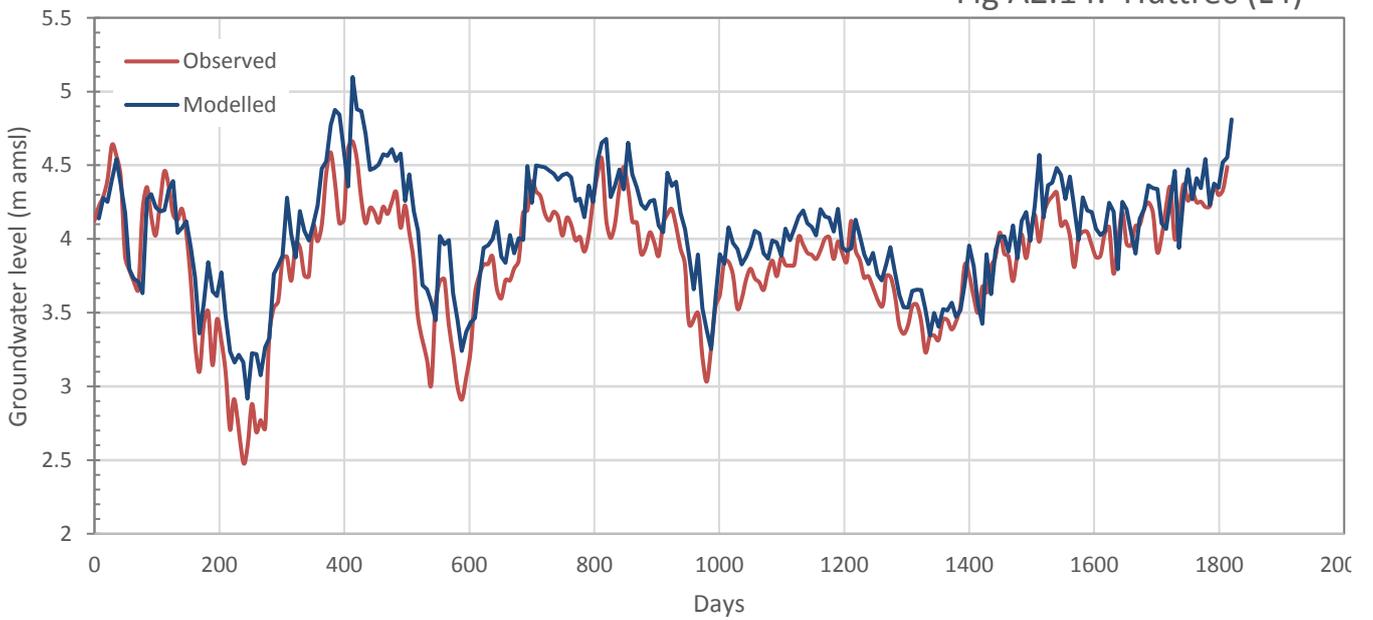
Fig A2.15: HVMTC (L4)
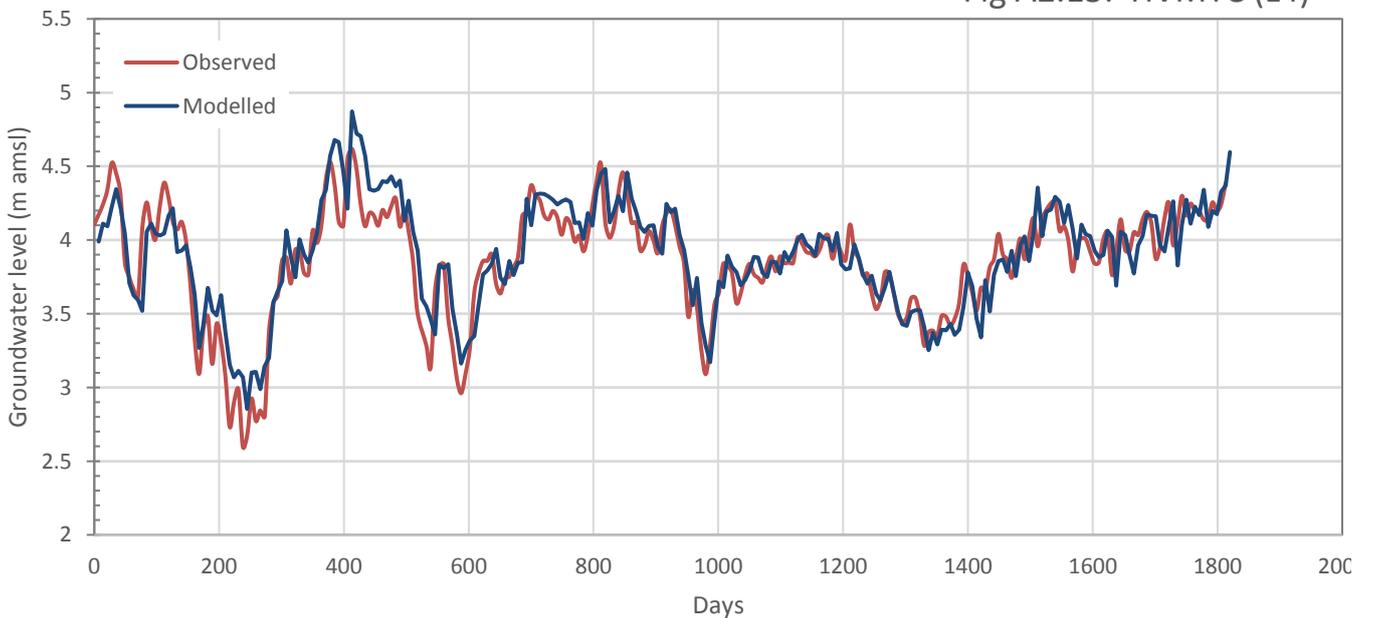
Fig A2.16: Port (L4)

Fig A2.17: McEwan Park - Shallow (L4)
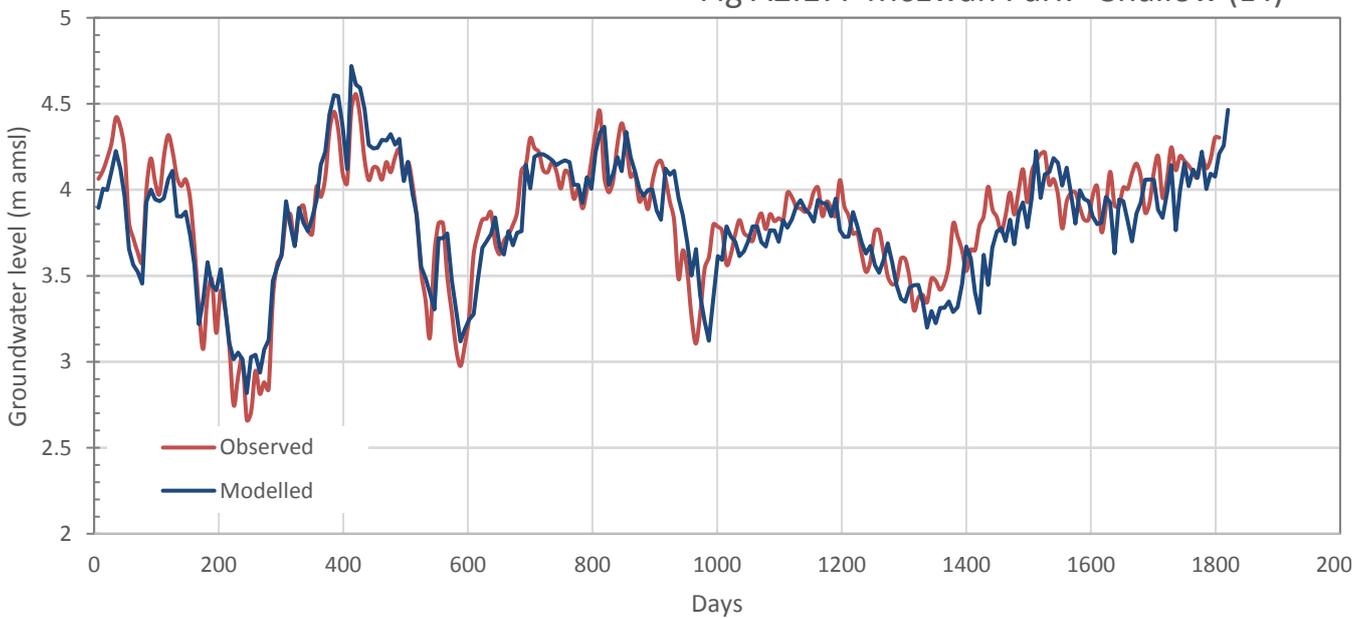
Fig A2.18: Tamatoa - Shallow (L4)
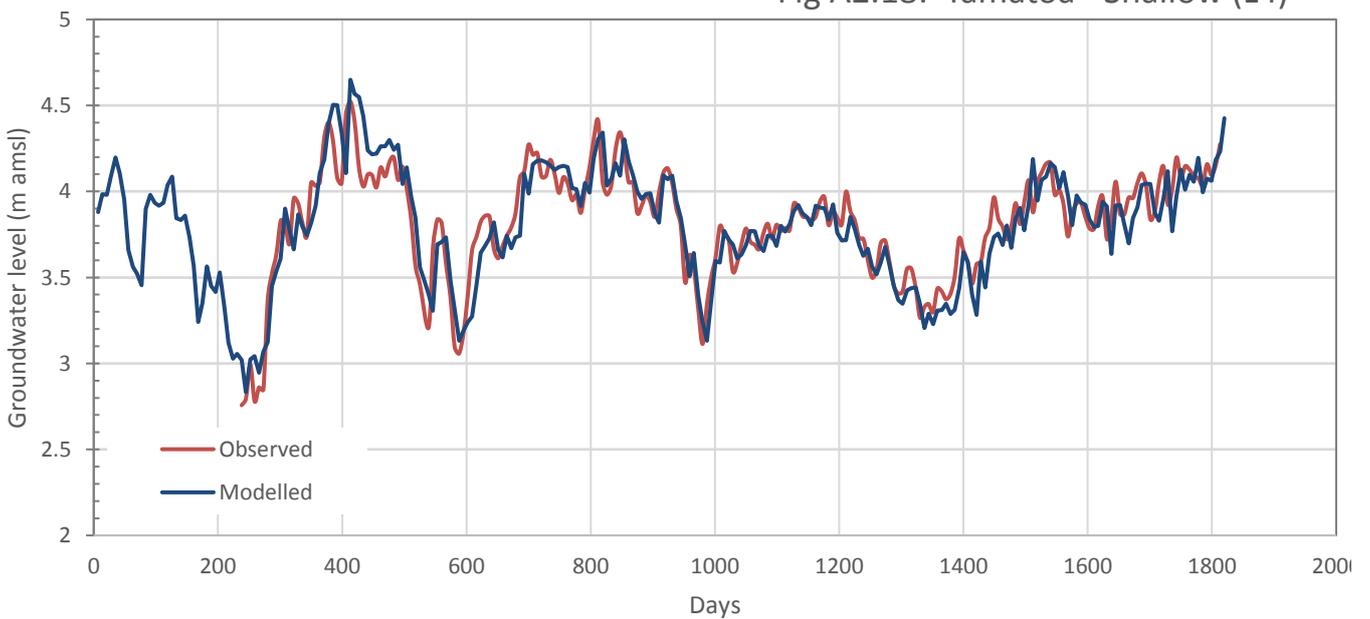
Fig A2.19: IBM2 (L4)
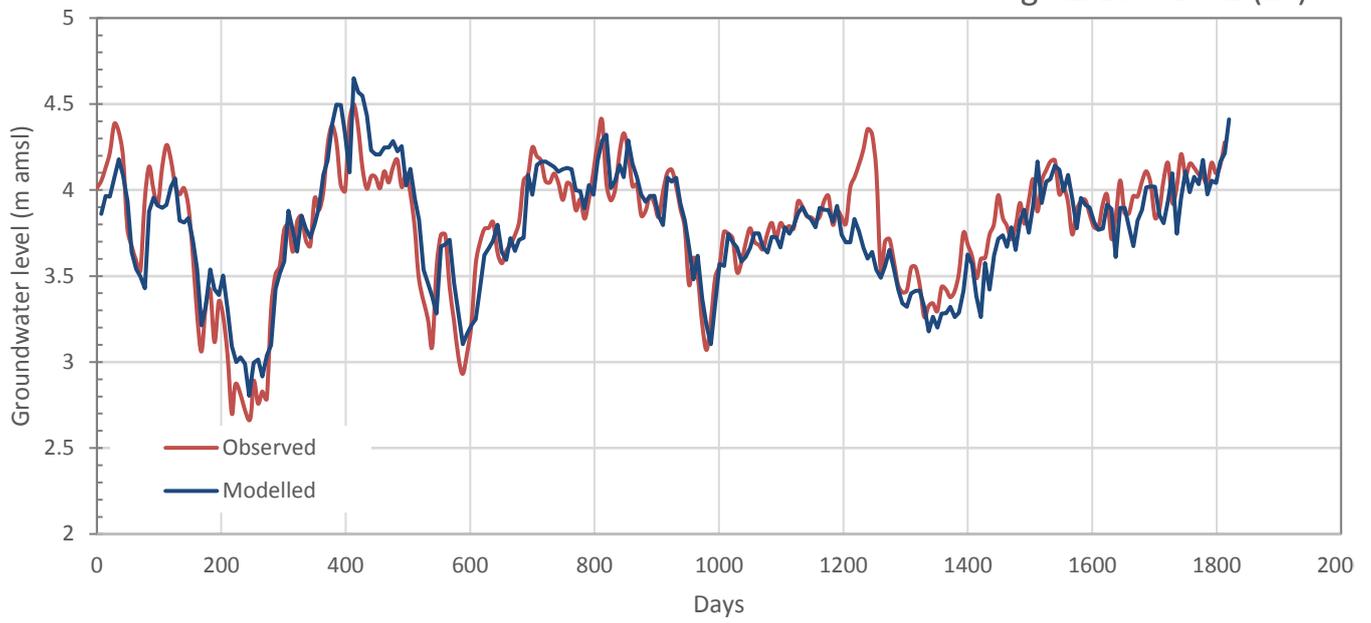
Fig A2.20: Somes Island (L4)
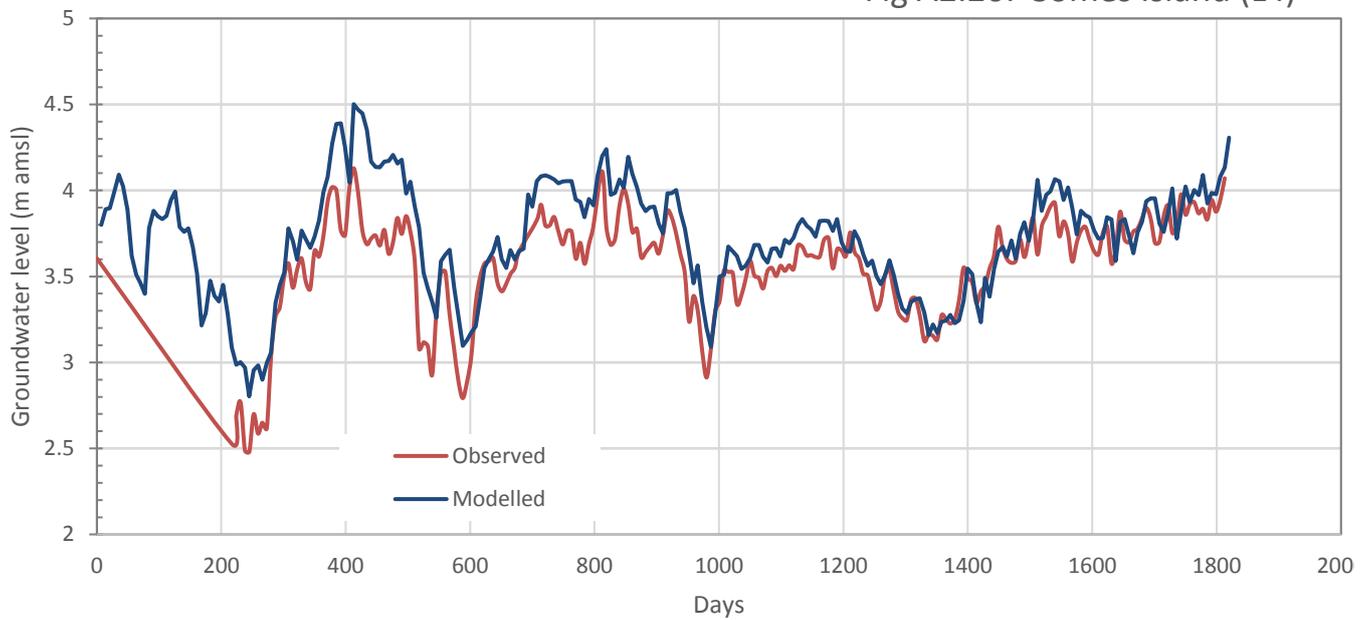
Fig A2.21: Tamatoa - Deep (L5)
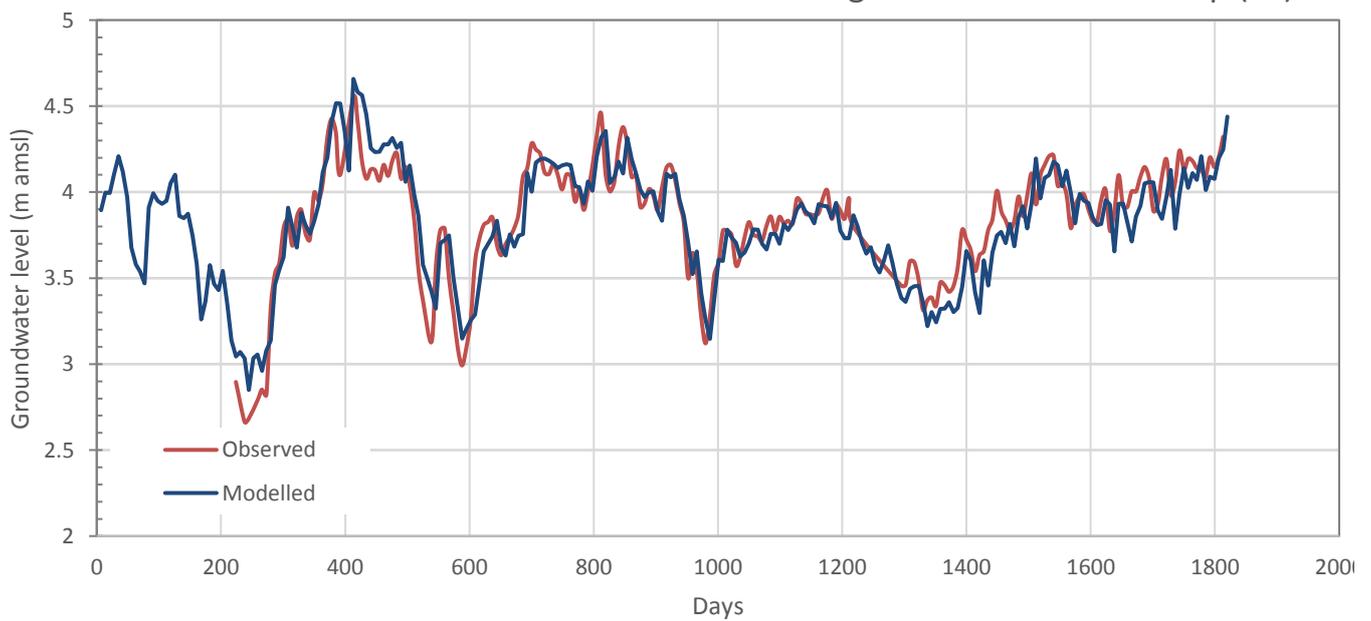
Fig A2.22: McEwan - Deep (L5)
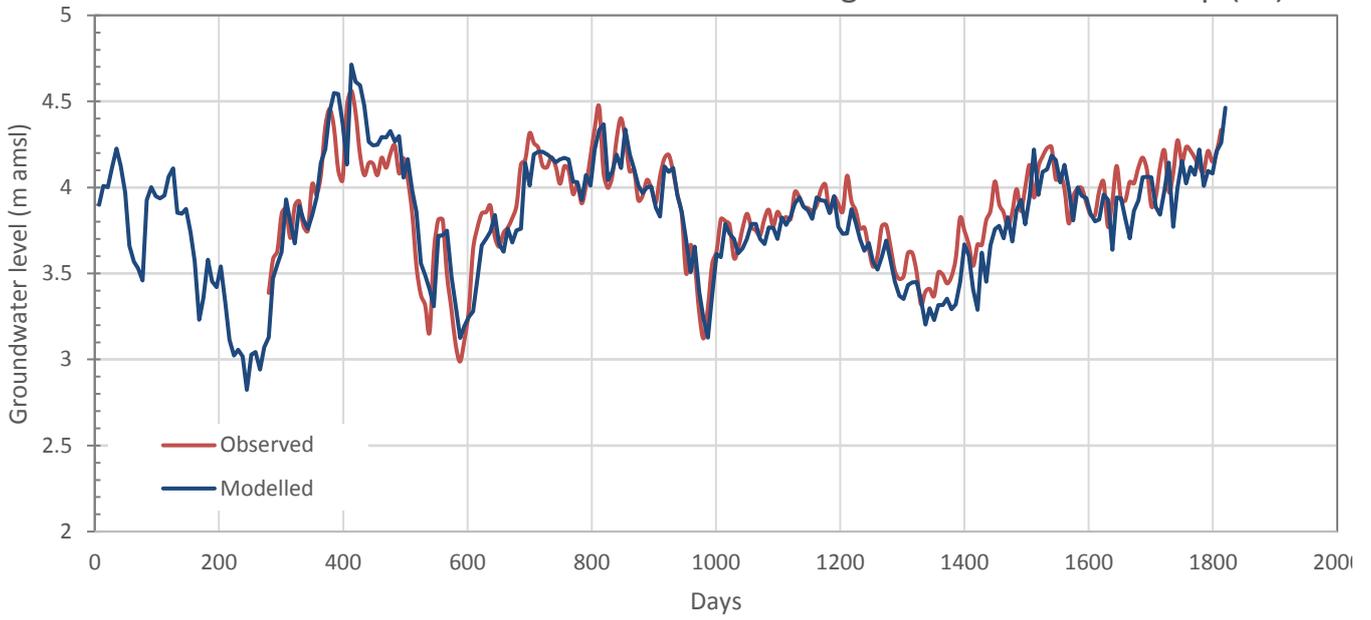
Fig A2.23: IBM1 (L7)
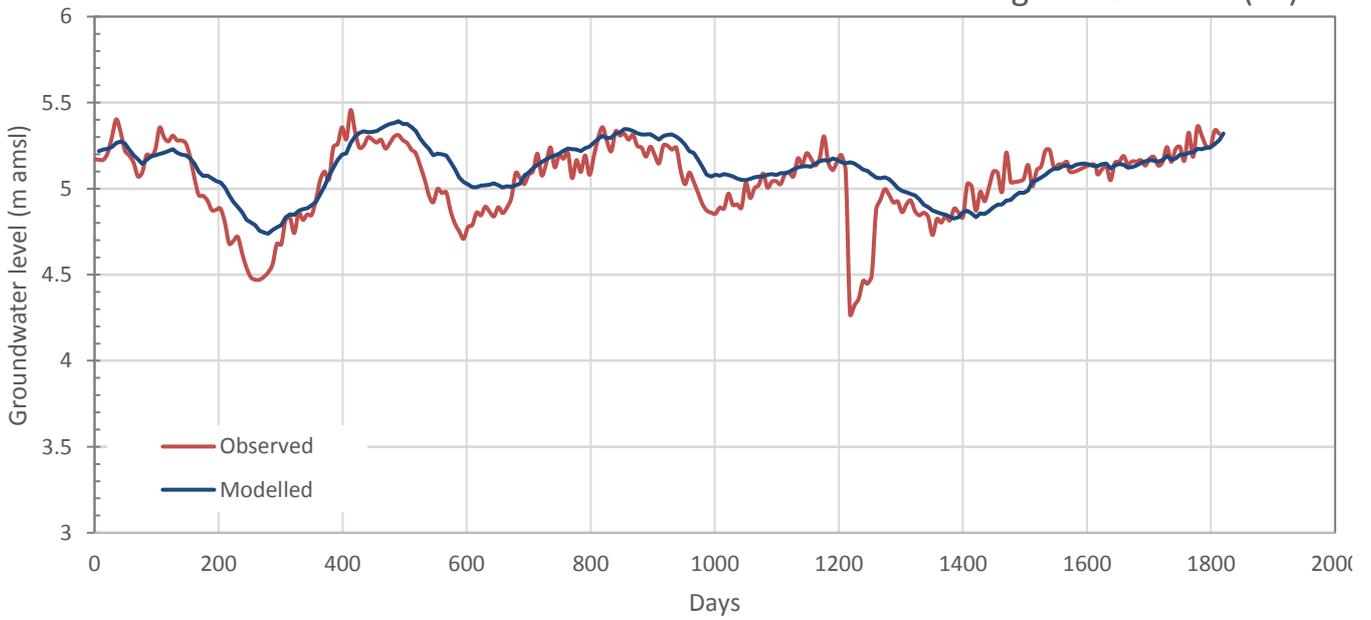
Fig A2.24: UWA3 (L7)
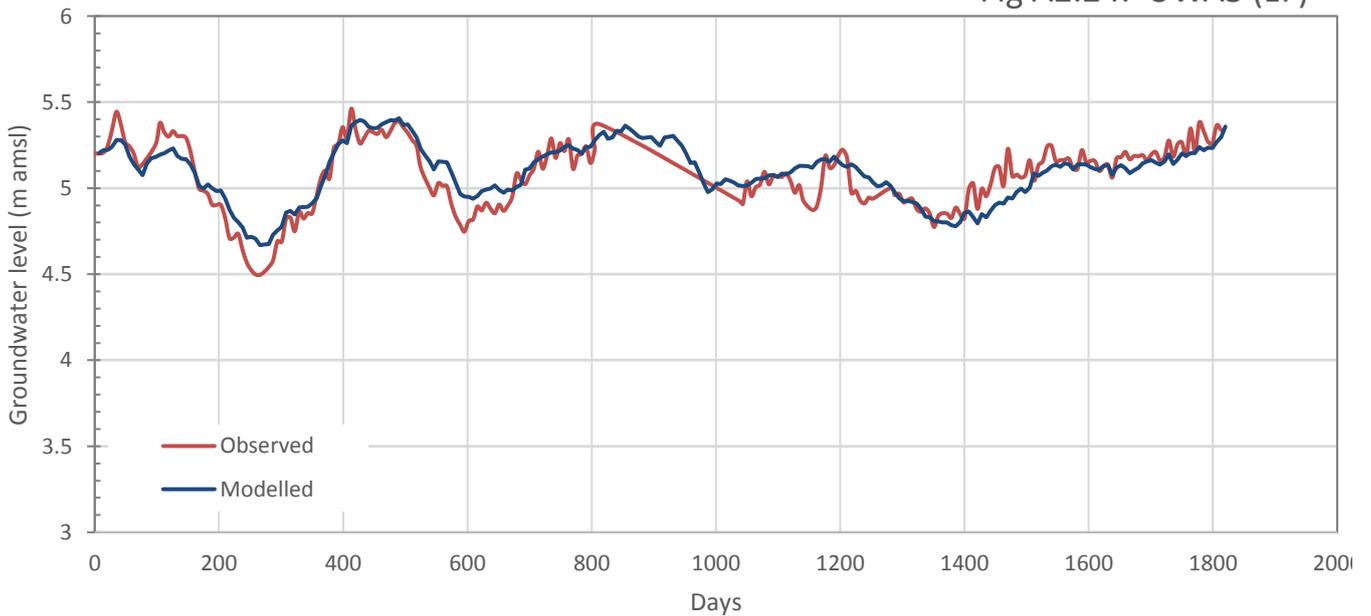
Appendix 3

HAM3 Water balance output plots for calibration run

Fig A3.1 Rainfall recharge
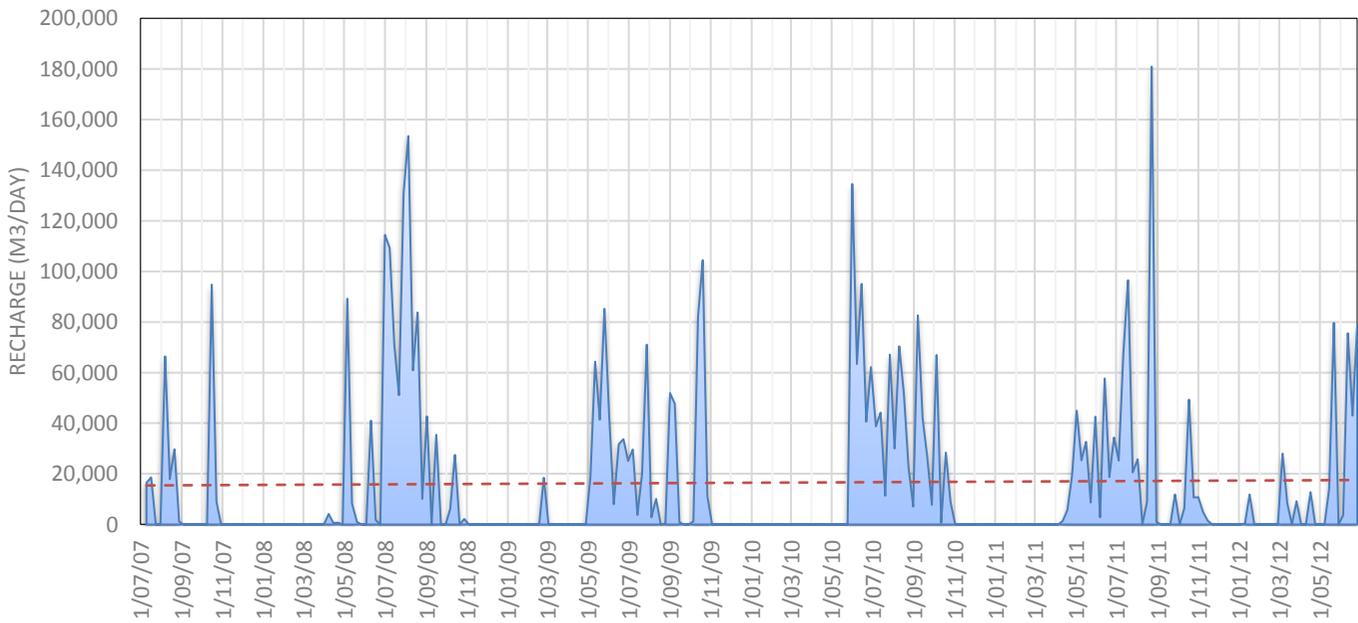
Fig A3.2: Abstraction
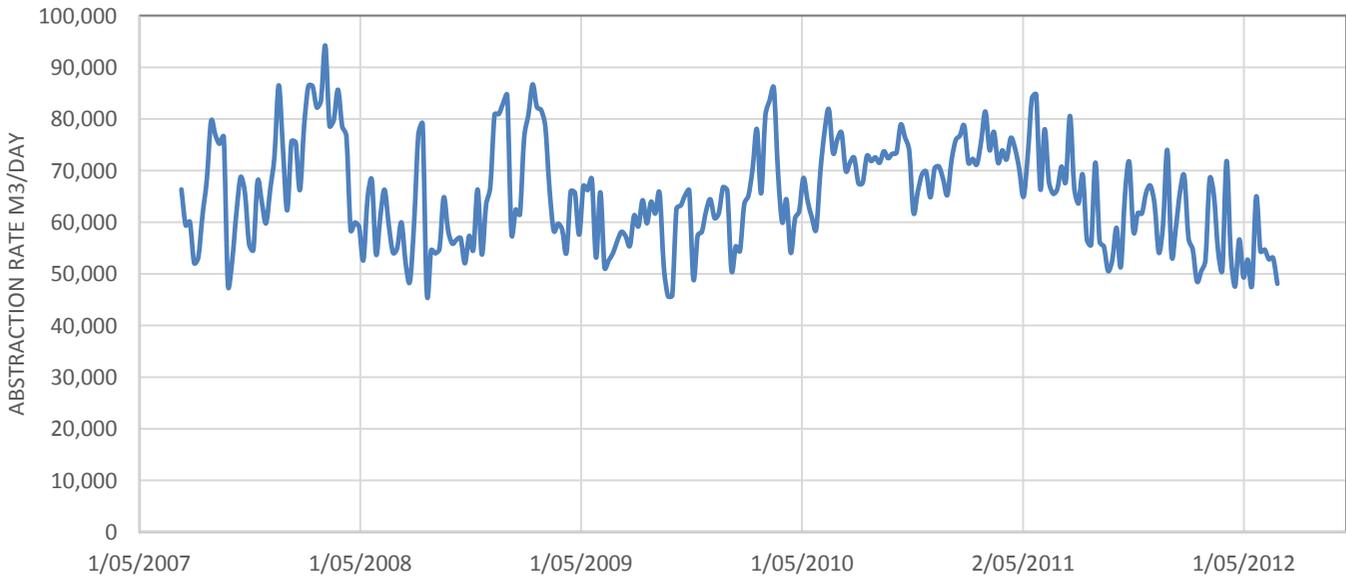
Fig A3.3: Hutt River aquifer recharge (Taita Gorge - Kennedy Good Bridge)

Net River IN (TG-Kennedy GB)
Range in gauged loss
Taita Int Level (Observed)
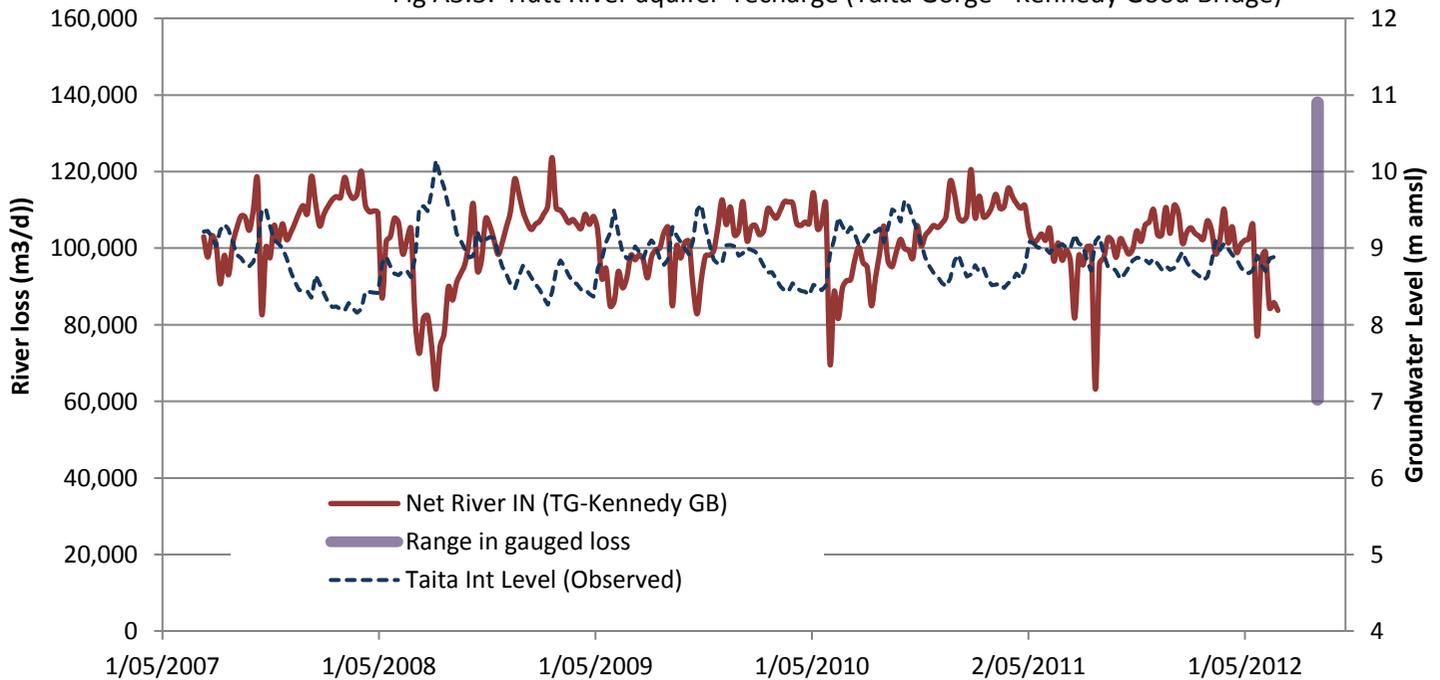
Fig A3.4: Return flow to Hutt River (downstream Kennedy Good Br)
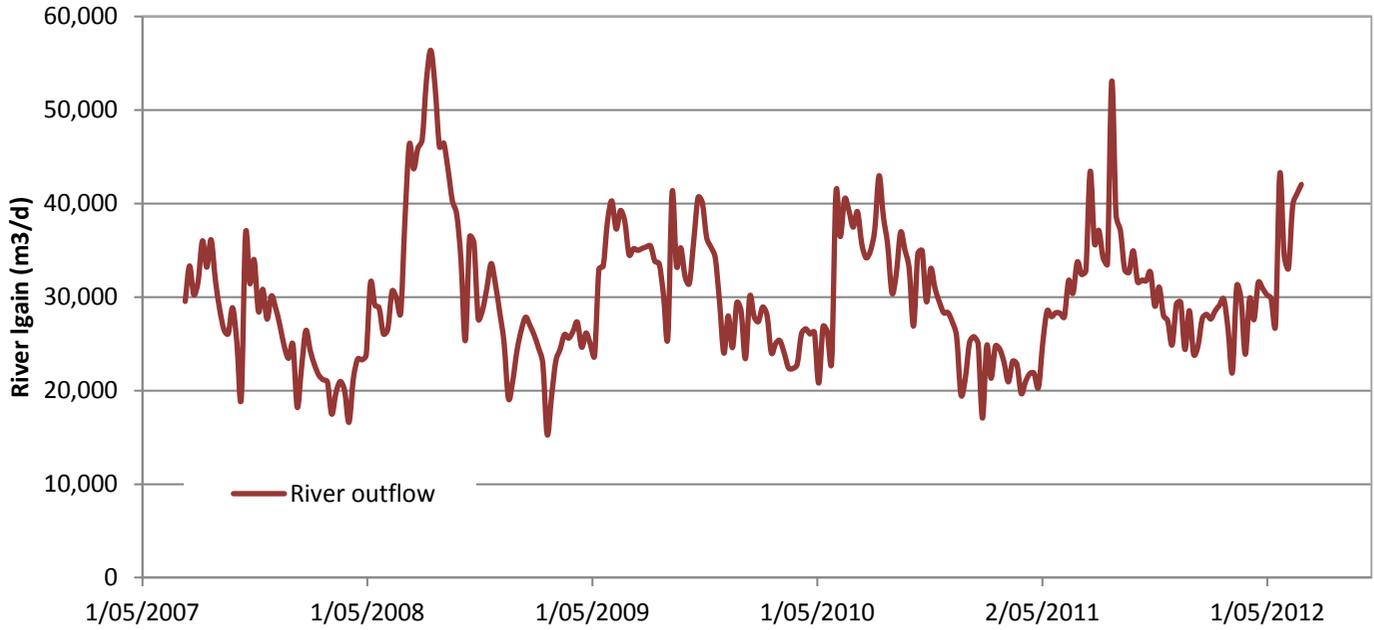
Fig A3.5: Discharge to Waiwhetu Stream (Drain Boundary)
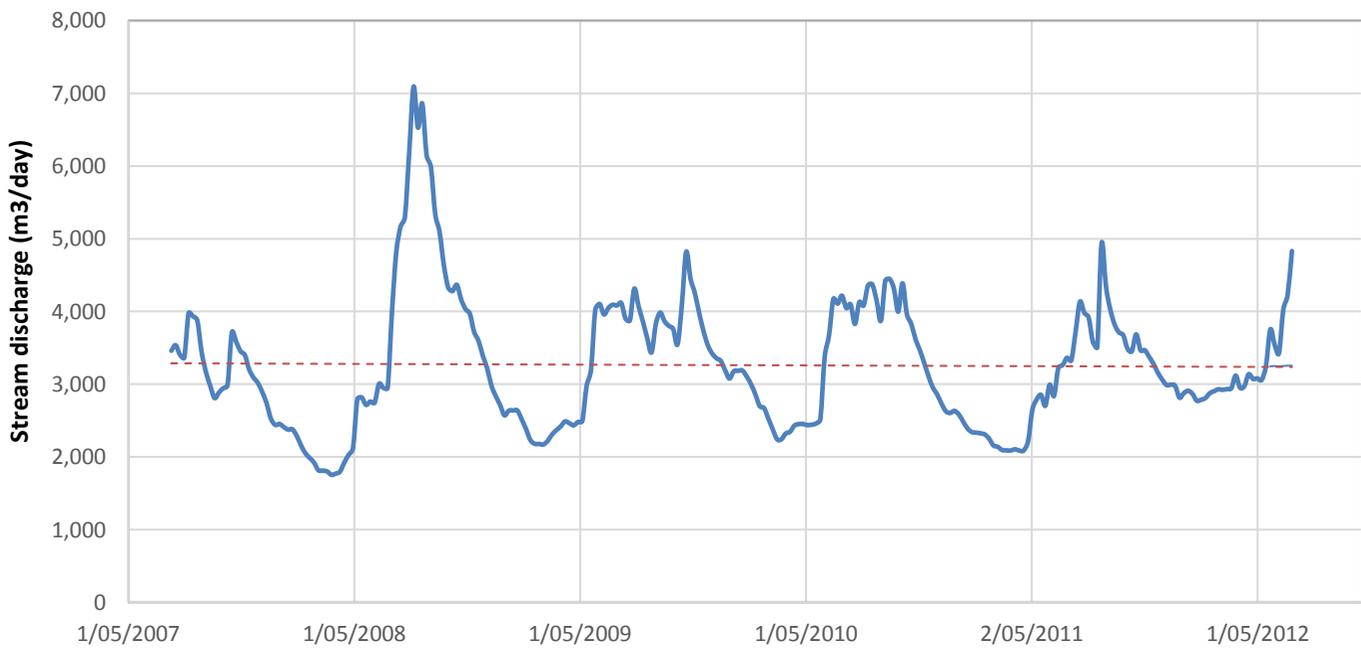
Fig A3.6: Total offshore discharge (constant head)
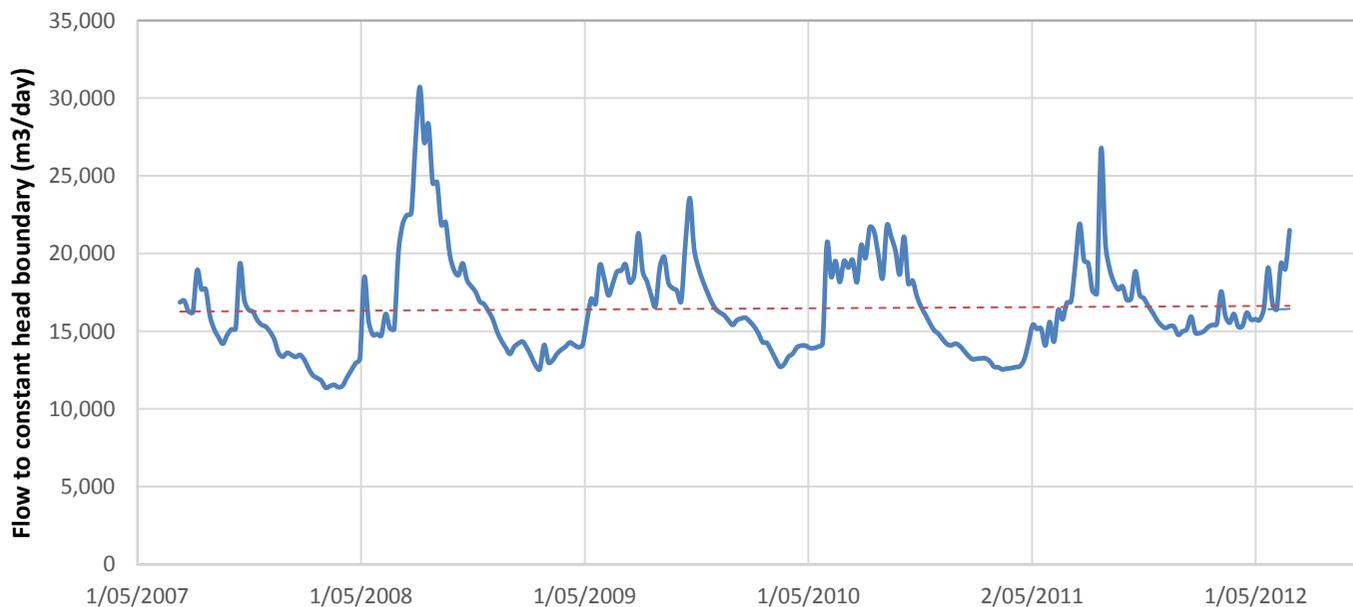
Fig A3.7: Total discharge to sea from submarine springs
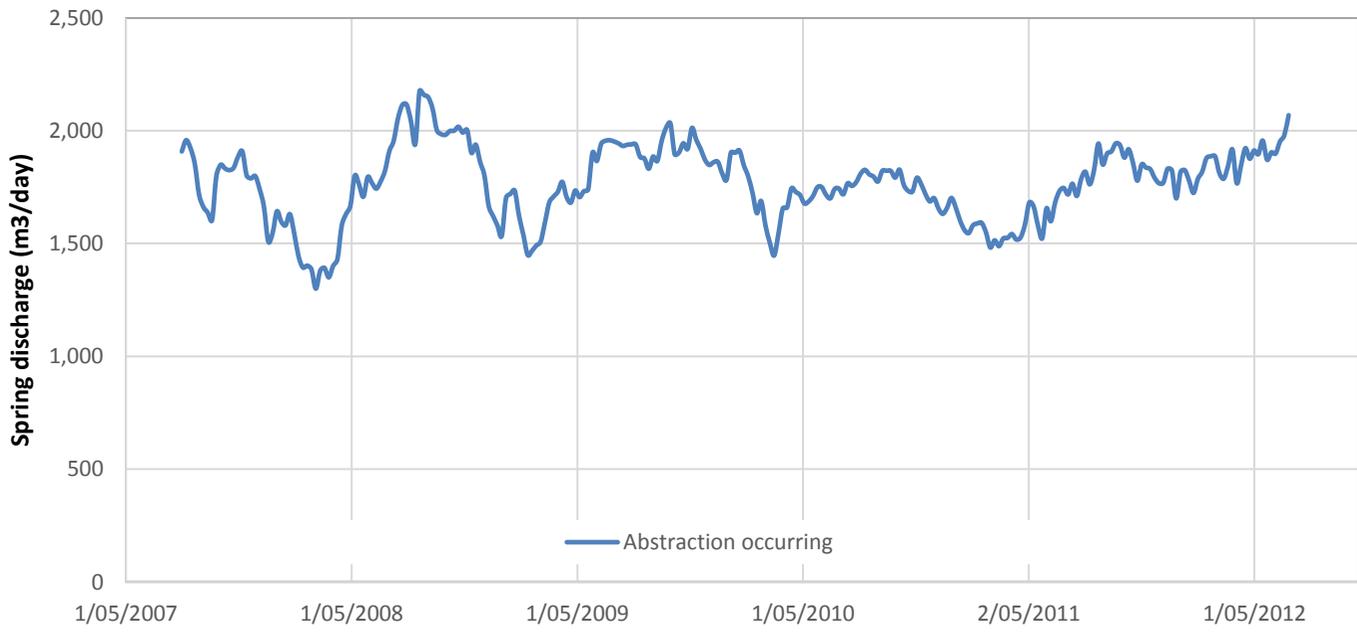
Appendix 4

HAM3 Verification run – head and water balance outputs

Fig A4.1: Head verification - IBM1 (Moera Gravels, Layer 7)
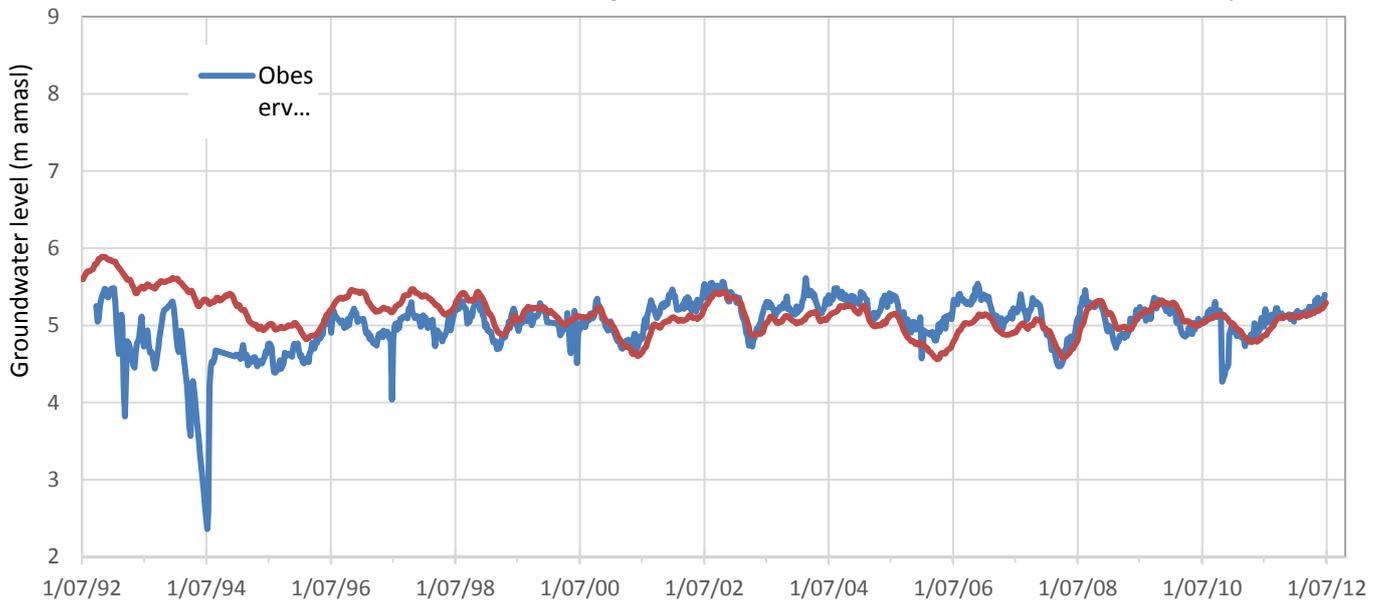
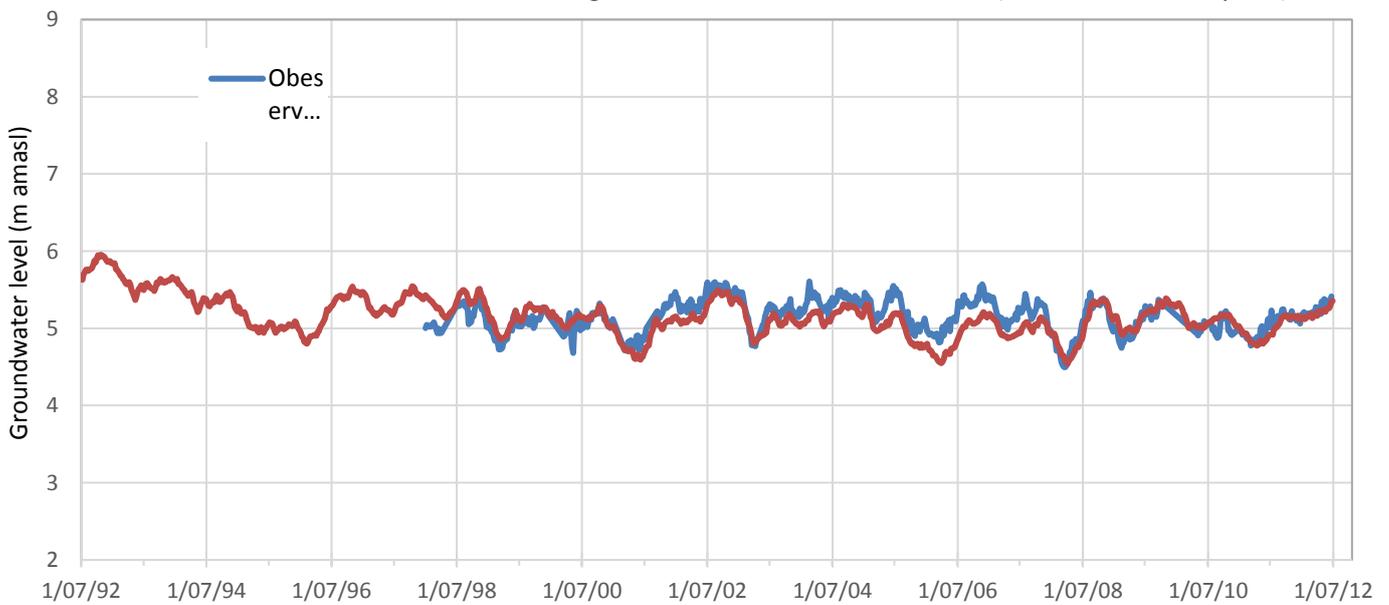Fig A4.2: Head verification - UWA3 (Moera Gravels, Layer 7)

Fig A4.3: Head verification - Mitchell Park (Moera Gravels, Layer 7)
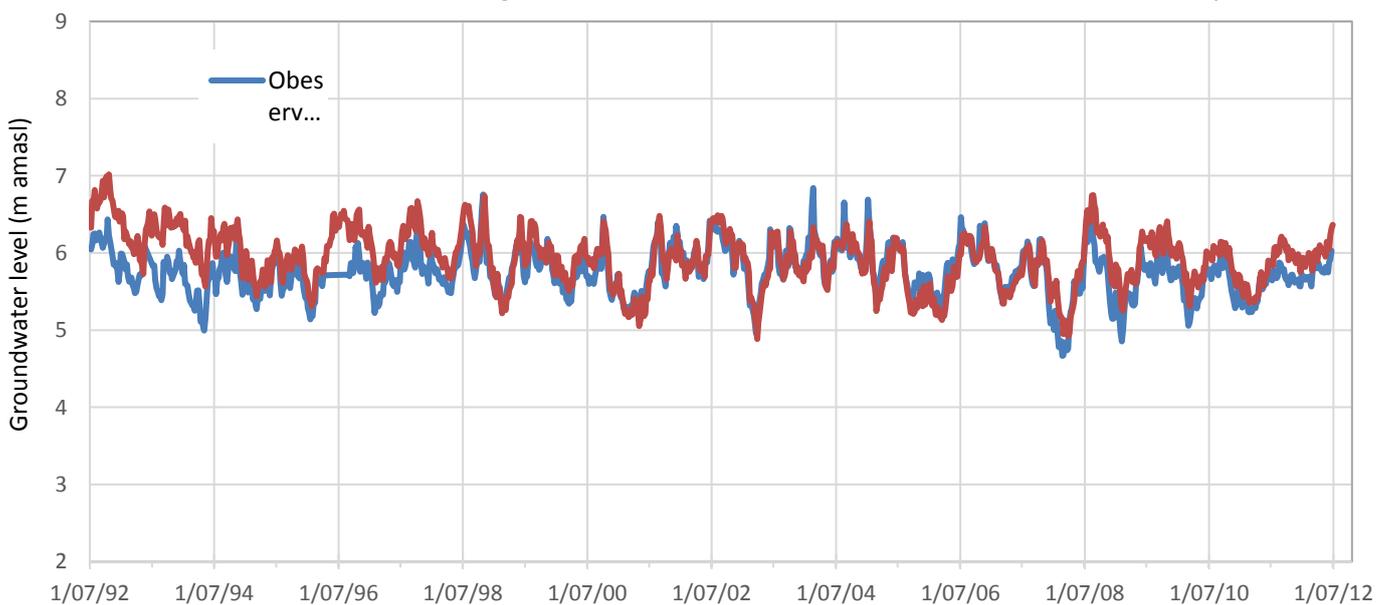
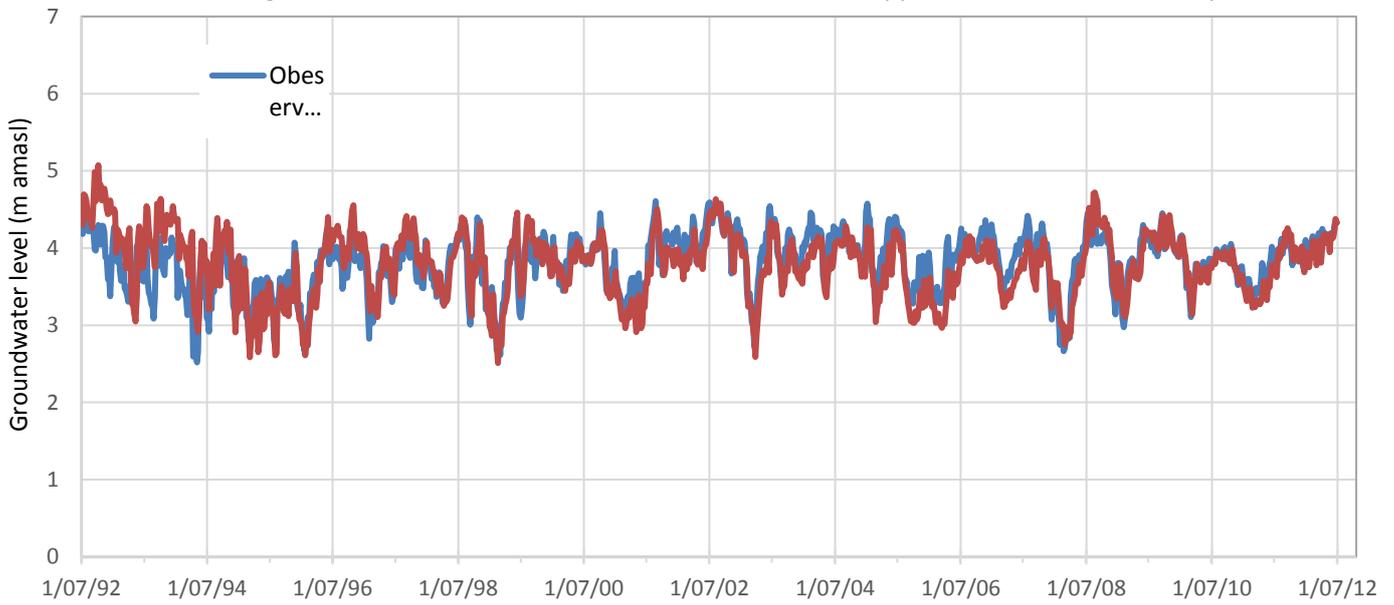Fig A4.4: Head verification - McEwan Park Shallow (Upper Waiwhetu Gravels, Layer 4)

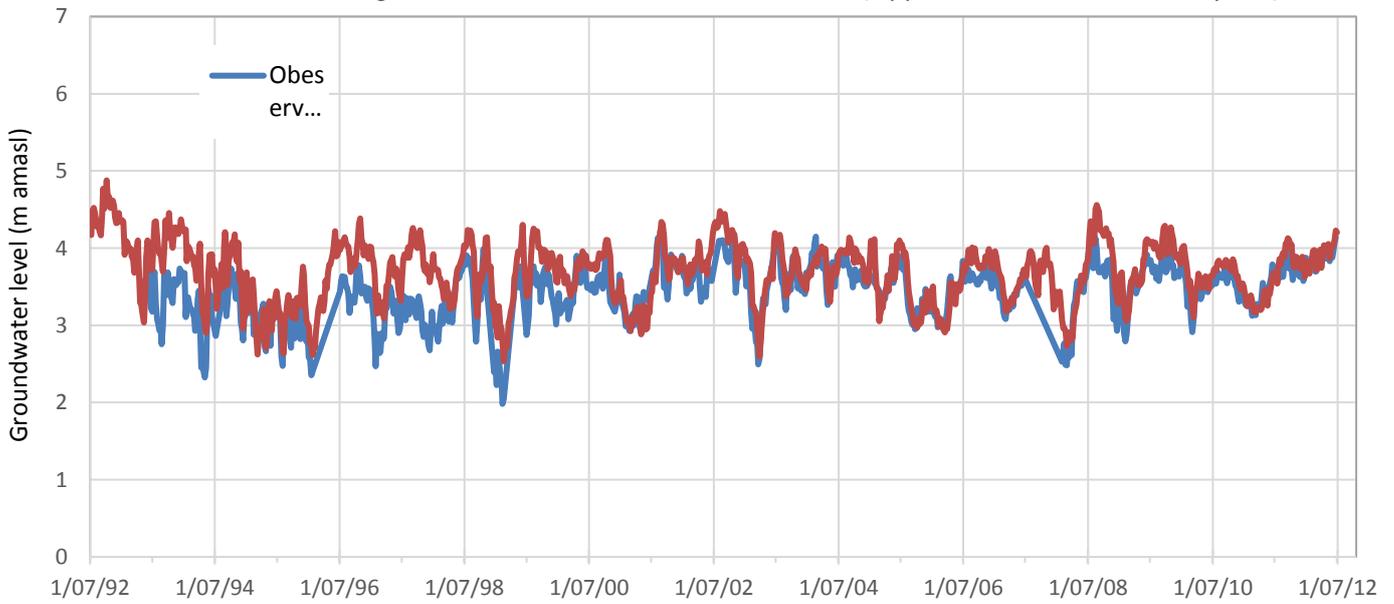Fig A4.5: Head verification - Somes Island (Upper Waiwhetu Gravels, Layer 4)

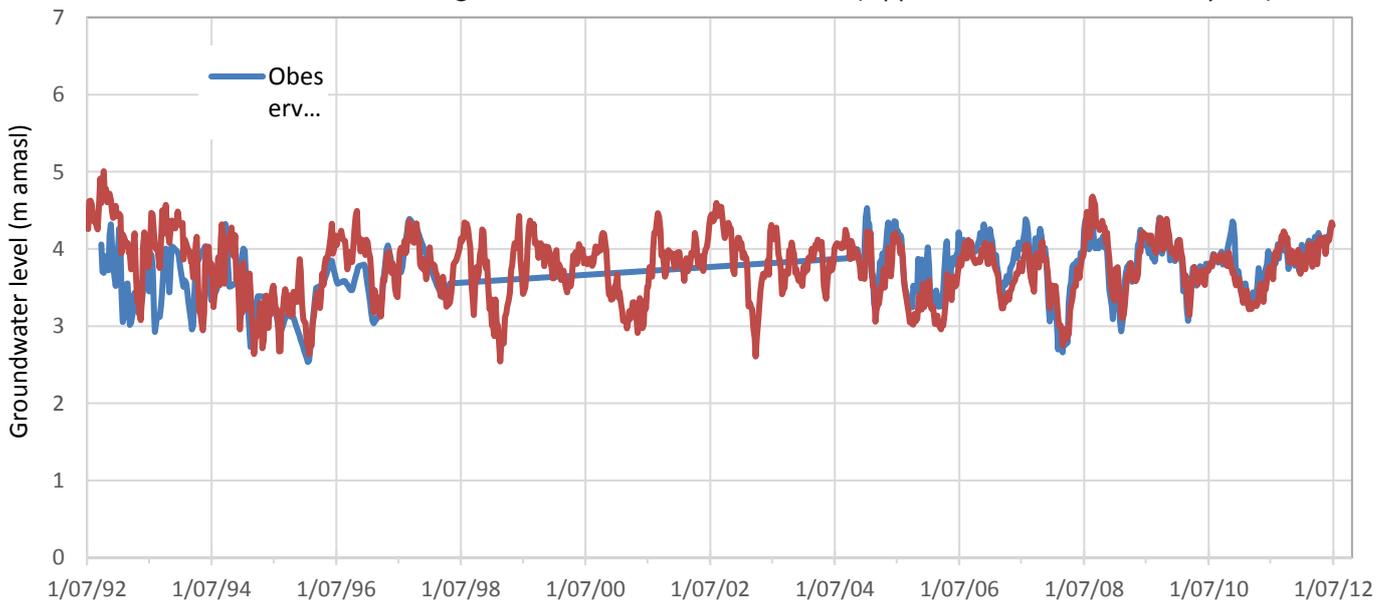Fig A4.6: Head verification - IBM 2 (Upper Waiwhetu Gravels, Layer 4)

Fig A4.7: Head verification - Hutt Rec (Upper Waiwhetu Gravels, Layer 4)
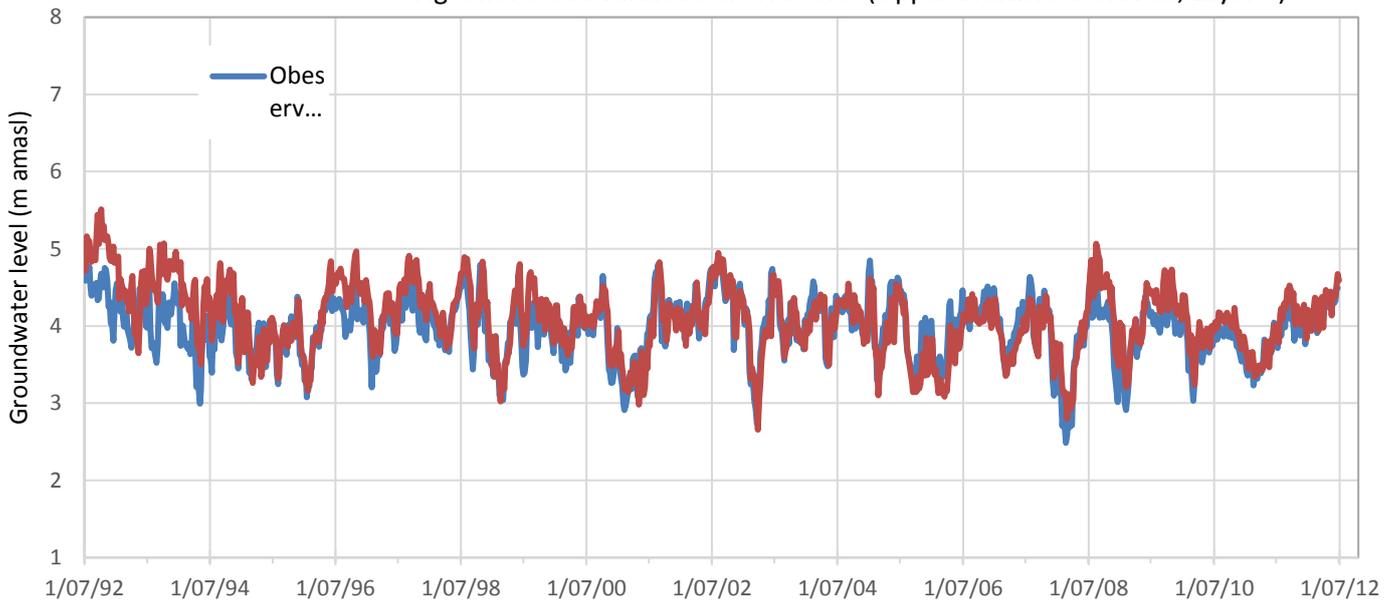

Fig A4.8: Head verification - Taita Intermediate (Taita Alluvium, Layer 4)
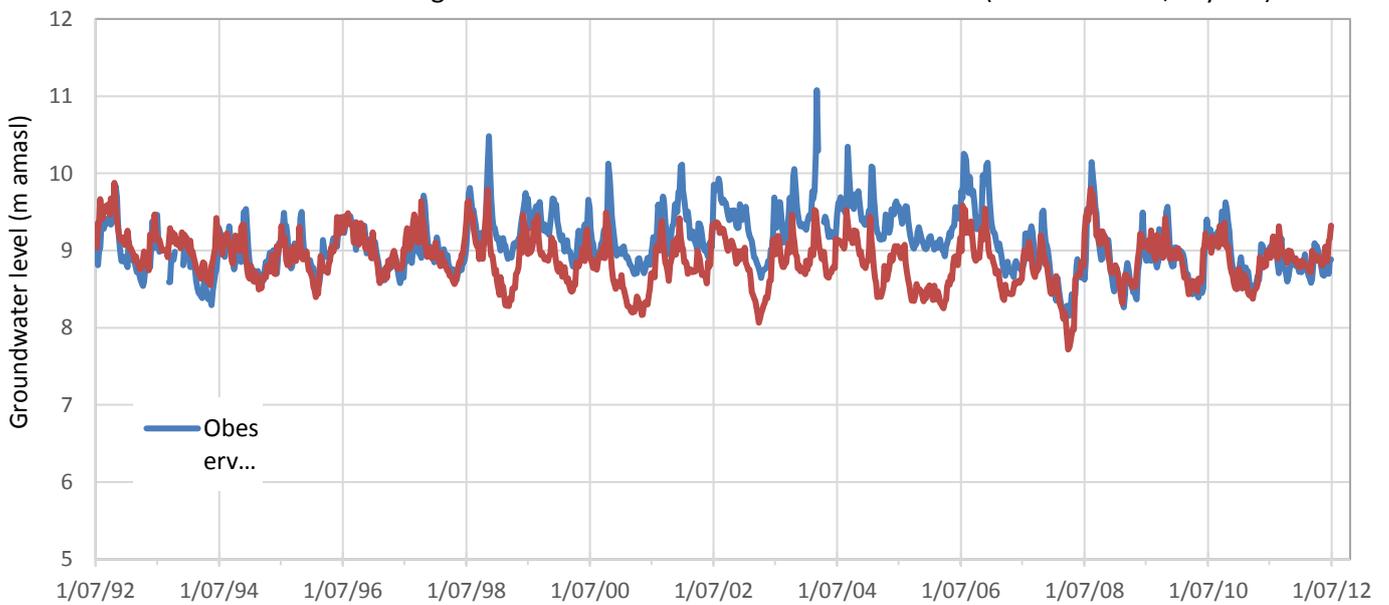

Fig A4.9: Head verification - Thorneycroft Ave (Taita Alluvium, Layer 1)
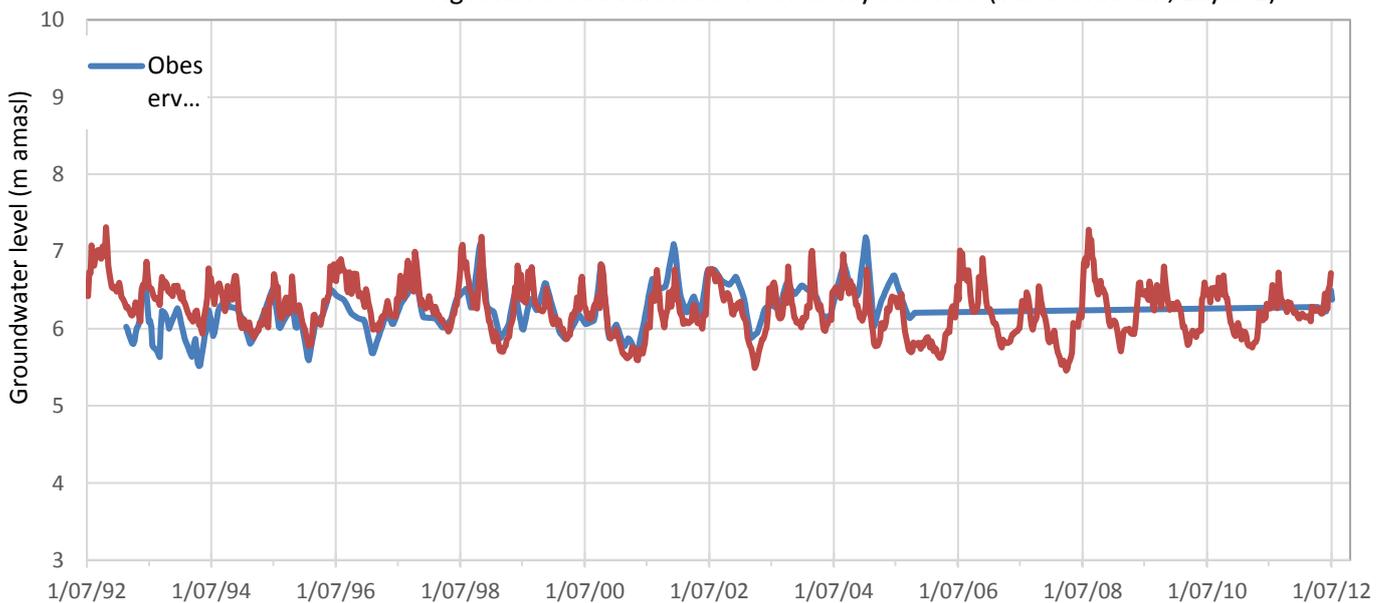
Fig A4.10: Water balance: Net river loss (to groundwater)
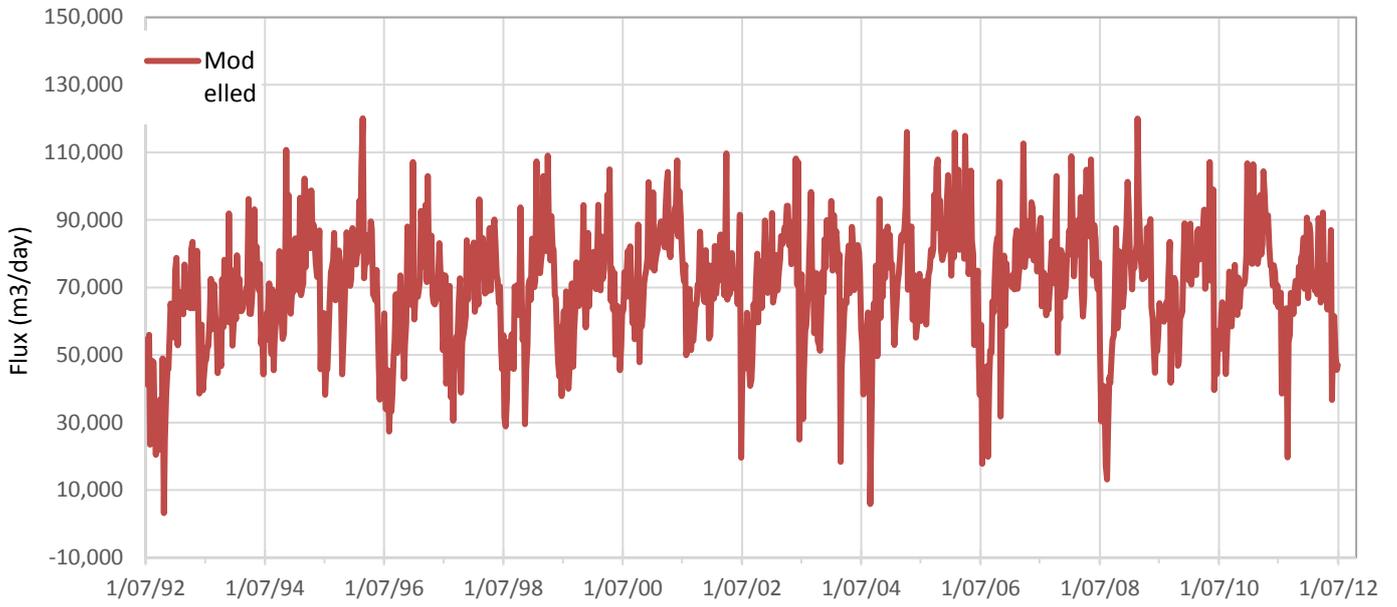
Fig A4.11: Groundwater abstraction
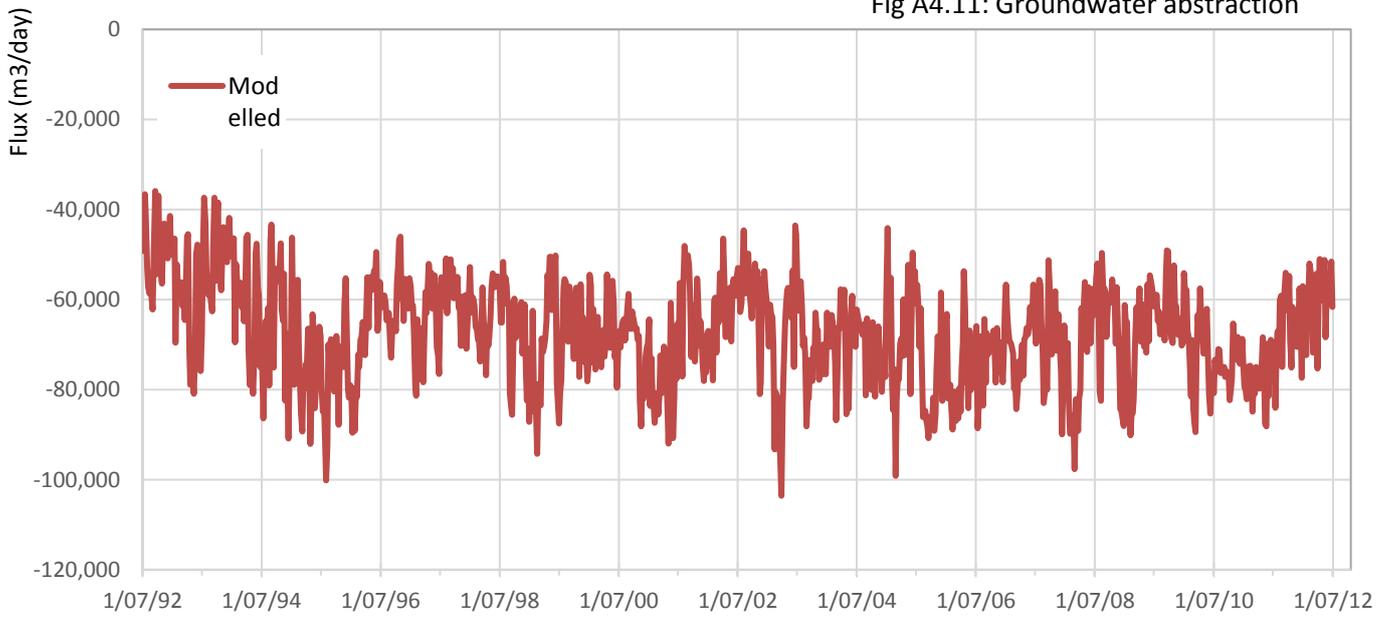
Fig A4.12: Rainfall recharge
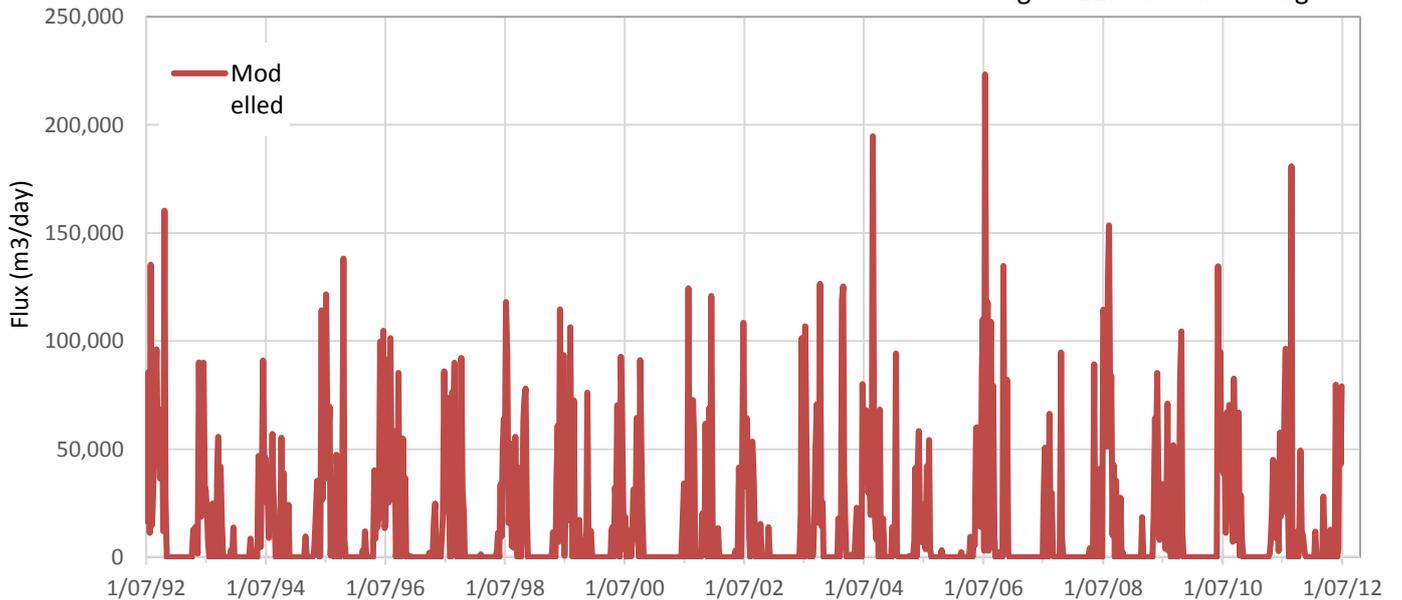
Fig A4.13: Constant head - total offshore aquifer discharge
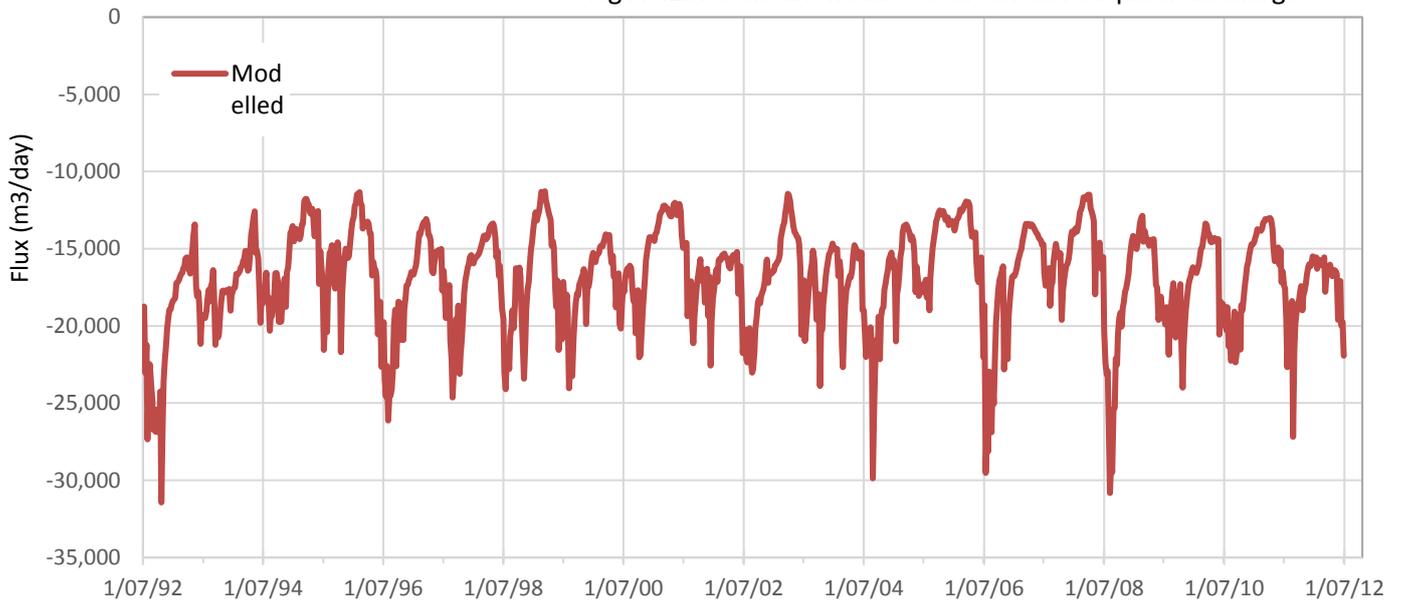
Fig A4.13: Constant head - storage change (+ve = storage loss)
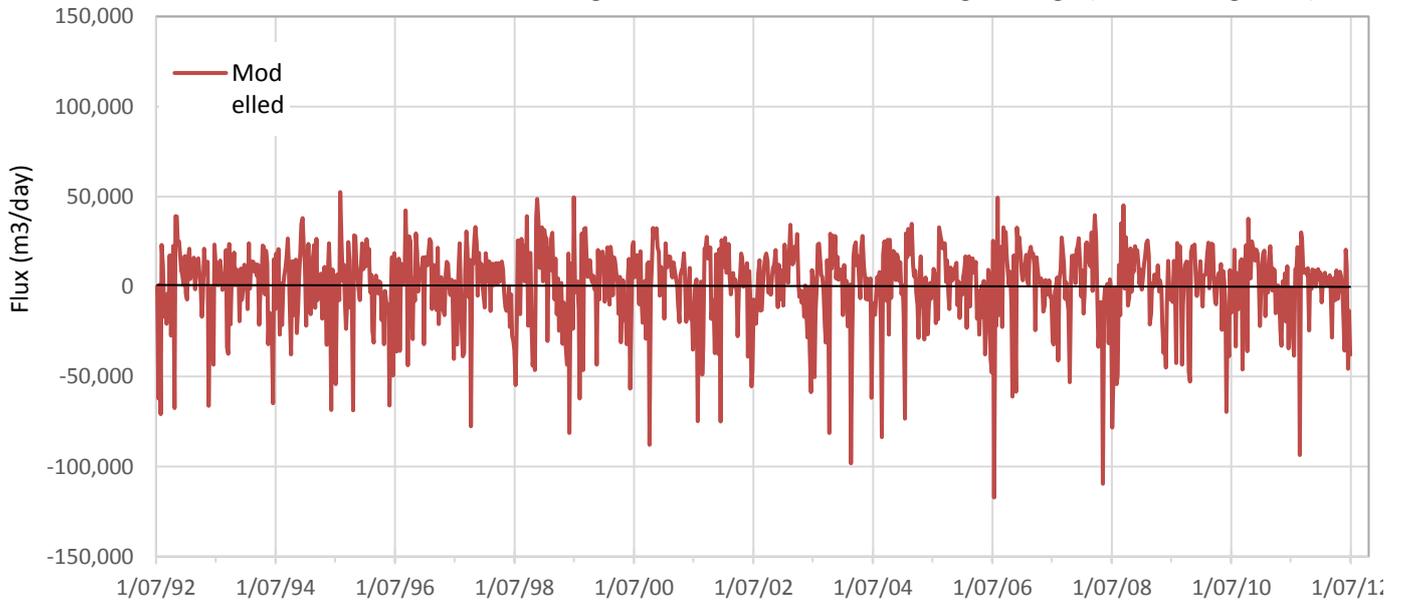
Appendix 5

Technical peer review of HAM3 (Dr C. Moore, ESR)

LOWER HUTT AQUIFER MODEL REVISION (HAM3): GROUNDWATER MODEL REVIEW

ESR

LOWER HUTT AQUIFER MODEL REVISION (HAM3): GROUNDWATER MODEL REVIEW

Prepared For Greater Wellington Regional Council

by

Catherine Moore

September 2013

Client Report

CSC 13008

LOWER HUTT AQUIFER MODEL REVISION (HAM3):

GROUNDWATER MODEL REVIEW

Science Programme Manager

Project Leader

Peer Reviewer

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SUMMARY

Greater Wellington Regional Council (GWRC) requested a review of the recently updated Lower Hutt Aquifer Model (HAM3). The Lower Hutt groundwater system comprises a layered sequence of unconsolidated sediments which fill an 18km long wedge-shaped and fault bounded basin, which is up to 350 m deep at the Petone foreshore and greater than 600m deep beneath Wellington Harbour. Gravel aquifers form the productive aquifers within this sedimentary sequence, with the Waiwhetu Artesian aquifer being the most productive. This Waiwhetu aquifer is exploited for Wellington water supply. The confined Waiwhetu aquifer is overlain with a low permeability marine aquitard, which continues beneath Wellington Harbour. The GWRC wellfield at Waterloo, used to supply much of Wellington's water supply, causes significant, widespread, and reasonably immediate dr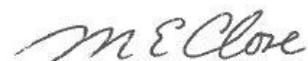awdown responses within the Waiwhetu artesian aquifer. The intersection of this drawdown cone onto the regional flow system must be managed to avoid salt water intrusion.

The groundwater model was developed for the purpose of analysing aquifer sustainability and security of supply under changing climatic conditions (including sea level rise), and to provide tools to assist the sustainable management of this resource. This report documents the conclusions of the model review which was based on the model report (Earth in Mind, 2013), and the HAM3 model files provided. The scope of the review was to comment on the modelling methodology employed in the context of the purpose for which the model is to be used.

The model review considers the likely impact on model calibration and predictive simulations that could result from the documented decisions and assumptions made for each component of the HAM3 groundwater modelling project. The review does not extend beyond this. In particular, the review does not critique the field data employed in the construction of the conceptual and numerical model of the HAM3 model, nor does it examine the credibility of model parameters, beyond the scope of what is considered general knowledge. The HAM3 model has been run but not tested under alternative parameter and aquifer system conceptualisations while undertaking this review.

The modelling methodology employed for HAM3 model was found to be comprehensive, well executed, robust, and fit for purpose, and consistent with the currently accepted definition of best modelling practise as outlined in a number of model guideline documents. The major findings of the model were:

- The maintenance of a minimum groundwater level of 2.7 m (amsl) at the Petone foreshore to avoid salt water intrusion was defined as the critical determinant of sustainable yield for the aquifer.
- To ensure the critical groundwater level of 2.7 m at the foreshore is maintained, an abstraction limit of 90 ML/day was estimated as being the safe yield during periods of low groundwater levels.
- A linear relationship between GWRC groundwater abstraction at the Waterloo groundwater pumping station and groundwater level drawdowns at the Petone

foreshore well was established. A linear relationship between groundwater levels at the Taita Intermediate groundwater monitoring well, and the Petone foreshore well was also developed. These relationships were incorporated into a spreadsheet model, the 'HADC', to allow 'real time' management of temporally changing sustainable groundwater abstractions, during varying climate cycles.

- A reduction in sustainable aquifer yield from 90 ML/day to 70 ML/day would be required to meet the critical groundwater levels at the foreshore given a sea level rise of 1.5 m.

- A number of comments relating to future monitoring, exploration of alternative aquifer conceptualisations, and the adoption of new advances in modelling approaches and analyses which could enhance the information provided by the HAM3 model are made in both the modelling report and additionally in this review. This further work would allow for robust future groundwater management decisions as resource availability is reduced. It is anticipated that these comments can be addressed and incorporated into future model work as appropriate.

It should be noted that some of the proposed future work i.e. formal uncertainty analysis, would not form part of a standard modelling project, as it is highly specialised and at the leading edge of modelling work. These analyses are recommended to be undertaken as a separate piece of work. Similarly, some qualitative exploration of alternative conceptualisations of offshore geology was already undertaken as part of the modelling project, as is appropriate. However, a formal structured exploration of different conceptualisations would instead form a separate piece of work. The lack of such analyses in this reviewed work should not be construed as a failing on the part of the modelling consultant, who has followed current accepted modelling practice.

A brief list of the components of this recommended future work is provided below:

- The continuity and conductance of the overlying confining layer (the Petone Marine Beds) was identified as a critical parameter in determining salt water intrusion risk for both the spring vent and diffuse migration mechanisms. The definition of the offshore extent of the aquifer is also a critical parameter. Exploration of the impacts of slightly different conceptualisations of the confining layer including hydraulic property heterogeneity and sea water fresh water interface is recommended as part of a formal hypothesis testing ('what would happen if') analysis. This exploration would also include alternative conceptualisations along the Wellington fault margin of the aquifer where there is a risk of tearing the aquitard seal during tectonic events.

- Additional data acquisition, particularly of offshore spring and diffuse discharges, and river flow losses and gains measurements, and offshore discharge estimates would improve the accuracy of the model when used to simulate sustainable abstraction under changing climatic and sea level rise conditions, as was identified in the modelling report. As such data acquisition is expensive, a formal 'data worth' optimisation is recommended to guide this process to ensure the most cost effective data acquisition.

- The calibration process followed standard best practice methods, as outlined in three modelling guideline documents, and these calibration results were very good. However it is well established that significant predictive error can exist even where calibration is perfect, as the calibration dataset samples only discrete aspects of the complex real world flow system. It is recommended is the quantification of confidence intervals around the sustainable yield estimates to both ensure that unforseen impacts do not occur, particularly where the predictive simulations incorporate climate and sea level changes beyond that of the calibration dataset. The incorporation of such analyses would provide important information to the resource allocation decision making process (as important as the prediction itself, is the knowledge of how reliably the prediction can be made).

- The adoption of more flexible model parameterisation would support robust parameter and predictive reliability estimation and would underpin any risk analysis. These parameterisations include: (i) the use of pilot points rather than zones of constant parameter value as spatial parameterisation devices, used in conjunction with parameter regularisation devices to incorporate more qualitative geological knowledge; and (ii) the formal inclusion of water balance components e.g .river losses, spring vent flow as quantitative calibration targets (albeit uncertain ones)

- Determination of the lag in the signal transport through the groundwater system between the Taita and Petone groundwater level monitoring sites is required before the time frame of early warning systems provided by linear analyses developed can be utilised. This determination would need to include signal analysis of water levels to separate the pumping impacts from the interacting climatic fluctuations.

1. INTRODUCTION

1.1 General

This report documents a review of the revised and recalibrated version of the model of the Lower Hutt Aquifer groundwater system in the Wellington region (HAM3), as requested by Greater Wellington Regional Council (GWRC). The Lower Hutt Aquifer groundwater system comprises a layered sequence of unconsolidated sediments which fill an 18km long wedge-shaped and fault bounded basin, which is up to 350 m deep at the Petone foreshore and greater than 600m deep beneath Wellington Harbour. Gravel aquifers form the productive aquifers within this sedimentary sequence, with the Waiwhetu Artesian aquifer being the most productive. This Waiwhetu aquifer is exploited for Wellington water supply. The confined Waiwhetu aquifer is overlain with a low permeability marine aquitard, which continues beneath Wellington Harbour. The GWRC wellfield at Waterloo, used to supply much of the water supply for Wellington, causes significant, widespread, and reasonably immediate drawdown responses within the Waiwhetu artesian aquifer. The intersection of this drawdown cone onto the regional flow system must be managed to avoid salt water intrusion.

The motivation for this work is a consequence of Greater Wellington Regional Council's dual responsibilities to:

- To ensure that the aquifer is managed sustainably.
- Provide a bulk water supply to the Wellington municipal area, whereby it must ensure a continuous and secure water supply for the City. Currently 40% of the City's bulk water supply is sourced from the Lower Hutt aquifer, and this abstraction is the predominant groundwater abstraction from this aquifer (the other 60% is abstracted directly from the Hutt River, when there are sufficiently high flows within the river).

The Hutt Aquifer Model 3 is an updated revision of a previous model of this aquifer system that incorporates an updated geological analysis, additional monitoring data, a finer grid resolution and a more robust model calibration methodology.

The review reported here was undertaken on the basis of the modelling report (Earth in Mind, 2013) which documents the revised transient model calibration, and the transient model files (HAM2_Final4) to show the general model file set-up.

The purpose of this review reported here is to comment on the modelling methodology employed in the context of the purpose the model is to be used for. It considers the likely impact on model calibration and predictive simulations that could result from the documented decisions and assumptions made for each component of the HAM3 groundwater modelling project. The review does not extend beyond this. In particular, the review does not purport to critique the field data employed in the construction of the conceptual and numerical model of the HAM3 model, nor does it examine the credibility of model parameters, beyond the scope of what is considered general knowledge. The operational model has not been tested under alternative parameterisations or conceptualisations while undertaking this review.

1.2 Review structure

There are many documented guidelines which describe the best practise modelling approaches to be used for groundwater modelling projects. The MfE Groundwater Model audit guidelines (2002), the Murray-Darling Basin Commission (MDBC) Groundwater Flow Modelling Guideline (2000), Effective Groundwater Model Calibration (Hill and Tiedeman, 2007), and the Australian Groundwater Modelling Guidelines (Barnett et al.,2012) were referred to as a starting point for this review. Checklists provided in these guidelines were used as a guide to verify the completeness of this review. A further and most useful document "Methodologies and Software for PEST-Based Model Predictive Uncertainty Analysis" (Doherty 2010) was also used to guide the review. All these documents describe various phases of the modelling exercise, and these are summarised below as:

- Identification of model purpose
- Model conceptualisation (data analysis, conceptualisation, model design)
- Model calibration (calibration methodology, calibration constraints, verification, prediction)
- Predictions and uncertainty analysis (sensitivity analysis, uncertainty analysis)
- Reporting

This review is structured such that discussion of the model follows through each of these main phases.

2. MODEL PURPOSE

The main objectives of the modelling were to:

- Review the sustainable yield estimates of the Waiwhetu Artesian Aquifer;
- Provide a basis for methodologies for reporting on and forecasting the 'state of the aquifer';
- Provide model based tools for assessments of sustainable yield, and security of water supply during periods of climatic stress; and
- Assess potential effects of sea level rise on the water supply security from the Waiwhetu aquifer

3. MODEL CONCEPTUALISATION

3.1 Data analysis

Available monitoring data and analyses have been carefully analysed by the modelling consultant and the logic, based on this information, that has been used to construct the model is sound and is clearly explained in the report. This conceptualisation and its resulting model design details are briefly summarised in the next two sections to provide context for the review of this model.

3.2 Model conceptualisation

The aquifer system is conceptualised as a layered sedimentary basin, with permeable alluvium interlaid with finer sediments. Unconfined aquifer conditions prevail at the upper inland extent of the aquifer system. The aquifer system then transitions to confined aquifer conditions towards Wellington harbour, as a result of the fine sedimentary layer which overly the sediments towards the harbour (the Petone Marine beds).

The most permeable and productive part of this aquifer system is the Waiwhetu gravel aquifer (layer 3 in the groundwater model). It is this aquifer which is used to augment GWRC water supply. A number of public water supply wells are drilled in this aquifer which can provide up to 90 ML/day to the GWRC, which represents the most significant abstraction from this resource (other abstractions total 3.5 m^3/day).

This GWRC groundwater abstraction contributes approximately 40% of the GWRC water supply, with the rest of the water supply being sourced directly from the Hutt River (60%). Typically groundwater abstraction is greater in summer, to augment the reducing river abstractions, as the Hutt River abstraction may become limited by low flow conditions during the summer period.

Around 80% of the recharge to the aquifer system occurs predominantly via losses from the upper reaches of the Hutt River, which are estimated on the basis of concurrent loss gaugings along the river bed. A smaller rainfall recharge component of around 20% is estimated based on soil moisture model analysis (the Rushton model, Rushton 2003). Discharge from the aquifer system occurs in three main ways. Firstly the aquifer contributes to baseflow in the mid-lower reaches of the Hutt River and to Waiwhetu stream. Secondly the aquifer discharges offshore both discretely via spring vents and also diffusely via the confining layer into Wellington harbour and beyond. The third discharge from the aquifer system occurs via well abstractions.

The boundaries to the aquifer system are generally represented as no-flow (i.e. no water is entering or leaving the model apart from the recharge and discharge mechanisms described above). The one exception to this is the overlying constant head boundary which is used to represent the harbour-sea water boundary to the aquifer system. Note that no open seawater – freshwater interface is represented in this system, as would occur in an unconfined coastal aquifer.

The sustainable yields from the aquifer have been defined in terms of avoidance of critical groundwater levels at which sea water intrusion would occur. These critical groundwater levels have been defined in three ways, considering seawater intrusion occurring either via:

- spring vents;
- diffuse migration;
- a seawater interface (as per Ghyben –Herzberg relationships).

The model has been used to estimate sustainable yield based on maintaining sufficient head at the Petone foreshore to prevent sea water intrusion into the aquifer system via all three of the

above mechanisms. The continuity and conductance of the overlying confining layer (the Petone Marine Beds) was identified as a critical parameter in determining this salt water intrusion risk for both the spring vent and diffuse migration mechanisms. The definition of the offshore extent of the aquifer is also a critical parameter. The report notes that there exists anecdotal evidence of dredging of the Hutt River mouth in the 1940's which punctured the confining layer, resulting in immediate and significant drops in the artesian pressures at the foreshore. The report and this review concur that further work exploring the associated risks associated with the current model conceptualisation should be undertaken, particularly for the sea water rise scenarios. This work should also include further investigation of the Wellington fault at the western margin of the groundwater system, which could cause tearing of the confining layer, and rapid aquifer depressurisation during tectonic events. Given that the fault disposition is not well understood, additional field investigations and a formal uncertainty and hypothesis testing analysis would be useful in quantifying the long term risks to aquifer sustainability from tectonic events.

3.3   Model design

MODFLOW 2000 was chosen as the model code (refer to USGS website http://water.usgs.gov/nrp/gwsoftware/modflow.html). This software solves the groundwater flow problem using a finite difference algorithm. MODFLOW is free to download from the USGS web site and is widely used globally. Groundwater Vistas was used as the graphical user interface for MODFLOW.

The model representation of the sedimentary sequence of the basin is as follows:

- An 8 layer system, with 64 rows and 179 columns. The model cells are generally 100 by 100m but this cell size increases to between 500 and 580 m for cells located at the model boundary. The model has a total of 260 stress periods, each for a 7 day period, representing a five year data set from 2007 to 2012. Each of these stress periods is further divided into 5 time steps for numerical stability.

- There are 184 river cells used to represent the Hutt River and 56 drain cells are used to represent Waiwhetu stream and the submarine springs that occur at discrete locations within the harbour. River stage fluctuations were estimated using Mike11 and river bed elevations were based on survey data. Spring elevations were based on updated bathymetry data.

- Diffuse rainfall recharge was determined based on outputs from the Rushton model (Rushton 2003).

- Pumping variations are based on GWRC monitoring data over a 7 day stress period in their representation in the transient model.

- The initial heads for the transient model run are specified within the MODFLOW discretisation file and were based on a pre-calibration run that represents the average aquifer conditions prior to the start of the calibration period. This is appropriate to avoid instability at the beginning of the transient calibration period.

- No-flow boundaries surround the model domain and a constant head boundary is used to represent the harbour-sea water boundary to the aquifer system.

- The hydraulic parameter discretisation is achieved via zones of constant parameter value.

Refer to modelling report for further details on the model design and conceptualisation.

This model conceptualisation and design was based on a comprehensive analysis of data, which is documented in the model report. The methodology used for this stage of the modelling project was robust and well executed.

There are only two suggestions in relation to the model conceptualisation and design that could be included in future work. Firstly, the parameter discretisation methodology, of zones of constant parameter values, while sufficient for the calibration exercise, the alternative of pilot points (in conjunction with regularisation based on geological knowledge) would offer the necessary flexibility for describing heterogeneity that is required for ancillary model reliability analyses as described in section (5). Secondly, while the model conceptualisation is considered sound, alternative and equally valid conceptualisations could also be explored when assessing the risks associated with the predictive simulations.

4. MODEL CALIBRATION (CALIBRATION, VERIFICATION, PREDICTION)

4.1 Calibration

The parameter estimation software PEST was used for model calibration in conjunction with manual comparisons of measurements. The calibration dataset was comprised of two parts.

- A quantitative fit to monitored ground water levels was used as an objective function for the parameter estimation algorithm employed by the parameter estimation software. A total of 11 manually monitored wells and 13 recorded wells provided a total of 3607 water level measurements within the calibration dataset. A correlation coefficient (R^2) of 0.99 for fits to historical groundwater level measurements was achieved over the calibration period with a root mean square error of 0.17m.
- A qualitative fit to monitored flow losses and spring flows, which are less reliable measurements, was also used to constrain the calibration. The model outputs of these flows provided reasonably good matches to the estimates of these losses (refer to Table 7.3 of the model report).

Analysis of the residuals indicated no systematic spatial or temporal bias was occurring in the model simulations.

Calibration parameters comprised:

- aquifer and aquitard storage and transmissivity parameters,
- river and drain conductances.

The credibility of estimated aquifer parameters was confirmed by comparison with parameter values with aquifer test data.

Volumetric budget terms were checked for the HAM3 files supplied. Note that these are figures from the model output files rather than water balance terms, and refer to numerical errors, and indicate the numerical stability of the solution. Generally these should be less than 1% for numerically reliable solutions, but up to 5% is generally considered acceptable. All volumetric budget terms were well below 1% for all stress periods.

The calibration process followed standard best practice methods, as outlined in more than three modelling guideline documents (e.g. Barnett 2012, and Ministry for the Environment 2002) and the calibration results achieved were very good. However it is well established that significant predictive error can exist even where calibration is perfect, as the calibration dataset samples only a few aspects of the real world complex flow system. This leads to correlation in parameter measurements (which were noted in the model report) which is propagated to predictive error. Therefore predictive uncertainty analyses are recommended to quantify confidence intervals around the sustainable yield estimates, particularly under new climatic and sea level conditions, to ensure unforseen risks do not occur. The incorporation of such analyses would provide important information to the resource allocation decision making process (as important as the prediction itself, is the knowledge of how reliably the prediction can be made). This was also noted in the modelling report and the reviewer concurs. To allow for such analyses, suggestions for future calibration include:

- These flow observations could have also been incorporated into the formal objective function definition, with associated lower observation weights to account for the greater uncertainty associated with these measurements. This inclusion of flow data into the objective function would be necessary if predictive uncertainty analyses and or formal optimisation of monitoring and data acquisition was to be undertaken in the future.
- The recharge to the system and the river stage estimates are fixed in this model calibration, however they are both have some error associated with them. An analysis of the impact of these uncertainties (including that created by the correlation between recharge and transmissivity estimates) on the estimated sustainable yield would be important when assessing predictive uncertainty.
- Incorporation of pilot points as a spatial parameter device accompanied with regularisation instead of zones of constant parameter value. Defining zones of parameter constancy is the traditional method of defining the spatial parameter disposition for a groundwater model, and this has been used for the Lower Hutt aquifer model for hydraulic conductivity and storage parameterisation. Recently evidence that the implementation of pre-calibration defined zones limits the extraction of information available in the measurements comprising the calibration dataset when determining parameter values has been reported in the scientific literature (Hunt et al 2007, Moore and Doherty, 2005, 2006, Fienen et al. 2010). Furthermore zones can limit the reduction in predictive uncertainty that is possible via the calibration process. An alternative spatial parameter device which is being used increasingly relies on "pilot point" parameters, which avoids the limitations listed above and allows for more realistic spatial description of these parameters and their potential heterogeneity,

as informed by the calibration dataset (refer to Doherty 2003, Doherty 2013a, for a full discussion of the implementation of pilot points in groundwater model calibration).

4.2 Model validation

Traditionally model guidelines typically recommend a model validation phase to check the reliability of the calibration. This involves splitting the calibration dataset in two, and using one part to calibrate the model, and the second to assess how well the calibrated model can simulate the second set of data under different aquifer stresses.

A validation exercise was carried out in this project. The PEST calibration was applied to the five year dataset from 1/7/2007 to 27/6/2012. The validation run was for the 20 year period from 1/7/1992 to 1/12/2012. This validation run indicated a good fit over the longer time period.

There is some debate over whether, now that we have automatic calibration tools, instead of a verification or validation exercise, all data should be used in the calibration exercise to maximise the information available to estimate parameters as reliably as possible. This alternative renders the validation phase redundant (e.g. Konikow and Bredehoeft, 1992), and instead measures such as parameter correlation, resolution and predictive uncertainty analysis are used to provide measures of the worth of the calibration exercise. The review recommends that such parameter correlation, parameter resolution and predictive uncertainty analysis are undertaken in future work on this model. The review also recommends that in future model calibrations the entire monitoring dataset could be included as calibration constraints.

4.3 Model prediction

The model was used to predict the maximum yield that would ensure a groundwater level of 2.7m at the Petone foreshore under dry climatic conditions. This yield was assessed as the 'sustainable yield' and was 90ML/day. The modelling report also noted however that greater yields could be achieved during periods of greater aquifer recharge. A temporal definition of sustainable yield could therefore be implemented to provide greater yields during wetter periods.

The HADC spreadsheet tool was developed to assist any such 'real time' management of sustainable yield within the aquifer system. This spreadsheet tool was based on the relatively linear relationships which were able to be established between aquifer pumping and upgradient (at Taita intermediate school well) and Petone foreshore groundwater levels. This has allowed useful and simple linear relationships to be derived to provide a temporal definition of sustainable yields based on groundwater levels at the Taita and foreshore wells.

The report noted that the Taita groundwater levels should in future be able to provide an early warning to allow abstraction rates to be adjusted downwards to avoid critical levels being reached. To achieve this, further work on water level analyses is recommended to establish

the lag between the Taita and foreshore monitoring wells, to provide a timeframe within which such adjustments need to be achieved given such an early warning.

Finally the changes to the sustainable yield estimate that could be expected given a sea level rise of 1.5 m was assessed, accounting for both the changes in relative sea water and groundwater heads (given the differences in density), and also accounting for the compression of the aquitard and aquifer that could be expected.

The model predictive simulations required careful and in some cases innovative analyses of the data, particularly in the HADC spreadsheet tool and in the predictive analysis of sea level rise impacts. The methodology adopted for designing these predictive simulations appears sound and the only recommendation in this section is that a predictive uncertainty analysis should be undertaken as part of future work (refer to the following section).

5. PARAMETER AND PREDICTIVE UNCERTAINTY ANALYSIS AND FUTURE WORK

5.1 Parameter correlation/resolution

The calibration of the Lowe Hutt groundwater model was very good. However as already noted, it is well documented that even a perfect fit to measured data and credible parameter values are not sufficient criteria for reliable parameter estimates and predictive simulations, because the subsurface system is not completely known. It has been shown that model parameters and predictions made by models with even perfect model-to-measurement fits can be greatly in error (Moore and Doherty 2005). The predictive error is a less significant issue where the calibration constraints are of the same type as the predictions being made, as is the case for the Lower Hutt Aquifer Model current sustainable yield predictions. However, as climatic changes that go beyond the calibration conditions, including sea level rise, are simulated, a greater degree of predictive error is expected. Additional measures from the calibration process, such as parameter correlation or parameter resolution (for distributed parameterisations), convey the precision or reliability of the calibrated parameter estimates and would assist in assessing uncertainties, particularly for the extrapolation of impacts beyond that experienced in the model calibration period.

Parameter correlation indicates that none of the correlated parameter values can be uniquely estimated, rather a range of combinations of the correlated parameters can be used to achieve the same fit to the data. This phenomenon occurs when there is not enough information in the calibration data set to uniquely determine each parameter separately. Therefore parameter correlation indicates the extent to which alternative parameter estimates may be likely given the available data (i.e. parameter non-uniqueness). Parameter resolution is used for distributed parameter models (e.g. models where pilot points are used to realistically represent real world heterogeneity) and indicates the extent to which parameter estimates are averages of real world hydraulic properties.

The Lower Hutt groundwater model already exhibits some parameter correlation, despite using devices such as zones of constant parameter value and fixing a number of uncertain model inputs. The impact of 'unfixing' uncertain parameters such as rainfall recharge would only increase this. Such parameter correlation should be explicitly explored however when assessing parameter and predictive reliability. Such measures are straightforward to obtain from automatic calibration exercises (e.g. when using PEST), when used in conjunction with pilot point parameterisation devices. For model outputs that are to be heavily scrutinised (e.g. via the consenting and hearing processes), it is useful to have undertaken such analyses that describe parameter reliability. Furthermore correlation and resolution are also commonly used as building blocks in estimating parameter and/or predictive uncertainty analysis, which is considered an important future analysis for this model.

5.2   Predictions, uncertainty analysis and sensitivity analysis

The parameter sensitivities from the PEST outputs and a more traditional sensitivity analysis was undertaken for the HAM3 model. Both analyses indicated the significance of the Petone Marine sediment parameterisation in terms of fitting to observed head measurements.

Predictive uncertainty analyses have not been undertaken to date in the modelling project but are planned for future model development. While the relativity of groundwater level fluctuations appears to be well represented in the model, spring flows and diffuse offshore discharges are less well understood. Similarly the river flow losses and gains have been considered only qualitatively in the model calibration due to measurement uncertainties. To address the lack of precision in sustainable yields expected as a result of these measurement uncertainties it would be informative to provide the prediction at the likely 95% calibration constrained confidence interval in addition to the presented calibrated model predictive simulations. PEST utilities PREDUNC, PREDVAR and the NULL SPACE MONTE CARLO are among some of the tools could be used to achieve such an analysis (refer to Doherty 2013). Furthermore these quantitative measures can also be used to determine relative worth of observations to model output variability, particularly PREDUNC or PREDVAR utilities in the PEST software suite. These can be used to describe the relative uncertainty of a model output given likely variability of model inputs.

Uncertainty analyses, even subjective ones, add significantly to the reporting of model predictive simulations. The importance of this planned future work for quantifying predictive uncertainty cannot be emphasised enough as an understanding of how reliably an allocation management prediction can be made is as informative to the decision making process as the prediction itself. Pappenberger and Beven (2006) point out that to not attempt to undertake an uncertainty analysis (though it will always be subjective) implies that the modelling undertaken is objective; which is evidence of misplaced faith in physically based modelling. They argue that to address the inevitable subjectivity of the modelling process, modellers need to attempt uncertainty analyses (though they themselves are subjective), but aim to be transparent in their reporting of the assumptions of the uncertainty assessment, much as occurs in the modelling conceptualisation and calibration phase.

Precalibration analysis of the worth of new (not yet gathered) observations in terms of how they reduce predictive uncertainty could also be undertaken to assess which new data would improve the reliability of sustainable yield predictions the greatest, and such an analysis could be used when considering the expenditure required for the gathering of such data (e.g. PREDVAR utilities in PEST, www.sspa.com).

Finally, while the above uncertainty analyses relate to parametric uncertainty, two additional uncertainty analyses are recommended. Firstly quantification of the impact of alternative model conceptualisations on sustainable yield estimates is also recommended as part of a formal hypothesis testing analysis. This would likely include alternative conceptualisations of the Wellington Fault and the offshore noflow boundary.

Secondly, the utility of an early warning system provided by the correlations of a temporal definition of sustainable yield with the groundwater levels at the Taita Intermediate monitoring well, require a definition of the system lag. This would require a separation of the impact of groundwater pumping from climatic variations in the monitoring well data as can be achieved by signal processing of water level data.

6.   CONCLUSIONS

The model that has been reviewed is fit for the purpose it was designed for, i.e. to estimate the sustainable yields for the Lower Hutt Valley Aquifer system and to assess risks to the security of water supply to the GWRC under varying climate conditions (including sea level rise).

The report documenting the model and its use demonstrates that available data have been carefully and comprehensively analysed and reviewed. The logic, based on this information, used to construct the model is sound and in general is clearly explained in the report.

The model calibration process followed standard best practice methods, was well executed and achieved good model to measurement fits. However because even perfect calibrations have been shown to produce model predictive errors it is recommended that future work Incorporates formal predictive uncertainty analyses, as described in the following paragraph. The adoption of "state of the art" spatial parameterisation methods (e.g. pilot points), combined with regularisation in future calibration and any accompanying uncertainty analysis is recommended so that both the reliability of calibrated parameters and of the model predictive simulations can be assessed in a quantitative sense.

A predictive uncertainty analysis is considered an important adjunct to this work that will better inform the resource management decision making process. Some methods to facilitate such analyses have been referred to in the review as requested. Such an uncertainty analysis would span both hypothesis testing to capture the risks associated by alternative valid model conceptualisations and assessment of parametric based uncertainty within any selected model conceptualisation caused by model parameter correlation and insufficient representation of real world detail. Such analyses would particularly focus on the continuity of the confining

bed and any risks to its integrity e.g. along the Wellington fault at the western margin of the aquifer system. Such predictive analyses could also be used to guide future data acquisition, to ensure that new measurements or monitoring is targeted to where the greatest reduction in uncertainty could be achieved.

Finally, the potential to provide an early warning system of reducing aquifer recharge based on the groundwater level monitoring at the Taita Intermediate School site, needs to be accompanied by an estimate of system lag, to provide a timeframe within which groundwater pumping changes must be applied without incurring adverse impacts. This would require a signal analysis approach to assist in distinguishing groundwater level pumping impacts from declining aquifer recharge.

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Appendix 6

Peer review: Resource management approach in the Lower Hutt aquifer model revision (HAM3). Peter Callander, Pattle Delamore Partners Ltd.

Review of Resource Management Approach in Lower Hutt Aquifer Model Revision (HAM3)

⁙ Prepared for

Greater Wellington Regional Council

⁙ June 2014

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Peter Callander

Limitations:

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Table of Contents

Introduction

A numerical groundwater flow model has been prepared by Earth in Mind Ltd (EiM) in order to estimate sustainable abstraction rates from the Waterloo well field and avoid seawater contamination affecting the productive parts of the groundwater system. A report describing the model has been prepared by EiM for the Greater Wellington Regional Council (GWRC) entitled "Lower Hutt Aquifer Model Revision (HAM3): Sustainable Management of the Waiwhetu Aquifer" Final Draft dated 14/5/14. At the request of GWRC Pattle Delamore Partners Ltd (PDP) has reviewed sections 8 and 9 of the EiM report which deals with the management strategies for the Waiwhetu aquifer and the Waterloo well field.

Review Comments

This report sets out the findings of that review, with reference to the specific sections of the EiM report.

<u>Introduction to Section 8</u>

The introduction to section 8 notes how the Waiwhetu Aquifer is currently managed on the basis of saline intrusion risk, but also points out that pumping from the Waterloo well field induces significant loss of flow from the Hutt River. It seems a very valid point that this should be recognised and allowed for in the water allocation regime for the Hutt River as the seepage losses are an important component of maintaining the sustainability of the Waterloo Well Field performance.

It would be useful for the GWRC planning documents for the Hutt River water allocation to allow for:

- the seepage losses induced by Waterloo Well Field, without any low flow restrictions on the well field pumping;
- the ability to carry out works in the river bed to scour or otherwise break up any build-up of silty sediment that might impede seepage losses from the river into the aquifer.

<u>8.1   Impacts of Current and Historical Abstraction</u>

This section provides a useful quantification of the significant effects that the public water supply has on the groundwater system. Namely:

- drawdown in groundwater pressures beneath Wellington Harbour of more than 2m;
- 289 – 463L/s induced seepage losses from the Hutt River, which represents around 45% of the total measured river seepage losses;
- A decrease of 50 – 70% of the submarine spring flows into Wellington Harbour.

These are significant changes to the natural groundwater system and it is helpful to understand that the Waterloo well field pumping has created a highly modified groundwater system.

<u>8.2   Saline Intrusion Risk Evaluation and Management</u>

This section emphasises the principal criterion for management of the Waiwhetu Aquifer is saline intrusion and the need to maintain a minimum groundwater level at the coast. We agree this is the critical issue from the perspective of preserving the water supply.

In Section 8.2.1 two sources of saline water are mentioned: saline water already in the aquifer or backflow of harbour water via spring vents. The discussion dismisses the presence of a saline interface within the aquifer based on geologic knowledge and the calibration of the numerical model.   This is accepted, although there could be other areas of old saline water present in less permeable strata within the aquifer/aquitard system which could be drawn towards the wells over time. This should be a relatively low risk as most water will be drawn through the more permeable strata that contain good quality fresh water. However, the possible presence of old saline water should not be dismissed completely and a wider range of monitoring points (as recommended in the report) will help to address this issue.

Section 8.2.2 describes three approaches for defining critical aquifer states. The wide ranging approach of looking at these critical criteria from several different angles is very helpful to ensure that the appropriate levels are set. The analyses for each criteria appear sound and can be summarised as follows:

Table 1: Summary of Critical Condition analyses		
Critical Condition	**Methods of Assessment**	**Indicated Critical Level**
1. Reversal of Offshore Flow	⁑ Stagnation point predicted by groundwater flow model (HAM3) ⁑ Offshore gradients relative to Somes Island monitoring well ⁑ Cessation of offshore flow indicated by groundwater flow model (HAM3)	⁑ 2.0m amsl at McEwan Park ⁑ 1.7 – 2.0m amsl ⁑ 2.0 – 2.5m amsl

2. Cessation of submarine spring discharge	⁑ Analytical equation for groundwater pressures
	   o Deepest springs south of Somes Island
	   o Shallow springs at Hutt River mouth
	   o Seepage water assessment of springs at Hutt River mouth
		o 2.0m amsl at McEwan Park
		o 1.73m amsl
		
		o 2.2m amsl

3. Traditional groundwater pressure analysis	⁑ Ghyben-Herzberg method	⁑ 1.7m amsl for Upper Waiwhetu aquifer ⁑ 2.2m amsl for Lower Waiwhetu aquifer

The use of multiple methods to consider the appropriate criteria is important. This is particularly so for the consideration of the reversal of offshore flow because the hydraulic gradient is so flat, as demonstrated on the left hand side of Figure 8.6.

The selection of 2.0m amsl as a 24 hour mean is a reasonable judgement. As noted in the report at the end of Section 8.2.3.5 a short term breach of that limit for a few hours due to tidal fluctuations should not cause any problems due to the generally slow movement of groundwater through the subsurface environment.

The only assessments in Table 1 above that indicate higher levels than 2.0m amsl are:

∴ The HAM3 assessment of offshore flow indicated that it ceased "when the foreshore flow is around 2-2.5m amsl." That range is an indication of the coarse scale of the modelling, but the recommended value of 2.0m amsl still fits within the model range.

∴ The seepage meter assessment of 2.2m amsl is based on an extrapolation from higher outflow measurements, which therefore involves an element of uncertainty. Even if the assessment is accurate, the recommended value of 2.0m amsl is likely to be within a range where the pressure difference between the groundwater and the sea water is so small that no significant seepage either into or out of the aquifer is likely to be occurring.

∴ The Ghyben-Herzberg approximation for the Lower Waiwhetu aquifer of 2.2m amsl is less critical than the equivalent value of 1.7m amsl for the Upper Waiwhetu aquifer due to the lower hydraulic conductivity of the deeper strata. However, we do note that the reference to the conservatism of the Ghyben-Herzberg method on page 111 of the report appears to be slightly contradictory to the reason given for the appropriateness of that method on page 104. In our view the Ghyben-Herzberg method is conservative for short term water level declines. However if the water level breaches the Ghyben-Herzberg criteria for longer periods then the risk of sea-water intrusion becomes more realistic.

Based on all these different analyses we consider that the choice of the critical minimum level of 2.0m amsl is not the most conservative judgement, but is a reasonable and pragmatic choice. It is made even more appropriate by the recommendation for "review" and "alert" levels at 2.5 and 2.3m amsl, which cover the full range of estimates that are summarised in Table 1 above.

We support the recommendation to monitor a range of criteria at multiple observation points, as indicated in Figure 8.18, rather than rely solely on McEwan Park. These multiple monitoring methods at multiple points are well summarised in Table 8.2 and the reference to water level limits, gradients between bores and electrical conductivity values are all important criteria that need to be jointly evaluated. It is indicated that only water levels are monitored at the Somes Island bore, although some monitoring of electrical conductivity from a bore at Somes Island could also be useful to identify any trends that might develop. Mark Gyopari has indicated to us that such monitoring may be feasible from the Somes Island water supply.

It is hoped that a new Port Road monitoring well can be added to that schedule once a reliable bore has been installed and background water level and electrical conductivity values have been established so that appropriate alert levels can be set. We presume that continuous monitoring of water levels and electrical conductivity is also carried out at the Waterloo well field itself. For all these monitoring points, even if specific trigger levels have yet to be set it

would be prudent to have an automatic alert generated if any of the water level or conductivity measurements show an unusual change.

This alert level system relies on accurate monitoring of water levels and electrical conductivity and the timely transmission of that information for review and action where required.

We note that Figure 8.19 has some straight lines across each graph which seem to serve no purpose, although we have been advised they are an artefact of the conversion to a pdf format and should be removed.

8.3   Aquifer Yield Evaluation and Management

The section on active aquifer yield management notes that whilst current consenting limits list a single maximum abstraction rate the aquifer system is quite dynamic such that a wider range of peak abstraction rates can occur at different times. Whilst the full numerical model (HAM3) is somewhat cumbersome to run, a simpler approximation of the relationship between maximum pumping rate and monitored groundwater level records has been prepared in the spreadsheet HADC. This appears to be a useful tool to assist the water supply operator to optimise the available abstraction whilst maintaining the aquifer pressures above the trigger water level conditions that have been defined.

The use of the Taita Intermediate and McEwan Park monitoring well data in HADC appears appropriate as they represent the recharge and discharge sides of the aquifer respectively.

The description of the various relationships between wells and pumping rates (on pages 122-124) emphasises that HADC is based on a series of inferred and inter-related relationships. This raises a caution about accepting it as an absolutely accurate predictor of sustainable yield, although it stands up well to the checks that are described in the report, particularly the water level response to pumping in Figures 8.29 and 8.30. However, because of its theoretical and approximate basis we recommend that it should be regularly used to further check its robustness over a wider range of conditions and time periods and for GWRC staff to gain familiarity and confidence in the reliability of HADC to manage the pumping rate: groundwater level relationship.

We note two small errors or inconsistencies on pages 123 and 124:

.   The first line under- Figure 8.24 should read, "The drawdown at Taita Intermediate iscan be calculated using Figure 8.238.24 which ..."

.   In step 2 at the end of page 123 the daily abstraction rate is averaged over the preceding 4 days, whereas in the paragraph above Figure 8.25 reference is made to 7-day average pumping rates (and also on page 139), which creates an apparent inconsistency.

In the last paragraph on page 125 reference is made to the observed recession curves over the last 6-7 years all having comparable summer pumping rates. We are unsure if this is correct and it is an aspect of the analysis that should be checked. If there are differences in the summer pumping rates then that should feed into the analysis of the recession curves, which may contribute to further refinement of the HADC spreadsheet.

We note that there is a factor of 10 difference in the relationship between equation 2 (page 122) and equation 4 (page 130). Equation 4 should read:

max pumping rate = 33,333 * available drawdown – 23,333

Figure 8.31 indicates acceptable sustainable yields of 100ML/day to maintain a foreshore level of 2.3m, although that appears to be not entirely consistent with scenario 2 in Figure 8.21. Furthermore, in the paragraph immediately following Figure 8.21 it is noted that, "if a minimum foreshore groundwater level of 2.0m is to be maintained, that a maximum yield from the Waterloo wellfield of 100 ML/day is appropriate during stressed summer conditions." However Figure 8.21 shows water levels declining below 2.0m which Table 8.2 would require pumping rates to reduce. We expect the difference is because Scenario 2 uses a continuous pumping rate of 100 ML/day, but some commentary to reconcile those differences would be helpful. This should include reference to the importance of variable pumping rates and that the peak rate should not be utilised continuously. In that regard, it does not seem right to recommend an annual allocation of 42,000 ML as is suggested at the end of section 8.3.5. That corresponds to a pumping rate of 116 ML/day every day of the year, which is a slight increase on Scenario 2 in Figure 8.21 that causes the 2.0m foreshore level to be breached, although in practical terms the management measures in Table 8.2 should prevent that occurring by requiring reduced pumping.

On page 132 reference is made to the depletion effect on flow in the Hutt River due to Waterloo Well Field pumping, which can be accommodated in the "core allocation" that is defined for that river. This is an important effect of the abstraction that should be covered off in the GWRC consents and planning framework. In particular, consideration should be given to reserving part of the "core allocation" for the effect of the water supply pumping. Such an apportioning of the allocation should also define whether or not any restrictions on water use should apply at times of low flow in the Hutt River.

We agree with the comments that recognise the Hutt River seepage as being an important recharge mechanism for the Waiwhetu aquifer. It may therefore be prudent to consider measures to disturb the river bed to break up any silt layers that may build up in the bed and lower the amount of seepage recharge into the aquifer. Although we are advised that the bed is highly mobile and regularly disturbed by gravel abstraction activities so at the present time any additional disturbance is unlikely to be required.

However, whilst depletion effects on the Hutt River are an important effect arising from the Waterloo Well Field pumping, we agree with the report that these river effects are less critical than management of the saline intrusion risk.

From a groundwater management perspective it seems useful to define an annual allocation volume (which could be defined as a mean daily limit over 365 days) and a maximum daily rate, both for the aquifer as a whole and for individual consent holders. That allows an equitable allocation process to be applied to all users and provides some certainty and security to users as to how much water is allocated to them within the overall allocation framework.

Based on the HAM3 model, a 365 day average daily abstraction for the Waiwhetu Aquifer of
100ML/day seems reasonable, which is approximately midway between Scenario 1 and
Scenario 2 in Figure 8.21 and should see McEwan Park water levels maintained above the
critical 2.0m amsl threshold, even without the safeguard of low water level restrictions. The
allocation of the 365 day average daily abstraction limit between consent holders would need
to be based on a consideration of existing consents and their consent conditions, but we
understand that an average daily limit of 100 ML/day should be able to accommodate existing
abstractions.

Table 8.3 recommends maximum daily abstraction rates from the aquifer based on water levels
in the Taita Intermediate well, although subsequent discussions with Mark Gyopari suggest
that the maximum abstraction at low water levels should be decreased to 105 ML/day (instead
of 110). From a water allocation point of view it is perhaps more straightforward to define a
single maximum daily allocation number (i.e. 140 ML/day) which would be allocated amongst
individual consent holders based on their individual requirements and the actual capacity that
their wells can achieve. Based on information from Dr Gyopari, this might mean a maximum
daily abstraction of 129 ML/day for the Waterloo wellfield, with 11 ML/day allocated to other
consent holders. However all these maximum daily abstractions should be subject to
progressively greater restrictions if monitoring data shows low water level conditions and/or
increasing electrical conductivity trends in the foreshore monitoring bore network, which is
related to the main threat to the sustainable use of the aquifer.

Such an approach means that if the aquifer is in good health, abstractions can continue without
restriction, but at times of stress, as demonstrated by actual monitoring data, abstractions must
reduce.

We are advised that around half of the other abstractions are from shallow wells close to the
Hutt River and will be subject to specific restrictions at times of low river flow. The impact of
these restrictions should be considered when determining the distribution of allowable
allocations between users of the Waiwhetu Aquifer.

8.4   Aquifer Storage Banking

The analysis of a water banking approach in this report seems reasonable. We do not expect a
"banking" approach to provide a significant long term benefit in such a highly transmissive
aquifer. Therefore we agree with the conclusion that banking would provide only a limited
benefit in helping to sustain a higher future abstraction rate.

9.0   Sea Level Rise/Land Subsidence Impact Assessment

This section discusses an extrapolation of the HAM3 model to simulate aquifer conditions that
are quite different to what has been experienced to date. Key differences are:

- the range of future sea level rise is uncertain, as described in the first paragraph of
  Section 9.

❖   the extra weight of sea water will compress the strata (as described in Section 9.1),
      which will reduce the hydraulic conductivity of the strata, particularly the fine
      grained Petone Marine Beds. However, the extent of that change cannot be
      determined and has not been incorporated into the HAM3 model.

Therefore we feel there is a greater degree of uncertainty in the predictions in Section 9
compared to the rest of the modelled scenarios described earlier.

However, the general message that the maximum sustainable pumping rates will reduce as sea
level rises (as shown in Table 9.1) is sound and is an important consideration for long term
water supply planning. However, the quantification of that decline carries a reasonable degree
of uncertainty.

Fortunately sea level rise is a situation that develops gradually and with careful monitoring and
occasional adjustments to both the HAM3 and HADC models they should continue to provide
useful information to assist in management of the water supply.

Conclusion

Sections 8 and 9 of the HAM3 report present a thorough review of the available data and
provide a useful description of management criteria for the Waterloo Well Field pumping. It is
important to recognise that whilst numerical groundwater flow models such as HAM3 and
HADC provide a useful guideline tool they are a gross simplification of the natural variability
of the groundwater flow system and therefore regular ongoing monitoring of pumping rates,
groundwater levels and groundwater quality must be maintained to check on the real
performance of the system. In that regard the recommendations of using extra monitoring
bores and monitoring both groundwater levels, hydraulic gradients between bores and
electrical conductivity are supported. Once those monitoring records become well established
it will be useful to establish trigger level criteria for all monitoring points.

The development of the HADC spreadsheet should provide a useful management tool to check
on optimal pumping rates and it is recommended that GWRC staff use it regularly to become
comfortable with its predictive capability or to make modifications to that spreadsheet until a
satisfactory level of usefulness is achieved. The peak daily pumping rates recommended in the
report seem reasonable, although they should not be utilised continuously and recommended
weekly, monthly and annual limits could usefully developed that represent lower average
abstraction rates over those longer time periods.

It would be prudent for GWRC to ensure that the effects of the Waterloo Well Field on the
Hutt River are recognised and allowed for in the allocation of water in the Hutt River.

The three stage trigger levels defined in Table 8.2 of the report seem appropriately defined.
Monitoring vigilance should be maintained and if the levels are ever breached then the
associated responses need to be implemented without delay.

	Para	Comment	Response/action
1	p.1; para 4. Comments on Introduction to Section 8	Pumping- induced seepage losses from the Hutt River should be accommodated in the river core allocation framework. Also, ability to carry out works to scour the river bed.	GWRC are in the process of incorporating into surface water allocation policy the induced flow losses from the Hutt River in the reach between Taita Gorge and Boulcott due to pumping from the Waiwhetu Aquifer. *Action*: none required - the HAM3 report already recommends that this be done. The Hutt River bed along the recharge reach is highly mobile and subject to gravel abstraction works for flood protection mitigation. It is therefore not necessary to scour the river bed – there is no evidence that recharge from the river has historically been impeded. *Action:* none required.
2	p.2; para 3. Comments on report section 8.2.	There could be areas of old saline water residing in the Waiwhetu Aquifer some distance offshore, or within less permeable strata. This is a low risk but should not be dismissed.	The proposed saline intrusion monitoring system will provide protection against the onshore migration of saline water. The calculated critical aquifer states and minimum levels will ensure that saline intrusion risk, regardless of its source (via submarine spring flow reversal or migration of saline water in the aquifer) will be mitigated. *Action*: none required
3	p.4; 3rd bullet point	Slight contradictions in texts in the discussion concerning the conservatism of the Ghyben-Herzberg equation. The reviewer comments that the method is conservative for short term water levels declines, but less so for longer term declines.	Text on p 111 (section 8.2.4.1) modified to reflect this. No further action required. *Action*: text modified
4	p.4; last paragraph:	Waterloo wellfield monitoring	The wellfield has a sophisticated automated and continuous water quality monitoring system capable of shutting off the abstraction if water quality changes are detected. *Action:* none required
5	p6; last para	HADC Taita Intermediate recession curves could be refined.	The recession equation for Taita Intermediate is based upon observed data during the summer period. Average abstraction rates during this period tend to be consistent between years – it is considered that there would be little merit in attempting to refine the recession curves. *Action:* none

6	p6; paras 2 and 7	This comments concern the sustainable allocation for the Waiwhetu Aquifer and questions the appropriateness of recommending an annual allocation of 42,000 ML (116ML/day) since the HAM3 model indicates that the foreshore level at McEwan Park would be breached. Revised allocation limits are discussed in paragraph 6 following discussion and agreement.	Discussion has been held with the reviewer around this subject, and further assessment has been carried out to refine the allocation recommendations. It was mutually agreed that an annual volume (or mean daily value), and a maximum daily abstraction rate would be appropriate in order to allow maximum flexibility in the operation of the wellfield within saline intrusion risk management constraints (which over-ride any allocation limit). *Action:* the recommended allocation limits have been revised as follows: **Mean daily allocation**: 100ML (12 month moving average) **Annual allocation:** 36,500 ML **Maximum daily abstraction rate**: 140 ML
7	p6; para 3 and 4	Induced depletion effect of GW abstractions on Hutt River should be accommodated in the river core allocation. Disturbance of river bed to break up silt layers.	See response to point 1 in this table. *Action*: none required
8	p7; comments on section 9.0	There is a larger degree of uncertainty associated with the sea level rise predictions due to the limitations of HAM3. However, the model predictions of a slow decline in aquifer yield are regarded to be valid.	This sentiment is concurred with. *Action*: none required.