Waiwhetu Artesian Aquifer Saltwater Intrusion Risk Management Review

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1. Introduction

The Waiwhetu Artesian Aquifer represents a highly productive groundwater resource in the Lower Hutt Groundwater Zone which supplies about one third of Wellington's water demand. The aquifer extends offshore and underlies much of Port Nicholson where it discharges into the harbour at discrete submarine springs and through widespread leakage in areas where the aquifer capping layer is thin or absent. Under critical conditions, saltwater inflow can potentially occur at vulnerable places in the harbour floor. Saline water is also thought to reside in parts of the offshore aquifer which has the potential, under stressed aquifer conditions, to encroach on the shoreline and affect water supply bores.

Increasing demand to extract the maximum safe yield of the aquifer requires that the risk of saline intrusion is a paramount resource management consideration. The consequences of saline intrusion within the Waiwhetu Artesian Aquifer beyond the Petone Foreshore would have severe detrimental effects on industrial groundwater users and on the Wellington public water supply. Industrial groundwater users located on the Petone area would be under immediate risk to saline water intrusion should critical conditions develop in the aquifer.

The first analysis of saltwater intrusion risk within the Waiwhetu Artesian Aquifer was produced by Donaldson and Campbell (1977) and the current aquifer management criteria, in the form of a minimum allowable foreshore groundwater level, is based on this work. A number of reviews have since been undertaken, although there has been no attempt to revise the management of saltwater intrusion risk on the basis the subsequent advances in understanding the groundwater system and its sub-harbour characteristics.

This report documents a re-assessment of the saltwater intrusion risk for the Waiwhetu Artesian Aquifer based on a review of previous studies, examination of the long-term groundwater level monitoring record, and analysis of system behaviour using the recently updated Hutt Aquifer Model (Phreatos Limited, 2001).

The findings documented in this report, following discussion and consultation, will be used to revise aquifer management criteria aimed at minimising the risk of saltwater intrusion in the Waiwhetu Artesian Aquifer.

2. Hydrogeological Setting

The Lower Hutt Valley south of Taita Gorge contains a tectonically active sedimentary basin bounded by low permeability greywacke basement rocks. The basin deepens offshore and underlies much of Port Nicholson. An accumulation of alluvial and marine sediments to several hundred metres in thickness occupy the basin in which a number of gravel aquifers occur. The Lower Hutt Groundwater Zone (LHGZ) is a multi-layered aquifer system comprising at least three confined artesian aquifers and a shallow unconfined aquifer.

Table 1 summarises the hydrostratigraphic units in the LHGZ.

Table 1: Hydrostratigraphical Units in the Lower Hutt Groundwater Zone

Stratigraphic Unit	Hydrogeological Unit
Taita Alluvium	*Unconfined and semi-unconfined aquifers*
Melling Peat and Petone Marine Beds	*Aquitard*
Waiwhetu Artesian Gravels – Upper and Lower	*Confined/unconfined aquifers and intervening aquitard*
Wilford Shell Bed	*Aquitard*
Moera Gravels	*Confined Aquifer*
Deeper glacial/interglacial deposits	*Aquifer/aquitard sequence*

The Waiwhetu Artesian Gravels, confined by the Petone Marine Beds over much of the onshore and offshore basin, represent the principal aquifer unit in the LHGZ. All major water supply wells abstract from the uppermost Waiwhetu Artesian Gravels at depths of 20 to 40 m in the Lower Hutt and Petone areas. Recent investigations (Brown and Jones, 2000; Phreatos, 2001), involving exploration drilling and re-interpretation of existing bore data, have identified a laterally persistent aquitard within the Waiwhetu Artesian Gravels effectively dividing the unit into two distinct parts – termed the *Upper Waiwhetu Aquifer* and the *Lower Waiwhetu Aquifer*. In this report, the term 'Waiwhetu Aquifer' refers to both upper and lower members except where specified.

Offshore, the Waiwhetu Aquifer is thickly confined by the Petone Marine Beds on the western side of the harbour. Harding (2000) showed that in the north-eastern quadrant of the harbour, the Petone Marine Beds are considerably thinner and interpreted them to be 10-12m thick. The aquitard appears to be absent in the harbour entrance area indicating that the Waiwhetu Aquifer is unconfined in this area and discharges into the sea. The Waiwhetu Aquifer also becomes unconfined between Kennedy Good Bridge and the northern margin of the LHGZ at Taita Gorge. In this area the gravel aquifers of the LHGZ receives recharge sourced from leakage through the bed of the Hutt River. A large proportion of the river bed losses remain in the shallow Taita Alluvium, with the remainder infiltrating to greater depths and recharging the confined aquifers.

Groundwater flow in the various aquifers in the groundwater basin occur down-valley towards the southern edge of the harbour. Throughout the confined zone, hydraulic gradients are always upwards and discharge from the aquifers appears to occur through several mechanisms; these being:

- diffuse vertical leakage through aquitard layers into overlying aquifers and into the sea;
- discrete submarine spring discharges;
- outflow in the harbour entrance area where the aquifers are in direct contact with the sea.

3. Previous Work

3.1 Overview

Donaldson and Campbell (1977) produced the first detailed study of the hydrogeology of the Hutt Valley-Port Nicholson alluvial basin which included an evaluation of the potential and risk of saline water intrusion in the Waiwhetu Artesian Aquifer. Critical to the assessment of saline water intrusion was the characterisation of the aquifer discharge processes. Three mechanisms of groundwater discharge into the harbour were perceived, these being the release from the uncapped aquifer area, discharge through discrete 'holes' in the aquitard taking the form of submarine springs, and general widespread leakage through the aquitard layer (Petone Marine Beds). Submarine discharges from the Waiwhetu Artesian Aquifer were regarded to have been considerably reduced as a result of increased abstraction which may have caused many of the spring leakage sites have ceased flowing.

Although information was very limited at the time of their study, Donaldson and Campbell concluded that a large depression south of Somes Island (31m/17 fathoms) was the principal aquifer discharge zone where the confining capping layer is absent or very thin. Other discrete 'holes' in the aquitard where discharge from the Waiwhetu Aquifer could occur were postulated to be around the Hutt River mouth, near the Point Howard Wharf and around Falcon Shoals.

The large sea floor depression to the south of Somes Island was assumed to represent an important potential access site for saltwater intrusion into the Waiwhetu Aquifer. It was realised that the critical condition whereby saline water backflow into the aquifer would be when the aquifer pressure equalises with the sea bed pressure following the prolonged reversal of the hydraulic gradient between the depression and the foreshore. Reversed gradients between Somes Island and the foreshore were observed diurnally during March 1973 towards the end of a long dry period.

The entry of salt water to the aquifer was described using the Darcy flow equation, taking into account the density difference between sea water and fresh water. For areas where the capping layer is absent, submarine spring discharge was quantified as:

$$Q_{out} = R\ (P - \rho_s\, g\, h)$$

where

R = the leak parameter incorporating the size of the leak and the resistance (kA)
P = the pressure in the aquifer immediately below the leak
ρ_s = density of salt water
g = acceleration due to gravity
h = depth sea water

According to this relationship, higher outflows will occur in shallower waters and, conversely, salt water inflow will occur preferentially at the deeper leak sites. Flow from the submarine springs will cease when

$$P = \rho_s g h$$

$$= \rho_f g \times 1.025h$$

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

Donaldson and Campbell subsequently set about investigating the limiting condition at which the 24 hour average pressure recorded at the Somes Island monitoring bore equalised with the aquifer pressure at the foreshore (i.e. a condition whereby no offshore flow occurs prior to reversal of the hydraulic gradient). By plotting the 24 hour average head difference between Somes Island and McEwan Park against the 24 hour average pressure at McEwan Park for noon and midnight on each day between January 25th and March 6th 1973, a level of 1.4m above the LHCC datum at McEwan Park was derived (Figure 2).

Later reviews of the saline water intrusion potential for the Waiwhetu Artesian Gravels included that of Reynolds (1993) who produced a numerical model for the Lower Hutt Groundwater Zone. Reynolds suggested that the foreshore groundwater level could be safely lowered to 1m amsl on the basis of past observations of the aquifer performance and from the calculated piezometric pressure at Somes Island when an equalisation with the harbour waters would occur (0.8m).

Groundsearch (1993) carried out a general overview of the saline water potential beneath the harbour including a study of water chemistry. The study tentatively concluded that there was no evidence for saline water intrusion.

Cussins (WRC, 1995) used the Donaldson and Campbell conceptual saltwater intrusion model and re-calculated the minimum foreshore piezometric level at which offshore hydraulic gradients would reverse in the Waiwhetu Aquifer. Using monitoring data for 1993 and 1994, the piezometric level at the foreshore (McEwan Park) at which the flow gradients reversed was found to be 2.8m above mean sea level. Cussins concluded that further investigations were needed in order to revise the minimum foreshore levels.

Harding (2000) carried out a study to characterise the sub-harbour Waiwhetu Aquifer and the submarine discharge characteristics. A number a active submarine discharge sites associated with the Waiwhetu Gravels were located and investigated. Re-interpretation of harbour seismic surveys showed that the Waiwhetu Aquifer is up to 70m thick along the west and north west side of the harbour, thinning to 20m or less in the eastern and north eastern areas. The Petone Marine Beds were also shown to be considerably thinner in the NE quadrant of the harbour. Prominent palaeo-channel structures within the gravels were identified from the seismic data, the largest and latest lying to the east of Somes Island. The thinnest area of aquiclude and the largest palaeochannel were found to coincide in the NE quadrant of the harbour where active submarine spring discharges occur. Sea floor depressions in this region were noted to occur where the aquiclude appeared to be very thin or even absent in some places.

Harding provided evidence to show that the Waiwhetu and older gravels extend through the harbour entrance area within a deep faulted valley cut into basement greywacke. In this area, it was suggested that confining layers of fine marine sediment could not have been deposited in this high-energy environment where strong current activity and tidal scouring would have persisted throughout the depositional history of the basin. Geophysical exploration was also used to support the concept that the Waiwhetu Gravels are not confined in this area. Evidence for widespread freshwater discharge related to the Waiwhetu Gravels and/or the deeper aquifers such as the Moera Gravels in the harbour entrance was examined.

3.2 Discussion

Donaldson and Campbell (1977) based their study and analyses on the information available to them from which a technically sound aquifer management policy was developed. There have since been several major hydrogeological investigations, including two phases of numerical groundwater flow modelling (Reynolds, 1993, Phreatos, 2001) and sub-harbour hydrogeological investigations (Harding, 2000). Coupled with the accumulation of an extensive monitoring database, a significant advancement in the understanding of the LHGZ flow system has been achieved over the past two decades. Placed in the context of this expanded knowledge and the changed abstraction regime, the appropriateness of the Donaldson and Campbell analysis and recommendations is discussed below.

Donaldson and Campbell based their aquifer management strategy on the assumption that the submarine depression south of Somes Island was a principal aquifer discharge site. Recent investigations involving measurement of submarine spring flows (Harding, 2000), calls into dispute this assumption as a negligible fresh water flow was measured in this depression at the time of investigation. The depression could have been active historically prior to major groundwater abstractions, but it represents only one in a number of similar harbour floor depressions. Several major spring discharges have since been identified considerably closer to the shore at the mouth of the Hutt River.

The McEwan Park – Somes Island relationship observed by Donaldson and Campbell was restricted to a very short monitoring period during the 1973 drought. It also represents a relationship observed under a quite different aquifer abstraction regime focussed at Gear Island and in the foreshore area. Abstraction near the foreshore has a significant drawdown effect on both the foreshore (McEwan Park) and Somes Island groundwater levels causing the gradient between the foreshore and Somes Island to apparently equalise at a lower piezometric level. Because the McEwan Park monitoring bore also lies within the immediate cone of depression of Gear Island, it is strongly influenced by abstraction drawdowns. Large abstractions from the Waiwhetu Aquifer cause a basin-wide depression in groundwater level but close to the pumping bores there is an increase in drawdown referred to as the 'immediate cone of depression'. The extrapolation of the head gradient between the foreshore and Somes Island may not be valid since a groundwater divide caused by the Gear Island drawdown is likely to occur between these two points. Figure 3 conceptually shows this relationship.

It should also appreciated that the reliability of the Somes Island record, upon which aquifer management is currently based, is questionable since this bore has regularly experienced leakage problems. It would therefore be imprudent to base the security of the aquifer entirely upon this record.

Reynolds similarly assumed that the depression south of Somes Island was the principal entry point for saline water intrusion. It was also assumed that the offshore hydraulic gradient could be extrapolated across the harbour using the Somes Island bore. However, it is feasible that the piezometric pressure in the vicinity of major leaks may locally depress piezometric levels in much the same way as an abstraction bore. A piezometric level at the foreshore of 1m could therefore produce a critical condition whereby saline water could enter the aquifer at submarine depression sites. Since the groundwater system is characterised as being ‘fast’ (i.e. transmissivities are locally very high), a high tide condition could also induce saline inflow. It is considered that Reynolds argument for a minimum foreshore level of 1m carries an unacceptably high risk of saline water intrusion. According to the Ghyben-Herzberg relationship (see Appendix 1), saltwater could reach the Waterloo Wellfield if the foreshore level is reduced to 1m above mean sea level.

Cussins (1995) reassessed the foreshore-Somes Island hydraulic gradient to derive a new minimum foreshore level of 2.8m above mean sea level following the Donaldson and Campbell model for saline water intrusion. As such, it is subject to the same limitations although the more recent monitoring data used to derive the relationship are appropriate to the current abstraction regime. However, the suggested foreshore level appears to be over-conservative since saline water cannot invade the Waiwhetu Aquifer at the foreshore when the piezometric head is at 2.8m amsl because the base of the aquifer would need to be deeper than 100m whereas its maximum depth is around 80m at the foreshore.

4. Sub-Harbour Aquifer Characterisation

4.1 Offshore Aquifer Geometry

Harding (2000) produced a revised isopach map for the Waiwhetu Gravels beneath the harbour based on the seismic data collected by Davy and Wood (1993). The map (Figure 4) shows that the gravels are widespread beneath the harbour and that they are thicker in the north and west, and shallower in the south and east. This configuration is consistent with the tectonic history of the area which has resulted in the formation of a fault angle depression associated with the Wellington Fault and accumulation of thicker deposits of sediment in the deepest part of the depression along the fault. Figure 5 shows a contour map for the base of the Lower Waiwhetu Gravels showing the deepening of the sedimentary basin towards the west. Geophysical interpretations suggest that the gravels are around 20m thick on the eastern side of the harbour, thickening to as much as 70m alongside the Wellington Fault. Evidence for prominent palaeochannels on the seismic lines indicate that the river historically remained close to the Wellington Fault depositing a large thickness of gravels. However, the river appears to have later shifted east of Somes Island as shown by a major well-defined palaeochannel towards the top of the gravels in this area (Harding, 2000). The confining beds are also recognised to be thinner in this area as discussed above, which together with a postulated preferential pathway represented by the palaeochannel, have an important bearing on the distribution of discharge from the Waiwhetu Gravels into the harbour, and conversely, for saltwater intrusion back into the aquifer.

4.2 Abstraction Stresses

The Waiwhetu Aquifer is exploited primarily for municipal water supply with a small number of industrial users. Since the mid-1980's municipal abstraction was shifted from Gear Island near the foreshore, some 3km inland, to the Waterloo Wellfield. The current wellfield comprises some 8 abstraction bores and has consent to abstract up to 85 ML per day on a moving average over a 12 month period and up to 115 ML per day for up to 90 days in any 12 month period. Figure 6 shows the average daily abstraction rates from 1994 to present. Prior to early 1999, the abstraction rate from the wellfield averaged about 40 ML/day and has been subsequently increased over a 12 month period to between 70 and 90 ML/day. The increased abstraction rate has caused the cone of depression associated with the wellfield to expand to the south by at least 1km as demonstrated by Figures 7 and 8 which show the relative gradients between the Hutt Recreation Ground, Randwick and McEwan Park monitoring bores. The locations of the various monitoring bores are shown in Figure 1. These plots demonstrate that in early 1999 the groundwater level at the Hutt Recreation Ground bore started to decline as a result of increased abstraction from the Waterloo Wellfield (Figure 8A) with a reversal of the flow gradient between the bores occurring at the beginning of 2000. The 2000/2001 summer period has seen the rapid decline of water levels at the Hutt Recreation Ground monitoring bore indicating that the wellfield's immediate cone of depression is expanding. Although Figure 8A shows a reversed gradient between McEwan Park and the Hutt Recreation Ground monitoring bores, this is probably not the case as the data from the intervening Randwick monitoring bore suggests that there is a relatively flat gradient between this site and the foreshore (Figure 8B). It appears that a groundwater divide exists somewhere between Randwick and McEwan Park that moved southwards during the 2000/2001 summer as groundwater was drawn from storage. Figure 9 is a schematic representation of the groundwater levels between the foreshore and the Waterloo Wellfield during this period illustrating this concept. Figure 10 shows the simulated head profiles along the LHGZ using the revised Hutt Aquifer Model to show the effects of pumping from Waterloo and from Gear Island.

Should drought conditions continue, the divide would eventually intercept the foreshore and migrate offshore causing a true reversal of flow gradients between the wellfield and the foreshore to develop. The development of such reversed flow gradients creates a potential for saline water intrusion.

4.3 Offshore Head Distribution

The offshore head distribution within the Waiwhetu Aquifer is poorly characterised and has been estimated using the Somes Island monitoring bore in combination with numerical modelling. The modelled head distribution is shown in Figure 11 indicating a very flat gradient, in the order of 1×10^{-4} near the foreshore and decreasing to 5×10^{-5} beneath the central harbour area. The modelled heads represent a broad approximation however and do not take into account localised increases in gradient around aquifer discharge zones and springs. The model does not incorporate an unconfined condition at the harbour entrance since it is assumed that minimal discharge occurs in this area due to the presumed presence of saline water in the aquifer here and that all aquifer throughflow is accounted for by abstractions and submarine spring discharge.

4.4 Potential Salt-Water Intrusion Entry Sites

Harding (2000) has identified a number of areas where spring discharges have been measured and these are indicated in Figure 12. Many spring discharges occur near basement outcrops, possibly as a result of a seismic decoupling of the unconsolidated sediments caused by the differential shaking velocities of the basement rocks and the sediments. There are also spring depressions in the harbour floor which are not associated with the basement contact which appear to occur in areas where the aquitard layer (Petone Marine Beds) is thin and may have been breached by high artesian pressures and/or liquefaction during seismic activity.

The principal active spring discharge zones identified by Harding (op. cit.) are those shown in Figure 12 and are as follows:

- off the Hutt River mouth (zone 1)
- off Seaview (zone 4)
- off the northern tip of Somes island (zone 5)
- Falcon Shoals and harbour entrance (zones 7 and 8)

Depressions previously considered to be a major source of artesian leakage from the Upper Waiwhetu Aquifer on the south side of Somes Island appeared to have exhibited no sign of submarine discharge (Harding, 2000).

The active spring discharge sites listed above, together with other unidentified discharge zones and formerly active submarine spring vents, are potential saltwater entry localities offering a fast route into the aquifer. It is postulated that many of the springs lie along highly active preferential flow paths within the aquifer (palaeochannels), and therefore the rapid backflow of saline water under appropriate aquifer conditions would be expected. The closest, and apparently the most active, submarine spring discharge zone lies at the mouth of the Hutt River less than 1km from the foreshore.

There is little evidence to suggest that there is significant fresh water discharge in the harbour entrance area. It is possible that saline water occupies the Waiwhetu aquifer in this area and that a saline wedge extends northwards beneath the harbour.

4.5 Present Salinity Distribution

The apparent hydraulic connection between the Waiwhetu Aquifer and the sea in the harbour entrance area suggests that saline water is present in parts of the sub-harbour aquifer. Assuming the validity of this premise, a saline wedge may extend from the harbour entrance area where the aquifer is unconfined, to some point beneath the harbour in the north. The position of the wedge will depend upon the aquifer base elevation and on the aquifer throughflow. The aquifer may also contain connate sea water, trapped as pockets in the aquifer during the deposition of the Petone Marine Beds. This saline water may reside in deeper less active parts of the offshore aquifer.

The past 50 years or so have seen a progressive decrease in the aquifer throughflow due to the exploitation of the Waiwhetu Aquifer. It is estimated that between 80 and 90% of the aquifer throughflow is currently abstracted. The remaining throughflow to the harbour area therefore represents less than 20% of the natural outflow which will have caused the hypothetical saline-fresh water interface to have moved landwards. There is no evidence to date that the wedge has encroached as far as Somes Island or the foreshore area. However, since the existing bores only extend into the most productive upper part of the Waiwhetu Aquifer, the occurrence of saline water intrusion into the base of the Lower Waiwhetu Aquifer in the foreshore area cannot be discounted.

Analytical solutions to calculate the position of the a sharp freshwater – saltwater interface within an aquifer are described in Appendix 1. The Ghyben-Herzberg relation describes the position of the interface under hydrostatic conditions, whereas the Glover solution takes into account aquifer throughflow which tends to push the interface offshore. The latter solution would normally be more appropriate than the conservative Ghyben-Herzberg relation since most coastal aquifer systems experience some throughflow. However, in the case of the sub-harbour Waiwhetu Artesian Aquifer, significant aquifer discharge is known to occur from submarine springs which lie to the north of the unconfined harbour entrance area. Since the springs together with the abstraction bores are regarded to account for most of the aquifer throughflow, the position of the interface can be most appropriately calculated using the hydrostatic Ghyben-Herzberg relation (Appendix 1).

Figure 13 shows the estimated position of the saline wedge toe using the Ghyben-Herzberg relation for groundwater levels of between 2.5 and 3m above mean sea level at the foreshore – the minimum level experienced under the present abstraction regime. The base elevation of the aquifer used to construct the map has been estimated from the re-interpretation of the sub-harbour seismic surveys (Harding, 2000). The offshore groundwater levels have been estimated using the foreshore -

Somes Island gradient, but steepened towards the harbour entrance area to represent an equilibrium condition between the aquifer and harbour pressures in this area. The harbour depth in the entrance area is about 25m, and therefore the groundwater pressure required to balance the column of salt water is 20m x the density of sea water (1.025g/cm^3) which equates to a groundwater pressure of 0.6m amsl.

Figure 13 is only an approximation of the likely position of a saline wedge toe based on the current understanding of the sub-harbour aquifer geometry. Using this model, saline water extends as far north as Somes Island during seasonally lowered piezometric conditions. The wedge is probably forced seawards as the aquifer levels recover. Given the extreme heterogeneity of the Waiwhetu gravels (both vertically and horizontally), the wedge is likely to be quite irregular, fingering along preferential flow paths. Due to the high postulated aquifer dispersion characteristics and seasonal groundwater level fluctuations, the transition (or mixing) zone is also likely to be broad. Figure 14 is a schematic cross-section through the sub-harbour Waiwhetu Aquifer system illustrating the calculated location of the saline wedge and the groundwater flow pattern.

5. Analysis of Saltwater Intrusion Potential in the Waiwhetu Aquifer

5.1 Mechanisms of Saline Water Intrusion

Flows of fresh and saline groundwater in the aquifer are determined by the magnitude and gradient of the piezometric surface which are in turn controlled by rates of recharge and discharge (natural and bore abstractions). Under critical groundwater level and gradient conditions, inflowing saline water will replace fresh groundwater which was originally present in the system. The saline water, which may presently occupy parts of the offshore aquifer, has the potential to encroach on the Petone foreshore area and move inland causing severe water quality problems through up-coning into supply bores.

A saltwater intrusion event within the LHGZ will tend to occur on a system-wide scale given the very high aquifer transmissivities and the flat hydraulic gradients between the Waterloo Wellfield and sub-harbour part of the aquifer. The high groundwater flow velocities also suggests that intrusion could occur rapidly (ie the Waiwhetu Aquifer is a ‘fast system’) and preferentially along rapid flow paths such as palaeochannels.

Two mechanisms of saline water intrusion are recognised in the LHGZ resulting from abstraction drawdowns:

- backflow of saline water currently residing in the offshore aquifer through the reduction in aquifer throughflow and reversal of flow gradients caused by abstraction at the Waterloo Wellfield.

- intrusion of sea water at submarine spring/depression sites and in areas where the capping layer is absent as a result of the lowering of groundwater levels and the equalisation of aquifer and harbour pressures.

The first mechanism relies on the premise that saline water is currently occupying parts of the offshore aquifer (Section 4.5). In the absence of information to the contrary, it must be assumed that this is the case. Reduction in groundwater throughflow with associated lowered groundwater heads and ultimately, reversed flow gradients, will cause the wedge of saline water to move landwards and encroach on foreshore bores. This mechanism does not require that the piezometric level in the aquifer attains an equilibrium with the harbour floor pressures at potential saltwater intrusion (spring) sites.

The second mechanism entails the lowering of groundwater heads in the vicinity of potential intrusion sites to such an extent that saline water is able to diffuse and flow back into the aquifer. This scenario could occur at a submarine spring site or sea floor depressions where the capping layer is absent or very thin.

Protection of the aquifer must therefore ensure that neither of these mechanisms are permitted to occur and that critical aquifer trigger conditions are recognised and managed accordingly.

5.2 Theoretical Ghyben-Herzberg Foreshore Levels

The maximum northerly migration of a saline wedge in the sub-harbour aquifer has been approximated using the Ghyben-Herzberg relation (Appendix One) in conjunction with the estimated base elevation of the aquifer and approximated offshore heads for representative foreshore groundwater levels (Section 4.5).

The Ghyben-Herzberg relation can also be used to derive minimum foreshore water levels for the Waiwhetu Aquifer to prevent saltwater intrusion. The calculations rely on a good knowledge of the base elevation of the Waiwhetu Aquifer along the Petone foreshore which is provided by numerous bore logs in the area. Table 2 shows minimum calculated water levels using the base of the Waiwhetu Aquifer (Lower Waiwhetu) at 500m intervals along the Petone foreshore using the Ghyben-Herzberg relation.

Table 2: Minimum Allowable Foreshore Groundwater Levels (Lower Waiwhetu Aquifer) Necessary to Prevent Saltwater Intrusion

	Distance eastwards along foreshore from Wellington Fault (metres)							
	0	**500**	**1000** PCM	**1500**	**2000** McEwan Pk	**2500**	**3000** Hutt Mouth	**3500**
Aquifer base, mamsl (approx)	-80	-80	-73	-66.5	-60	-54	-48	-51
Minimum allowable foreshore ground-water level, mamsl *Lower Waiwhetu Aquifer*	2	2	1.8	1.7	1.5	1.4	1.2	1.3

For the current minimum allowable level at the foreshore of 1.4m amsl, the maximum theoretical extent of saltwater intrusion into the Lower Waiwhetu Aquifer is shown in Figure 15. This assumes that the minimum level applies to the lower part of the aquifer. It can be seen that saline water could migrate along the deep eastern part of the aquifer and reach the Waterloo Wellfield under this scenario. Although the municipal production bores are located in the Upper Waiwhetu Aquifer, there exists the threat of saline water upconing through the thin interstadial aquitard layer as a result of pumping drawdowns and the occurrence of strong vertical flow gradients across the aquitard layer. Other major abstraction bores, principally on the western side of the Hutt River (such as Gear Island and Unilever), could also be affected.

Should the foreshore groundwater level be permitted to drop to 2m amsl, the extent of the saline wedge is considerably less (Figure 15) and only the extreme western edge of the Petone foreshore would be affected. Under this scenario, the Somes Island bore may also experience salt water intrusion but this is considered unlikely due to the low abstraction rates and the protection offered by the interstadial aquitard layer (Section 2).

A minimum theoretical groundwater head in the at the Petone Foreshore within the *Lower Waiwhetu Aquifer* of 2m must therefore be maintained to ensure that the saline wedge cannot migrate to the north and affect existing groundwater users in the LHGZ (Table 2). The rapidity of potential saline water intrusion, given the extremely high permeability of the Waiwhetu gravels, suggests that the groundwater level should be maintained at 2m amsl continuously, or at a 24 hour mean level of 2.4m amsl taking into account the average tidal fluctuation in the aquifer of 0.8m. These levels apply to the Lower Waiwhetu Aquifer which has a higher head than the Upper Waiwhetu Aquifer. The Hutt Aquifer Model suggests that there is a head difference of between 0.4 and 0.5m between the upper and lower parts of the aquifer. Since there are no monitoring bores located in the Lower Waiwhetu Aquifer, an equivalent minimum level for the Upper Waiwhetu Aquifer would therefore be 2m amsl (24 hour mean).

5.3 Throughflow Reduction and Hydraulic Gradient Changes

Increased groundwater abstraction rates and seasonal reductions in recharge through the Hutt River bed can result in a flattened or reversed hydraulic gradient between the Waterloo Wellfield and the sub-harbour aquifer causing a reduction or cessation in groundwater throughflow.

The Waterloo Wellfield has a significant impact on the groundwater levels and gradients throughout the Waiwhetu Aquifer. Increased abstraction at Gear Island also has a large impact on foreshore and sub-harbour groundwater levels. Figure 10 shows simulated groundwater head profiles from Taita Gorge to the harbour entrance using the revised Hutt Aquifer Model. The effects of the wellfield on the groundwater system is illustrated at various pumping rates in comparison to the natural (no pumping) head profile. Capture of the groundwater throughflow by abstraction results in a system wide reduction in groundwater head and flatter offshore groundwater gradients. Close to the wellfield, the immediate cone of depression causes a reversal of flow gradients towards the wellfield. As abstraction increases, or recharge decreases, the cone of depression will migrate southwards past the foreshore and beneath the harbour. The spread of the cone of depression and reversal of hydraulic gradients past the foreshore would not immediately result in saline water intrusion. Initially, water would be drawn from the sub-harbour aquifer storage resulting in a widespread lowering of aquifer pressures and in the landward migration of the saltwater wedge. Once the aquifer pressure equalises with the pressure at the sea floor, saline water diffusion and backflow would occur at the potential entry sites. This is likely to happen theoretically where the harbour is deeper (ie the sea water pressure is higher). However, since most active discharge appears to occur in the shallower eastern areas, the risk of saline intrusion is likely to be highest in these areas where open leakage paths have been established.

5.3.1 Prediction of Throughflow Cessation and Gradient Reversal

Prediction of the cessation of groundwater throughflow and associated reversal of flow gradients at the foreshore will occur when the Waterloo Wellfield drawdown influence (cone of depression) intercepts the foreshore. This condition can be assessed through studying several lines of evidence based upon historical monitoring data and the revised Hutt Aquifer Model; these are:

- modelled groundwater throughflows in relation to measured groundwater heads to estimate the aquifer conditions under which throughflow ceases at the foreshore.

- relating measured groundwater heads at various monitoring bores to each other to determine when offshore hydraulic gradients reverse (cf Donaldson and Campbell method)

- measured submarine spring discharges in relation to measured foreshore groundwater levels

Groundwater throughflows at the Petone foreshore have been derived from the Hutt Aquifer Model (Phreatos, 2001) using calibration data for the period 1984 to 1998. The simulation employs 30-day stress periods during which all system stresses and groundwater levels are averaged. It therefore provides a broad indication of system behaviour and does not take into account short term variability. The model provides a good calibration against groundwater level monitoring data (also averaged over 30 days). Figure 16 shows the model-predicted aquifer throughflow at the Petone Foreshore for the Upper Waiwhetu Aquifer (calculated using the Visual Modflow zone budget routine), plotted against the observed groundwater level at the McEwan Park monitoring bore. The plot highlights the ‘normal’ throughflow-foreshore groundwater level relationship when abstractions and river recharge are relatively stable. During peak demand periods, and when the river is seasonally low, the relationship changes as groundwater gradients flatten and throughflow drops. Under this situation, the data plot below the normal trend. Under both stress regimes, the trends tend to converge at approximately the same foreshore water level of about 2.5 mamsl.

Donaldson and Campbell (1977) used the Somes Island and McEwan Park bore records to determine when the offshore hydraulic gradients would reverse. Their relationship, as discussed in Section 3, used monitoring data covering a very short period of time when the abstraction focus was at Gear Island. The same relationship has been re-examined using monitoring data for the period from January 1994 to March 2001 and is shown in Figure 17. Because both bores are affected by the tidal cycle, and there is generally a large apparent fluctuation in the offshore gradient, 10-day mean water levels have been used. The Somes Island record prior to 1994 is subject to periodic wellhead leakage effects and has been excluded from the analysis. Figure 17 shows that the gradient between McEwan Park and Somes Island becomes neutral at between 2.3 and 2.5m amsl and that offshore gradients will reverse at foreshore water levels below this value. This will result in a saline wedge encroaching on the foreshore, but not meeting the foreshore according to the Ghyben-Herzberg relation.

Harding (2000) measured submarine discharges from a cluster of sea floor depressions off the Hutt River mouth, which represent possible sites for salt-water intrusion. The leakage site is regarded to lie on a palaeochannel in the Upper Waiwhetu gravels representing a preferential flow path of higher transmissivity. Successful measurements were taken from one of the spring vents in June/July 1998 and compared to concurrent piezometric levels measured at McEwan Park on the Petone Foreshore (Figure18A). A 12 hour time lag was applied to the McEwan Park record to achieve a match between spring discharge and the tidal fluctuations in the aquifer as shown in Figure 18B. When the spring discharge data are plotted against the corresponding McEwan Park foreshore water levels, a good correlation is obtained as shown in Figure 19 (Harding 2000). The relationship assumes that there is a positive correlation between tidal height and spring flow; at high tide, the spring discharge increases as a result of an increased piezometric head in the aquifer, but with a 12 hour time lag. This observation is difficult to reconcile with the time lag in the aquifer which is only several minutes (Butcher, 1996). It would also be expected that the spring discharge should rather be negatively correlated with tidal height – high tidal conditions increase the column of sea water above the spring site and cause the spring flow to decrease. Such a relationship was tested by lagging the spring discharge data measured by Harding by only 6 hours behind the McEwan Park monitoring data but a very poor correlation was achieved.

It is suggested that there is a more complex relationship between the tidal cycle in the harbour and submarine spring discharge involving tidal pressure waves travelling through the aquifer away from the foreshore creating throughflow surges. For example, a low tide may temporarily increase the horizontal flow gradient in the aquifer which has the effect of increasing spring flow some 12 hours later - dampened by the then high tidal condition.

Regardless of the mechanism responsible for the observed relationship between submarine spring discharge and the foreshore piezometric levels, Figure 19 suggests that spring discharge will cease when the level in McEwan Park reaches approximately 2.3m amsl. At this level, the aquifer pressure will have equalised with the groundwater pressure and a critical condition will exist whereby saline water can diffuse and backflow into the aquifer. This assumes that the straight line extrapolation of the trend in Figure 19 is correct. However, some credence can be given to this assumption since Figures 16 and 17 indicate that reversed offshore flow gradients would occur at about the same level.

5.3.2 Effects of Pumping from Gear Island

Pumping from Gear Island has a large effect on foreshore water levels and monitoring bores such as McEwan Park lie in the cone of depression. The relationships between foreshore water levels, throughflow and offshore hydraulic gradients discussed above are only applicable to abstraction from the Waterloo Wellfield. When Gear Island is pumping, an immediate offshore reversal of flow gradients occurs as the cone of depressions expands. The offshore extent of reversed flow gradients at an extraction rate of 25ML (with Waterloo abstraction occurring simultaneously) has been estimated using the Hutt Aquifer Model to be approximately 1000 – 1500m (Figure 10). The foreshore water level during abstraction from Gear Island is dependent upon several factors such as pre-pumping aquifer levels, aquifer throughflow and abstraction rate from Gear Island and Waterloo. Under seasonally low recharge and throughflow conditions, use of the Gear Island bores would immediately draw the foreshore water level below the theoretical minimum saline water protection level of 2m in the Upper Waiwhetu Aquifer. Use of Gear Island during such conditions should therefore be avoided to maintain safe foreshore levels.

5.4 Critical Offshore Aquifer Levels

Previous discussions have focussed in the movement of a postulated saline wedge already residing in the sub-harbour Waiwhetu Aquifer, the position of which is controlled by the Waiwhetu piezometric level.

When the piezometric level reaches a critical level in the vicinity of the submarine spring sites, or other potential entry sites (i.e. sea floor depressions where the Petone Marine Beds capping layer is absent or very thin), backflow into the aquifer can occur creating an immediate risk to water quality.

There is very little evidence to relate foreshore water level observations to the head in the vicinity of submarine discharge points. Historically, the Somes Island bore has been used to extrapolate groundwater gradients to the rest of the sub-harbour zone (Section 3). However, use of the Somes Island bore may not provide a valid approximation to the piezometric conditions in the vicinity of submarine discharge sites. This is because the piezometric heads around the discharge zones in the harbour floor are likely to be depressed, much in the same way as a cone of depression associated with an abstraction bore. An extrapolated gradient between the foreshore and Somes Island would probably under-estimate the actual gradient between the foreshore and submarine spring discharge sites, such as those off the Hutt River mouth.

Harding (2000) provided convincing evidence that this is in fact the case using measurements of spring discharge at a vent located off the Hutt River mouth. Assuming the straight-line extrapolation of the trend in Figure 19 is valid, the point at which spring flow ceases must correspond to an equalisation of the aquifer head with the sea water pressure at the floor of the spring vent depression caused by the mass of the overlying column of sea water. The piezometric pressure in the aquifer under this critical condition can be calculated using the following relationship:

$$h = (d_s \times \rho_s) - d_s$$

where:
h = head in the Waiwhetu Aquifer at the spring site (L)
ρ_s = density of sea water (ML^{-3}) = 1.025 g/cm^3
d_s = depth of sea water above the spring vent (L)

The depth of sea water above the spring vent measured off the Hutt River mouth is 19.4m. This implies that the piezometric head in the Waiwhetu Aquifer when spring flow ceases is approximately 0.5m amsl corresponding to a level at the foreshore (McEwan Park) of 2.3m amsl. The hydraulic gradient between the foreshore and the Hutt River mouth spring discharge zone is therefore approximately 1×10^{-3} which is an order of magnitude higher than the average gradient measured between the foreshore and Somes Island of 1×10^{-4}. This difference suggests that the springs locally depress the piezometric surface.

Until more information becomes available, it must be assumed that the straight-line extrapolation in Figure 19 is valid and that salt-water intrusion is likely to occur at the Hutt River mouth when the Petone foreshore level drops below 2.3m amsl. The discharge vents off the Hutt River mouth should therefore be regarded as a high-risk salt water intrusion site in close proximity to foreshore industrial groundwater users (<1000m).

6. Recommended Saline Water Intrusion Risk Management

6.1 Approach

The objective of saline water intrusion risk management is to prevent the ingress of saltwater into the base of the Waiwhetu Aquifer at the Petone foreshore. Ingress of saltwater could occur either through causing the postulated existing saline water interface to move towards the shore, and/or through the backflow of harbour waters at submarine discharge sites close to the foreshore. Should the lowermost part of the Waiwhetu gravels contain saltwater in the vicinity of a major abstraction bore, there is a serious risk that the bore would be contaminated through upconing of the saline water as a result of abstraction-related stresses.

This study has attempted to identify critical aquifer stress conditions whereby saltwater intrusion is likely to occur based upon the current conceptual understanding of the Lower Hutt Groundwater Zone and the sub-harbour characteristics of the Waiwhetu Aquifer. These critical conditions occur when the cone of depression associated with the Waterloo Wellfield intercepts the shoreline and moves offshore; they are:

1. Cessation of aquifer throughflow
2. Cessation of submarine spring discharge
3. Reversal of offshore groundwater gradients
4. Foreshore water levels less than the calculated minimum Ghyben-Herzberg safe level
5. Offshore groundwater levels lower than harbour pressures at potential saltwater entry sites

It has been possible to quantitatively assess conditions 1 – 4 using a combination of long-term aquifer monitoring data, recent sub-harbour investigations, and numerical modelling.

6.2 Recommended Minimum Foreshore Levels

It appears to be most appropriate and practical to assess the critical saltwater intrusion risk conditions in terms of foreshore water levels. Four different lines of investigation provide good consistency and are summarised in Table 3.

Table 3: Minimum Petone Foreshore Water Levels Associated With Saltwater Intrusion Risk Aquifer Conditions

Aquifer Condition	Reference	Critical Foreshore Level m amsl (24 hour mean)
Cessation of Aquifer Throughflow at Foreshore	Fig. 16	2.5
Cessation of Submarine Spring Discharge	Fig. 19	2.3
Reversal of Offshore Hydraulic Gradients	Fig. 17	2.3-2.5
Ghyben-Herzberg minimum foreshore level	Table 2	2.0*

* *equivalent level in Upper Waiwhetu Aquifer*

Aquifer throughflow will cease prior to a reversal of offshore flow gradients and the 2.5m level should serve as an alert to impending onset of critical saltwater intrusion conditions. The cessation of submarine spring discharge and reversed offshore hydraulic gradients would apparently occur at a critical level of between 2.3 and 2.5 m amsl indicating that there would be a risk of saline intrusion to the offshore aquifer which would not reach the foreshore until the level in the Upper Waiwhetu Aquifer drops to 2.0m amsl (the Ghyben-Herzberg level)

On the basis of this evidence, the following tiered foreshore aquifer management levels are recommended (24 hour means):

Warning level: 2.5m amsl
Critical level: 2.3m amsl
Minimum allowable foreshore level: 2.0m amsl (2.4 mamsl in the Lower Waiwhetu Aquifer)

The above levels apply to the Upper Waiwhetu Aquifer.

The recommended revision to the minimum foreshore groundwater level will not have any impact on current municipal and private abstractions from the Waiwhetu Aquifer. Following the 2000/2001 prolonged drought condition, the foreshore level remained at, or just below, 3m amsl indicating that the Waiwhetu Aquifer can sustain the current demand under prolonged stressed conditions.

6.3 Recommended Monitoring Requirements

Saltwater intrusion risk management for the Waiwhetu Aquifer is reliant upon a dependable and well designed monitoring system. Monitoring of both groundwater levels and water quality using strategic monitoring bores is currently taking place at the foreshore (McEwan Park) and at Somes Island. Following the analysis of saline water intrusion risk in this report, improvements to the current monitoring system are recommended to provide increased level of resource protection.

The McEwan Park bore is currently the only continuously monitored site on the foreshore. Monitoring of water level and, more recently, conductivity occurs at this site. The bore extends into the top of the Upper Waiwhetu Aquifer and therefore records water levels in this part of the Waiwhetu gravels only. Deeper levels in the gravels are expected to have slightly higher groundwater pressures. Due to the heterogeneous nature of the gravels, and the existence of preferential flow paths along palaeochannels, it is important that additional monitoring sites along the foreshore be installed. A single bore extending only into the top of the aquifer in an area where the aquifer base is approximately 20m shallower than at the western end of the foreshore is not regarded to provide adequate monitoring coverage for the protection of the aquifer.

It is recommended that a second monitoring site in the vicinity of the old PCM monitoring bore, or further to the west, is constructed. This site should be designed to monitor the Waiwhetu Gravels at two levels – in the Upper Waiwhetu Aquifer, and in the Lower Waiwhetu Aquifer below the interstadial aquitard. Intrusion of a saline wedge beneath the foreshore will initially occur at the base of the aquifer where it is deeper and therefore continuous water level and conductivity monitoring in the lower aquifer zone would be judicious.

The Somes Island bore represents a valuable monitoring site which has enabled offshore hydraulic gradients to be studied. However, the artesian bore located on the harbour floor frequently experiences leakage problems at the wellhead, often due to damage sustained by boat anchors. Data collected form the bore when it is leaking are unusable. It is recommended that the wellhead is strengthened that regular maintenance checks are carried out to improve confidence in the data provided by this site. Water quality samples should be taken from the bore periodically, especially during the summer months.

Other inland existing water level monitoring sites have also proved useful to track the Waterloo Wellfield cone of depression as it expands during summer months and during periods of increased abstraction. These sites include Hutt Recreation Ground and Randwick. Observation of the relative flow gradients between these bores and the foreshore provides an insight into changes in the wellfield cone of depression and advance warning of declines in the foreshore water level (see Figure 8). It is recommended that the relationships between these bores are routinely evaluated.

Water quality monitoring is an important component of monitoring system because the groundwater chemistry can provide an early warning of the early stages of encroaching salinisation. Continuous conductivity monitoring has been recommended in two bores (McEwan Park and a new foreshore bore near PCM). These bores, together with the Somes Island bore should additionally be sampled on a monthly basis during the summer months and bi-monthly at other times. The samples should be analysed for a standard major anion-cation determinand suite, pH and conductivity. Study of temporal trend parameter ratios (Na/Cl, Ca/Mg, Ca/(HCO_3 + SO_4)) will provide a valuable contribution to the monitoring programme.

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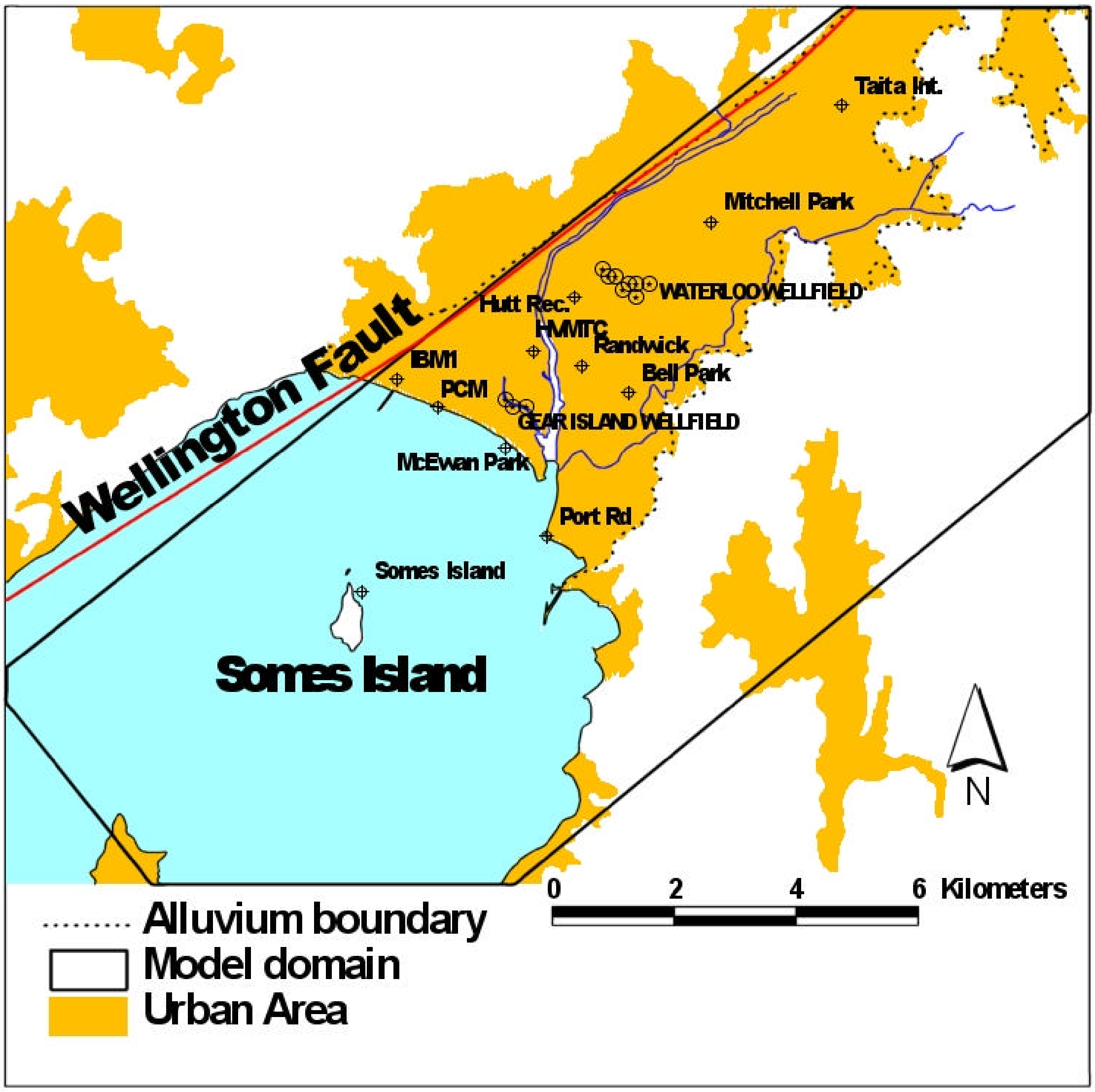

Figure 1: Location map showing the Council's water level monitoring sites and the public water supply wellfields that are the principal abstraction points in the valley.

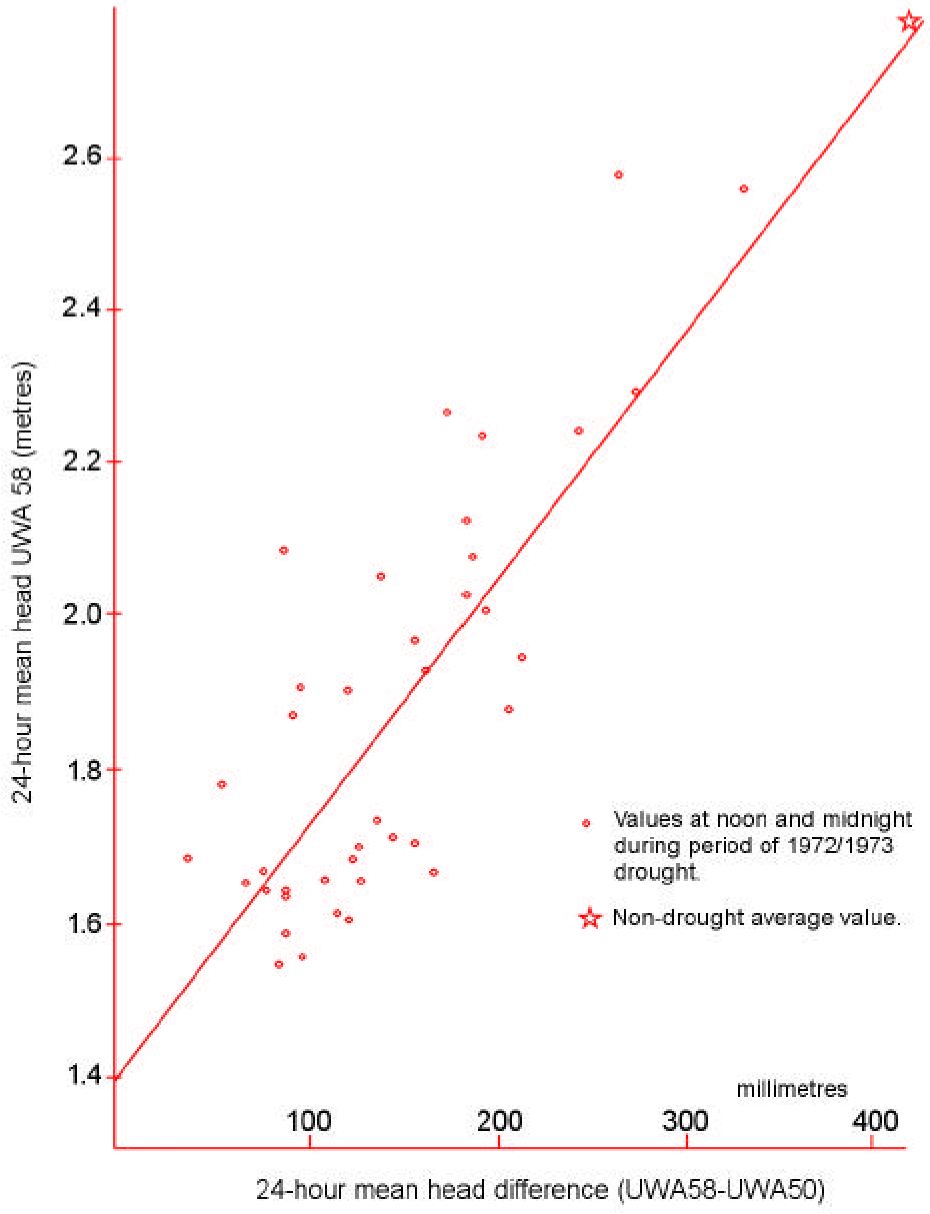

Figure 2: The realtionship between the head difference between well UWA 58 (McEwan Park) and UWA 50 (Somes Island) during the 1972/73 drought. From Donaldson and Campbell (1973).

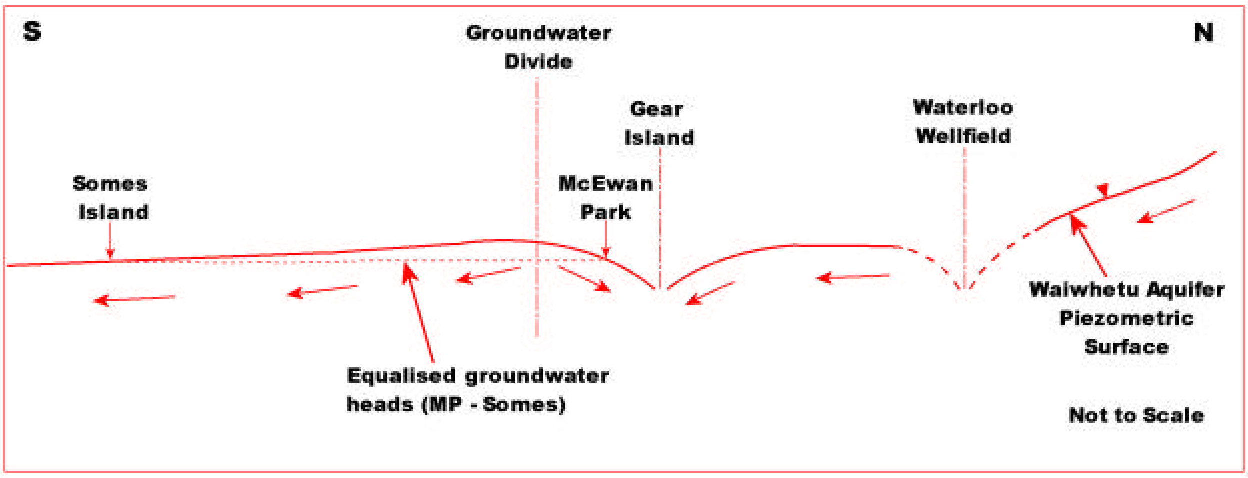

Figure 3: Schematic representation of the foreshore piezometric surface with Gear Island pumping.

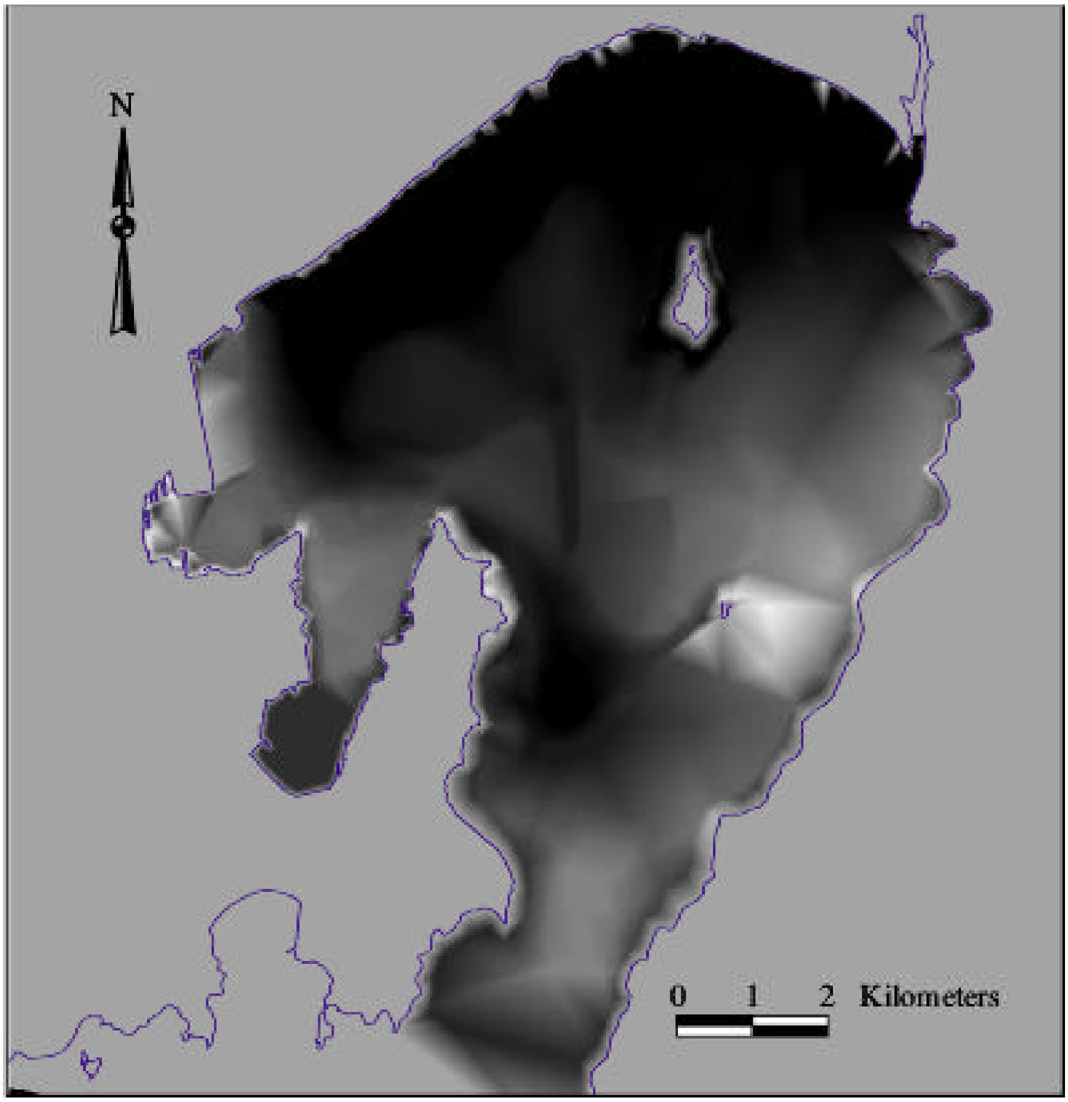

Figure 4: **Isopach image of the Waiwhetu Aquifer based on seismic data collected by Davy and Wood (1993). The darkest areas are in the order of 70 metres thick, grading to about 20 metres thick in the lightest areas.**

The apparent thickening seen in southern Evans Bay is an artefact of the way the image has been created; the aquifer actually continues to thin to the south. Likewise the thin area between Ward Island and Eastbourne is a function of the extrapolation process and this portion of the aquifer is expected to grade in thickness from north to south.

From *Harding* (2000).

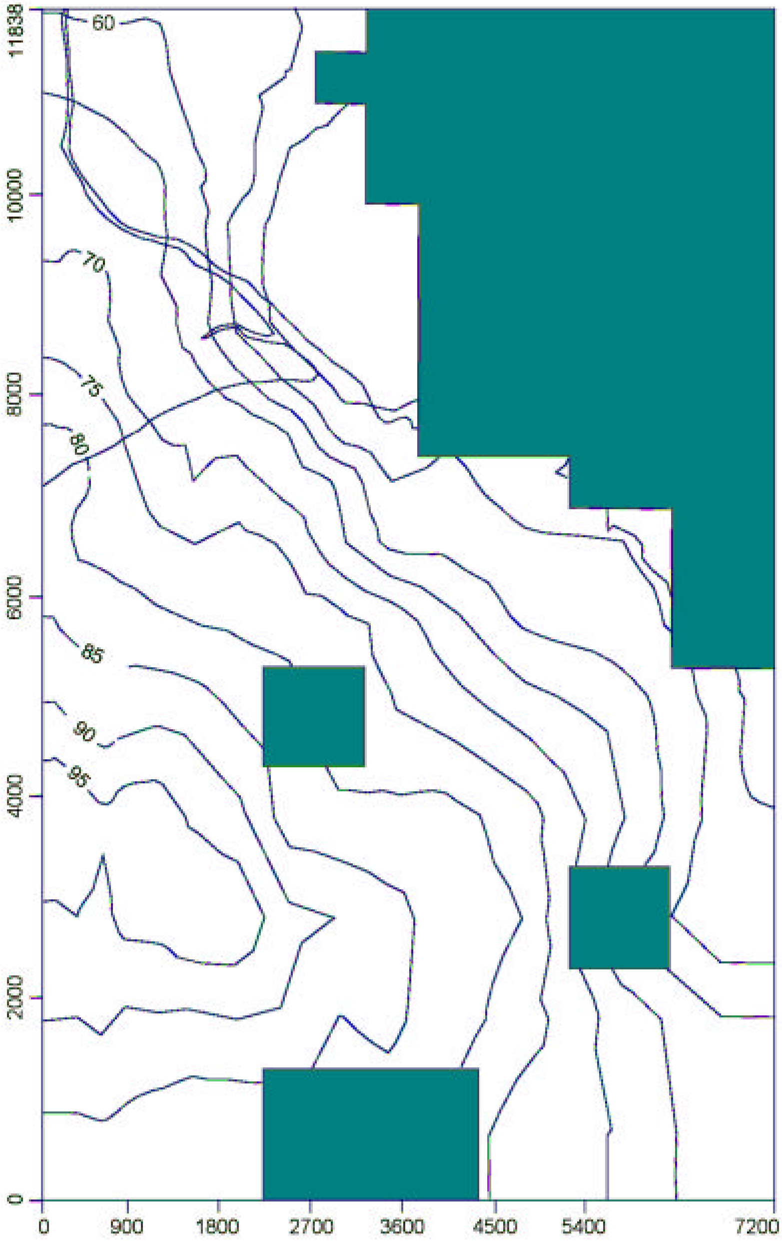

Figure 5: **Contour map for base elevation (metres below mean sea level) of the Waiwhetu Gravels.**

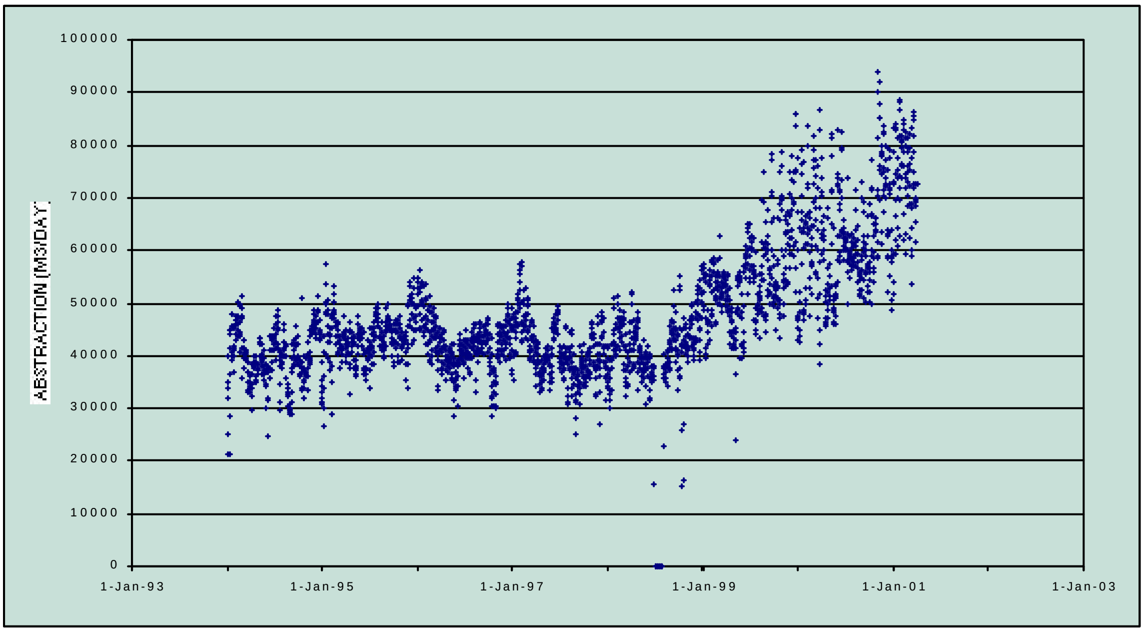

Figure 6: **Waterloo wellfield abstraction.**

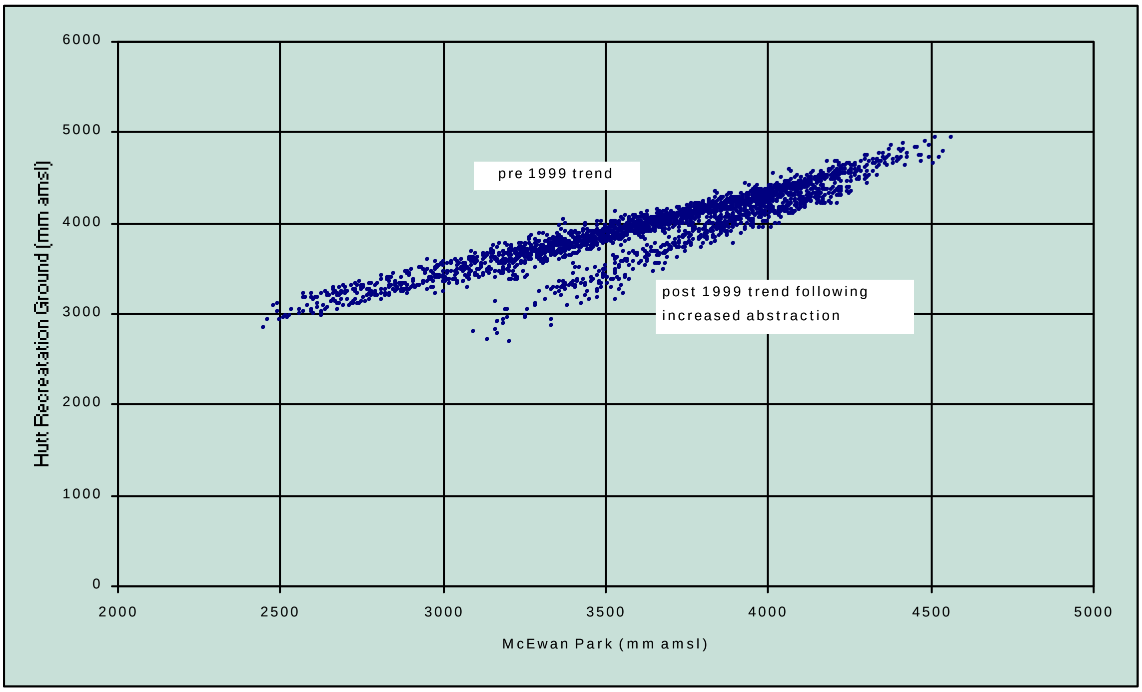

Figure 7: **Relationship between Hutt Recreation Ground and McEwan Park (24 hour means) 1994 to present.**

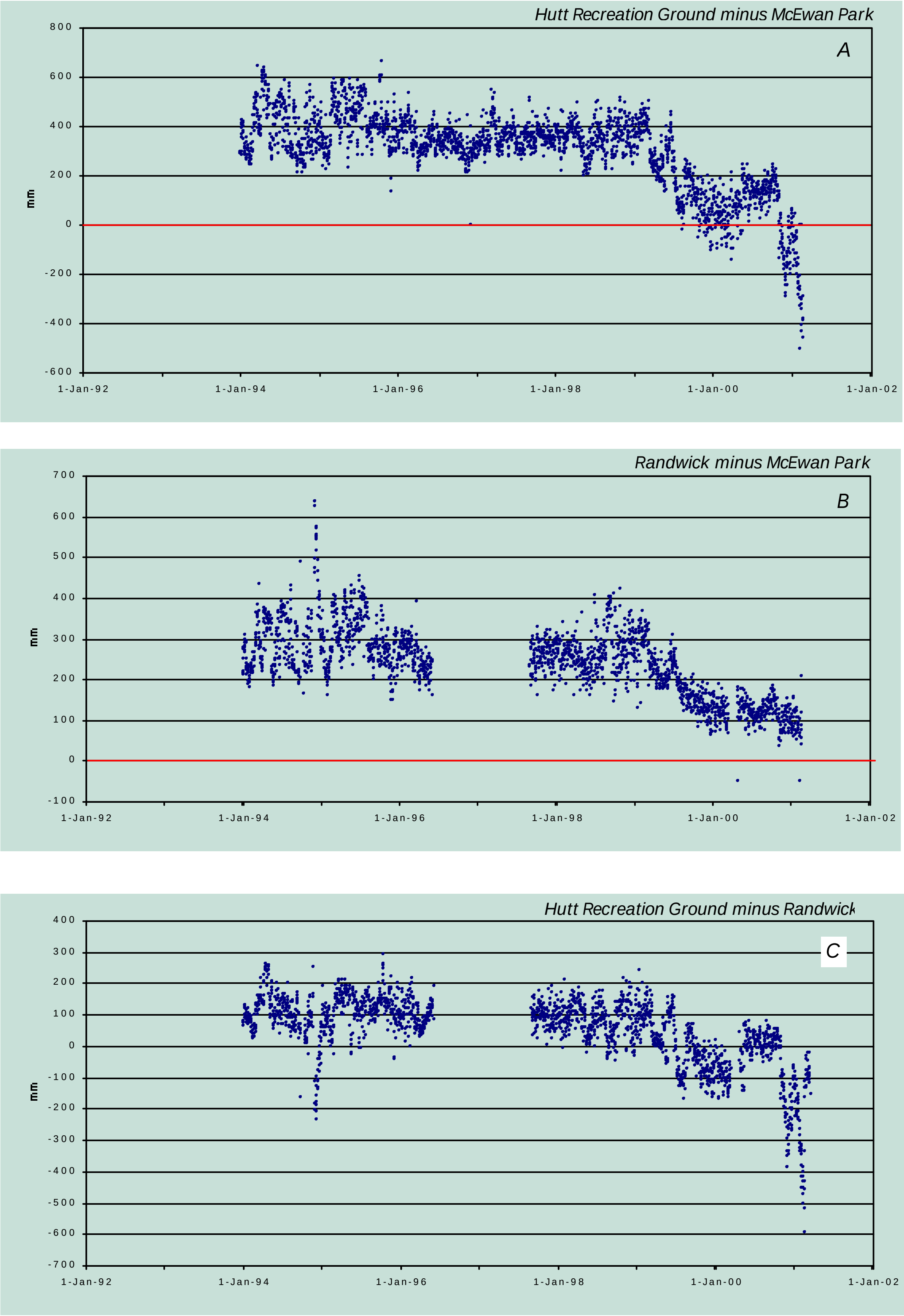

Figure 8: **Differential head plots for selected monitoring bores between the Waterloo Wellfield and the foreshore.**

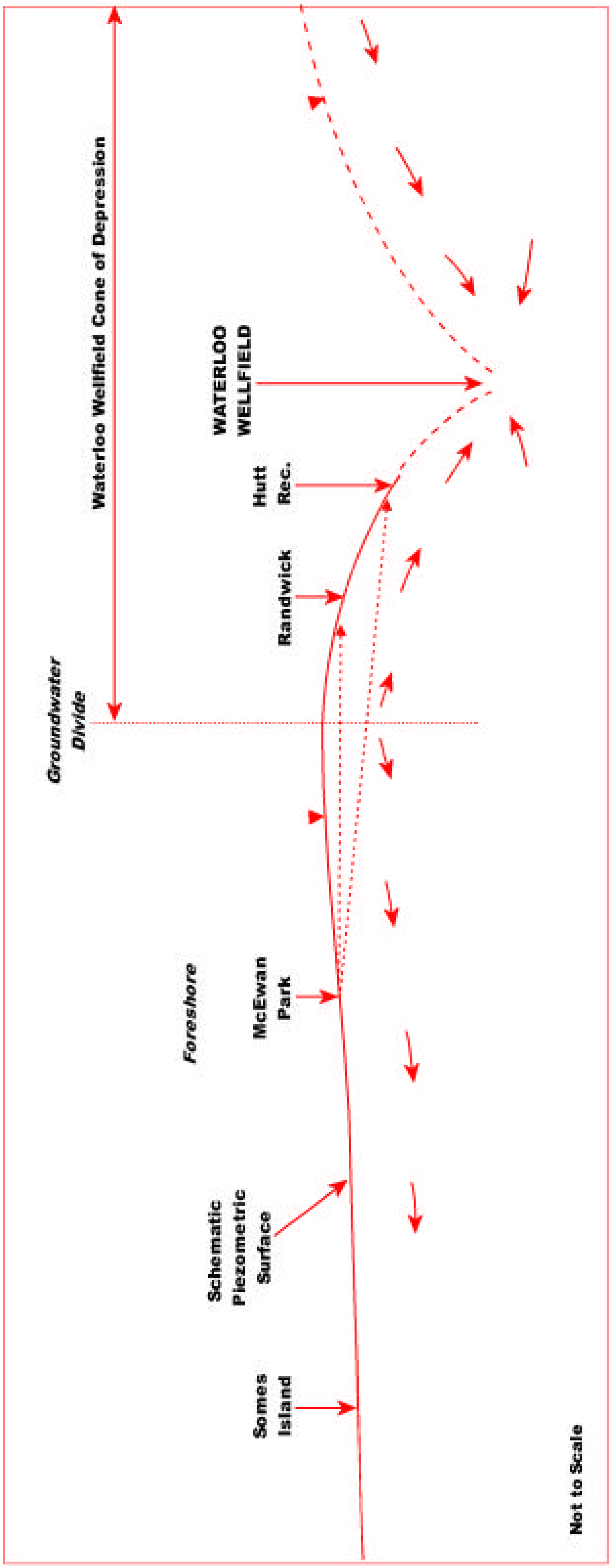

Figure 9: Current groundwater divide location - Waiwhetu Aquifer.

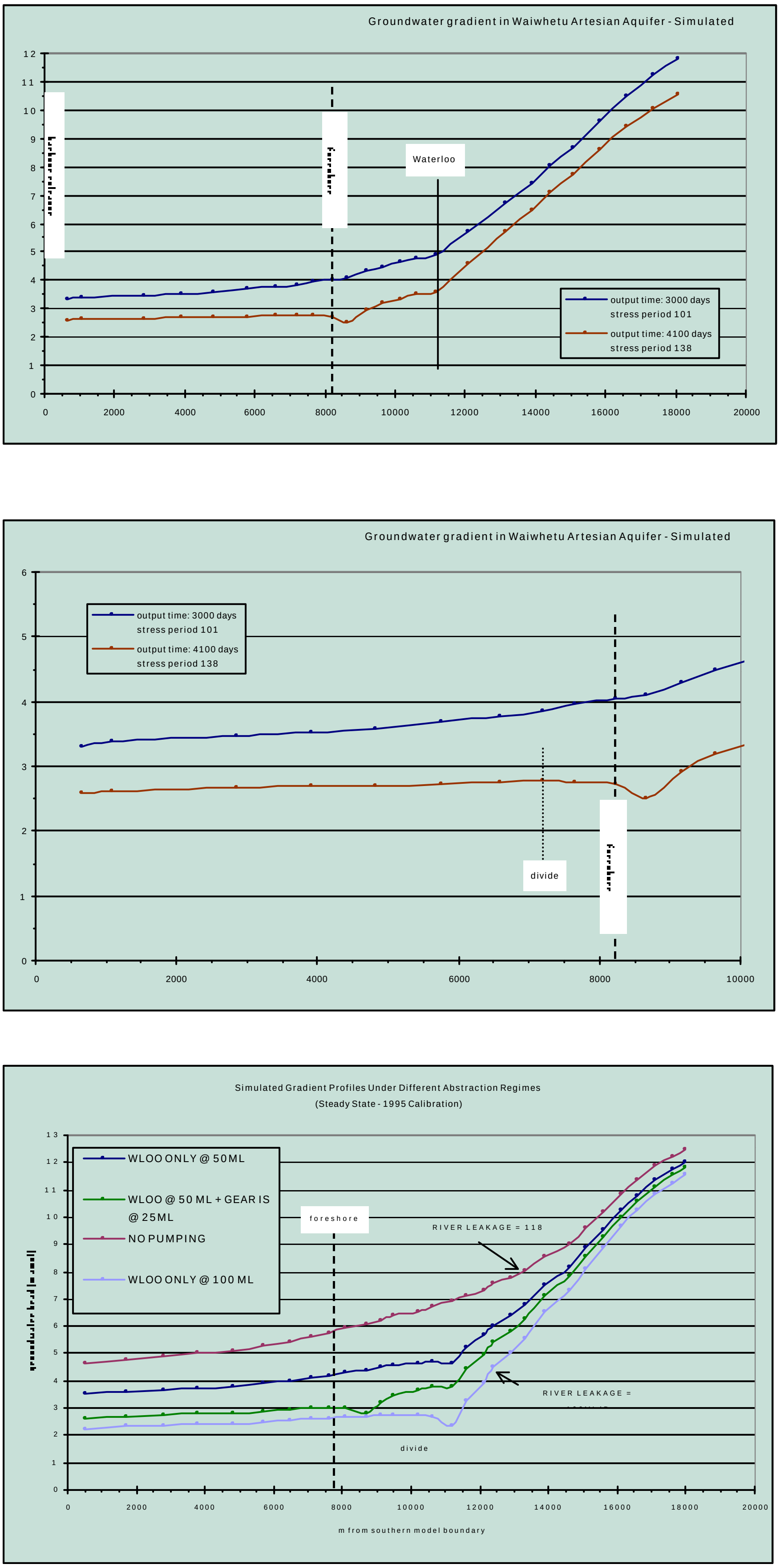

Figure 10: Simulated head profiles for the Waiwhetu Aquifer from Taita Gorge to Ward Island.

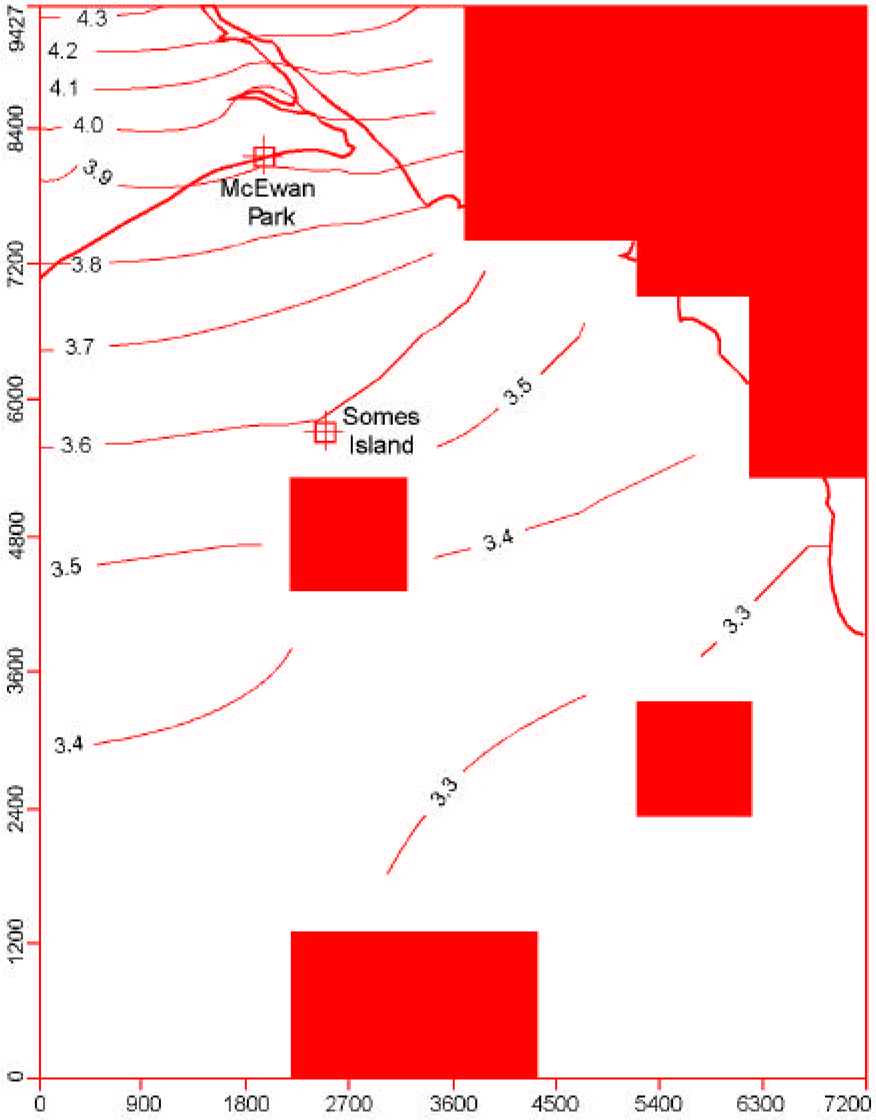

Figure 11: Modelled offshore groundwater heads - Upper Waiwhetu Aquifer.

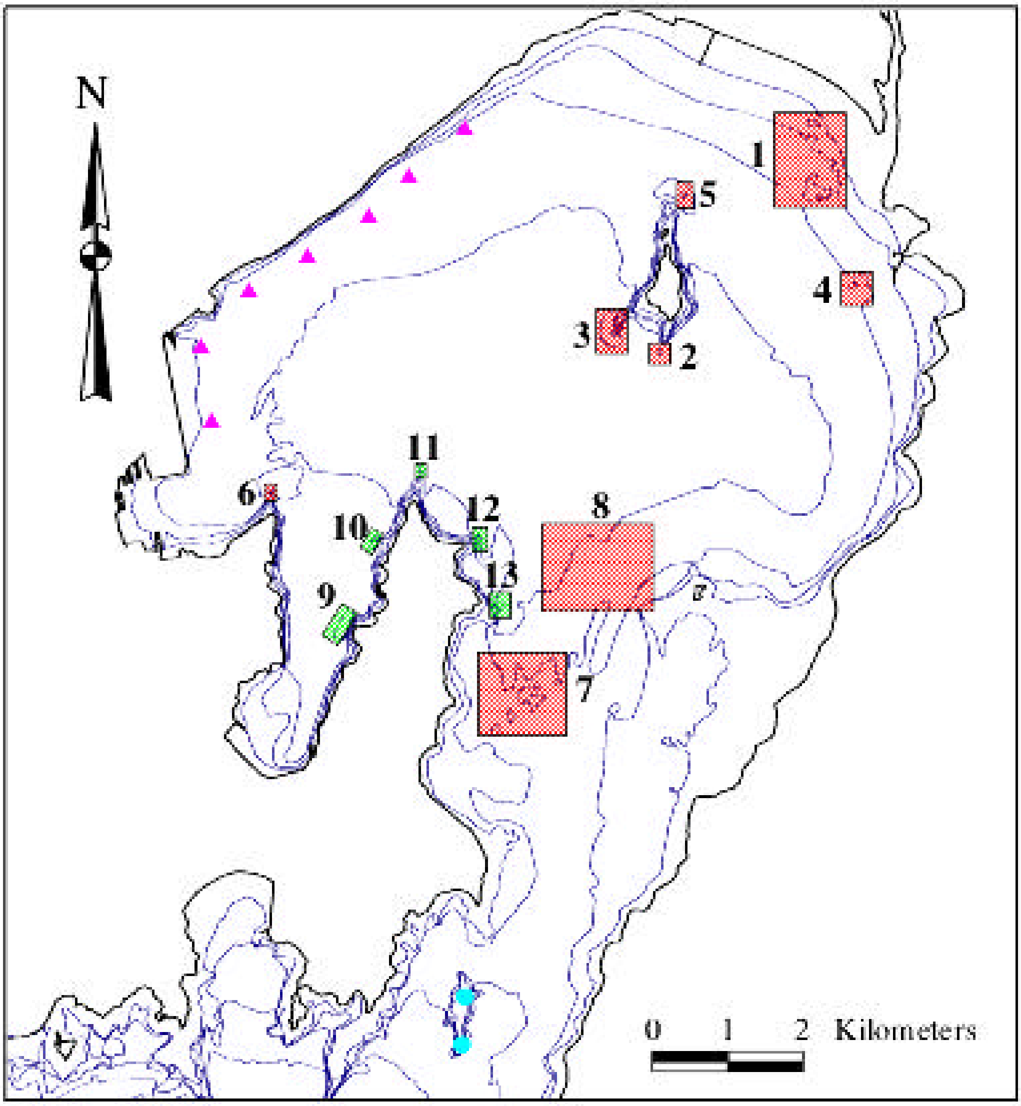

Figure 12: **Location map of the areas of suspected, or known, submarine dishcarge. The numbered areas were inspected by Harding (2000). The triangles show locations that have been identified in the past as having leakage, but were not inspected because there were no sea floor depressions to facilitate location. Bathymetric contour lines are shown at five metre intervals.**

From *Harding* (2000).

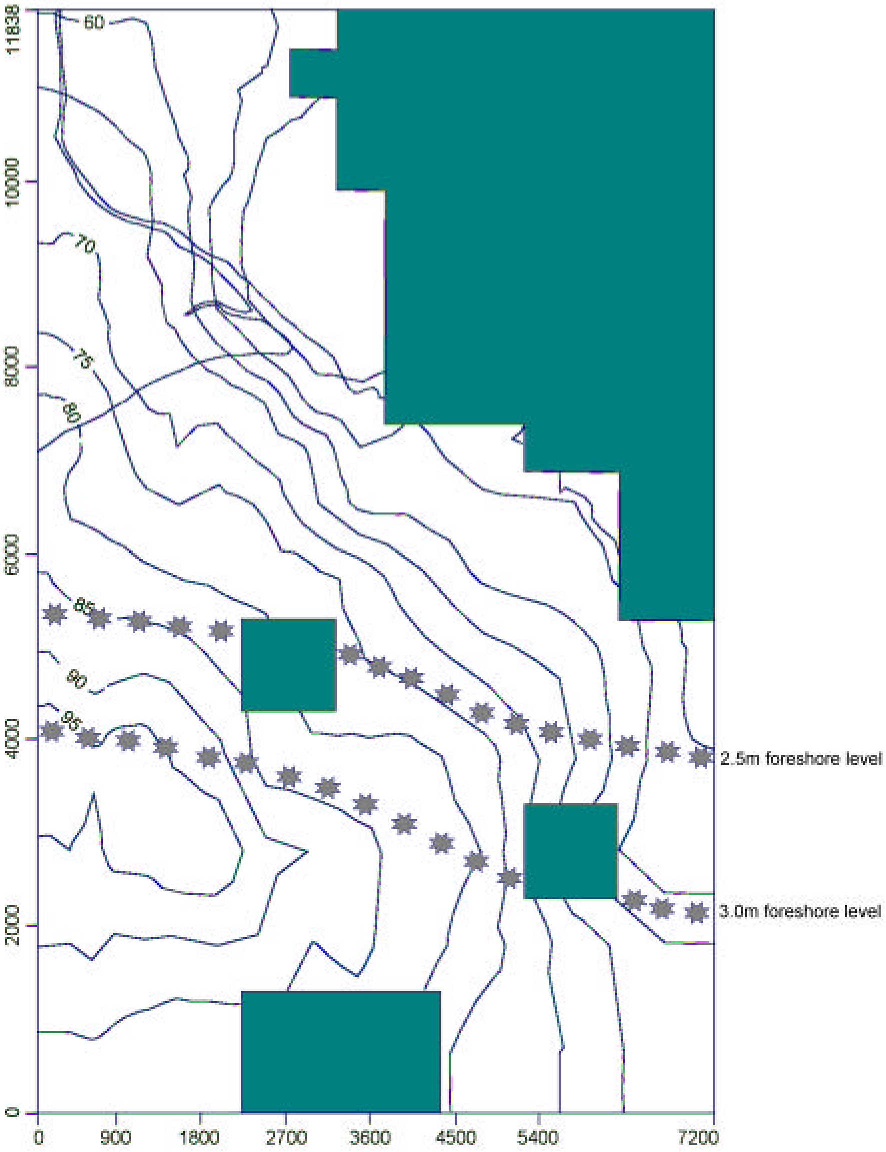

Figure 13: Estimated current position of the saline wedge in the Lower Waiwhetu Aquifer.

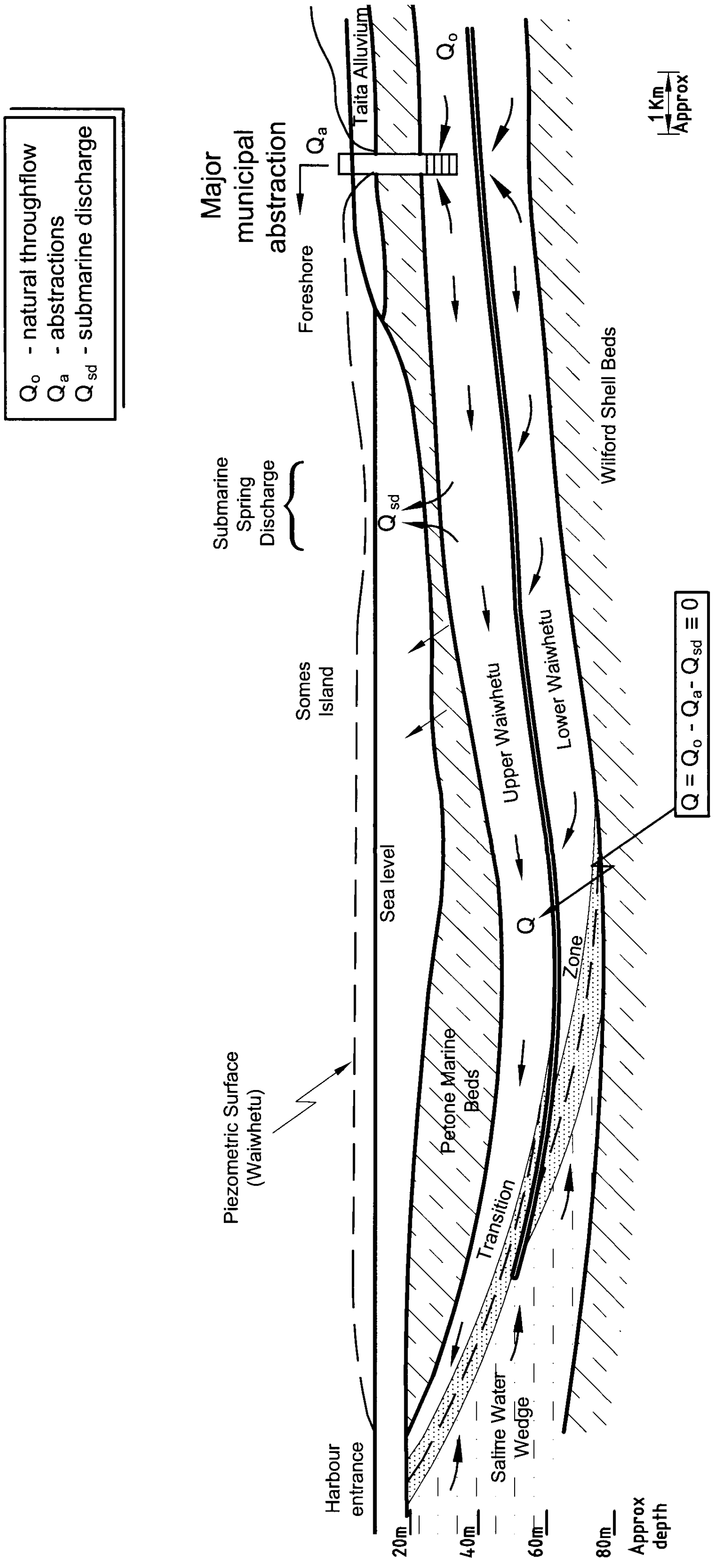

Figure 14: **Conceptual cross section from Petone forshwore to the Harbour entrance showing the percieved location of the saline water wedge in the Waiwhetu Aquifers.**

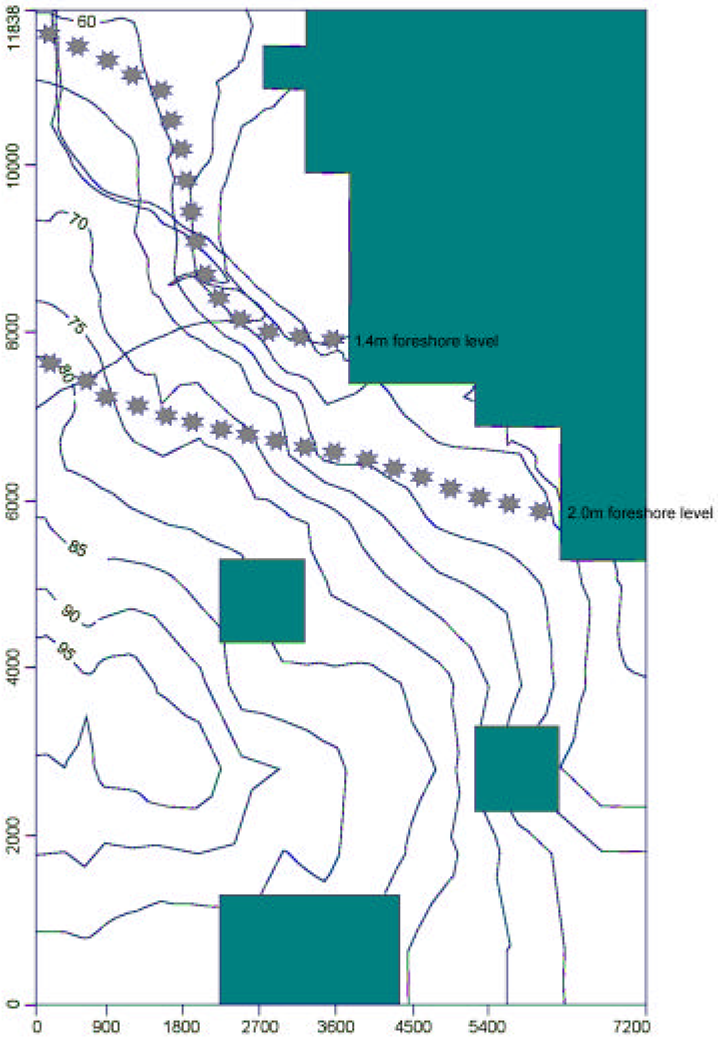

Figure 15: **Predicted position of the saline wedge in the Lower Waiwhetu Aquifer for groundwater levels of 1.4m and 2.0m at the Petone foreshore.**

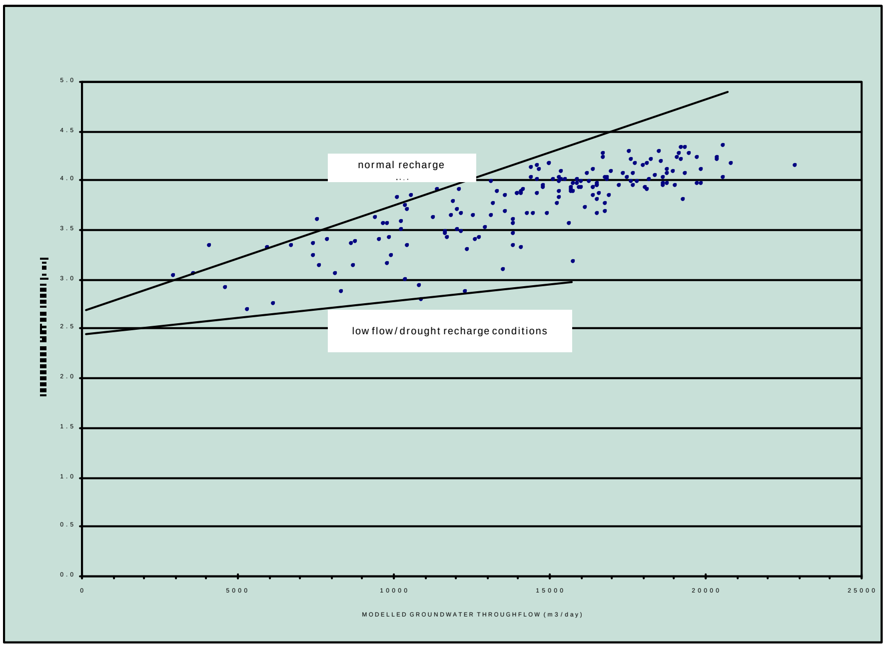

Figure 16: Foreshore Upper Waiwhetu Aquifer groundwater levels vs simulated aquifer throughflow (30 day means, 1984 to 1998).

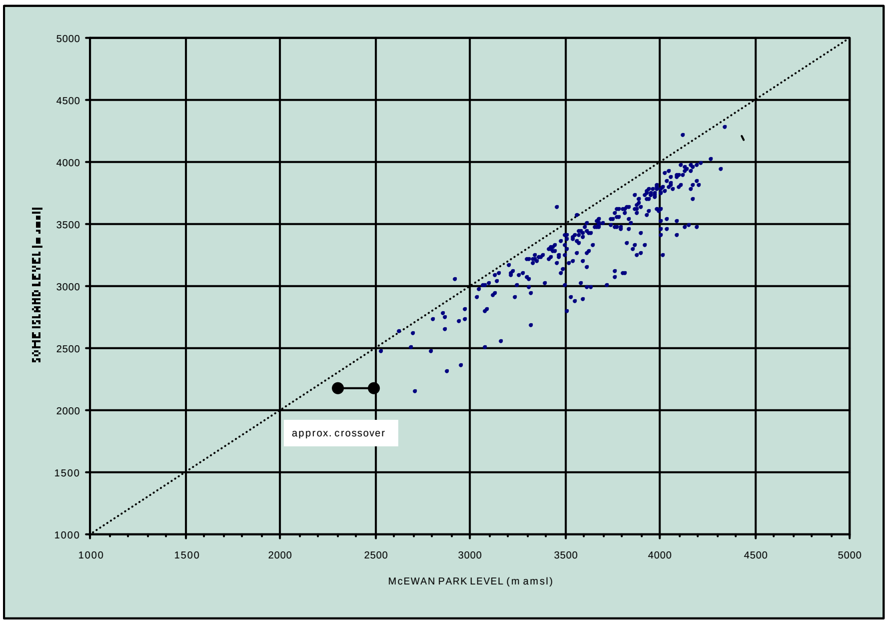

Figure 17: **Relationship between McEwan Park and Somes Island groundwater levels (10 day means, 1994 to present).**

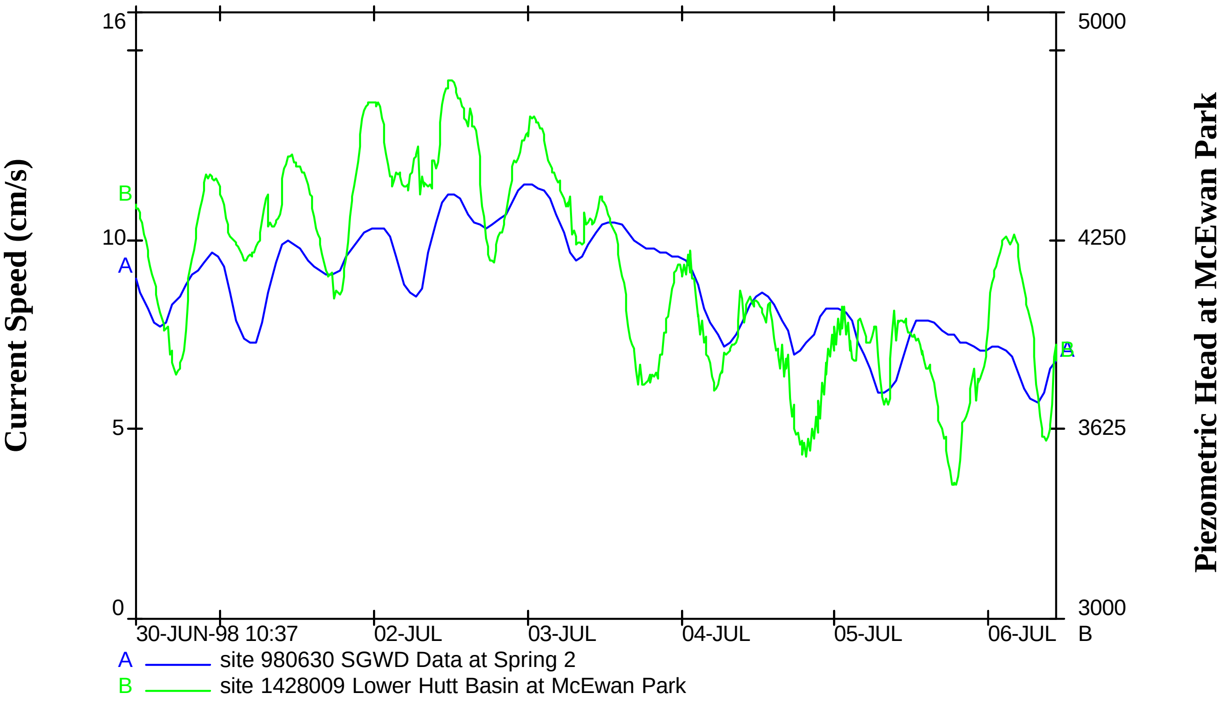

Figure 18a: Plot showing the relationship between current speed recorded at Depression 6, Zone 1, and Piezometric Head Level as recorded at McEwan Park from 30th June to 6th July 1998.

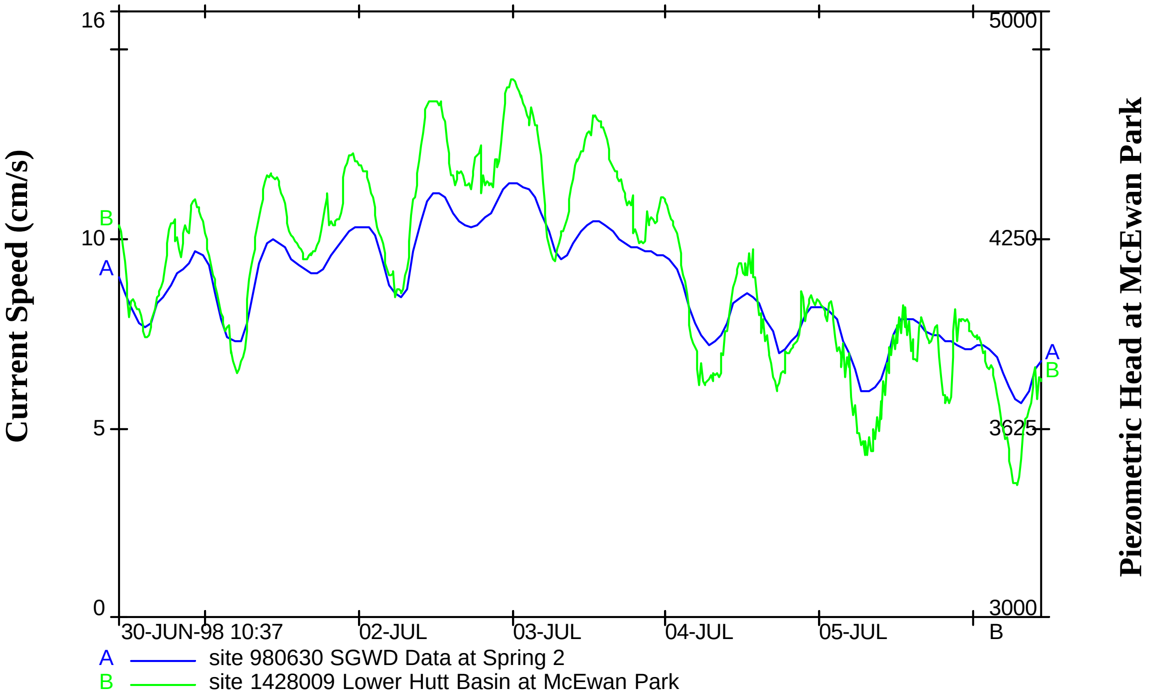

Figure 18b: Same plot as above except that the McEwan Park head water level has been lagged by 12 hours. As can be seen, a strong correlation between spring discharge and the lagged piezometric head at McEwan Park is apparent.
From *Harding* (2000).

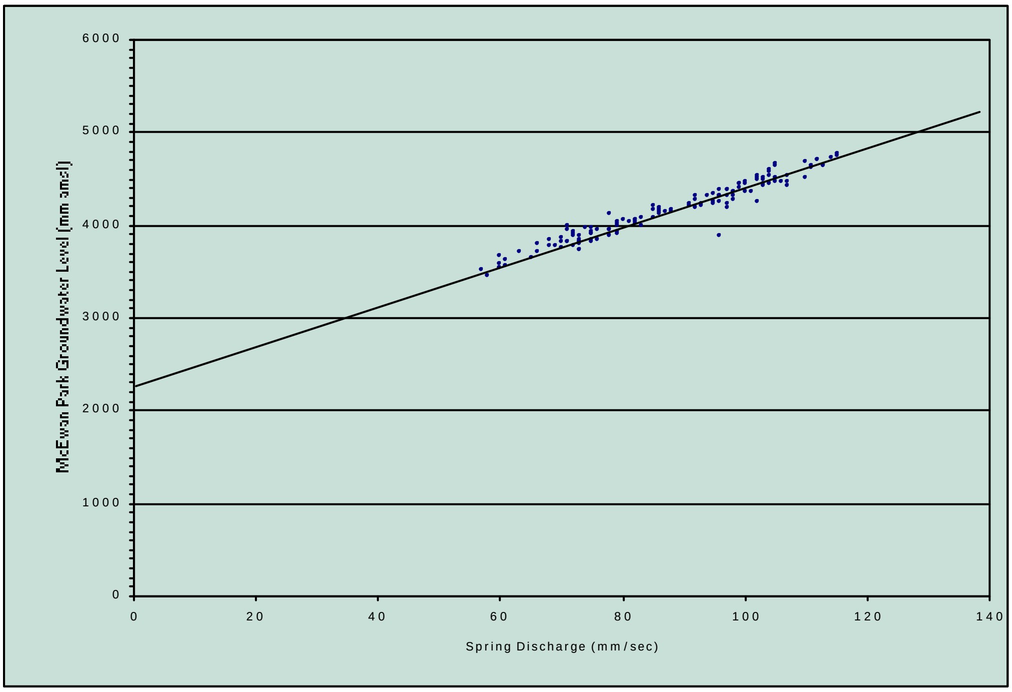

Figure 19: **Realtionship between spring discharge and McEwan Park groundwater level after application of 12 hour time lag to spring discharge (Harding, 2000).**

Appendix 1

Analytical Methods for Calculation of Fresh-Saline Water Interface

Ghyben-Herzberg

The hydrostatic balance between fresh and saline water can be expressed by:

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

where

ρ_a and ρ_f = the densities (ML^{-3}) of saline and fresh groundwater respectively
z = depth to saline water interface from mean sea level
h_f = height of water table / piezometric surface above mean sea level
For typical sea water conditions, $\rho_s = 1.025$ g/cm^3 and $\rho_f = 1.000$ g/cm^3, so that

$z = 40 h_f$

Glover

Glover (1964) recognized the approximations inherent in the Gyyben-Herzberg relation which is restricted to a hydrostatic condition. Freshwater flow causes the interface to occur at greater depths and further from the coast and a more exact solution to describe the shape of the interface is provided by the following relationship:

$z^2 = 2\rho_f q x / \Delta\rho_f k + (\rho_f q / \Delta\rho k)^2$

x and y are defined in Figure A1, $\Delta\rho = \rho_s - \rho_{f,}$, k is the hydraulic conductivity, and q is the freshwater flow per unit length of shoreline. The depth of the interface at the shoreline, z_o, occurs where x = 0, so that:

$z_o = \rho_f q / \Delta\rho k$

van Dam (1999) modified the Glover relationship to calculate the length of the saline wedge, taking into consideration the aquifer throughflow and transmissivity (Figure A2)

Assuming a sharp interface between the fresh and saline groundwater, the length of the saline water wedge under natural throughflow conditions, L_1, is expressed as:

$$L_1 = \frac{\alpha\, kD^2}{2q_o}$$

where:
q_q = natural groundwater throughflow (L^2T^{-1}) per unit width of aquifer
q_a = groundwater abstraction (L^2T^{-1}) per unit width of aquifer
kD = aquifer transmissivity (L^2T^{-1})

ρ_s and ρ_f = the densities (ML^{-3}) of saline and fresh groundwater respectively
$\alpha = \rho_s - \rho_f / \rho_f$

If, at time t = 0 the outflow q_o is reduced by abstraction q_a, the length of the saline wedge L_2 now becomes:

$$L_2 = \frac{\alpha kD^2}{2(q_o - q_a)}$$

Figure A1: Flow pattern of fresh water in an unconfined coastal aquifer

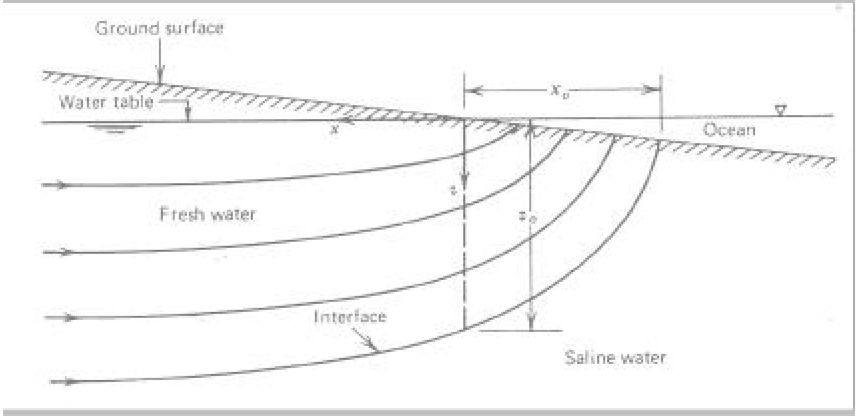

Figure A2: Outflow of confined groundwater with position of salt water wedge with and without abstraction (van Dam, 1999)