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# Revision of the numerical model for the Lower Hutt groundwater zone

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Prepared for:
Greater Wellington – The Regional Council

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GROUNDWATER CONSULTING

# Contents

# 1. Introduction

The Lower Hutt – Port Nicholson sedimentary basin (Figure 1) contains a regionally important groundwater resource which supplies up to 40% of the water demand for the greater Wellington region. The basin contains several confined artesian, semi-confined and unconfined gravel aquifer units which collectively constitute a layered aquifer system known as the Lower Hutt Groundwater Zone (LHGZ). Currently, major municipal abstraction takes place only from the most productive Upper Waiwhetu Artesian Gravels at an average rate of approximately 60 ML/day but peaking at 100 ML/day during the summer months. Management of the groundwater resource is reliant upon a robust evaluation of the sustainable yield in conjunction with a strategic groundwater level and water quality monitoring system to ensure that saline coastal waters do not invade the aquifers.

Given increasing abstraction demands on the Lower Hutt Groundwater Zone, there is a need to review the safe yields for groundwater system, and to review management safeguards to minimise the risk of saline water intrusion.

Recent advances in the geological and hydrogeological understanding of the groundwater system prompted the Wellington Regional Council to revise the existing numerical model (HAM1) built some eight years ago (Reynolds, 1993). To avoid inherent limitations of the old model, which focussed only upon the Waiwhetu Artesian Gravels and was limited by poor definition of the system recharge and discharge mechanisms, construction of an entirely new model has been required (HAM2).

The HAM2 has a less complex the spatial zonation of hydraulic properties than the previous model, and a more detailed layer structure based upon revised geological interpretation of the sedimentary sequence. The model boundaries have been re-designed allowing aquifer discharge processes to be more appropriately modelled, and the simulation of recharge through the Hutt River bed has been refined. These changes have resulted in an improved calibration which has undergone sensitivity and uncertainty analysis using the automated parameter estimation routine, PEST (Watermark Computing, 1998).

The objectives of re-building the Hutt Aquifer Model can be summarised as follows:

- Facilitate the re-assessment and refinement of the sustainable and safe yield of the Waiwhetu Aquifer with greater confidence.
- Enable an assessment of the feasibility and advantages of abstracting groundwater from lower stratigraphic levels in the Waiwhetu Aquifer thereby increasing the overall safe yield from this aquifer.
- Enable a preliminary safe yield for the Moera Aquifer to be made, together with an effects assessment on the overlying Waiwhetu Aquifer.

- Provide an improved understanding of river recharge processes and an improved understanding of the effects of abstraction on groundwater levels under various river recharge conditions.

- Contribute towards the process of reviewing the minimum allowable Waiwhetu Aquifer water level at the Petone foreshore.

- Provide a basis for review of the WRC monitoring network.

- This report documents the rebuilding and calibration of the new model - HAM2.

# 2. Previous modelling

Prior to the current re-build, the most recent version of the Hutt Aquifer Model - HAM1 was based upon an earlier finite difference model developed by Reynolds (1993) and later transferred to a more convenient model platform (Visual Modflow) by Pattle Delamore Partners Ltd (1999). This model was able to simulate a reasonable regional groundwater balance and provide an acceptable transient calibration for the Waiwhetu aquifer. However, it had a number of inadequacies which had an important bearing on the accuracy of the model and its predictive capability. These were:

- River – aquifer relationships were not simulated with sufficient accuracy or sensitivity. Bed losses from the Hutt River control the availability of recharge to the Waiwhetu and Moera aquifers. The current model assumed that the river bed conductance was constant regardless of the river stage, whereas in reality the wetted area for infiltration is highly dependent upon stage.

- The coarse model grid and layer structure inhibited the accurate simulation of local vertical and horizontal flow gradients (ie around wells, rivers and discharge zones)

- The model was vertically divided somewhat coarsely into an over-simplified layered system, with one layer representing each aquifer unit (i.e. one layer each for the unconfined, Waiwhetu and Moera). It has since been recognised that that the two confined aquifers are internally highly stratified and exhibit vertical variations in hydraulic conductivity and groundwater head. The current model also assumed fully penetrating wells, whereas all major abstractions occur from only the top portion of the Waiwhetu gravels.

- On the basis of recent research, the discharge from the Waiwhetu and Moera aquifers as leakage into Wellington harbour was not appropriately represented.

- The Moera aquifer was largely ignored and no attempt was made to calibrate the model for this aquifer.

# 3. Data sources

## 3.1 Geological data

Re-interpretation of existing and new bore log data, combined with an analysis of the depositional environment of the Lower Hutt valley, have been used to revise the geometry of the LHGZ and characterise the constituent hydrogeological units.

A large number of logs relating to bores drilled over the past century are available are stored within a database compiled by the WRC and IGNS. The database has recently been reviewed and updated (L. Brown, pers comm.).

In the course of the current modeling task, geological logs for bores greater than 35m depth were re-examined and interpreted on the basis of the present understanding of the Lower Hutt – Port Nicholson depositional environment. These logs (numbering 30), and the revised interpretations, are contained in Appendix 1. Additional data from some 130 shallower bores stored in the database having depths of between 10m and 35m were used to supplement the deeper logs and define the three-dimensional nature of the shallower geological units.

Together, additional bore data and the re-interpreted bore logs were used to re-define the geometry of the various hydrogeological units in the LHGZ. Spatial data defining the top/base boundaries of each unit were then derived by extrapolating the bore data and relying on the anticipated depositional configuration of the sedimentary sequence. Although there is a reasonable spread of bore data throughout the LHGZ, most of the deeper bores are located in the Lower Hutt City/Petone area. However, in the upper catchment area, there is sufficient bore data to adequately define the geometry of the shallow unconfined gravels.

The recently drilled Moera Gravel Investigation Bore 6386 (Brown and Jones, 2000) was used to supplement the interpretation of the hydrostratigraphy for the Lower Hutt Groundwater Zone on the basis of detailed geological and geophysical logging, pump testing and chemical analysis of groundwater and various levels in the succession. This bore was drilled to a depth of 151.3m in Lower Hutt. Although this bore represents just one geospatial point, the information derived from it has aided the re-interpretation other deep bores which has in turn aided the revision of the hydrostratigraphic sequence and depositional characteristics of the LHGZ.

Definition of offshore geology has relied on marine geophysical data (Davy and Wood, 1992; Wood and Davy, 1993; Harding 2000) in conjunction with the revised depositional model for the basin (L. Brown, pers. comm.). The Somes Island bores have also been used to locally define the depth and elevation of the base of the Petone Marine Beds. This information has been used to approximate the offshore geometry and thickness of the various hydrostratigraphical units used in the model.

## 3.2 Harbour bathymetry

Harbour bathymetry was derived from the 1:200,000 New Zealand Oceanographic Institute Chart 'Cook Straight Bathymetry' (1996). The data were used to define the base of the model fixed head cells over the harbour.

## 3.3 Groundwater levels

The WRC hold a large volume of continuously and intermittently recorded groundwater level data relating to numerous monitoring sites in the LHGZ stored in the Council's TIDEDA database. The site locations are shown in Figure 2 and details of the bore depths and the available monitoring record are contained in Table 1.

**Table 1: Groundwater level recording sites**

| Monitoring Bore | Depth and aquifer | Length of Record |
|---|---|---|
| McEwan Park | 26.2 Upper Waiwhetu | 1971 – present |
| Somes Island | 21.2 Upper Waiwhetu (?) | 1969 – present |
| Hutt Recreation Ground | 23.5 Upper Waiwhetu | 1967 – present |
| Randwick Reserve | 24.4 Upper Waiwhetu | 1975 – present |
| Petone Centennial Museum PCM | 26.2 Upper Waiwhetu | 1968 – May 1996 |
| Port Road | 28.7 Upper Waiwhetu | 1970 – June 1997 |
| Bell Park | 23.2 Upper Waiwhetu | 1975 – Dec 1995 |
| Hutt Valley Mem Tech Coll HVMTC | 29.6 Upper Waiwhetu | 1968 – June 1996 |
| Mitchell Park | 51.8 (?) upper Waiwhetu | 1968 – present |
| Taita Intermediate | 14.6 Upper Waiwhetu | 1968 – present |
| IBM1 | 114.6 Moera Gravels | 1992 – present |

The monitoring sites listed in Table 1 were used for model calibration. Most of the sites are influenced by tidal effects which have been removed from monitoring data used for steady state model calibration. For transient model calibration, 30-day or 10-day mean water levels were used thereby averaging out the tidal effects.

The Somes Island bore has periodically experienced leakage due to damage at the wellhead. As a consequence, parts of the monitoring record for this bore are unreliable. Periods when the bore was leaking are easily recognisable from the bore hydrograph when noticeably lower pressures were recorded. Large leaks are known to have occurred in the following periods:

1/11/71 – 20/12/71
1/1/75 – 29/4/93
1/7/97 – 10/2/98

These periods have been omitted from the model calibration dataset.

The Somes Island monitoring site also appears to exhibit random erratic fluctuations in levels which are not associated with leakage of the wellhead. Nearby spring vents through which the artesian aquifers discharge may explain this phenomenon. Leakage may not occur at a consistent rate from the springs but rather be characterised by irregular flow and periodic 'blow-outs' which may be reflected in the aquifer pressures recorded at the nearby Somes Island monitoring site. Further discussion on the aquifer discharge mechanisms is contained in Section 4.5.

### 3.4 River stage data

Continuous monitoring of river stage at Taita Gorge (site no. 29808) was acquired from the Council's TIDEDA database and averaged over the required stress period interval for transient flow modelling. The data were then used to calculate river stage and river width in the model cells between Taita Gorge and Kennedy Good Bridge (KGB). The methodology is described in Section 5.5.

### 3.5 Groundwater usage

Groundwater usage data from the WRC production wells at the Waterloo and Gear Island wellfields, and from industrial bores, was sourced from the Council's WELREC database. At the time of this study, the WELREC database contained data only up to August, 1998. Figure 3 shows the locations of current major groundwater users in the LHGZ.

## 4. Hydrogeology

### 4.1 The Lower Hutt groundwater zone (LHGZ)

A sedimentary basin bounded by low permeability greywacke basement rocks occupies the Lower Hutt Valley continuing offshore beneath Port Nicholson. The basin contains a sequence of alluvial and marine sediments of several hundred metres in thickness. Collectively, the numerous gravel aquifers occurring within this sequence constitute the Lower Hutt Groundwater Zone (LHGZ). The basin structure within greywacke basement is a fault–angle depression formed as a result of downthrow on the eastern side of the Wellington Fault zone. The depth to basement, and the folding/fault dislocation of the basement rock, determines the total thickness and attitude of infilling sediment. The greatest depth to basement occurs on the western side of the valley adjacent to the fault which defines the western margin of the basin

Aquifers have been formed by the thick accumulations of alluvial gravels deposited by the Hutt River. These are separated by beds of fine grained marine sediments which form low permeability confining layers extending across much of the basin but petering out north of the Kennedy Good Bridge area where the aquifers become unconfined. The LHGZ therefore consists of a multi-layered aquifer system containing a series of confined artesian and unconfined aquifers.

## 4.2 Hydrostratigraphy

The principal hydrostratigraphic units within the Lower Hutt – Port Nicholson sedimentary basin have been formally described by Stevens (1956) and are summarised in Table 2.

**Table 2: Hydrostratigraphic units of 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 aquifers separated by interstadial aquitard. Unconfined in north and harbour entrance* |
| Wilford Shell Bed | *Aquitard* |
| Moera Gravels | *Confined Aquifer, semi-confined in north* |
| Deeper glacial/interglacial deposits | *Confined aquifer/aquitard sequence* |

### 4.2.1 Taita alluvium

The postglacial Taita Alluvium deposits were defined by Stevens (1956) to include all postglacial fluvial deposits filling the Hutt Valley downstream of Taita Gorge. These deposits form the present day surface of the valley. The alluvium consists mainly of buried river channel and fan gravel deposits, but the sequence also includes flood and over bank deposits of sand, silt and clay. The near surface gravels constitute an unconfined aquifer whilst deeper layers in the alluvium exhibit semi-unconfined and confined conditions due to the stratified nature of the deposits.

Inland of the Lower Hutt CBD and north of Kennedy Good Bridge, the Taita Alluvium is a composite gravel, sand and silt deposit underlying a floodplain surface conformable with the present day river bed gravels. Groundwater levels in this area are generally between 3 and 10m depth but are locally influenced by river stage and tidal fluctuations. From Lower Hutt City to the coast, the Taita Alluvium overlies, is interbedded with, and underlies contemporaneous postglacial Petone Marine Beds and Melling Peat.

Brown and Jones (2000) subdivided the Taita Alluvium into units relevant to the Hutt Valley hydrogeology which has been carried through to the present study during re-interpretation of bore logs. The depositional relationship of the Taita Alluvium to the Petone Marine Beds and Melling Peat identifies a transgressional (T3), progradational (T2: 6500 - 4000 year BP) and progradational (T1: 4000 year BP to present day) subdivision of the Taita Alluvium. This distinction is based on depth, sediment colour and stratigraphic relationship to units with ages constrained by established geological history and radiocarbon dating (e.g. Melling Peat and Petone Marine Beds). T3 was deposited during the postglacial period of rising sea level from about 14 000 to 6500 years BP. The Hutt River was adjusting to the shortening of its course imposed by the sea transgressing over the land, by entrenching into the last glaciation floodplain surface, and reworking and spreading the derived material downstream of Taita Gorge and across the Hutt Valley floodplain surface. Down valley from Melling and Waterloo, T3 underlies the Petone Marine Beds as deposition occurred prior to the rising sea transgressing over the land surface and reaching the maximum distance inland 6500 years ago. The progradational Taita Alluvium deposits (T2) represent former Hutt River courses and floodplains, associated with the coast being built out into the harbour during the relatively stable sea level period of the last 6500 years. The progradational Taita Alluvium deposits can be divided into two units on the basis of the 4000 year BP Melling Peat. The peat and wood layer is interbedded with the Taita Alluvium. T2 underlies Melling Peat and T1 overlies it in the form of near surface gravel channel deposits extending almost to the coast. Both T1 and T2 are water bearing and hydraulically connected to the Hutt River, with groundwater outflows from these units forming springs on the valley floor and in the harbour.

### 4.2.2 Petone marine beds and melling peat

The Petone Marine Beds form an extensive confining strata or aquitard overlying the Waiwhetu Gravels and are predominantly fine-grained silt, sand and coarse sand deposits which commonly contain shell and wood fragments. There are also occasional shelly gravel or gravel and sand strata. These deposits accumulated as the sea transgressed over the land during the postglacial rise in sea level. The coast prograded at its present position once sea level stabilized around 6500 years BP. The most conspicuous surface expression of the Petone Marine Beds are the beach ridges which occur to the west of the Hutt River from the Petone foreshore inland as far as Alicetown (Stirling 1992). The Petone Marine Beds are generally 10-20 m thick at the southern (or harbour) end of the Hutt Valley, and thin inland forming a wedge shape deposit. The Petone Marine Beds extend inland as far as Melling Bridge in the west, Waterloo in the centre, and Gracefield in the eastern Lower Hutt Valley. They are also thicker towards the western side of the valley, probably as a result of the greater subsidence associated with movement on the Wellington Fault. Re-interpretation of seismic reflection surveys carried out by Davy and Wood (1993) by Harding (2000) showed that in the north-eastern quadrant of the harbour, the Petone Marine Beds are considerably thinner and interpreted to be 10-12m thick. Beneath the rest of the inner harbour, the marine beds were estimated to be up to 30m thick.

### 4.2.3 Waiwhetu artesian gravels

Waiwhetu Artesian Gravels underlie either Petone Marine Beds or Taita Alluvium and represent the principal aquifer in the LHGZ. Water supply wells in the Lower Hutt and Petone areas abstract from the uppermost Waiwhetu Artesian Gravels at depths of between 20 and 40 m.

The Waiwhetu Artesian Gravels accumulated in a braided fluviatile environment during the last glaciation and extend from Taita Gorge to the harbour entrance area. 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. Geophysical interpretations (Davy and Wood, 1993; Harding, 2000) 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. Evidence for prominent palaeochannels from seismic surveys indicates 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. This channel, representing a possible preferential flow path in the aquifer, is overlain by considerably thinner Petone Marine Beds and could be an important conduit for the discharge of groundwater into the harbour.

The materials comprising this hydrostratigraphical unit are highly variable. Gravel clasts are the predominant lithological component, but there are also sandy gravel, silty gravel, gravelly sand and sand beds. Sand deposits within the Waiwhetu Gravels intersected by some wells are as much as 10m thick. The highly permeable upper gravels are characteristically separated by discontinuous lenses of silt, peat and clay of limited lateral extent. However, detailed logging of the recent WRC6386 bore (Brown and Jones 2000) and the re-interpretation of other bore logs have identified a laterally persistent aquitard within the Waiwhetu Artesian Gravels effectively dividing the unit into two distinct parts – the *Upper Waiwhetu Aquifer* and the *Lower Waiwhetu Aquifer*.

The intra-Waiwhetu aquitard occurs at a depth interval of 46.3 to 54.0m in the WRC6386 bore and consists of sand, silt and clay with interbedded carbonaceous material. The unit is recognisable in all other deep bores typically being up to 10m thick and occurring at a depth range of 40 to 70m. The aquitard is probably associated with deposition during a period of warmer climate (interstadial) coincident with the last interglacial about 30 – 40,000 years ago. It appears to have a significant effect on groundwater flow in the aquifer 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 45 years (66.4 m).

The Lower Waiwhetu Artesian Gravels are not rust or black stained like the Upper Waiwhetu Gravels and the matrix is composed of a gritty clay, silt and sand. The down hole neutron log for WRC 6386 shows higher silt and sand content compared with the Upper Waiwhetu Gravels. The groundwater level in the lower gravels is also about 0.5 m higher than above the aquitard.

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

### 4.2.4 Wilford shell bed

The Wilford Shell Bed underlies the Lower Waiwhetu Gravels and comprises predominantly silt, clay and sand deposits containing shells and minor peaty silts. The unit represents an aquitard separating the Lower Waiwhetu Gravels from the underlying Moera Gravels. The aquitard is regarded to be thicker beneath Port Nicholson and in the Petone Foreshore area where it attains approximately 25m. The depth and thickness of the unit decreases up-valley.

The Wilford Shell Bed was deposited during the high sea levels associated with the last interglacial period (Kaihihu). In the Hutt Valley, the geographic distribution of the 12 drillholes penetrating the Wilford Shell Bed is restricted, but the inland extension appears to be at about Knights Road in Lower Hutt. 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 palaeo-environment) occur inland as far as Mitchell Park. There are thin water bearing sand and gravel layers within the Wilford Shell Bed.

### 4.2.5 Moera gravels

The Moera Gravels are poorly sorted weathered brown gravels associated with river deposition during the penultimate (Waimea) glaciation and are underlain by a marine aquitard layer and a considerable thickness of older alluvial and marine deposits. Toward Taita Gorge, the Moera Gravels appear to lie directly on greywacke basement.

The unit has a thickness of approximately 25m in the Petone/Lower Hutt area and constitutes a deep artesian aquifer extending beneath Port Nicholson. North of Lower Hutt, the Wilford Shell Beds thin and disappear providing a vertical hydraulic continuity between the Moera gravels and the higher Waiwhetu Gravels and Taita Alluvium. Recharge to the deeper aquifers occurs in this area.

Only 10 bores (including 4 water supply wells) penetrate Moera Gravels at approximately 100m depth in the Petone area. However, no wells are presently abstracting groundwater from this unit.

Artesian pressures within the Moera Gravels are higher than in the overlying Waiwhetu aquifers. However, due to the relatively high clay content in the weathered gravels, the hydraulic conductivity is low and recent dating of the groundwater (Brown and Jones, 2000) has revealed a mean residence time of > 60 years and a slightly older residence time at the base of the unit (> 70 years). Groundwater chemistry shows a slight increase in cations and anions compared with the overlying Waiwhetu Artesian Aquifer with conductivity increasing slightly with depth.

### 4.2.6 Deep strata

Beneath the Moera Gravels, a thick succession of ancient alluvial and marine sediments lie on greywacke basement. These sediments thicken southwards from Taita Gorge and occupy the deeper central parts of the Lower Hutt – Port

Nicholson Basin. Groundwater chemistry in the deeper gravel zones shows an increase in total major cations and anions, conductivity, bicarbonate, total hardness and temperature with depth. This information infers a limited or negligible groundwater throughflow in the deeper strata.

WRC 6386 was drilled below the base of the Moera Basal Gravels to a total depth of 151.3m within a sequence of silty brown-grey gravels and thin silt-rich aquitards units. Prior to the drilling of WRC 6386, only three boreholes (Gear Meat Company - WRC 151; Wellington Meat Export Company well UWA 2 – WRC 1085; and Parkside Road, Seaview - WRC 1086) had been drilled and logged to provide lithological information on strata underlying the Moera Gravels. In these bores, Begg and Mazengarb (1996) differentiated a sequence of temperate interglacial and cold glacial climate deposits based on pollen assemblages identified by Mildenhall (1995). The glacial/interglacial sequence covers two glacial and three interglacial climate events with deposition extending back to the Ararata Interglacial (oxygen isotope (OI) climatic stage OI11) of Pillans (1990). In the deepest testbore (WRC 151), stratum immediately overlying greywacke basement can be tentatively correlated with oxygen isotope stages back as far as OI13.

#### 4.2.7 Greywacke

The LHGZ is bounded by low-permeability greywacke basement rocks. The depth to basement and the folding and fault dislocation of the basement rock has controlled the total thickness and attitude of infilling sediment. There are 48 wells located on the floor of the Lower Hutt Valley that penetrate greywacke. However, only four bores intersect the greywacke basement in the deeper part of the basin within the confined aquifer zone.

Bore WRC 151 at Petone, just to the east of the Wellington Fault, is located in the deepest part of the onshore basin and intersects greywacke at 299m. Offshore, the basin is regarded to be considerably deeper adjacent to the fault with the infilling sediment sequence thinning to the east and to the north. Along the Petone foreshore and in the vicinity of the Somes Island, there is evidence to suggest a complex warping and faulting of the basement. Greywacke outcrops on Somes Island appear to represent part of a fault-bounded horst structure extending to the north beneath the Lower Hutt Valley. Uplift and erosion on the horst may have caused the deeper part of the Quaternary sediment sequence to be truncated.

### 4.3 Hydraulic properties

#### 4.3.1 Taita alluvium

The Taita Alluvium ranges in thickness from 0 to 16m, thickening towards Taita Gorge. However, since only one reliable pumping test has been performed in the shallow gravels, the hydraulic properties of the Taita Alluvium are poorly characterised. The pumping test was carried out in a shallow bore at Avalon Studios (R27:732004) and provided a range of transmissivity values from 2,700 to 52,700 $m^2$/day, with an average of 4,500

$m^2$/day. The test results demonstrate the highly heterogeneous nature of the Taita Alluvium.

### 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 10 to $1x10^{-4}$ m/day (WRC, 1995). Vertical hydraulic conductivity is expected to be several orders of magnitude 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 above the interstadial aquitard have been extensively tested during the course of resource investigations over the past 70 years or so. The gravels exhibit a wide range of hydraulic properties due to the rapid fluviatile depositional environment which accumulated laterally and vertically variable sediments. This variability is reflected by the range of transmissivity values derived from pump testing.

The WRC (1995) have reviewed and re-interpreted existing pump test data for the Upper Waiwhetu aquifer, the most significant large-scale tests being:

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

A further pumping test at a rate of 50 ML/day was carried out in the Waterloo Wellfield in November 1995 (Butcher, 1996).

Due to difficulties in the interpretation of the early data (Wellington Meat 1933, Gear Island, 1957/67 and Hutt Park 1974), only the latest three tests have been used up to derive an average transmissivity and storativity 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 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 may as a consequence underestimate the aquifer transmissivity.

**Table 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) | | |
| Bores within 500m of pumping | 23,400 | $1 \times 10^{-3}$ |
| *All observation data* | 22,000 | $8 \times 10^{-4}$ |
| Waterloo 1993 (40 hours) | | |
| Wellfield bores | 34,900 | $9 \times 10^{-4}$ |
| *All observation data* | 28,000 | $7 \times 10^{-4}$ |
| Waterloo 1995 (108 hours) | | |
| Wellfield bores | 38,900 | $3 \times 10^{-4}$ |
| *All observation data* | 27,980 | $5 \times 10^{-4}$ |

The Waterloo pumping tests suggest that the average 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.

The tests indicate a range in the confined storage coefficient for this aquifer of between $3x10^{-4}$ and $1x10^{-3}$.

### 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 gravels 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 $m^2$/day and a storage coefficient of 2 $x10^{-4}$. More recently, borehole WRC 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. 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 $m^2$/day, and a storage coefficient in the range of 4 – 8 x $10^{-5}$.

### 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 WRC 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 $m^3$/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. Since this is the highest yielding zone within the top of the deeper strata encountered in WRC 6386, and since the groundwater chemistry becomes rapidly mineralised with increasing depth, the deep strata are likely to have a horizontal hydraulic conductivity at least an order of magnitude lower than 70$m^2$/day. The vertical hydraulic conductivity is regarded to be several orders of magnitude lower due to the silt layering within numerous aquitard zones. Consequently, the deeper strata have been regarded to be hydraulically isolated from the higher groundwater environment for modelling purposes.

#### 4.3.8 Greywacke

The greywacke basement rocks have an extremely low primary permeability with localised secondary permeability developed along fracture zones and in joint systems. However, many of the larger fracture systems are clay-filled and hence overall the greywacke basement has been assumed to be impermeable.

### 4.4 Recharge

The Taita Alluvium, Waiwhetu and Moera aquifers receive recharge sourced from leakage through the bed of the Hutt River in the upper part of the LHGZ catchment where the aquifers become unconfined (between Taita Gorge and Kennedy Good Bridge). The river has a complex recharge-discharge relationship with the shallow unconfined Taita Alluvium aquifer, but generally looses water to underlying aquifers in the area between Taita Gorge and Boulcott/Kennedy Good Bridge. This area is termed the ‘recharge zone’. Between Boulcott and the coastline in the area where the Waiwhetu aquifers are confined, the river is tidal and generally gains groundwater.

A large 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 the lower reaches. Of the total amount of river bed leakage, only a small percentage 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 recharge dynamics are, however, regarded to be strongly influenced by the abstraction regime.

Direct rainfall infiltration and infiltration of hillslope runoff also contribute recharge to the Taita Alluvium.

#### 4.4.1 River recharge

Quantification of river recharge by the WRC (1995) has relied upon a limited amount of concurrent flow gaugings, mostly under low flow conditions when flow measurements are more easily undertaken and when the measurement errors are small. There are very few concurrent flow gaugings coincident with mean or high flow conditions.

In the LHGZ, the river section between Kennedy Good Bridge and Taita Gorge is in hydraulic connection with the Taita Alluvium, Waiwhetu Gravels and Moera Gravels due to the absence of continuous impermeable strata. Significant river losses occur in this section of the river where the deeper aquifers are unconfined. Further losses may occur downstream but will not contribute recharge to the Waiwhetu or deeper aquifers due to the intervening confining Petone Marine Beds.

Historical concurrent flow gaugings have been carried out mostly under very low flow conditions using WRC river gauging stations at Taita Gorge (29809), Kennedy Good Bridge (29824), and downstream at Boulcott (29811) for the period 1939 - 1993. The mean monthly flows at Taita Gorge range from approximately 12 to 36 $m^3$/sec whereas all of the concurrent gauging prior to 1995 were taken during flows of between 2.3 and 5.7 $m^3$/sec. During the 1995 pumping test, Butcher (1996) carried out five concurrent gaugings during November for flows at Taita Gorge of between 11 and 30 $m^3$/sec. The 1995 readings provide the only direct quantification of river losses under normal flow conditions to date.

Figure 4 shows the relationship between flow at Taita Gorge and flow at Kennedy Good Bridge using all of the Taita Gorge – Kennedy Good Bridge concurrent gauging data. The trend line in Figure 4 is highly dependent upon the 1995 gauging data which lie on the same straight-line trend as the earlier low-flow data. Regression analysis of the data in Figure 6 provides the following equation which relates flow at Taita Gorge to Flow at Kennedy-Good Bridge:

Kennedy-Good Bridge = 0.974(Taita Gorge) – 912 L/sec

The relationship is similar to that derived by WRC (1995) using the low flow data only.

Using this relationship and assuming that the straight-line trend can be extrapolated to higher flows, river losses between Taita Gorge and Kennedy Good Bridge during average river flow conditions range from approximately 100,000 to 160,000 $m^3$/day but do not exceed 80,000 – 85,000 $m^3$/day under low flow conditions (for flows of less than 6 $m^3$/sec). The reduction in losses during low flows is assumed to be related to the reduced wetted perimeter of the river bed (reduced river bed conductance) and the reduced vertical head gradient between the river and underlying aquifer. The broad, flat nature of the channel profile means that a small change in stage of only half a metre or so will produce a large change in the wetted channel perimeter and river bed conductance.

### 4.4.2 Rainfall recharge

Infiltration of rainfall is a secondary source of recharge to the Taita Alluvium and is of minor significance to the deeper Waiwhetu and Moera aquifers. Reynolds (1993) produced a simple soil moisture model to estimate the average monthly rainfall recharge. The model is based on the following assumption:

Recharge = Rainfall - Actual Evapotranspiration - Soil Moisture Deficit

Mean monthly recharge values calculated for the Lower Hutt Catchment are shown in Table 4.

**Table 4: Estimated rainfall recharge to the Lower Hutt groundwater zone (Reynolds, 1993)**

| Month | Mean Recharge mm |
|---|---|
| Jan | 18 |
| Feb | 8 |
| Mar | 36 |
| Apr | 58 |
| May | 117 |
| Jun | 135 |
| Jul | 138 |
| Aug | 108 |
| Sep | 73 |
| Oct | 72 |
| Nov | 41 |
| Dec | 45 |
| Annual Mean | 833 |

Since much of the Lower Hutt – Petone is built-up, a high proportion of the land area is now impermeable and stormwater is diverted to the sea or the river. As a consequence, the actual recharge will be significantly lower than the soil moisture balance estimate and it is estimated that only approximately 40% of the catchment is open to rainfall recharge.

## 4.5 Groundwater flows and aquifer discharge

Groundwater flow in the various aquifers occupying the groundwater basin occurs down-valley to the foreshore, continuing offshore to the southern edge of the harbour (Figure 5). Throughout the confined zone, hydraulic gradients are always upwards and discharge from the aquifers occurs through diffuse vertical leakage through aquitard layers into overlying aquifers and into the sea. Discharge from the Upper Waiwhetu Aquifer is also known to occur at discrete points as submarine springs where the aquitard layer is thin and has been breached. Harding (2000) has identified a number of areas where spring discharges have been identified and measured. The locations of these areas are shown in Figure 6. Many submarine springs occur near basement outcrops, possibly as a result of a seismic decoupling of the unconsolidated sediments caused by the different shaking velocities between the basement rocks and the sediments. There are also spring depressions in the harbour floor which are not associated with the basement contact and which appear to occur in areas where the aquitard layer (Petone Marine Beds) is thin or has been breached by high artesian pressures and/or liquefaction during seismic activity.

The principal spring discharge zones identified by Harding (op. cit.) are as shown in Figure 6 and are as follows (zone numbers refer to Figure 6):

- 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 were found to exhibit no signs of submarine discharge (Harding, 2000).

The Somes Island monitoring bore lies close to a submarine discharge zone (zone 5, Figure 6) and the monitoring record form this bore may be influenced by the springs. The Somes Island bore periodically experiences large fluctuations in water level and changes in tidal response which could be explained by accumulations of silt in the spring depressions and intermittent ‘blow-outs’ or changes in discharge rate caused by a build-up of artesian pressures, tidal scour or seismic activity.

# 5. Numerical model design

## 5.1 Model code

The USGS finite difference numerical model code MODFLOW (McDonald and Harbaugh, 1988) has been used to re-model the Lower Hutt Groundwater Zone. The ‘Visual Modflow’ graphical interface (Waterloo Hydrogeologic, 2000) was used to assist with the processing and analysis of model input and output data.

## 5.2 Finite difference grid design

MODFLOW uses a finite difference solution method which requires the use of a rectilinear, block-centred spatial grid and one or more layers. The new Hutt aquifer model grid covers an area of 19500m x 7200m and is considerably larger than the previous model domain incorporating much of Port Nicholson, extending southwards to Falcon Shoals at the harbour entrance. To avoid numerical errors, the grid has been aligned with the principal groundwater flow vector parallel to the valley walls (NE-SW). A variable grid size ranging from 1300m at the model boundaries and condensing down to 250m in the area around the Hutt River and over the unconfined aquifer area has been employed (Figure 7).

The new model has a different layer structure to the previous Hutt aquifer model (Reynolds, 1993). Since Visual Modflow does not support an implicit quasi 3-D representation of aquitard units using the MODFLOW VCONT term, the aquitard units have been explicitly modelled as separate layers. This adds an unavoidable increased complexity to the model but has the advantage of enabling the storage effects of the aquitard layers to be incorporated. Consequently, the new model has seven layers based upon the hydrostratigraphical divisions discussed in Section 4.2.

One of the most significant changes in the new model is the splitting of the Waiwhetu Gravels into upper and lower members, the incorporation of the interstadial aquitard, and the simulation of abstraction from only the upper member. Although the existence of the interstadial aquitard is based on relatively few deep bores, the inferred depositional environment for this unit (Section 4.2.3) suggests that it is relatively widespread but may be eroded or very thin in some places. The distinct difference in hydraulic conductivity between the upper and lower Waiwhetu gravels, and the absence of abstraction from the Lower Waiwhetu Aquifer, means that such uncertainty has minor implications in terms of the simulation of the Upper Waiwhetu Aquifer. The aquitard will however exert some control on the system response to abstraction scenarios in the Lower Waiwhetu Aquifer.

Table 5 summarises the model layers and the MODLFOW layer types assigned to each of them. Some of the layers (e.g. layers 2, 4 and 6) represent more than one hydrostratigraphic unit because the aquitard units represented by these layers do not extend into the unconfined aquifer area north of Kennedy Good Bridge. In the unconfined area, the layers have been assigned properties consistent with the overlying or underlying aquifer units. Layer Type 3 allows the cells in a particular layer to switch between confined or unconfined depending upon whether the modelled head lies above or below the elevation of the layer top. For instance, in the unconfined area, Layer 2 may become unconfined but will remain confined when the overlying Taita Alluvium is partially saturated. Layers deeper than Layer 2 however maintain confined aquifer conditions at all times.

**Table 5: Model layers**

| Model Layers | MODFLOW Layer Type |
|---|---|
| Layer 1: Taita Alluvium | Type 1 – Unconfined |
| Layer 2: Petone Marine Beds – Upper Waiwhetu Gravels | Type 3 – Confined/Unconfined, variable S/T |
| Layer 3: Upper Waiwhetu Gravels | Type 0 – Confined, constant S/T |
| Layer 4: Interstadial deposits – Upper Waiwhetu Gravels | Type 0 – Confined, constant S/T |
| Layer 5: Lower Waiwhetu Gravels | Type 0 – Confined, constant S/T |
| Layer 6: Wilford Shell Beds – Moera Gravels | Type 0 – Confined, constant S/T |
| Layer 7: Moera Gravels | Type 0 – Confined, constant S/T |

The model layer elevations were derived from bore logs contained in the revised geological database (Section 3.1) and imported into Visual Modflow as x, y, z coordinate files. The spatial data for each layer boundary was then contoured externally using surfer and carefully edited in areas where no observation points occur to ensure the generated surfaces maintained consistency with the conceptual geological model. This entailed inserting artificial data points to control the contouring process. The Surfer '.grd' files were then imported into Visual MODFLOW.

## 5.3 Model boundaries

Maintaining consistency with the conceptual hydrogeological model, the following model boundaries have been assigned:

| | |
|---|---|
| *western boundary* | coincident with the Wellington Fault |
| *eastern boundary* | coincident with the junction between the unconsolidated alluvial and marine sediments and the basement greywacke which plunges towards the Wellington Fault. |
| *northern boundary* | at Taita Gorge where the sediments thin and are constricted within the gorge. Minimal throughflow occurs at this boundary since the gravels become very thin. |
| *southern boundary* | the estimated southern extent of the aquifers within the basin coinciding approximately with the southern boundary of Port Nicholson and the harbour entrance around Falcon Shoals. |

The model boundaries and model domain showing the finite difference grid are shown in Figure 7. No-flow conditions have been assigned to all boundaries. In the unconfined aquifer zone, the base of the model coincides with the greywacke basement contact, but to the south as the basin deepens rapidly, the base of the model coincides approximately with the base of the Moera Gravels, which has been assumed to have a relatively constant thickness of 25-30m.

## 5.4 River simulation

The Hutt River above Kennedy Good Bridge (KGB) is a critical hydrogeological control since recharge to the aquifers within Lower Hutt Groundwater Zone occurs principally via flow losses to groundwater from this section of river.

Previous models of the groundwater system did not take into account the effects of significant changes in river bed conductance associated with the relationship between channel width and river stage. The current model has attempted to incorporate this relationship to simulate temporally variable leakage rates through the bed of the Hutt River north of Kennedy Good Bridge.

### 5.4.1 River bed elevation

River bed levels and channel profiles measured at approximately 100m intervals down the entire length of the river are available for 1987, 1993 and 1998 (Hutt River Gravel Analysis Study, WRC1998). Table 6 shows the river bed elevations taken from cross sections coinciding with approximately with the centre point of each river cell (identified by model row number). The recharging segment of the river is represented by twenty-three 250$m^2$ model cells.

**Table 6: River cell data – bed loss reach from Taita Gorge to KGB as used in the transient flow model**

| River cross section umber 1200 = Taita Gorge | Model Row | Minimum bed elevation 1998 m RL | Mean bed level changes (mm) 1987 - 1998 |
|---|---|---|---|
| 1200 | 1 | 23.63 | -603 |
| 1200 | 2 | 23.63 | -603 |
| 1170 | 3 | 22.4 | -466 |
| 1130 | 4 | 22.14 | -205 |
| 1110 | 5 | 21.2 | 69 |
| 1090 | 6 | 20.9 | -425 |
| 1050 | 7 | 18.7 | -486 |
| 1030 | 8 | 17.3 | -386 |
| 1000 | 9 | 16.9 | -350 |
| 980 | 10 | 16.6 | -177 |
| 950 | 11 | 15.5 | 10 |
| 930 | 12 | 14.6 | -96 |
| 910 | 13 | 13.8 | -57 |
| 880 | 14 | 12.6 | -135 |
| 850 | 15 | 12.3 | 87 |
| 830 | 16 | 10.7 | 112 |
| 810 | 17 | 10 | 577 |
| 790 | 18 | 8.9 | 247 |
| 770 | 19 | 9 | 834 |
| 760 | 20 | 9.02 | 752 |
| 720 | 21 | 6.6 | 234 |
| 690 | 22 | 6.7 | 513 |
| 640 | 23 | 6 | 805 |

Table 6 shows that the bed elevation of the Hutt River between Taita Gorge and KGB has experienced changes of up to about 0.8m over the past decade. Progradation of the bed has occurred towards KGB in response to reductions in gravel extractions whilst at Taita Gorge the bed has experienced a gradual reduction in level of approximately 0.6m over the same period. This complex shifting of bed levels has not been taken into account in the model for the long-term transient calibration, rather the Taita Gorge monitoring recorded has been corrected for changes in bed level at Taita Gorge (using the methodology described below). The long-term recession in river stage in response to the reduction in bed level as shown by Figure 8 has important implications on the long-term transient model calibration (Section 5.4.2).

### 5.4.2 River stage

The development of a relationship between the measured Taita Gorge stage and the stage at each cross-section has been an important requirement of the new model. The model relies upon the calculation of a river stage at each cross-section location (Table 6) using the continuous river stage monitoring record for Taita Gorge (29809). The WRC have, on the basis of intermittent flow measurements made at various localities down the river, modelled the Taita Gorge stage – cross section stage relationships. These are listed in Appendix 2.

Since the Taita Gorge stage record has shifted in response to the declining bed elevation at this location (Figure 8), the stage monitoring data used for long-term transient calibrations have been normalised to 1998 bed level conditions. During a model calibration run spanning several years, a significant error in downstream river stage calculations will occur if the bed elevation at Taita Gorge be assumed to be constant. This is because river cell stage in the model is referenced to a datum (mean sea level) and not the river bed. An alternative and more accurate approach would have been to calculate the change the river bed levels and the corresponding change in stage for each river cell during the transient simulation. However, this has not proved possible because the relationships are complex and there are insufficient data for river bed changes to adopt such an approach.

Presently, the relationship between the Taita Gorge stage and downstream locations is known for 1998 bed level conditions (Appendix 2). Such relationships have not been developed for earlier periods. Therefore, the river bed elevations in the model have been held constant during transient simulations (1998 conditions) and the gauging data for Taita Gorge has been 'normalised' to the 1998 bed level at this site. For instance, if the bed level at Taita Gorge was 0.6m higher than it is now (ie 1987 levels), the measured Taita Gorge river stage has been reduced by this amount to compensate for the lower bed level set in the model. In this way, the model will allow the correct amount of water into the underlying aquifer using the correct vertical head gradients.

### 5.4.3 River bed conductance

River bed conductance is a parameter used by MODFLOW which is calculated using the length of a reach (L) in each river cell, the width of the river (W) in the cell, the thickness of a river bed (M), and the hydraulic conductivity of the river bed material (K). The streambed conductance, C, is expressed as:

$$C = K L W / M$$

The river width (W) is dependent upon river stage and can vary enormously in response to a relatively small change in river stage resulting in a large change in the river bed conductance. To account for this in the model, the profiles corresponding to each river cell (Table 6) were used to derive a relationship between stage and width (channel wetted perimeter). The relationship is different for each profile due to changes in channel geometry. Therefore each river cell between Taita Gorge and KGB has a unique stage – width relationship. The relationships, contained in Appendix 3, are based upon 1998 channel profiles derived from the Hutt River Gravel Analysis Study (WRC1998). Comparison of the profiles with those of 1987 and 1993 shows there to be a relatively small change in channel geometry and therefore the relationships developed for 1998 are considered to be valid for the preceding 10 years or so.

### 5.4.4 River spreadsheet

To calculate the set of unique river bed elevation, river stage and river bed conductance values for each individual river cell between Taita Gorge and KGB for transient flow modelling, a spreadsheet was constructed to perform the following calculations for each model stress period:

- correct the Taita Gorge record for bed level changes if necessary
- calculate the river stage for each river cell based on the corrected Taita Gorge record (Appendix 2)
- calculate the channel width based on the river stage in the cell (Appendix 3)
- calculate the river bed conductance
- format the data for each river cell for importing to Visual Modflow

### 5.4.5 Hutt River south of KGB and Waiwhetu Stream

To the south of Kennedy Good Bridge (KGB) the Waiwhetu and Moera aquifers become confined and the river interacts only with the Taita Alluvium. South of Boulcott, flow losses and gains become difficult to evaluate because the Hutt River becomes tidal. It is likely that there is a significant return of groundwater to the Hutt River from the unconfined aquifer (Reynolds, 1993) but a complex discharge-recharge relationship associated with tidal cycles and stage conditions is anticipated near to the river.

Since there are no groundwater level monitoring sites and river loss/gain measurements for the Taita Alluvium south of Boulcott, the model cannot be calibrated in this area. The modelling has focussed on the simulation of recharge to the aquifers in the unconfined zone north of KGB, the accurate representation of the confined aquifers and discharge processes. Provided that general head and gradient conditions in the Taita Alluvium are reasonably represented, errors in river losses will not affect the deeper confined aquifer system.

In the absence of an adequate understanding of the interaction between groundwater and the river in the confined aquifer zone, and the likely complexity of the relationship, the river has been simplistically represented in the model using drain cells south of KGB to the river mouth. MODFLOW's Drain Package removes water from the aquifer at a rate proportional to the difference between the head in the aquifer and the elevation of the drain. The Drain Package assumes that the drain has no effect if the head in the aquifer falls below the fixed head of the drain and only enables water to be removed from the model. The elevation of the drain cells used in the model have been taken from the 1998 bed levels contained in the Hutt River Gravel Analysis

Study (WRC1998) consistent with the bed levels used for the river cells north of KGB. Drain bed conductance values (cf stream bed conductance) were estimated during calibration.

The Waiwhetu Stream has also been treated as a drain as it is regarded to be a spring-fed stream. Reynolds (1993) also modelled this stream as a drain using bed levels estimated by the WRC Rivers Department plans and topographical maps. The drain levels and bed conductance values used by Reynolds were transferred to the new model.

### 5.5 Discharge simulation

Discharge from the confined aquifers takes place through vertical upwards leakage into the harbour over a broad area, although discharges are also locally manifest as discrete submarine springs (Section 4.5). The individual springs have not been simulated since their locations and relative discharge characteristics are not completely understood. The model handles aquifer discharge as diffuse leakage principally in areas where the confining beds are thin and where a number of submarine springs have been identified (Harding, 2000). Such areas occur in the NE part of the harbour between the Hutt River mouth and Somes Island, along the eastern edge of the harbour, and near to the harbour entrance. Unlike the previous model, the new simulation does not contain any ‘holes’ in the confining beds to facilitate aquifer discharge.

## 6. Model calibration

### 6.1 Procedure

The steady state and transient flow calibration process has been carried out in four stages; these are as follows

- initial estimation of parameters and manual (forward) steady-state calibration
- calibration testing using a second calibration data set
- assessment of parameter uncertainty through sensitivity analysis
- transient flow calibration (in three stages)

In accordance with standard modelling procedure, the new model was first subject to a steady-state calibration process whereby the modelled heads were fitted to a set of assumed steady-state groundwater levels through manipulating model input parameters to achieve a satisfactory match. The calibration process also assessed the predicted water balance for the groundwater system against the model water balance to ensure that the simulation was reasonably approximating the conceptual model.

An aquifer is assumed to be in steady-state when the groundwater system is in equilibrium when the stresses and head conditions do not significantly change with time. In reality, this condition rarely occurs and some stable period during which quasi steady-state conditions are observed was chosen for calibration. The calibrated steady state model was then checked by testing another set of steady-state data.

The following observation data sets were chosen for steady-state calibration:

- 1993 pump test period
- 1995 pump test period

The steady-state groundwater flow model was constructed using a reasonable data set of initial parameters based on the known hydraulic properties of the formations (Section 4.3), and approximate water balance estimates. The input parameters (hydraulic conductivity, recharge, river bed conductance) were then adjusted within the constraints of the established range of values until the fit between model-generated and observed groundwater heads was minimised and a realistic water balance achieved (by minimising the mean square error). A manual sensitivity analysis was then carried out on the steady state calibrated model to assess the degree of certainty with which the parameters had been estimated.

Following steady-sate calibration, the model was then run in transient mode for a representative 12 month period (June1996- May1997) and then checked against a 14-year monitoring record for the period 1984 to1998 to confirm the capability of the model to accurately simulate the long-term behaviour of the system under variable stress conditions. The latter simulation was chosen to commence in 1984 since prior to this there was a major difference in the abstraction regime in the Waiwhetu Artesian Aquifer. The municipal supply wellfield was located at Gear Island (Figure 3) until 1981 and a large number of industrial abstractions existed in the foreshore area prior to the mid 1980's. The municipal abstraction wellfield has since moved inland to Waterloo and most of the large industrial users have gone. Since there are known gaps and errors in the abstraction database (WELREC) prior to 1984, the long-term calibration has not included this period.

The transient calibration has partly relied upon the model-independent parameter estimator – PEST (Watermark Computing, 1998) to optimise hydraulic conductivity zone values. PEST is based on the Gauss-Marquardt-Levenberg non-linear least squares algorithm. Hydraulic conductivity values were subsequently assessed in terms of sensitivity, uncertainty, covariance and correlation from the PEST run. During the PEST run, storage coefficient values were held constant and adjusted manually following optimisation of hydraulic conductivity.

A final transient calibration check was subsequently carried out using monitoring data collected during the 2000 – 2001 drought period when extreme and prolonged low-flow conditions were experienced in the Hutt River and when the aquifer was under severe stress.

## 6.2 Steady state calibration

Steady state model calibration was initially performed using the groundwater level and abstraction data recorded towards the end of the 1993 pumping test.

The data represent assumed quasi steady-state conditions and were used by Reynolds (1993) to test the steady state calibration of the earlier model. During this test, the Waterloo Wellfield was abstracting at a constant rate of 36,000 $m^3$/day and the Buick Street wells (Figure 3) had a constant output of 6,000 $m^3$/day.

The semi-recovered aquifer condition prior to the 1993 test was used by Reynolds to calibrate the earlier model before testing the calibration using the data towards the end of the pumping test. During a recovery period, only the Buick Street wells were pumping. However, it is questionable whether the pre-test groundwater heads represent fully recovered conditions; it is probable that they do not. As a consequence, this data has not been used to calibrate the new model.

### 6.2.1 Input parameters

***Hydraulic conductivity***

Table 7 lists the hydraulic conductivity values used in the steady-state model, based largely upon the established range of values discussed in Section 4.3. Values for vertical hydraulic conductivity ($k_z$) were derived through the calibration process with each layer having a constant value except for those layers containing aquitards. The latter have hydraulic conductivity values assigned on the basis of where the aquitard layer is present. Approximate transmissivity values have been calculated using the average layer thickness.

**Table 7: Steady state calibrated hydraulic conductivity values**

| Layer # | Hydrostratigraphic Unit | Confined Zone | | | Unconfined Zone | | |
|---|---|---|---|---|---|---|---|
| | | $k_{x,y}$ m/d | $k_z$ m/d | approx T $m^2$/d | $k_{x,y}$ m/d | $k_z$ m/d | approx T $m^2$/d |
| 1 | Taita Alluvium | 2600 | 0.5 | 20000 | 2600 | 0.14 | 20000 |
| 2 | Petone Marine Beds/Melling Peat | 0.1 | 0.002 | | 1300 | 0.14 | 35000 |
| 3 | Upper Waiwhetu Gravels | 1120 | 0.1 | 28000 | 1300 | 0.14 | 35000 |
| 4 | Interstadial Aquitard/UC Gravels | 0.1 | 0.002 | | 1300 | 0.14 | 30000 |
| 5 | Lower Waiwhetu Gravels | 600 | 0.5 | 10000 | 600 | 0.5 | 10000 |
| 6 | Wilford Shell Beds/UC Gravels | 0.1 | 0.002 | | 80 | 0.1 | 2500 |
| 7 | Moeara Gravels | 80 | 0.1 | 2500 | 80 | 0.1 | 2500 |

***Recharge***

River recharge in the unconfined aquifer zone has been based upon the river stage at Taita Gorge from which the stage in each model cell was calculated using the methodology described in Section 5.4.4. The river bed conductance value assigned to each cell has assumed a river bed vertical hydraulic conductivity of 10 m/day and a bed thickness of 10m. Table 8 lists the bed conductance values and calculated stage for each model river cell in the unconfined aquifer zone.

**Table 8: River stage and bed conductance values used in steady state model calibration**

| River Cell (row number) | Calculated River Stage | River Bed Conductance $m^2$/day |
|---|---|---|
| 1 | 24.05 | 15600 |
| 2 | 24.05 | 15600 |
| 3 | 23.29 | 15600 |
| 4 | 22.5 | 18200 |
| 5 | 22.01 | 15600 |
| 6 | 21.09 | 15000 |
| 7 | 19.45 | 16200 |
| 8 | 17.96 | 15000 |
| 9 | 17.62 | 17500 |
| 10 | 16.84 | 17000 |
| 11 | 15.82 | 13000 |
| 12 | 14.58 | 13000 |
| 13 | 14.27 | 13000 |
| 14 | 13.48 | 15600 |
| 15 | 12.84 | 15000 |
| 16 | 11.59 | 9000 |
| 17 | 10.53 | 6500 |
| 18 | 10.12 | 7800 |
| 19 | 9.53 | 10000 |
| 20 | 9.3 | 12000 |
| 21 | 8.31 | 10400 |
| 22 | 7.47 | 16900 |
| 23 | 6.26 | 10000 |

Recharge from rainfall infiltration was conservatively estimated at 300mm/year for the entire model domain north of the foreshore, but increased to 1000mm/year along the contact between the valley fill alluvium and the greywacke along the eastern side of the unconfined zone to represent hillslope runoff recharge. The model is however insensitive to this parameter.

***Fixed heads***

Layer 1 in the harbour area has a base elevation coincident with the sea floor. The model cells in this area for the top layer were assigned a fixed head condition of 0m RL to represent the body of water above the Petone Marine Beds which line the harbour floor.

### 6.2.2 Steady state model calibration results

A number of model runs were performed in order to match the observed groundwater heads for the initial steady state calibration involving a trial and error process of adjusting input parameters. Table 9 show the results at the end of this process and Figure 9 is a plot of the same data showing the calibration statistics. The root mean square error for the observation data was 0.13m with the largest residual being 0.29m at the Taita Intermediate observation site.

**Table 9: Groundwater levels at end November 1993 pumping test used for steady state model calibration**

| Monitoring Bore | Observed Groundwater level m RL *(corrected for tidal effects)* | Modelled Level m, RL | Residual m |
|---|---|---|---|
| McEwan Park | 3.82 | 3.84 | 0.02 |
| Somes Island | 3.61 | 3.49 | 0.12 |
| Hutt Recreation Ground | 4.19 | 4.32 | 0.13 |
| Randwick Reserve | 4.15 | 4.2 | 0.05 |
| Petone Centennial Museum | 3.78 | 3.74 | 0.04 |
| Port Road | 3.73 | 3.81 | 0.08 |
| Bell Park | 4.15 | 4.31 | 0.16 |
| Hutt Valley Mem Tech Coll | 3.98 | 4.07 | 0.09 |
| Mitchell Park | 5.68 | 5.62 | 0.06 |
| Taita Intermediate | 8.7 | 8.99 | 0.29 |

The good initial steady state calibration confirms the integrity of the revised conceptual groundwater model and the rationalisation of recharge and discharge processes, together with changes in the model boundaries and layer definition.

The water balance for the steady sate calibration is shown in Table 10.

**Table 10: Steady state water balance (1993 Waterloo pump test conditions)**

| Flow Component | Inflow $m^3$/day | Outflow $m^3$/day |
|---|---|---|
| Constant head (Harbour outflow) | | 28,829 |
| Drains (Hutt River + Waiwhetu Stream) | | 76,490 |
| Rainfall recharge | 28,048 | |
| River losses above KGB (Net) | 119,271 | |
| Pumping wells | | 42,000 |
| *Balance* | *147,319* | *147,319* |

### 6.2.3 Steady state calibration verification

The steady state calibration was subsequently tested using a second set of observation data relating to the November 1995 Waterloo pump test (Butcher, 1996). The test had a duration of 4.5 days at a discharge rate of 49.25 ML per day. Quasi-steady state groundwater level conditions were observed towards the end of the test. Table 11 and Figure 10 show the water balance and head residuals respectively for the steady state model verification to 1995 pump test conditions. A reasonable good fit is evident using the same aquifer parameters as the 1993 steady state calibration but using river stage and river bed conductance values based upon the measured Taita Gorge stage during the 1995 test.

**Table 11: Steady state water balance (1995 pump test conditions)**

| Flow Component | Inflow $m^3$/day | Outflow $m^3$/day |
|---|---|---|
| Constant head (Harbour outflow) | | 28,476 |
| Drains (Hutt River + Waiwhetu Stream) | | 92,276 |
| Rainfall recharge | 28,785 | |
| River losses above KGB (Net) | 141,967 | |
| Pumping wells | | 50,000 |
| *Balance* | *170,752* | *170,752* |

During the pumping test period, flow losses from the Hutt River were gauged at between 67,000 and 190,000 with a mean of 130,000 $m^3$/day (Butcher, 1996).

Table 12 shows an internal flow analysis for the aquifer system for the 1995 calibration using the Zone Budget capability of Visual Modflow to provide an understanding of the recharge to each of the aquifer units and the discharge into the harbour.

**Table 12: Steady state calibration – flow analysis**

| Flow Component | $m^3$/day |
|---|---|
| Throughflow in Taita Alluvium south of KGB | 67,830 |
| Total recharge to confined aquifers | 94,800 |
| Recharge to confined Upper Waiwhetu Aquifer | 77,200 |
| Recharge to confined Lower Waiwhetu Aquifer | 14,500 |
| Recharge to confined Moera Gravel Aquifer | 3,100 |
| Leakage from Upper Waiwhetu Aquifer to harbour | 30,000 |

Table 12 shows reasonable agreement with the throughflow (recharge) estimates for the various aquifers made by the WRC (1995, Table 6.16) except that the modelled throughflow for the Upper Waiwhetu is significantly higher (77,200 vs 42,000 $m^3$/day). However, the throughflow in each of the aquifers is influenced by the abstraction regime and the associated change in flow gradients.

### 6.2.4 Steady state model sensitivity analysis

A manual sensitivity analysis has been carried out on the steady state model to evaluate the degree of uncertainty inherent in the estimation of the principal model parameters and stresses during the calibration process. The recognition of parameter sensitivity has enabled the identification of those parameters which have been optimised with a reasonable degree of certainty. The reliability of the water flux estimations and the predictive capability of the model hinges on such sensitivity interrogation. Use of the parameter estimation model, PEST, has also been used to assess the correlation and sensitivity of the hydraulic properties assigned to each hydrostratigraphic unit under transient flow conditions.

Hydraulic conductivity (horizontal and vertical) and river bed leakage north of Kennedy Good Bridge are the dominant parameters to which the model is most sensitive. These parameters are however strongly correlated and a unique solution can be achieved only through observance of the estimated water balance for the system and the range of hydraulic conductivity values derived from test pumping investigations.

The model boundaries are defined with a high degree of certainty and therefore a sensitivity analysis for them has not been necessary.

Manual sensitive analysis has consequently been performed on the parameters listed in Table 13 and graphically reported in Figure 11.

**Table 13: Sensitivity analysis parameters**

| Sensitivity Parameter |
|---|
| rainfall recharge |
| river bed conductance |
| $k_z$ for the unconfined recharge zone |
| $k_{x,y}$ for the unconfined zone |
| $k_z$ for the Petone Marine Beds/Melling Peat |
| $k_z$ for the Upper Waiwhetu Confined Aquifer |
| $k_{x,y}$ for the Upper Waiwhetu Confined Aquifer |
| $k_z$ = vertical hydraulic conductivity; $k_{x,y}$ horizontal hydraulic conductivity in x and y dimensions |

The sensitivity analysis involved systematically changing each parameter in turn from the calibrated value by a factor of 0.1, 0.5, 0.75, 1.25, 1.5 and 10. The observed sensitivity of the model to these parameters is shown in Figure 11, expressed in terms of the mean of the square root from the sum of the squared differences between the calculated and observed heads (RMS). A large change in the modelled heads resulting from the minor change in a parameter value demonstrates that the model is highly sensitive to that parameter and the calibrated value is likely to be more accurate depending upon its correlation to other parameters.

Figure 11 shows that the heads in the Upper Waiwhetu Aquifer are particularly sensitive to the vertical hydraulic conductivity of the Petone Marine Beds, being most sensitive to a decrease in magnitude. This is because this parameter effectively controls the amount of water allowed to flow vertically upwards and discharge into the harbour from the confined aquifers. Conversely, the model appears to be relatively insensitive to small changes in the hydraulic conductivity (vertical and horizontal) for the confined Upper Waiwhetu Aquifer. Within the unconfined aquifer zone, a higher sensitivity is observed for both vertical and horizontal hydraulic conductivity because these parameters control the transmittal of water from the river downwards to the underlying confined aquifers.

The river bed conductance has a relatively small impact on the groundwater heads in the Upper Waiwhetu Aquifer because the hydraulic properties of the underlying unconfined gravels control the downwards flow of recharge to the confined aquifers. Water which is not able to percolate to deeper levels remains in the Taita Alluvium, or is returned to the river. The river bed conductance value has therefore been estimated on the basis of the amount of water released into the model using the concurrent river gauging data as a guideline (Section 4.4).

The model is also insensitive to rainfall recharge which appears to have little bearing on groundwater head in the Upper Waiwhetu Aquifer. Increasing the rainfall recharge by a factor of ten has the effect of raising the RMS by only 0.4m. Much of the rainfall recharge in the model is applied to the upper model layer (Taita Alluvium) over the confined aquifer zone and therefore has no influence on the artesian heads unless it is increased greatly over the unconfined zone.

## 6.3 Transient flow calibration

The objective of undertaking a transient model calibration was to provide verification and confidence that the steady-state model is able to accurately simulate the groundwater system under a wide range of boundary and abstraction stress conditions. This has been achieved using a three-step process by first matching the modelled heads to observed heads for a representative 12-month period (1996-97) and undertaking further interrogation of the transient calibration using the model-independent parameter estimator – PEST (Watermark Computing, 1998) to assess parameter uncertainty and optimise the hydraulic parameter values. The transient calibration was then tested against a 14 year historical monitoring data set (1984 – 98) and against another 12-month dataset (2000-2001) to test the model calibration during a severe drought scenario.

### 6.3.1 1996-1997 transient calibration

The monitoring period June 1996 to May 1997 period was chosen from the long-term groundwater level record for preliminary transient flow calibration being an apparent 'average' year in terms of river stage and groundwater level conditions. Transient stresses applied to the model were river recharge based on the stage record for Taita Gorge, abstraction (derived from the WELREC database) and rainfall recharge. River bed conductance as a function of channel width (Section 5.4.4), and river stage were the time-dependent variables controlling river recharge. The river stage at Taita Gorge was not corrected for bed level variations as these were regarded to be negligible over the 12-month calibration window.

The 12-month calibration used a 10-day stress period over which abstraction rate, river stage and groundwater levels at observation sites were averaged. Each stress period had ten time steps with a time step multiplier of 1.2.

Figure 12 shows the total groundwater abstraction and the observation bore data (dashed lines) for the calibration period.

The process of transient calibration involved assigning storage properties to the hydrostratigraphic units within the established envelope of values derived from test pumping. Since the storage properties of the Upper Waiwhetu Aquifer are known to a reasonable degree of certainty, and the model is relatively insensitive to river bed conductance, hydraulic conductivity is the most critical and sensitive model parameter. Therefore, the transient calibration has involved optimisation and further sensitivity analysis of hydraulic conductivity using the non-linear automated parameter estimator – PEST (Watermark Computing, 1998).

PEST was run using the calibrated transient model with the five adjustable parameters listed in Table 14 . The $k_y$ values for parameters 1 and 4 were tied to the $k_x$ values. The optimum objective function (or sum of the squared weighted residuals of groundwater heads) was achieved after 14 optimisation iterations and 163 model calls. The run time for optimisation was approximately 8 hours. The optimised parameters and their composite sensitivity is shown in Table 14.

**Table 14: Transient model parameter optimisation - hydraulic conductivity**

| Parameter # | Zone | Optimised value m/day | Composite sensitivity | 95% confidence limits | |
|---|---|---|---|---|---|
| | | | | lower | upper |
| 1 | $k_{x,y}$ Upper Waiwhetu confined | 1200 | 0.17 | 1047 | 1213 |
| 2 | $k_z$ Petone Marine Beds – N foreshore | 0.002 | 0.085 | 0.0013 | 0.0024 |
| 3 | $k_z$ Petone Marine Beds – harbour | 0.002 | 0.16 | 0.0013 | 0.0017 |
| 4 | $k_{x,y}$ Upper Waiwhetu unconfined | 1350 | 0.2 | 1290 | 1462 |
| 5 | $k_z$ Upper Waiwhetu unconfined | 0.14 | 0.2 | 0.13 | 0.16 |

The composite sensitivity (unitless) is a measure of the sensitivity of all model outputs to a particular parameter. If a parameter has a low composite sensitivity, it will be poorly estimated. Table 14 shows that the vertical hydraulic conductivity ($k_z$) for the Petone Marine Beds north of the foreshore is relatively insensitive and this parameter has dominated the objective function during the estimation process. This means that this parameter may not have been estimated well but the 95% confidence interval is small. Comparison with the $k_z$ for the same unit in the harbour zone shows that both zones can be assigned the same value. The composite sensitivities for the remaining adjustable parameters are relatively high and this is reflected by the small 95% confidence intervals. These parameters will consequently be estimated reasonably well depending upon the level of correlation with other parameters.

PEST produces a parameter covariance matrix from which a correlation coefficient matrix is calculated. The correlation coefficient matrix shows the degree of cross-correlation between elements in the matrix and is shown in Table 15.

**Table 15: Correlation coefficient matrix**

| Parameter | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| **1** | 1 | 0.04 | 0.83 | 0.04 | 0.53 |
| **2** | 0.04 | 1 | -0.35 | 0.3 | 0.62 |
| **3** | 0.83 | -0.35 | 1 | 0.05 | 0.32 |
| **4** | 0.04 | 0.3 | 0.05 | 1 | -0.17 |
| **5** | 0.53 | 0.62 | 0.32 | -0.17 | 1 |

The diagonal elements of the correlation coefficient matrix are always unity. The off-diagonal elements always lie between 1 and –1 and the closer the off-diagonal element is to 1 or –1 the more highly correlated are the parameters corresponding to the row and column numbers (listed in Table 14). If parameters are well correlated they can be varied in harmony with little effect on the model calibration and, as a consequence, there will be a high degree of uncertainty associated with their estimation. Such parameter non-uniqueness can be overcome by fixing one of the correlated parameters to within a known range on the basis of prior information.

The correlation coefficient matrix shows that parameter 3 ($k_z$ Petone Marine Beds – harbour zone) shows a high correlation with parameter 1 ($k_{x,y}$ Upper Waiwhetu confined). However, prior information available for the latter parameter was used to restrict its range during the optimisation process and therefore the optimisation of parameter 3 could be more confidently assigned. A less strong correlation exists between parameters 5 and 1 and parameters 5 and 2. Again, since parameter 1 has been restricted using prior information, parameter 5 will have less uncertainty associated with it.

Specific storage and specific yield values used for the calibration lie in the middle of the range obtained from test pumping investigations and are shown in Table 16 (it should be noted that specific storage = storage coefficient/aquifer thickness). The plots show a good visual fit between the two datasets for all monitoring bores within the Upper Waiwhetu Aquifer and for the IBM1 bore within the Moera Gravel Aquifer.

**Table 16: Calibrated storage properties**

| **Hydrostratigraphic Unit** | **Specific storage, $S_s$** | **Specific yield, $S_y$** |
|---|---|---|
| Taita Alluvium and Upper Waiwhetu Aquifers | $7 \times 10^{-5}$ | 0.2 |
| Lower Waiwhetu Aquifer | $1 \times 10^{-5}$ | 0.15 |
| Moera gravel Aquifer | $1 \times 10^{-5}$ | 0.15 |
| Aquitard units | $1 \times 10^{-6}$ | 0.15 |

Figure 12 shows the simulated and observed hydrographs for each of the observation sites using the optimised model. Also shown are the abstraction, river leakage and recharge rates to the Upper Waiwhetu Aquifer. The river leakage rate is highly variable and controlled by river stage and the groundwater level in the Taita Alluvium. During the 12 month calibration period, net river leakage rates ranged from approximately 100,000 to 170,000 $m^3$/day (as 10-day averages) although actual daily rates may have been significantly more or less than this average. The flow to the Upper Waiwhetu Aquifer remained relatively constant at between 80,000 and 90,000 $m^3$/day and appears to be influenced by abstraction rate, i.e. higher abstraction rates induce more recharge to the aquifer.

Figures 13 and 14 provide further detailed information to demonstrate that the new methodology used to simulate the river (Section 5.4) leads to an improved and reasonable representation of river losses. Figure 13 shows the net river losses for representative river cells between Taita Gorge and KGB. The river cell in model row 2 is located at the northern boundary of the model (Taita Gorge), whilst row 23 is the southernmost river cell at KGB. Significantly greater losses of between 5,000 and 15,000 $m^3$/day per 250$m^2$ cell occur between rows 1 and 5 in the upper 1 – 1.5km reach below Taita Gorge. Between river rows 6 and 20 (3.5km river section), losses per cell are lower and relatively constant at between 3,000 and 7,000 $m^3$/day per cell. Below row 20, the river begins to gain flows back from the aquifer in the confined-unconfined transition zone. The pattern of river losses and river gains shown in Figure 13 is generally consistent with the conceptual hydrogeological model.

Figure 14 shows the flow at Taita Gorge, as input to the model as a river stage but converted to a flow using the appropriate rating curve, plotted against the simulated net flow losses (red squares). Also shown are the concurrent gauging data (as represented in Figure 4) to check the calibration of the model (blue circles). The simulated flow losses show a good agreement with the gauging data for the 1996-97 transient calibration and also for the extended transient 1984-98 calibration (Section 6.3.2).

The model indicates that at flows of greater than approximately 20,000 L/sec (20 cumecs), there is a marked change in the relationship between bed loss and river flow. Beyond this flow rate, losses tend to reach a plateau at around 1,500 – 2,000 L/sec (approx. 130,000 – 170,000 $m^3$/day). However, the accuracy of this observation cannot be verified in the absence of concurrent gauging data at flow rates of greater than 20,000 L/sec.

### 6.3.2 14-year calibration

The calibrated transient model was used to simulate historical water level trends and recharge fluxes during a 14 year period commencing on 1/1/84. The simulation was divided into 30-day stress periods over which system stresses and monitoring data were averaged. Groundwater monitoring data, uncorrected for tidal effects, were also averaged over the stress period. The use of 30-day average water levels effectively removes the diurnal tidal fluctuations form the record. Corrections were however performed on the Taita Gorge stage record to compensate for the reduction bed levels over the simulation period using the methodology described in Section 5.4.2.

Figure 15 shows the modelled and observed hydrographs for the calibration. A good visual fit between the data is apparent for all monitoring in terms of short- and long-term trends in groundwater level. The Somes Island observed record is unreliable prior to early 1993 (3200 days) due to leakage at the wellhead. After this, the model closely matches the monitoring record for this bore.

The recharge to the Upper Waiwhetu Aquifer is also shown on Figure 15 showing a relatively consistent 30-day average recharge rate of 80,000 $m^3$/day, but increasing to approximately 90-100,000$m^3$/day in response to increased abstraction rates occurring at about 3700 days (early 1994) . Seasonal decreases in river leakage rate have a notable effect on groundwater levels as shown by the particularly dry period during the summer of 1994/95 (4100 days) which produced a marked depression in groundwater levels which in turn induced greater recharge into the Upper Waiwhetu Aquifer. Within the calibration window, using 30-day averages, abstraction rates did not exceed recharge rates to the aquifer. However, this assessment may not hold should a smaller stress period length be considered.

### 6.3.3 2000-2001 calibration

Following the initial transient calibration procedure, calibration checking was performed against the 2000-2001 summer drought period during which river flows were the lowest on record (1 in 40 year six-monthly low flow rate) and the aquifer system was under unusual stress.

Figure 16 shows the model calibration for the 2000-2001 year which was run under 10-day stress periods. Water levels for observation bores and production data for the principal abstraction wells (Waterloo Wellfield and Gear Island) were derived from WRC records. Adjustments were made to the river bed conductance value since, under such extreme stress, the river cells were not supplying sufficient water to the Waiwhetu Gravels. The previous model calibration proved to be relatively insensitive to river bed conductance, but it became evident during the calibration checking process that the accuracy of this parameter is important when vertical hydraulic gradients between the river bed and the underlying aquifer are accentuated during dry periods.

River bed conductance values were subsequently increased by a factor of 2.4 in order to achieve a good calibration (Figure 16). No other parameters were altered. Following re-calibration, the 14 year calibration run was checked. A slightly better match between observed and modelled data is evident as shown in Figure 17, particularly during low-flow periods when the model previously tended to over-predict drawdown as a result of insufficient recharge.

The water balance for the calibration, also shown on Figures 16 and 17, shows an increase in river losses which still fall within the range of values obtained from concurrent river gauging data (100 – 200 ML/day). During the 200-2001 drought period, recharge to the confined Upper Waiwhetu Aquifer fluctuated between 80 and 100 ML/day, being dependent upon the abstraction rate from the Waterloo Wellfield. As extreme low flow conditions in the Hutt River continued through the summer months, it appeared that water was sourced both from river leakage and from storage release. The latter is shown by a gradual recession in water level in observation bores (Figure 16).

The re-calibrated model (called HAM Version 2.1) has been adopted for scenario modelling.

# 7. Summary and Conclusions

The Lower Hutt Groundwater Zone contains a regionally important water resource which is being exploited from bores located in the Upper Waiwhetu Aquifer at a rate approaching the maximum sustainable capacity of the system.

All aquifers are at risk of sea water intrusion should over-abstraction occur, and it is therefore important to quantify the available resource whilst safeguarding it from the risks of salinisation.

A number of numerical groundwater flow models have been produced for the Lower Hutt Groundwater Zone to help assess the characteristics of the system and predict safe abstraction volumes. Whilst recent models have progressed some way towards achieving this objective, they possessed limitations in terms of being capable of appropriately simulating recharge and discharge processes.

The conceptual hydrogeological model for the Lower Hutt Groundwater Zone has been refined during the course of the present study on the basis of re-evaluation of existing geological information, the drilling of a deep exploration bore, and new investigations regarding offshore aquifer discharge mechanisms.

The revised conceptual model has provided the basis for the construction a new Hutt Aquifer Model (HAM2). The model has a revised boundary and layer design, and an improved method of simulating river recharge. Recharge rates from the river bed to the underlying aquifers have been correlated with river stage using a temporally variable bed conductivity and calibrated against measured bed losses. Discharge from the confined aquifers has been simulated to reflect current understanding of sub-harbour aquifer seepage and spring flow characteristics.

The principal aquifer unit – the Waiwhetu Artesian Gravels, has been divided into two distinct units on the basis evidence from recent drilling, a re-evaluation of pre-existing bore logs, and groundwater chemistry. The Upper Waiwhetu Aquifer contains all current major abstraction bores and is considerably more productive than the Lower Waiwhetu Aquifer which lies beneath an intervening, laterally persistent, aquitard.

The parameter zonation within the HAM2 has been simplified to avoid the unjustified transmissivity zonation adopted in previous models. This has resulted in an improved steady-state and transient model calibration for the Waiwhetu and Moera aquifers.

Model calibration has been carried out using a combination of manual and automated methods to optimise input parameters and assess parameter uncertainty and sensitivity. Since critical input parameters and water balance components (storage coefficient, transmissivity, river losses) have been evaluated through field measurement, there is a reasonable degree of confidence associated with the calibration.

Model calibration indicates that the recharge to the Upper Waiwhetu Aquifer normally lies in the range of 80,000 to 100,000 $m^3$/day. Increased abstraction rates appear to induce more recharge to the aquifer from the river. The short-term maximum recharge rate appears to be approximately 95-100,000 $m^3$/day under an abstraction regime of approximately 80,000 $m^3$/day, but is dependent upon concurrent and antecedent river stage conditions.

Further interrogation of the model is required through simulation of various abstraction and river stage scenarios to provide a comprehensive re-evaluation of the resource.

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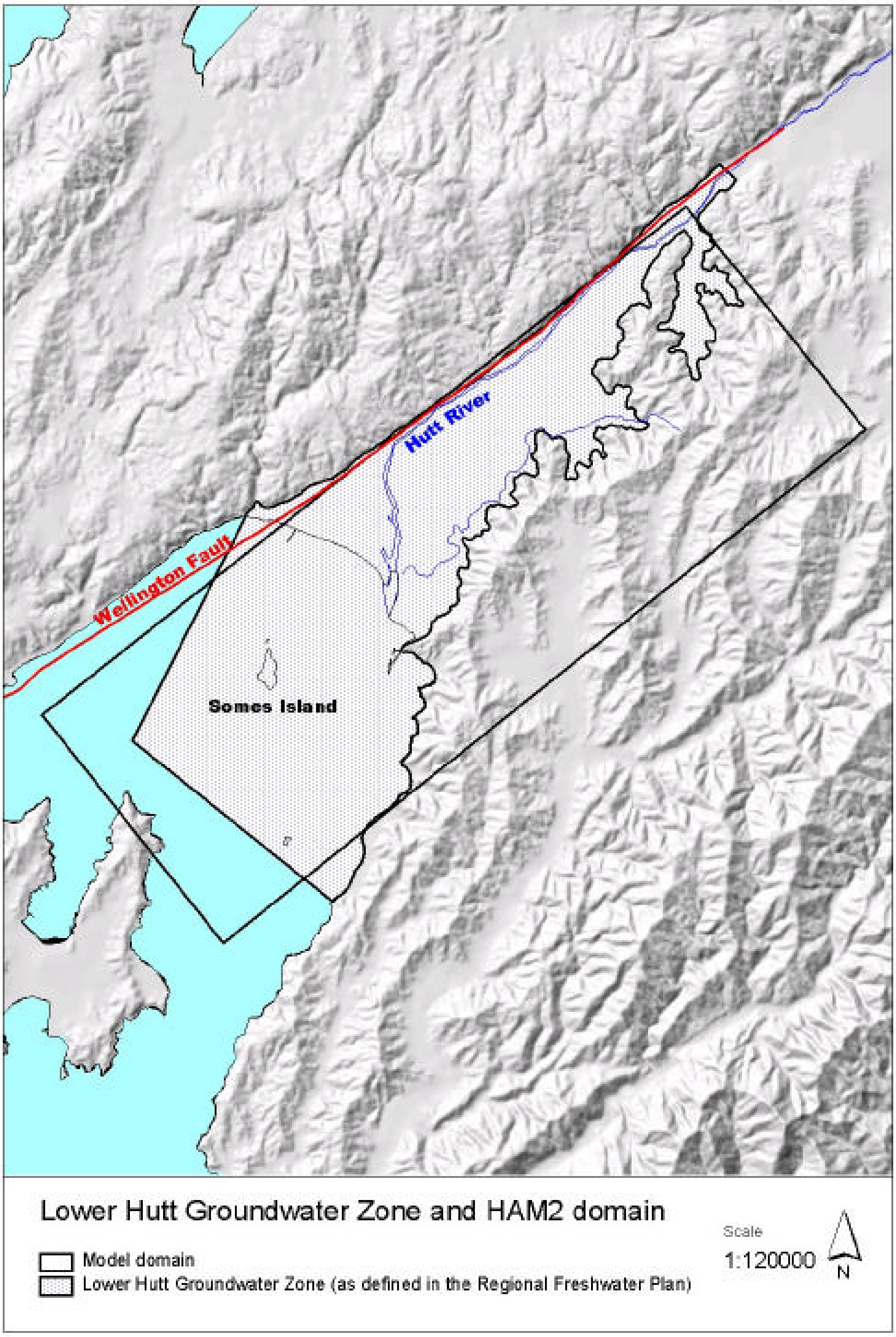



**Figure 1 : Location map**

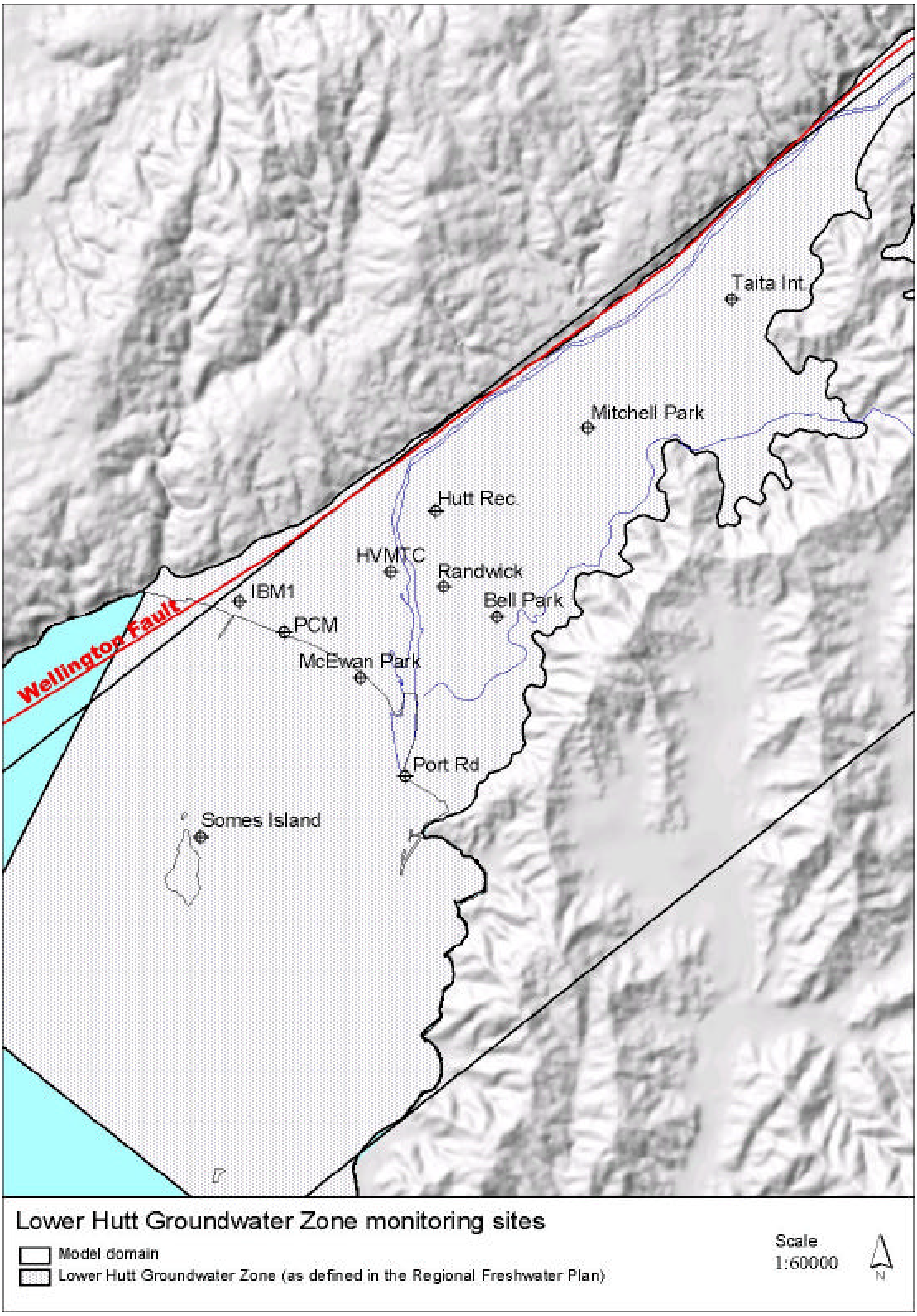



**Figure 2 : Groundwater level monitoring sites**

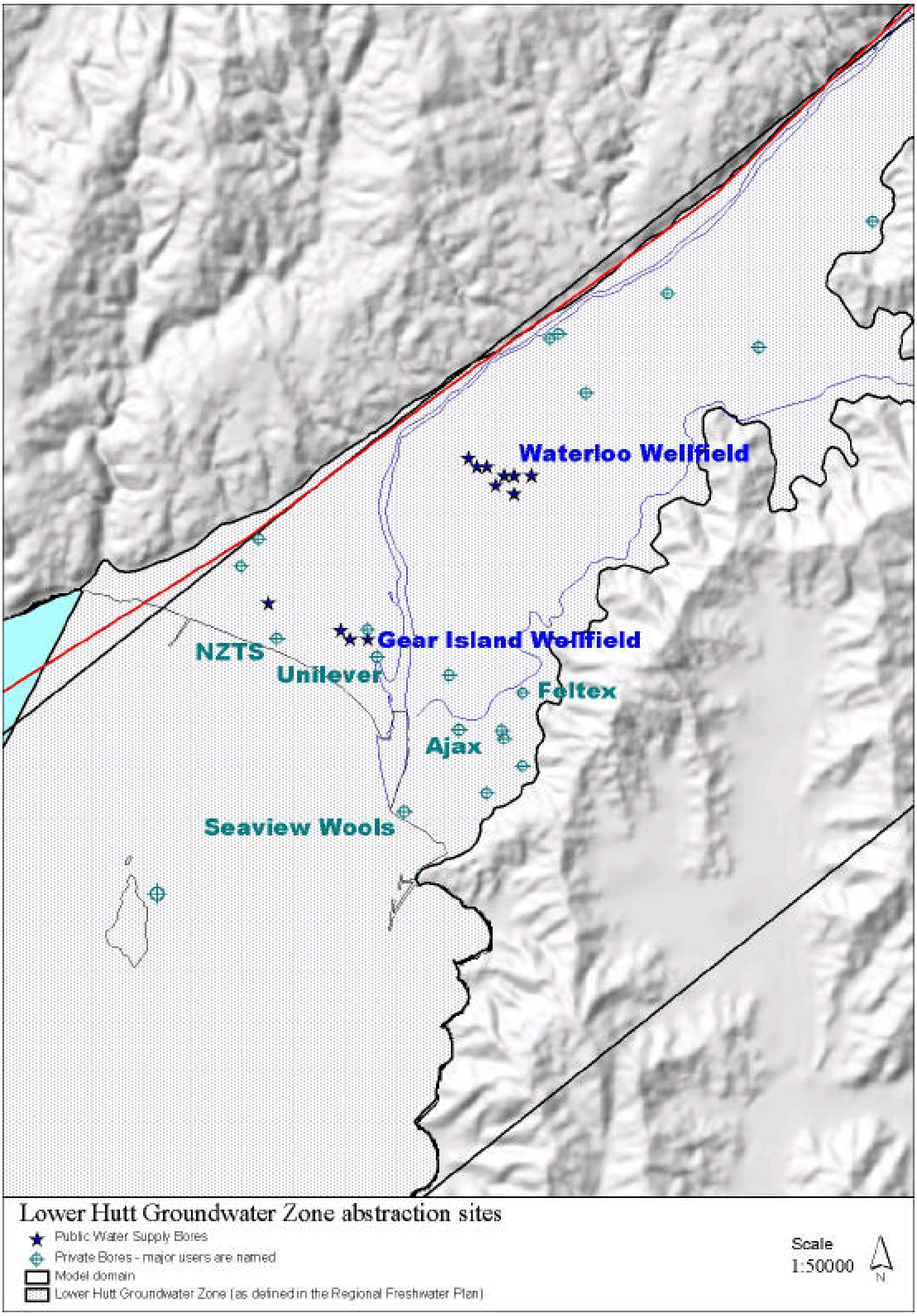



**Figure 3 : Abstraction sites**

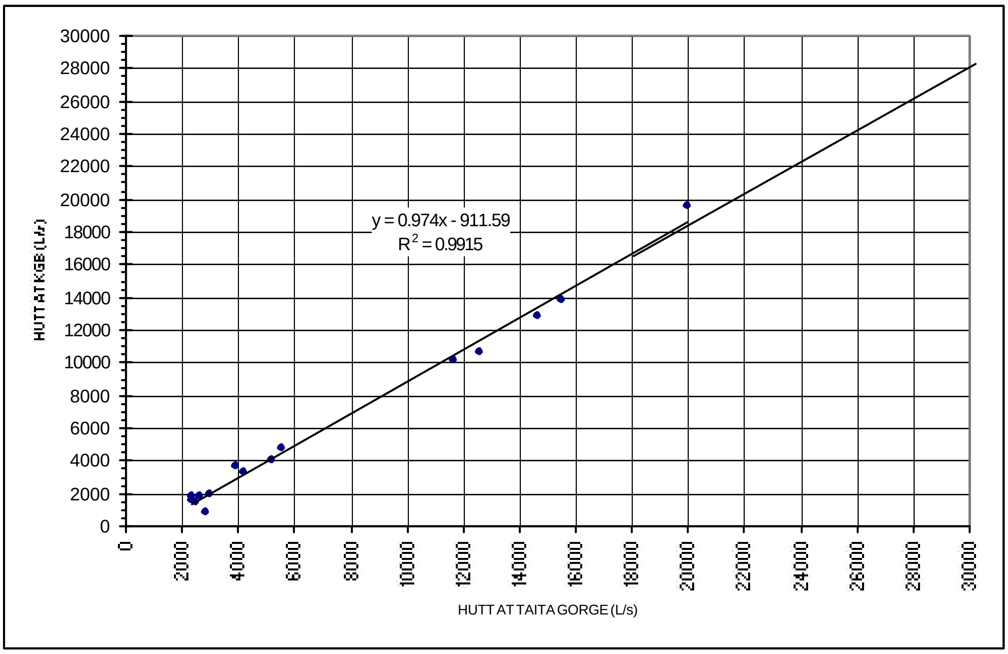



**Figure 4 : Relationship between flow at Taita Gorge and flow at Kennedy Good Bridge**

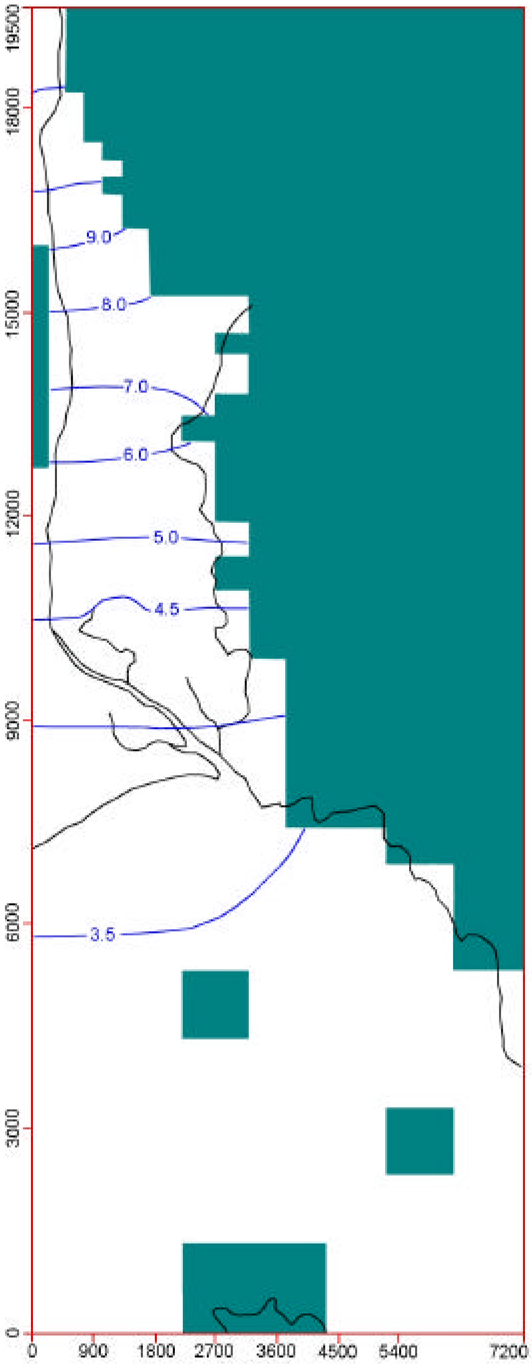



**Figure 5 : Groundwater head pattern – upper Waiwhetu aquifer**

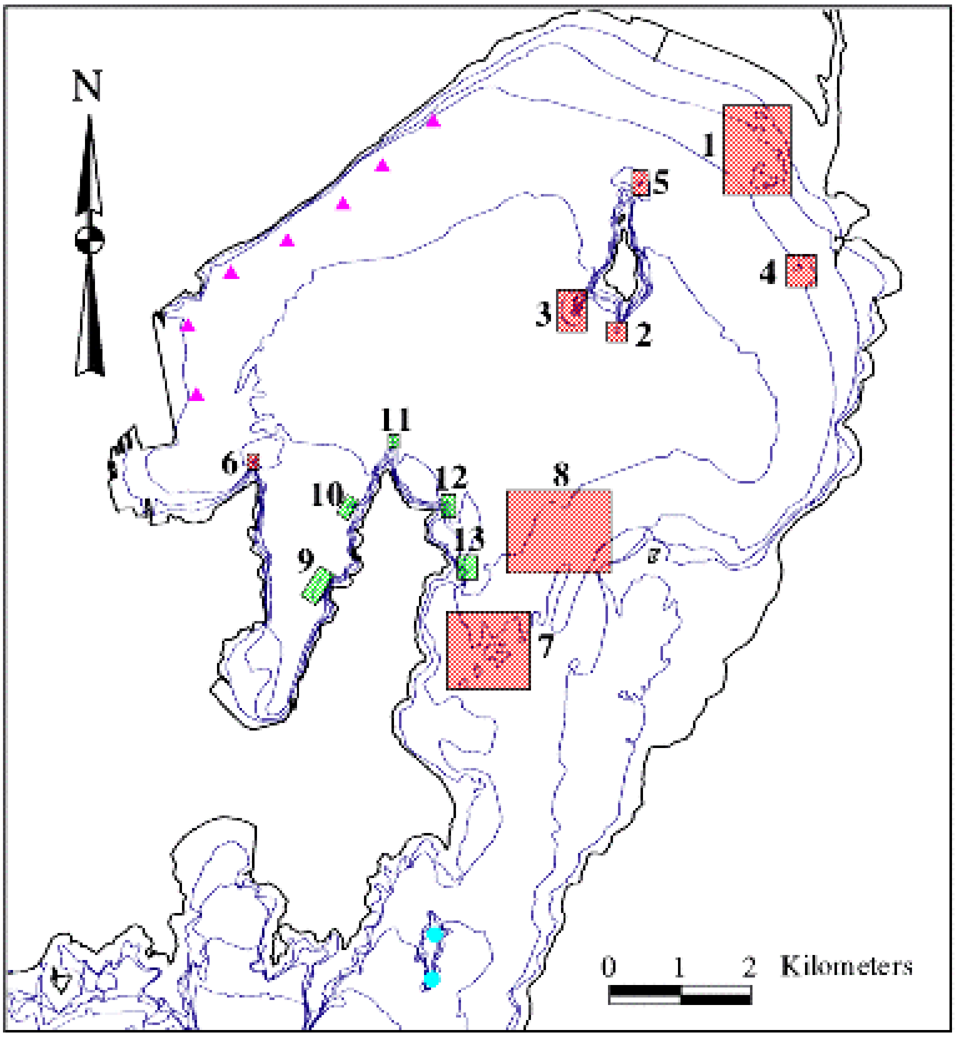



**Figure 6 : Location map of identified submarine spring discharge zones in Wellington Harbour (from Harding, 2000).**

The red regions represent areas that exhibited signs of present day artesian leakage. The green regions represent other areas investigated by Harding because they contained sea floor depressions but were found to have no signs of artesian leakage. The pink triangle show those locations that have been identified in the past as having artesian leakage, but were not investigated by Harding because there were no sea floor depressions present on which to base investigations. The blue dots represent areas around Barrett's Reef where SCUBA divers have noted disturbance in the water that fits the description of artesian leakage, but were not investigated because Harding considered the leakage unlikely to be related to the Waiwhetu Artesian Aquifer. The dark red dot represents a suspected submarine spring discharge as detected by NIWA using side scan sonar during an unrelated study in 1987. Bathymetric contour lines are shown in blue at 5m intervals.

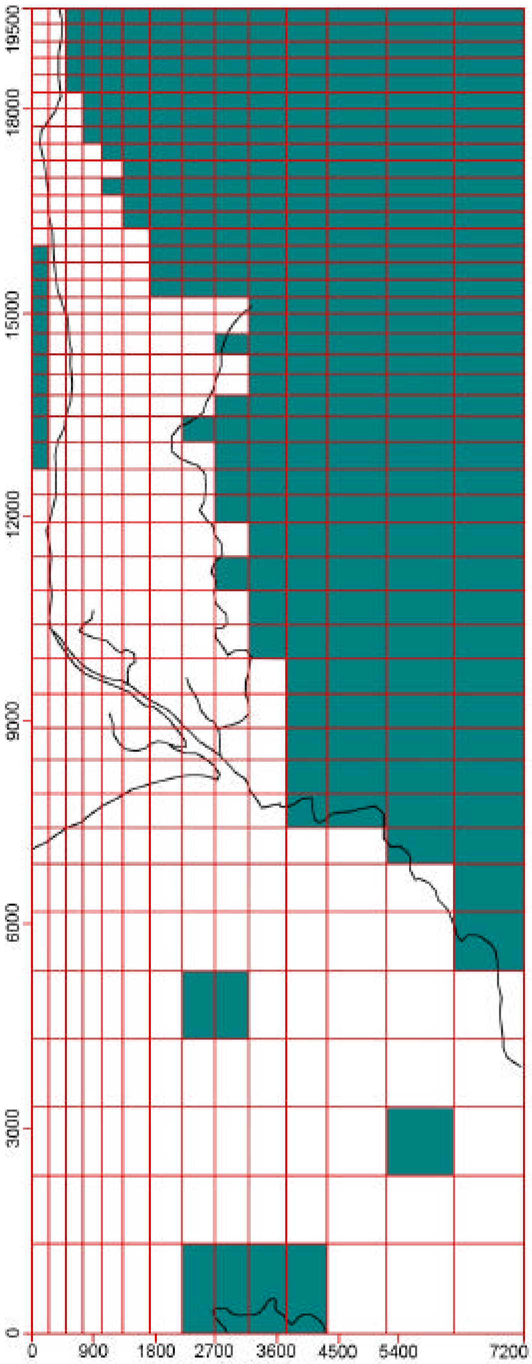



**Figure 7 : Model grid**

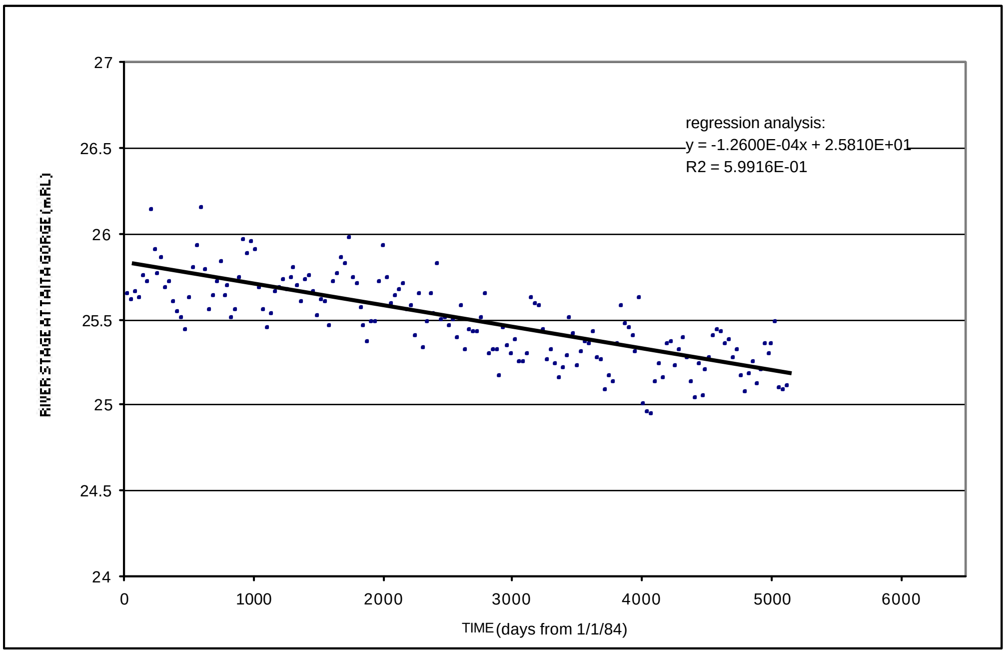
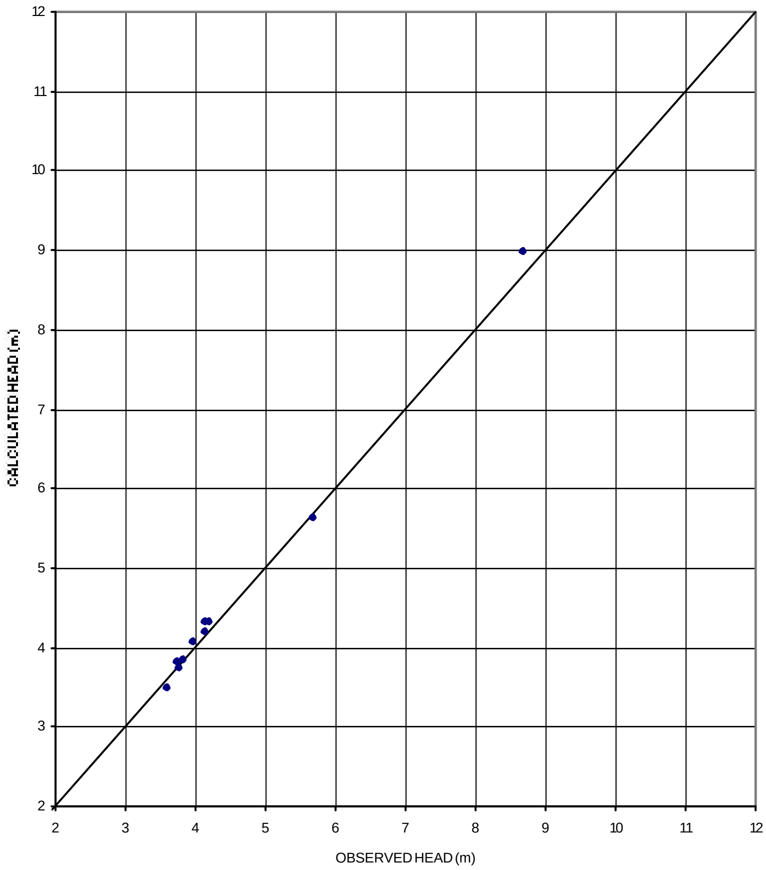



**Figure 8 : Long-term change in Taita Gorge stage associated with bed level degradation.**




Num.Points : 10

Mean Error : 0.05951333 (meters)

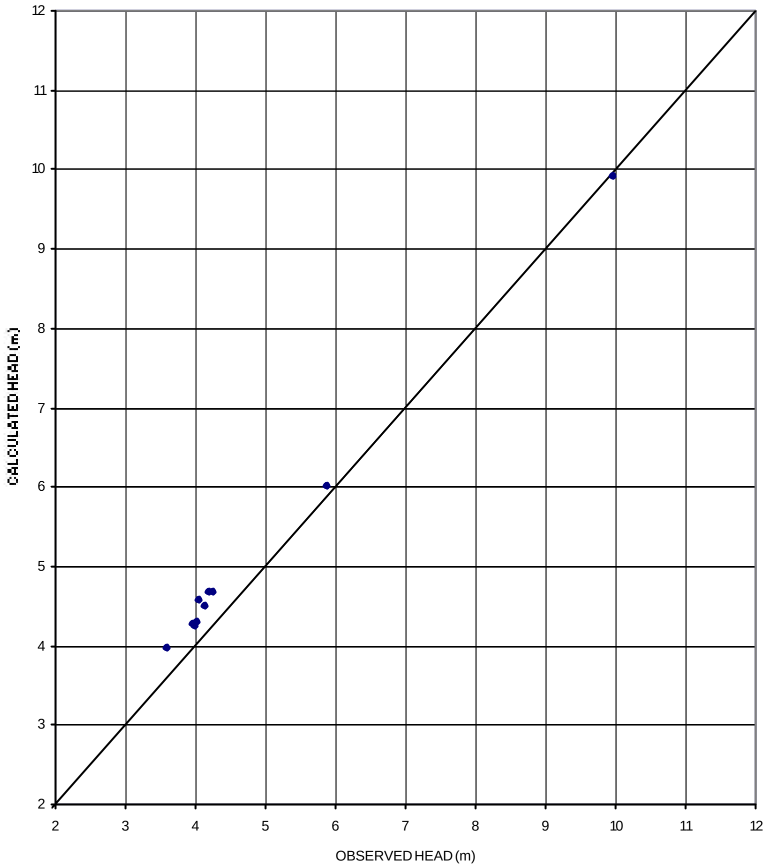
Mean Absolute : 0.1045442 (meters)

Standard Error of the Estimate : 0.03797196 (meters)

Root mean squared : 0.1285249 (meters)

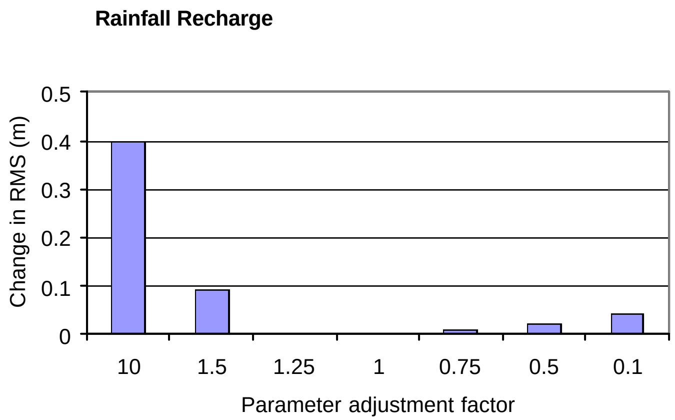
Normalized RMS : 2.525048 ( % )

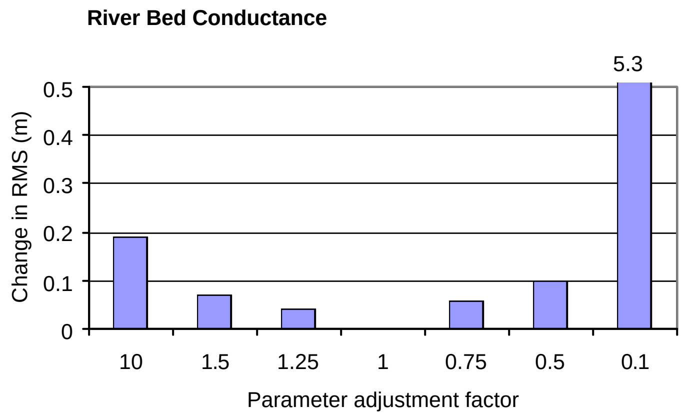
**Figure 9 : Steady state calibration: 1993 Waterloo pumping test**

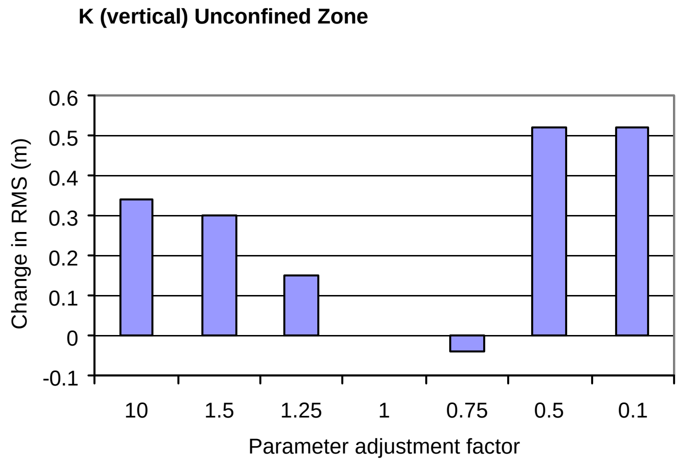


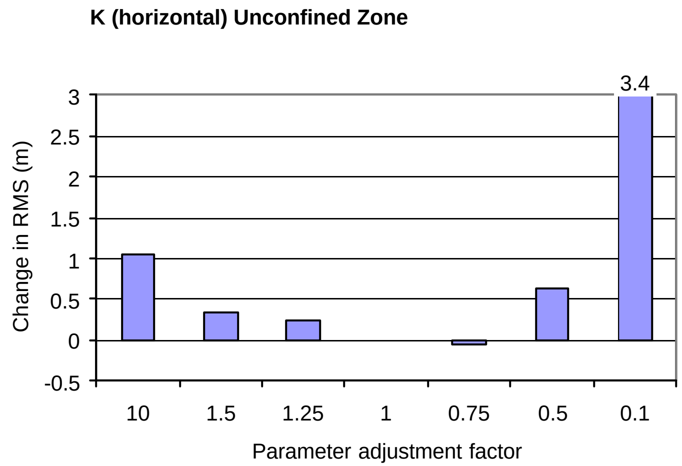

Num.Points : 10
Mean Error : 0.2958776 (meters)
Mean Absolute : 0.3077586 (meters)
Standard Error of the Estimate : 0.05292115 (meters)
Root mean squared : 0.3357817 (meters)
Normalized RMS : 5.263037 ( % )

**Figure 10: Steady state calibration: 1995 Waterloo pumping test**


Rainfall Recharge
Change in RMS (m)
0.5
0.4
0.3
0.2
0.1
0
10
1.5
1.25
1
0.75
0.5
0.1
Parameter adjustment factor


River Bed Conductance
5.3
Change in RMS (m)
0.5
0.4
0.3
0.2
0.1
0
10
1.5
1.25
1
0.75
0.5
0.1
Parameter adjustment factor


K (vertical) Unconfined Zone
Change in RMS (m)
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
10
1.5
1.25
1
0.75
0.5
0.1
Parameter adjustment factor


K (horizontal) Unconfined Zone
3.4
Change in RMS (m)
3
2.5
2
1.5
1
0.5
0
-0.5
10
1.5
1.25
1
0.75
0.5
0.1
Parameter adjustment factor

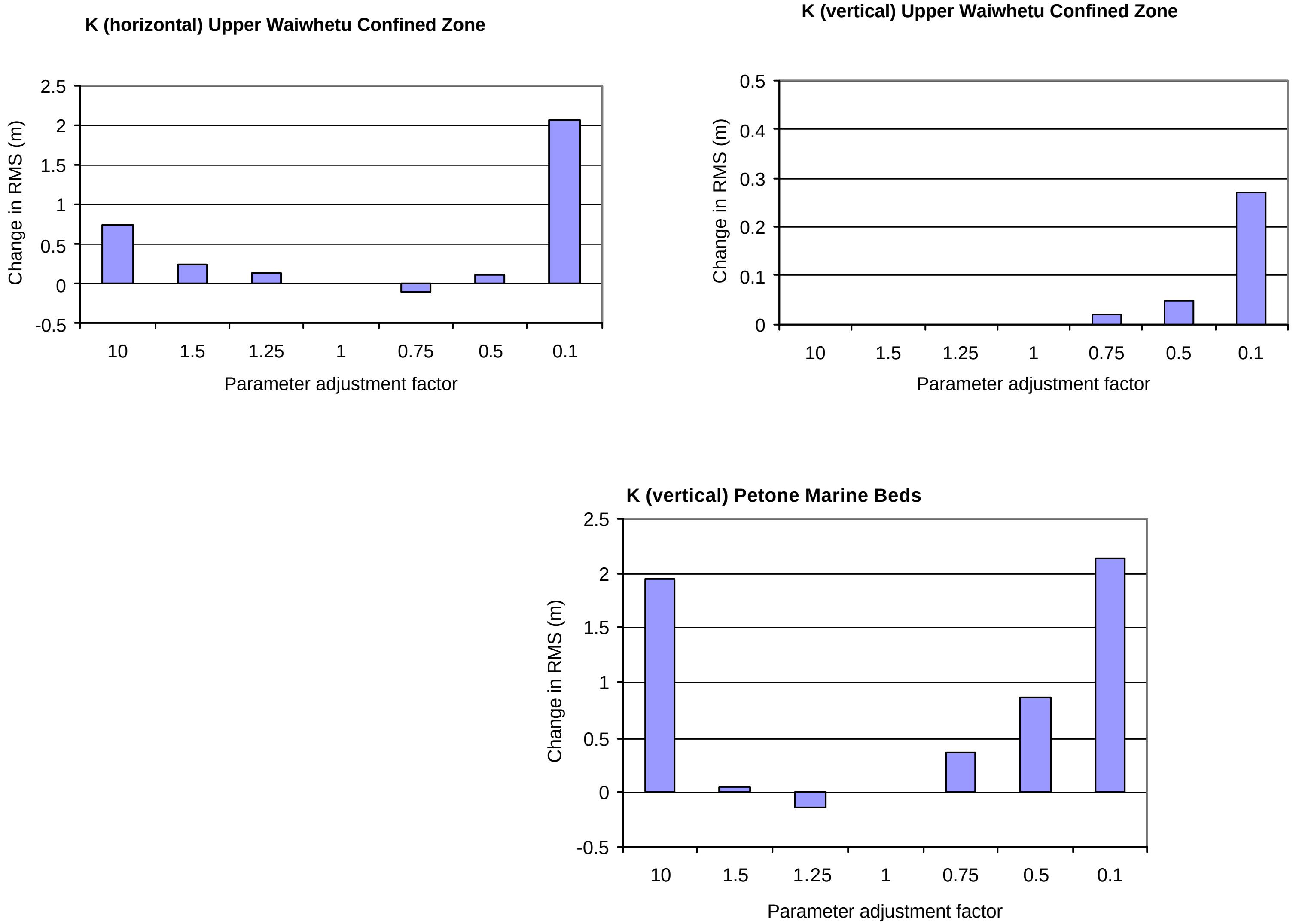
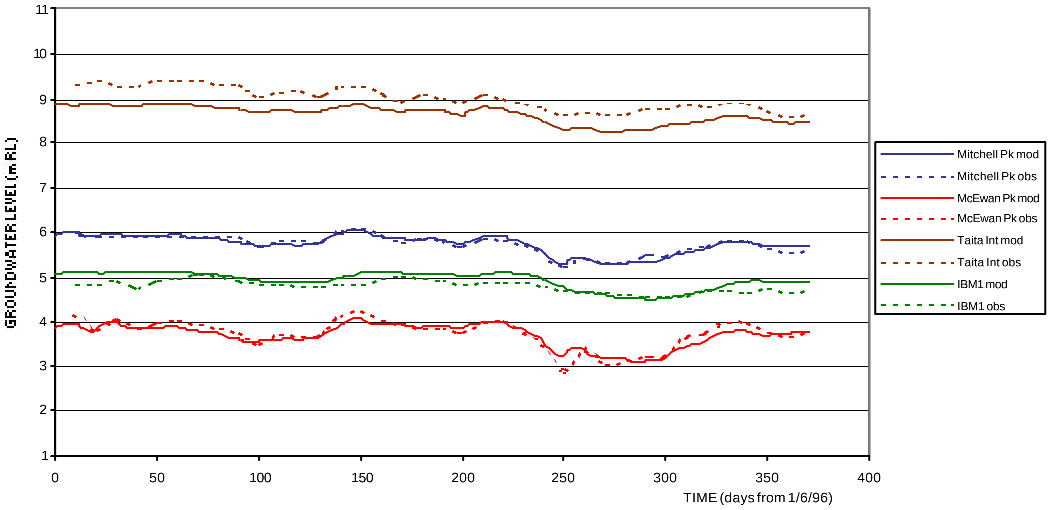
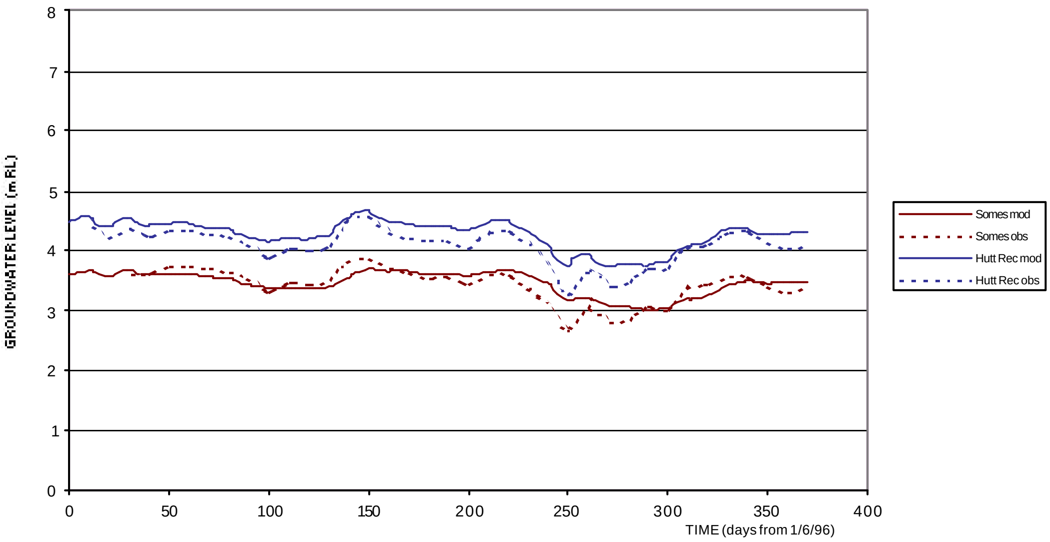



**Figure 11 : Steady state model sensitivity analysis**



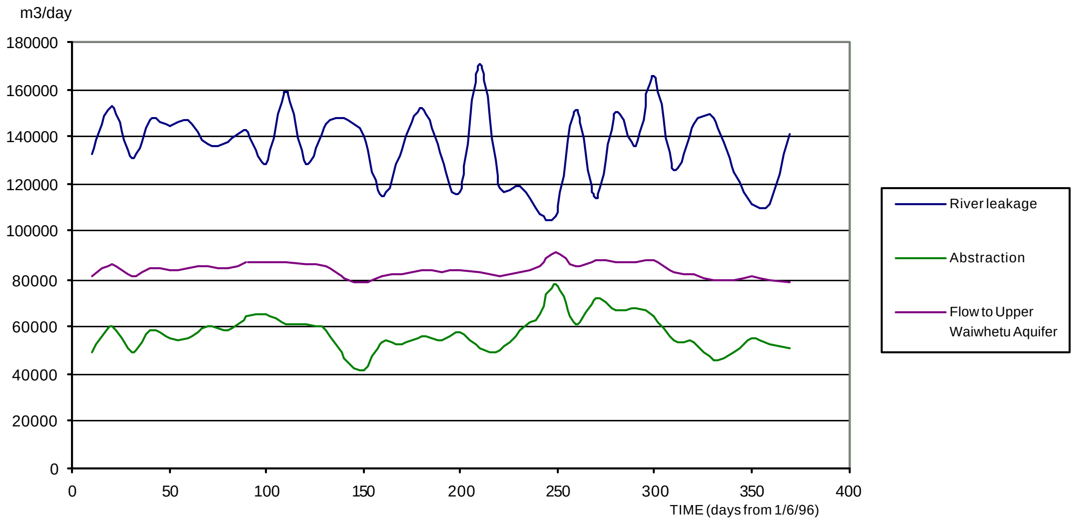




**Figure 12 : Transient calibration June 1996 – June 1997 (10-day stress periods)**

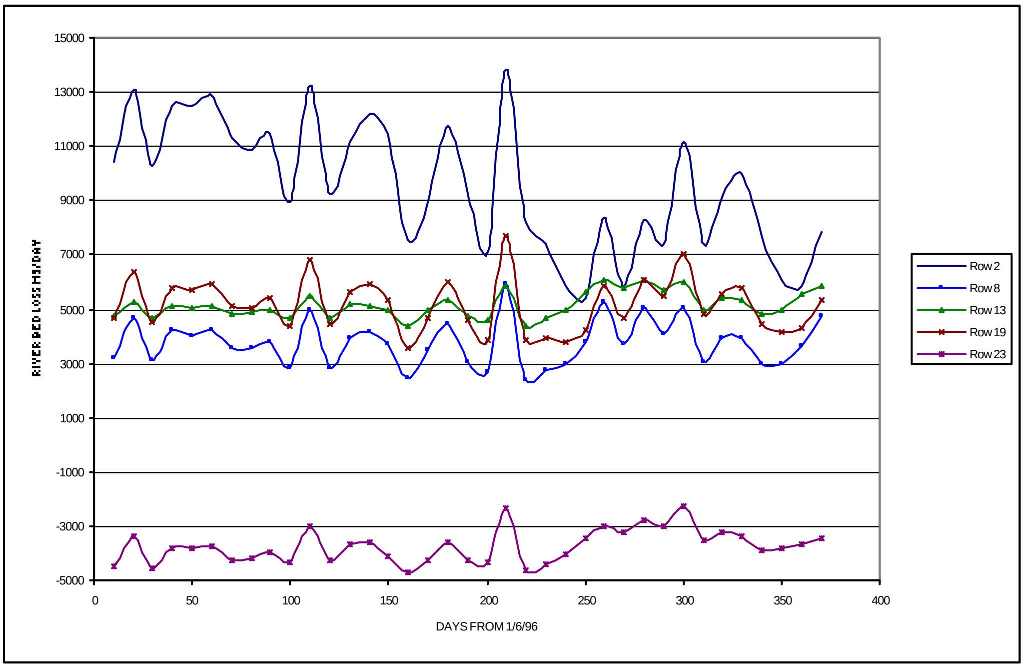
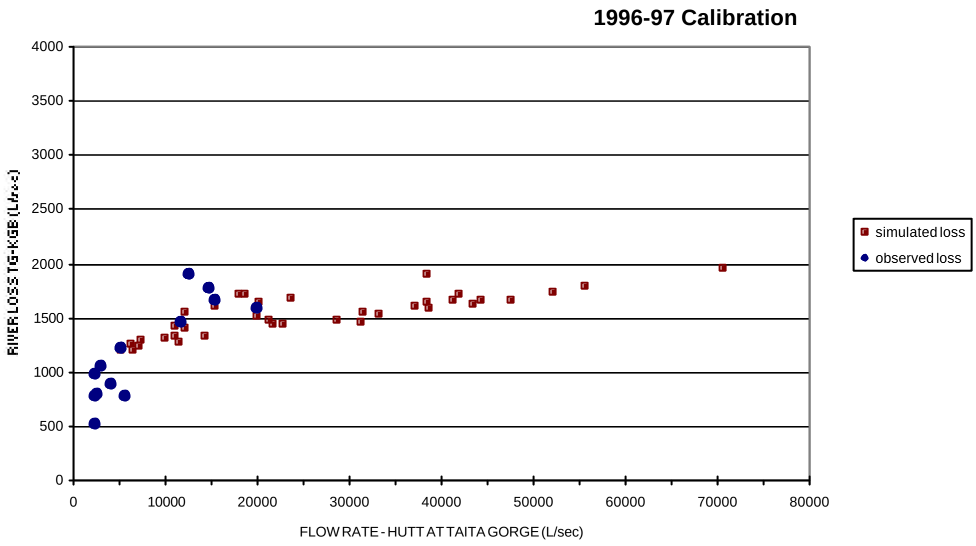



**Figure 13 : Simulated river bed losses at selected model rows.**



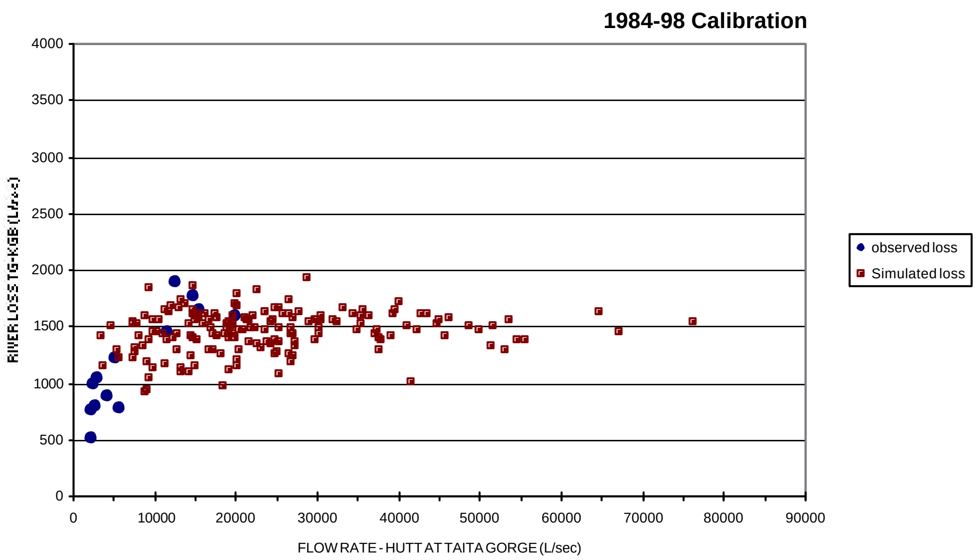




**Figure 14 : Model calibration – simulated river bed losses vs flow at Taita Gorge**

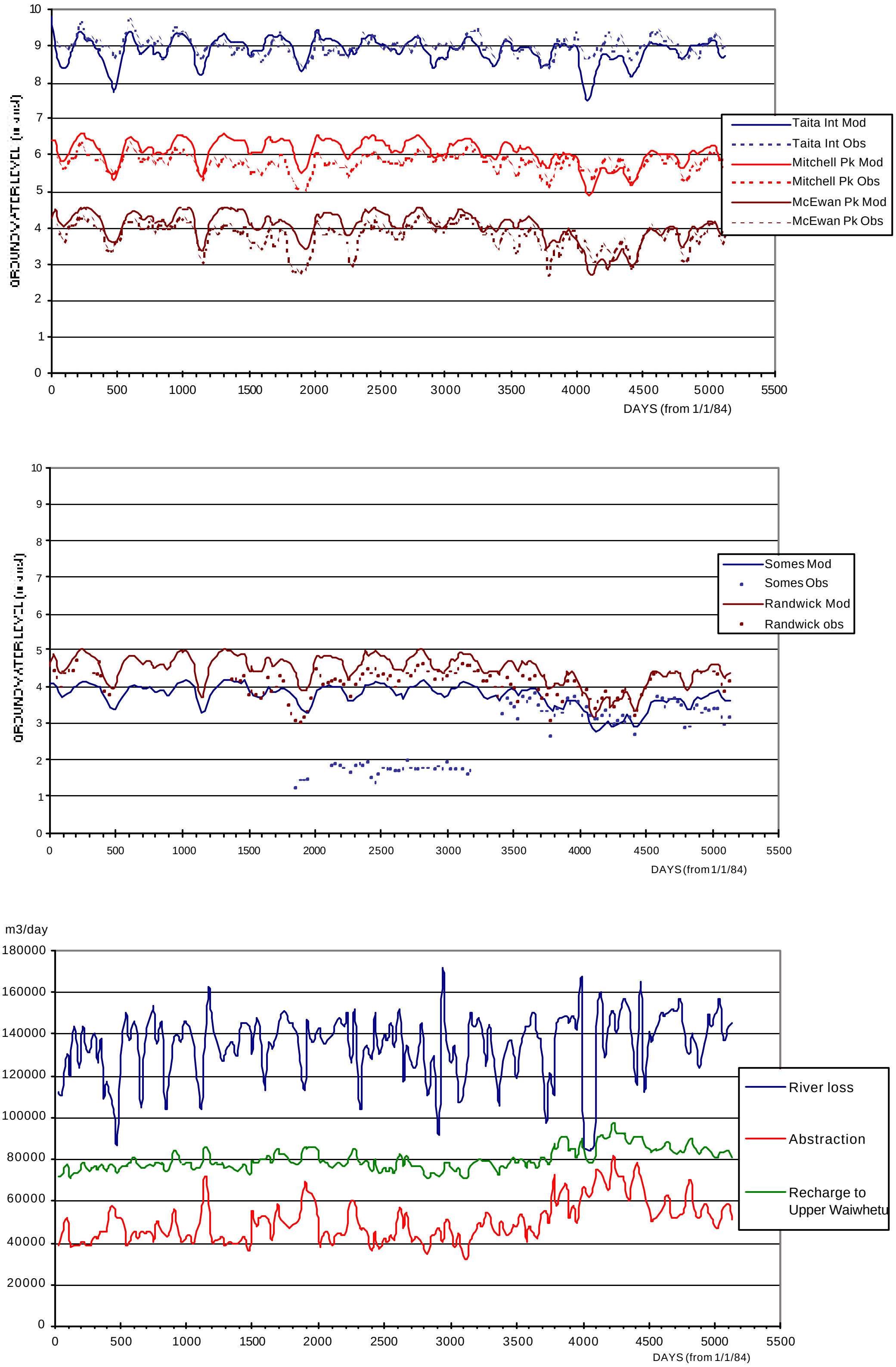



**Figure 15 : Transient model calibration – 14 year period (1984-1998).**

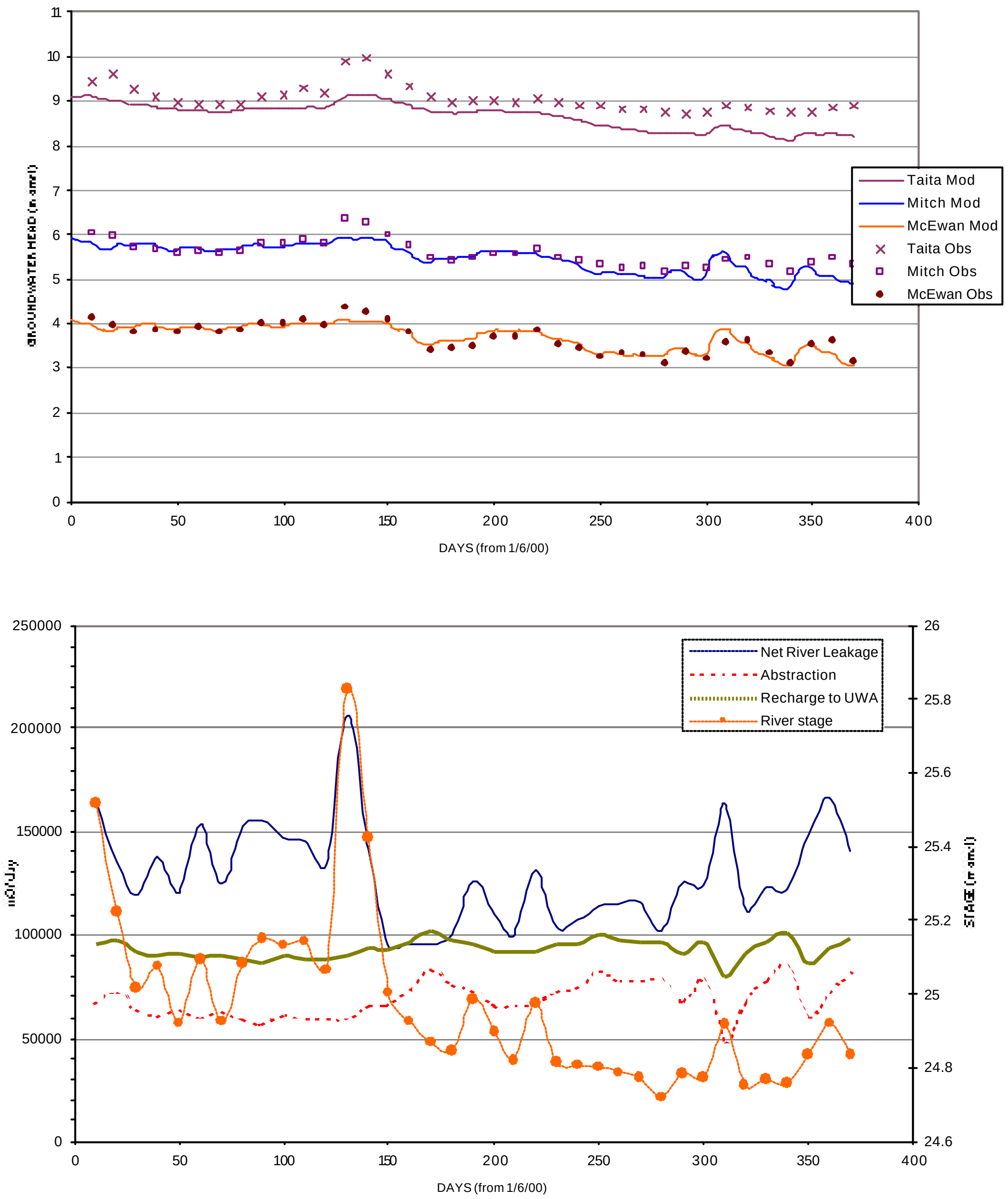



**Figure 16 : Transient calibration verification**

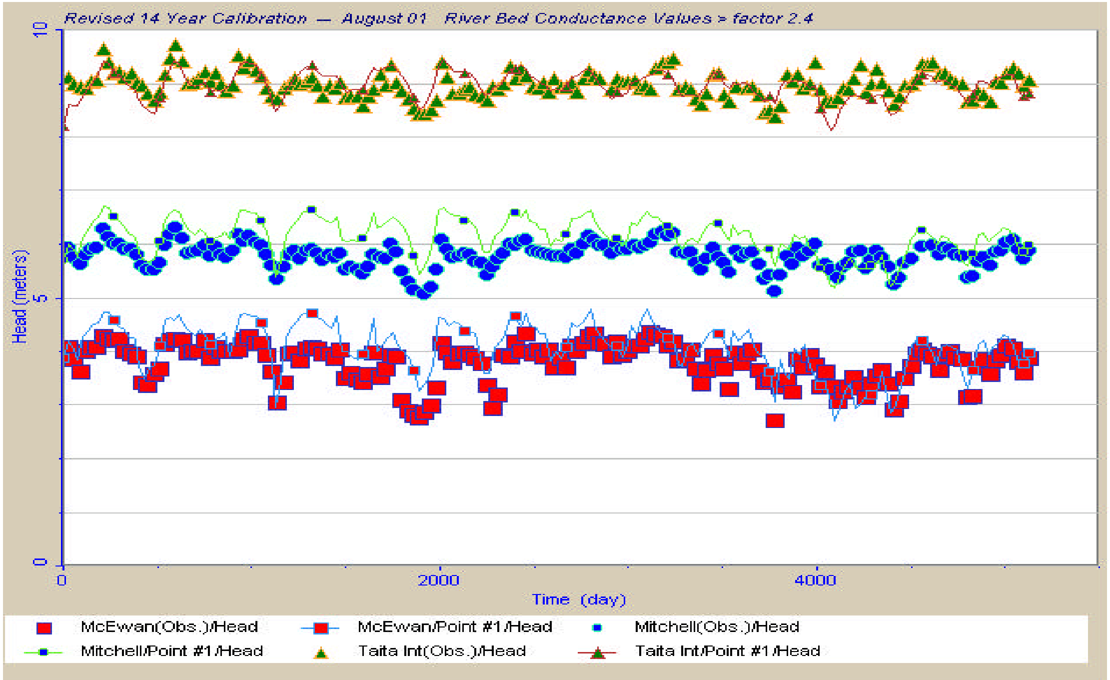



**Figure 17 : HAM2 2000-2001 recalibration: 14 year run (1983-1998)**

# Appendix One – Reinterpretation of deep bore logs

Coding of stratigraphic and aquifer units –

| | |
|---|---|
| Fill | f |
| Recent fluvial | r |
| Taita 1 | 1 |
| Taita 2 | 2 |
| Taita 3 | 3 |
| Taita undifferentiated | t |
| Melling peat | m |
| Petone | p |
| Waiwhetu | h |
| Interstadial | a |
| Deep Waiwhetu | w |
| Wilford | l |
| Moera | o |
| OI 7 | 7 |
| OI 8 | 8 |
| OI 9 | 9 |
| OI 10 | 10 |
| OI 11 | 11 |
| OI 12 | 12 |
| OI 13 | 13 |
| Greywacke | g |
| Colluvium | c |

Wells used to revise the Hutt Aquifer model:

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 124 | 2667060 | 5996350 | 2.1 | 0 | 0.7 | 2.1 | 1.4 | f |
| | | | | 0.7 | 27.7 | 1.4 | -25.6 | p |
| | | | | 27.7 | 30.8 | -25.6 | -28.7 | 3 |
| | | | | 30.8 | 45.1 | -28.7 | -43 | h |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 141 | 2670124 | 5994942 | 1.5 | 0 | 0.5 | 1.5 | 1 | r |
| | | | | 0.5 | 1.5 | 1 | 0 | p |
| | | | | 1.5 | 10.1 | 0 | -8.6 | 1 |
| | | | | 10.1 | 15.2 | -8.6 | -13.7 | p |
| | | | | 15.2 | 18.3 | -13.7 | -16.8 | 3 |
| | | | | 18.3 | 30.2 | -16.8 | -28.7 | h |
| | | | | 30.2 | 32.2 | -28.7 | -30.7 | a |
| | | | | 32.2 | 41.5 | -30.7 | -40 | w |
| | | | | 41.5 | 47.2 | -40 | -45.7 | l |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 142 | 2668820 | 5996640 | 1.5 | 0 | 4.6 | 1.5 | -3.1 | 1 |
| | | | | 4.6 | 12.8 | -3.1 | -11.3 | 2 |
| | | | | 12.8 | 20.1 | -11.3 | -18.6 | p |
| | | | | 20.1 | 21.6 | -18.6 | -20.1 | 3 |
| | | | | 21.6 | 43.6 | -20.1 | -42.1 | h |
| | | | | 43.6 | 47.6 | -42.1 | -46.1 | a |
| | | | | 47.6 | 66.5 | -43.1 | -65 | w |
| | | | | 66.5 | 83.8 | -65 | -82.3 | l |
| | | | | 83.8 | 114.6 | -82.3 | -113.1 | o |
| | | | | 114.6 | 128 | -113.1 | -126.5 | 7 |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 151 | 2666910 | 5996110 | 2.4 | 0 | 0.9 | 2.4 | 1.5 | f |
| | | | | 0.9 | 4 | 1.5 | -1.6 | l |
| | | | | 4 | 28 | -1.6 | -25.6 | p |
| | | | | 28 | 32.3 | -25.6 | -29.9 | 3 |
| | | | | 32.3 | 52.1 | -29.9 | -49.7 | h |
| | | | | 52.1 | 53.9 | -49.7 | -51.5 | a |
| | | | | 53.9 | 82.8 | -51.5 | -80.4 | w |
| | | | | 82.8 | 106.1 | -80.4 | -103.7 | l |
| | | | | 106.1 | 135.2 | -103.7 | -132.8 | o |
| | | | | 135.2 | 143.9 | -132.8 | -141.5 | 7 |
| | | | | 143.9 | 151.3 | -141.5 | -148.9 | 8 |
| | | | | 151.3 | 183.8 | -148.9 | -181.4 | 9 |
| | | | | 183.8 | 204.5 | -181.4 | -202.1 | 10 |
| | | | | 204.5 | 216.7 | -202.1 | -214.3 | 11 |
| | | | | 216.7 | 239.3 | -214.3 | -236.9 | 12 |
| | | | | 239.3 | 299 | -236.9 | -296.6 | 13 |
| | | | | 299 | 311.2 | -296.6 | -308.8 | g |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 319 | 2666880 | 5996170 | 2.7 | 0 | 2.7 | 2.7 | 0 | p |
| | | | | 2.7 | 4 | 0 | -1.3 | l |
| | | | | 4 | 23.8 | -1.3 | -21.1 | p |
| | | | | 23.8 | 30.5 | -21.1 | -27.8 | 3 |
| | | | | 30.5 | 49.4 | -27.8 | -46.7 | h |
| | | | | 49.4 | 52.9 | -46.7 | -50.2 | a |
| | | | | 52.9 | 84.1 | -50.2 | -81.7 | w |
| | | | | 84.1 | 104.9 | -81.7 | -102.2 | l |
| | | | | 104.9 | 114.6 | -102.2 | -111.9 | o |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 320 | 2666820 | 5996220 | 2.6 | 0 | 0.9 | 2.6 | 1.7 | f |
| | | | | 0.9 | 25.6 | 1.7 | -23 | p |
| | | | | 25.6 | 28.7 | -23 | -26.1 | 3 |
| | | | | 28.7 | 53.7 | -26.1 | -51.1 | h |
| | | | | 53.7 | 61.9 | -51.1 | -59.3 | a |
| | | | | 61.9 | 82.9 | -59.3 | -80.3 | w |
| | | | | 82.9 | 103.9 | -80.3 | -101.3 | l |
| | | | | 103.9 | 114.6 | -101.3 | 112 | o |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 1085 | 2668350 | 5997000 | 1.4 | 0 | 0.3 | 1.4 | 1.1 | f |
| | | | | 0.3 | 5.2 | 1.1 | -3.8 | l |
| | | | | 5.2 | 22.9 | -3.8 | -21.5 | p |
| | | | | 22.9 | 23.5 | -21.5 | -22.1 | 3 |
| | | | | 23.5 | 50.6 | -22.1 | -49.2 | h |
| | | | | 50.6 | 53.3 | -49.2 | -51.9 | a |
| | | | | 53.3 | 73.2 | -51.9 | -71.8 | w |
| | | | | 73.2 | 90.5 | -71.8 | -89.1 | l |
| | | | | 90.5 | 116.7 | -89.1 | -115.3 | o |
| | | | | 116.7 | 124.1 | -115.3 | -122.7 | 7 |
| | | | | 124.1 | 134.1 | -122.7 | -132.7 | 8 |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 1086 | 2669835 | 5994960 | 1.8 | 0 | 1.8 | 1.8 | 0 | f |
| | | | | 1.8 | 5.8 | 0 | -4 | l |
| | | | | 5.8 | 21 | -4 | -19.2 | p |
| | | | | 21 | 23.3 | -19.2 | -21.5 | 3 |
| | | | | 23.3 | 41.8 | -21.5 | -40 | h |
| | | | | 41.8 | 42.4 | -40 | -40.6 | a |
| | | | | 42.4 | 48.8 | -40.6 | -47 | w |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 48.8 | 65.2 | -47 | -63.4 | l |
| | | | | 65.2 | 73.2 | -63.4 | -71.4 | o |
| | | | | 73.2 | 83.5 | -71.4 | -81.7 | 7 |
| | | | | 83.5 | 123.7 | -81.7 | -121.9 | 8 |
| | | | | 123.7 | 130.1 | -121.9 | -128.3 | 9 |
| | | | | 130.1 | 151.9 | -128.3 | -150.1 | 10 |
| | | | | 151.9 | 156.4 | -150.1 | -154.6 | 11 |
| | | | | 156.4 | 175.3 | -154.6 | -173.5 | 12 |
| | | | | 175.3 | 181.4 | -173.5 | -179.6 | g |

| **Sequence No.** | **Easting** | **Northing** | **Collar RL** | **Depth from** | **Depth to** | **RL Depth from** | **RL Depth to** | **Unit** |
|---|---|---|---|---|---|---|---|---|
| 1116 | 2671620 | 5998530 | 9 | 0 | 1.4 | 9 | 7.6 | r |
| | | | | 1.4 | 3 | 7.6 | 6 | l |
| | | | | 3 | 7 | 6 | 2 | 2 |
| | | | | 7 | 15.2 | 2 | -6.2 | 3 |
| | | | | 15.2 | 38.7 | -6.2 | -29.7 | h |
| | | | | 38.7 | 45.4 | -29.7 | -36.4 | a |
| | | | | 45.4 | 51.8 | -36.4 | -42.8 | w |

| **Sequence No.** | **Easting** | **Northing** | **Collar RL** | **Depth from** | **Depth to** | **RL Depth from** | **RL Depth to** | **Unit** |
|---|---|---|---|---|---|---|---|---|
| 1129 | 2669950 | 5994840 | 1.8 | 0 | 0.9 | 1.8 | 0.9 | f |
| | | | | 0.9 | 1.8 | 0.9 | 0 | r |
| | | | | 1.8 | 5.2 | 0 | -3.4 | l |
| | | | | 5.2 | 18.5 | -3.4 | -16.7 | p |
| | | | | 18.5 | 19.2 | -16.7 | -17.4 | 3 |
| | | | | 19.2 | 45.1 | -17.4 | -43.3 | a |
| | | | | 45.1 | 45.7 | -43.3 | -43.9 | h |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 1139 | 2670425 | 5994650 | 2.6 | 0 | 1.8 | 2.6 | 0.8 | f |
| | | | | 1.8 | 18.7 | 0.8 | -16.1 | p |
| | | | | 18.7 | 21.3 | -16.1 | -18.7 | 3 |
| | | | | 21.3 | 38.4 | -18.7 | -35.8 | h |
| | | | | 38.4 | 40.2 | -35.8 | -37.6 | a |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 1149 | 2670040 | 5995500 | 1.9 | 0 | 1.8 | 1.9 | 0.1 | p |
| | | | | 1.8 | 4.6 | 0.1 | -2.7 | l |
| | | | | 4.6 | 6.1 | -2.7 | -4.2 | m |
| | | | | 6.1 | 14.9 | -4.2 | -13 | p |
| | | | | 14.9 | 18.3 | -13 | -16.4 | 3 |
| | | | | 18.3 | 41.2 | -16.4 | -39.3 | h |
| | | | | 41.2 | 44.4 | -39.3 | -42.5 | a |
| | | | | 44.4 | 48.8 | -42.5 | -46.9 | w |
| | | | | 48.8 | 61.6 | -46.9 | -59.7 | l |
| | | | | 61.6 | 73.6 | -59.7 | -71.7 | o |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 1176 | 2671010 | 5997510 | 6.3 | 0 | 0.6 | 6.3 | 5.7 | f |
| | | | | 0.6 | 2 | 5.7 | 4.3 | r |
| | | | | 2 | 7 | 4.3 | -0.7 | 2 |
| | | | | 7 | 7.2 | -0.7 | -0.9 | p |
| | | | | 7.2 | 30 | -0.9 | -23.7 | 3 |
| | | | | 30 | 43.2 | -23.7 | -36.9 | h |
| | | | | 43.2 | 48.7 | -36.9 | -42.3 | a |
| | | | | 48.7 | 61 | -42.3 | -54.7 | w |
| | | | | 61 | 65.2 | -54.7 | -58.9 | l |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 1177 | 2669960 | 5997750 | 4.5 | 0 | 1 | 4.5 | 3.5 | f |
| | | | | 1 | 4.9 | 3.5 | -0.4 | l |
| | | | | 4.9 | 7.9 | -0.4 | -3.4 | m |
| | | | | 7.9 | 9.8 | -3.4 | -5.3 | 2 |
| | | | | 9.8 | 11 | -5.3 | -6.5 | p |
| | | | | 11 | 17.5 | -6.5 | -13 | 3 |
| | | | | 17.5 | 42 | -13 | -37.5 | h |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 1223 | 2666435 | 5996255 | 2.3 | 0 | 0.8 | 2.3 | 1.5 | f |
| | | | | 0.8 | 12.2 | 1.5 | -9.9 | p |
| | | | | 12.2 | 25.8 | -9.9 | -23.5 | 3 |
| | | | | 25.8 | 48.9 | -23.5 | -46.6 | h |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 1224 | 2666375 | 5996235 | 0.5 | 0 | 9.4 | 0.5 | -8.9 | p |
| | | | | 9.4 | 14.9 | -8.9 | -14.4 | 3 |
| | | | | 14.9 | 40 | -14.4 | -39.5 | h |
| | | | | 40 | 43 | -39.5 | -42.5 | a |
| | | | | 43 | 79.3 | -42.5 | -78.8 | w |
| | | | | 79.3 | 107.6 | -78.8 | -107.1 | l |
| | | | | 107.6 | 112.4 | -107.1 | -111.9 | o |
| | | | | 112.4 | 117 | -111.9 | -116.5 | 7 |
| | | | | 117 | 118.4 | -116.5 | -117.9 | g |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 1238 | 2667750 | 5996330 | 3.5 | 0 | 1.2 | 3.5 | 2.3 | f |
| | | | | 1.2 | 5.7 | 2.3 | -2.2 | l |
| | | | | 5.7 | 28.3 | -2.2 | -24.8 | p |
| | | | | 28.3 | 29.9 | -24.8 | -26.4 | 3 |
| | | | | 29.9 | 48.2 | -26.4 | -44.7 | h |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 1239 | 2667720 | 5996340 | 3.5 | 0 | 2.4 | 3.5 | 1.1 | l |
| | | | | 2.4 | 6.1 | 1.1 | -2.6 | 2 |
| | | | | 6.1 | 29 | -2.6 | -25.5 | p |
| | | | | 29 | 30.2 | -25.5 | -26.7 | 3 |
| | | | | 30.2 | 48.8 | -26.7 | -45.3 | h |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 1242 | 2668040 | 5997000 | 1.7 | 0 | 2.1 | 1.7 | -0.4 | f |
| | | | | 2.1 | 6.4 | -0.4 | -4.7 | 2 |
| | | | | 6.4 | 25 | -4.7 | -23.3 | p |
| | | | | 25 | 26.2 | -23.3 | -24.5 | 3 |
| | | | | 26.2 | 49.4 | -24.5 | -47.7 | h |
| | | | | 49.4 | 52.9 | -47.7 | -51.2 | a |
| | | | | 52.9 | 64.9 | -51.2 | -63.2 | w |
| | | | | 64.9 | 67.1 | -63.2 | -65.4 | l |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 1265 | 2667000 | 5996210 | 2.4 | 0 | 4 | 2.4 | -1.6 | l |
| | | | | 4 | 23.5 | -1.6 | -21.1 | p |
| | | | | 23.5 | 30 | -21.1 | -27.6 | 3 |
| | | | | 30 | 48.3 | -27.6 | -45.9 | h |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 4004 | 2669080 | 5995500 | 1.9 | 0 | 9.1 | 1.9 | -7.2 | r |
| | | | | 9.1 | 24.4 | -7.2 | -22.5 | p |
| | | | | 24.4 | 28.7 | -22.5 | -26.8 | 3 |
| | | | | 28.7 | 38.1 | -26.8 | -36.2 | h |
| | | | | 38.1 | 48.5 | -36.2 | -46.6 | a |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 4005 | 2669140 | 5995450 | 1.6 | 0 | 1.3 | 1.6 | 0.3 | r |
| | | | | 1.3 | 4.3 | 0.3 | -2.7 | l |
| | | | | 4.3 | 17.7 | -2.7 | -16.1 | 2 |
| | | | | 17.7 | 21.3 | -16.1 | -19.7 | p |
| | | | | 21.3 | 31.1 | -19.7 | -29.5 | 3 |
| | | | | 31.1 | 38.7 | -29.5 | -37.1 | h |
| | | | | 38.7 | 40.4 | -37.1 | -38.8 | a |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 4057 | 2670375 | 5997610 | 6 | 0 | 0.7 | 6 | 5.3 | f |
| | | | | 0.7 | 4.6 | 5.3 | 1.4 | l |
| | | | | 4.6 | 11.6 | 1.4 | -5.6 | 2 |
| | | | | 11.6 | 17.4 | -5.6 | -11.4 | p |
| | | | | 17.4 | 17.7 | -11.4 | -11.7 | 3 |
| | | | | 17.7 | 38.5 | -11.7 | -32.5 | h |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 4063 | 2669964 | 5997776 | 4.5 | 0 | 0.5 | 4.5 | 4 | f |
| | | | | 0.5 | 5.1 | 4 | -0.6 | l |
| | | | | 5.1 | 8.9 | -0.6 | -4.4 | 2 |
| | | | | 8.9 | 9.8 | -4.4 | -5.3 | p |
| | | | | 9.8 | 17.8 | -5.3 | -13.3 | 3 |
| | | | | 17.8 | 39.8 | -13.3 | -35.3 | h |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 6097 | 2671110 | 5997640 | 6.5 | 0 | 2 | 6.5 | 4.5 | r |
| | | | | 2 | 14.9 | 4.5 | -8.4 | p |
| | | | | 14.9 | 27.4 | -8.4 | -20.9 | 3 |
| | | | | 27.4 | 38.7 | -20.9 | -32.2 | h |
| | | | | 38.7 | 46.9 | -32.2 | -40.4 | a |
| | | | | 46.9 | 46.9 | -40.4 | -40.4 | w |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 6111 | 2666350 | 5996560 | 3.6 | 0 | 4.3 | 3.6 | -0.7 | f |
| | | | | 4.3 | 16.5 | -0.7 | -12.9 | c |
| | | | | 16.5 | 61 | -12.9 | -57.4 | g |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 6169 | 2669110 | 5995460 | 1.9 | 0 | 9.1 | 1.9 | -7.2 | r |
| | | | | 9.1 | 18.9 | -7.2 | -17 | p |
| | | | | 18.9 | 25.3 | -17 | -23.4 | 3 |
| | | | | 25.3 | 39.5 | -23.4 | -37.6 | h |
| | | | | 39.5 | 42.3 | -37.6 | -40.4 | a |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 6170 | 2669170 | 5995440 | 1.4 | 0 | 1.8 | 1.4 | -0.4 | r |
| | | | | 1.8 | 4.8 | -0.4 | -3.4 | l |
| | | | | 4.8 | 18.3 | -3.4 | -16.9 | p |
| | | | | 18.3 | 25 | -16.9 | -23.6 | 3 |
| | | | | 25 | 38.1 | -23.6 | -36.7 | h |

| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 6171 | 2669200 | 5995430 | 1.5 | 0 | 9.1 | 1.5 | -7.6 | r |
| | | | | 9.1 | 18 | -7.6 | -16.5 | p |
| | | | | 18 | 24.7 | -16.5 | -23.2 | 3 |
| | | | | 24.7 | 38.4 | -23.2 | -36.9 | h |
| | | | | 38.4 | 44.2 | -36.9 | -42.7 | a |

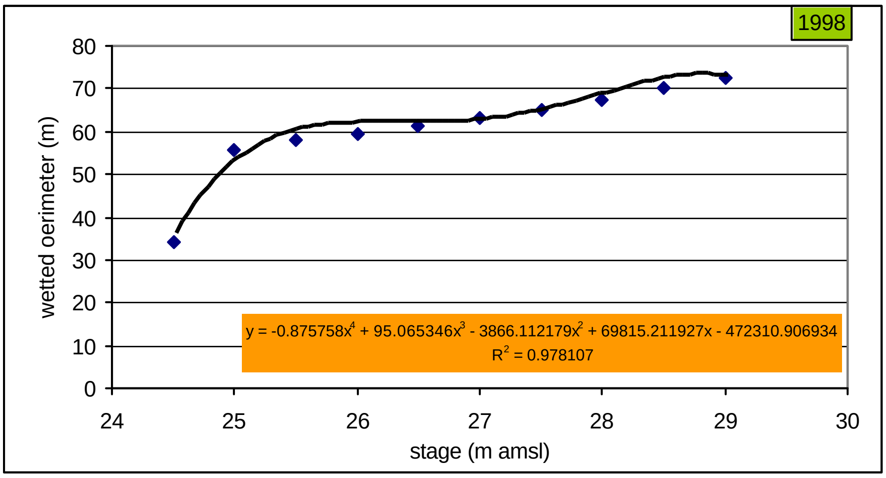
| Sequence No. | Easting | Northing | Collar RL | Depth from | Depth to | RL Depth from | RL Depth to | Unit |
|---|---|---|---|---|---|---|---|---|
| 6386 | 2669150 | 5997750 | 4.9 | 0 | 1.8 | 4.9 | 3.1 | f |
| | | | | 1.8 | 4.5 | 3.1 | 0.4 | l |
| | | | | 4.5 | 4.5 | 0.4 | 0.4 | m |
| | | | | 4.5 | 8.8 | 0.4 | -3.9 | 2 |
| | | | | 8.8 | 18.9 | -3.9 | -14 | p |
| | | | | 18.9 | 23.5 | -14 | -18.6 | 3 |
| | | | | 23.5 | 46.3 | -18.6 | -41.4 | h |
| | | | | 46.3 | 54 | -41.4 | -49.1 | a |
| | | | | 54 | 73.5 | -49.1 | -68.6 | w |
| | | | | 73.5 | 102.3 | -68.6 | -97.4 | l |
| | | | | 102.3 | 125.4 | -97.4 | -120.5 | o |
| | | | | 125.4 | 128.3 | -120.5 | -123.4 | 7 |
| | | | | 128.3 | 145.4 | -123.4 | -140.5 | 8 |
| | | | | 145.4 | 148.5 | -140.5 | -143.6 | 9 |
| | | | | 148.5 | 151.3 | -143.6 | -146.4 | 10 |

# Appendix Two: Taita Gorge – Cross Section Stage Relationships
# (Equations for calculation of cross section stage from Taita Gorge stage)

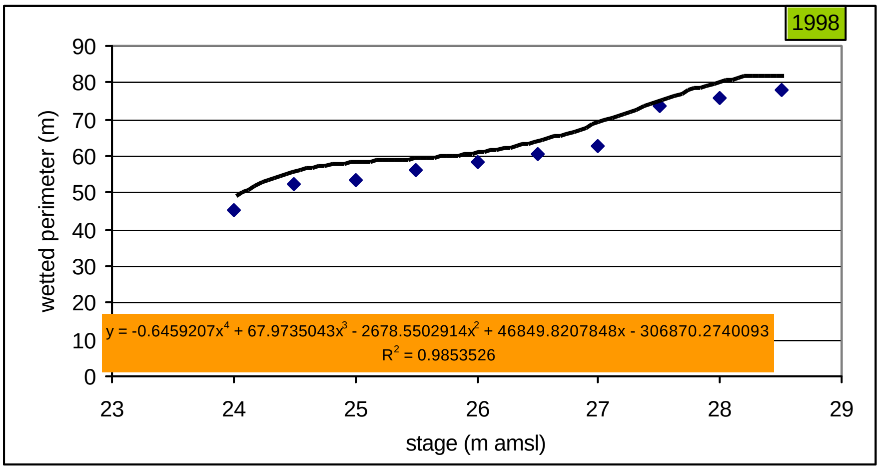
| Row | Section | Polynomial regression equation |
|---|---|---|
| 1 | 1220 | 0.010527x2 + 0.455706x + 6.761951 |
| 2 | 1200 | -0.027360x2 + 2.473033x – 20.645348 |
| 3 | 1210 | -0.054004x2 + 3.850378x – 39.188961 |
| 4 | 1130 | -0.089150x2 + 5.510579x – 59.507023 |
| 5 | 1110 | -0.069915x2 + 4.422984x – 44.849540 |
| 6 | 1090 | 0.207148x2 – 9.918327x + 139.594321 |
| 7 | 1050 | -0.0195190x2 + 1.8384786x – 14.2865989 |
| 8 | 1030 | -0.238973x2 + 13.672941x – 174.463921 |
| 9 | 1000 | -0.033038x2 + 2.603040x – 26.786589 |
| 10 | 980 | -0.062306x2 + 4.183068x – 48.766282 |
| 11 | 950 | -0.082783x2 + 5.183291x – 61.998859 |
| 12 | 930 | -0.144105x2 + 8.606582x – 110.488957 |
| 13 | 910 | -0.118322x2 + 7.055759x – 88.074373 |
| 14 | 880 | -0.087752x2 + 5.39867x – 66.612497 |
| 15 | 850 | -0.031321x2 + 2.291088x – 24.840337 |
| 16 | 830 | -0.079667x2 + 4.995218x – 63.477679 |
| 17 | 810 | -0.156990x2 + 9.221517x – 121.855370 |
| 18 | 790 | -0.215103x2 + 12.191893x – 160.201172 |
| 19 | 770 | -0.214337x2 + 12.165325x – 160.609831 |
| 20 | 760 | -0.181220x2 + 10.387276x – 137.083943 |
| 21 | 720 | -0.178532x2 + 10.151901x – 133.878042 |
| 22 | 690 | -0.062822x2 + 4.076129x – 55.141497 |
| 23 | 640 | -0.189696x2 + 10.683831x – 142.179344 |

# Appendix Three: Stage – Wetted Perimeter Relationships for River Model Cells

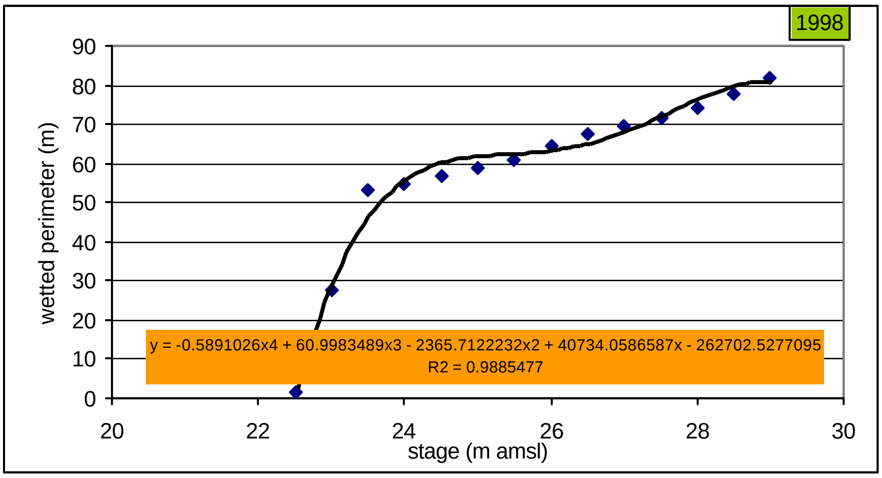
Model Row 1
X Section 1220



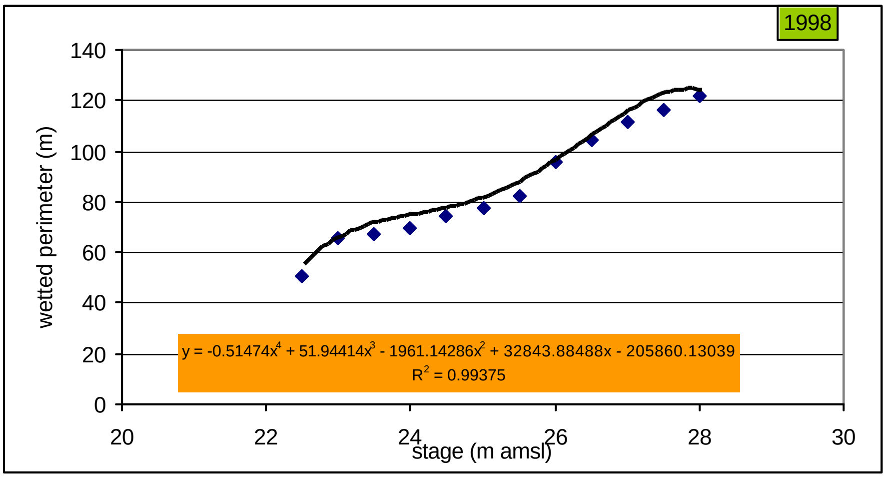

Model Row 2
X Section 1200



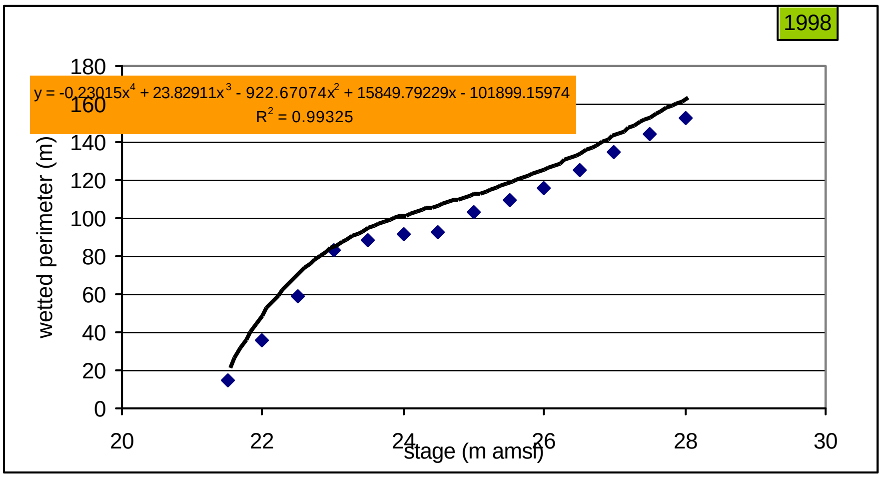

Model Row 3
X Section 1170



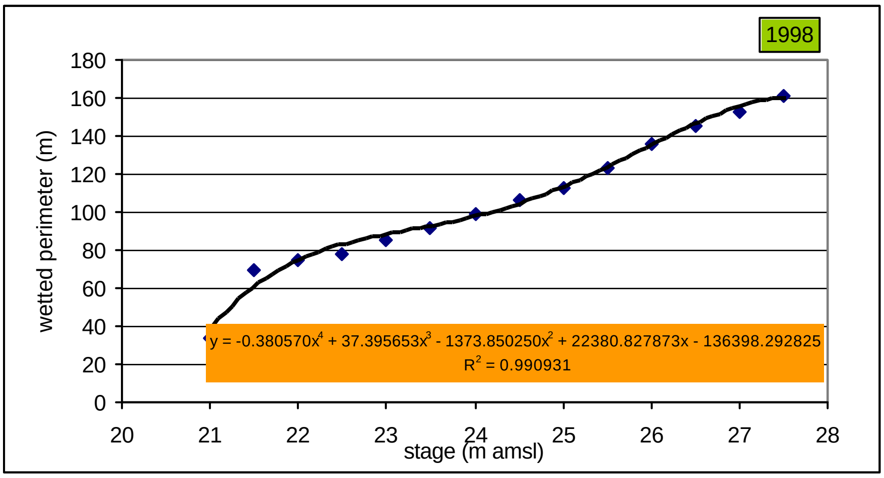

Model Row 4
X Section 1130



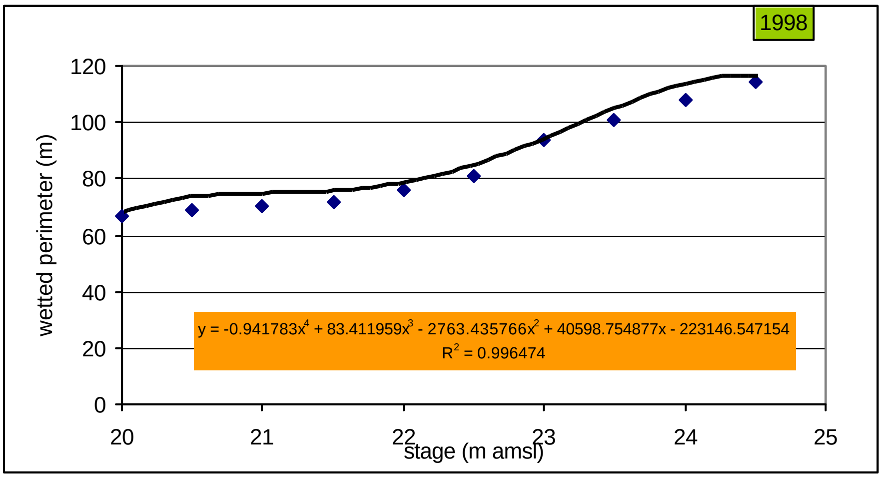

Model Row 5
X Section 1110



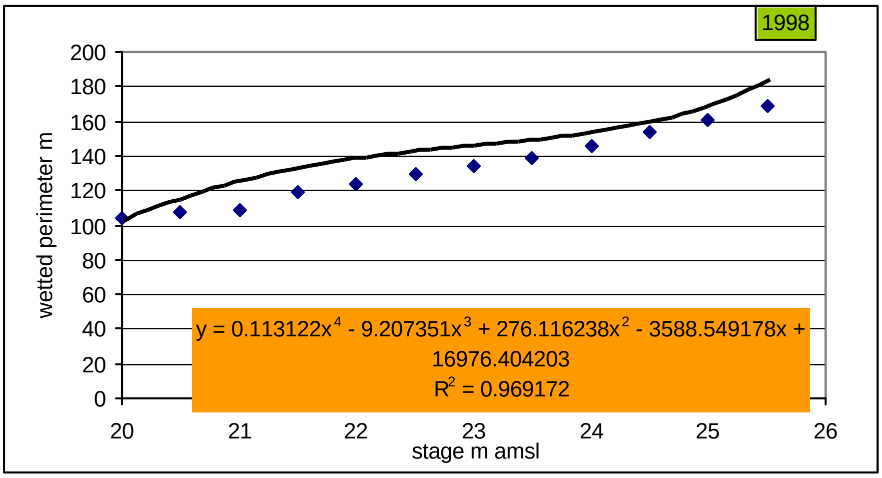

Model Row 6
X Section 1090



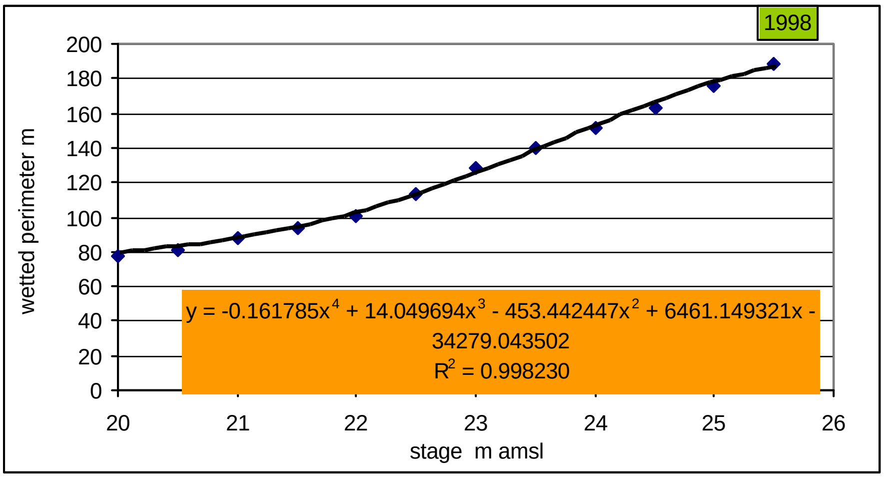

Model Row 7
X Section 1050



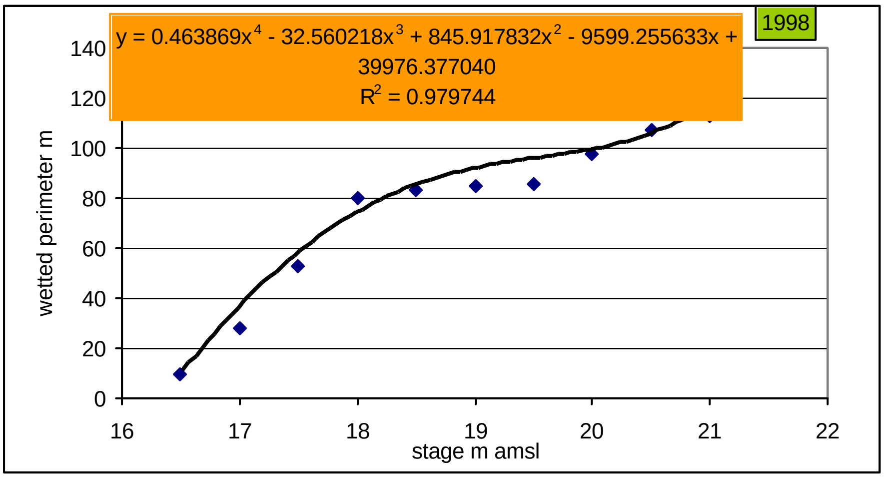

Model Row 8
X Section 1030



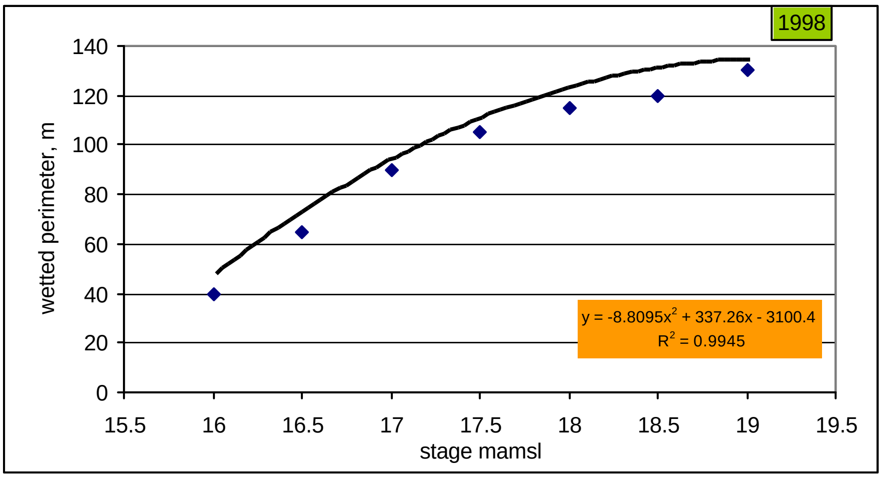

Model Row 9
X Section 1000



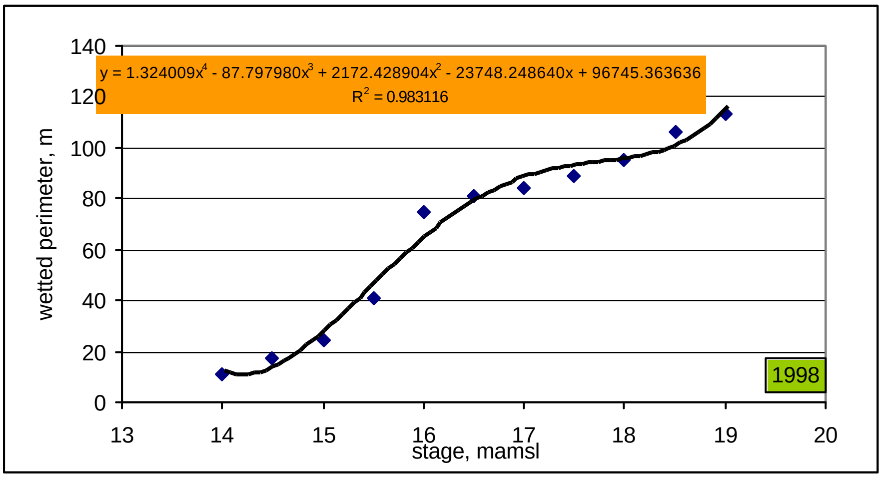

Model Row 10
X Section 980



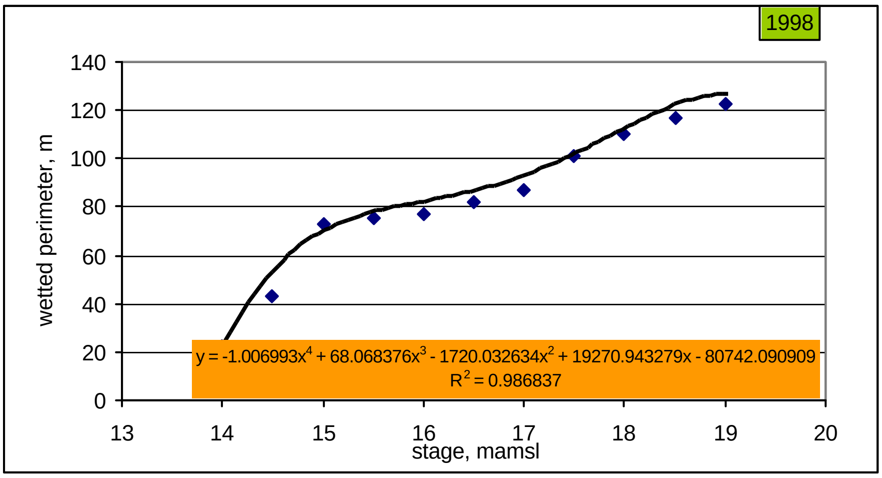

Model Row 11
X Section 950



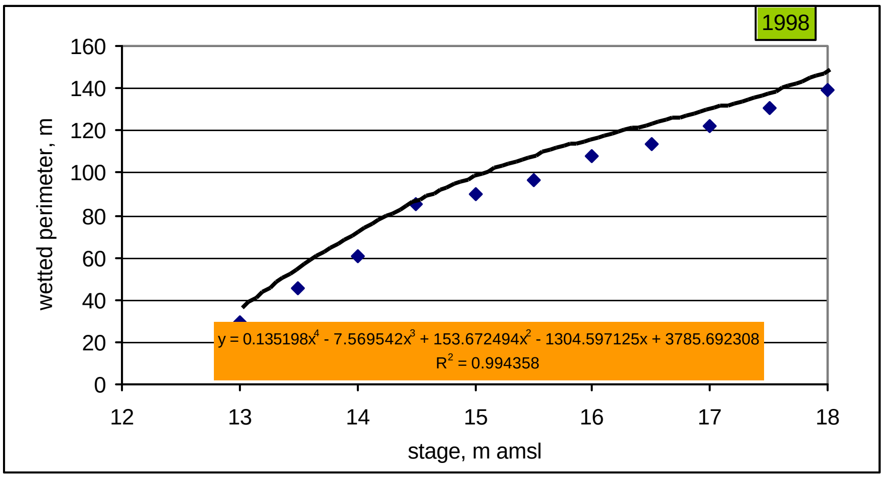

Model Row 12
X Section 930



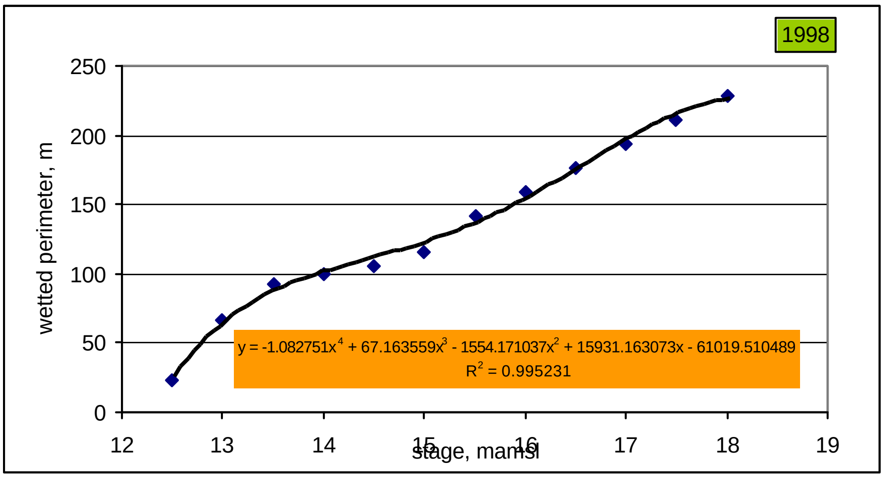

Model Row 13
X Section 910



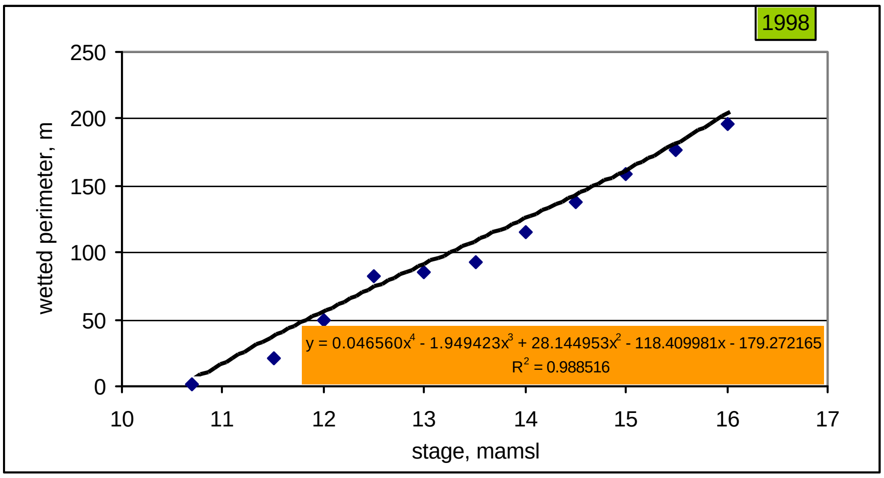

Model Row 14
X Section 880



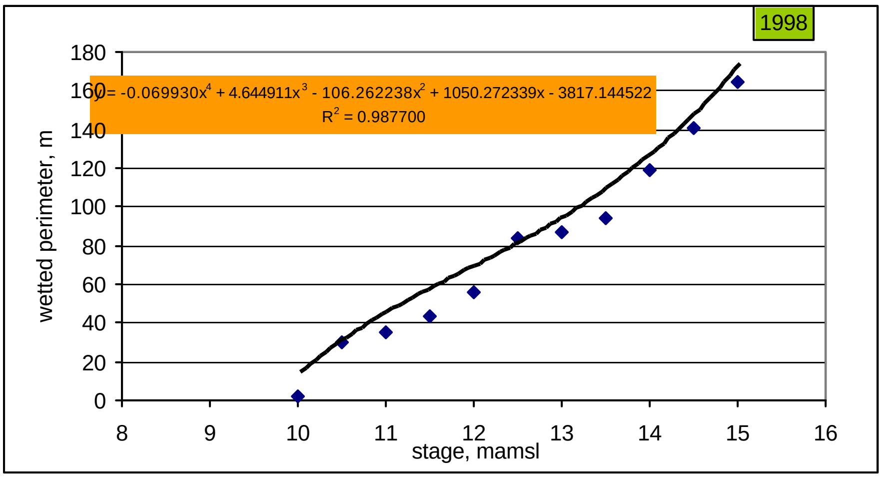

Model Row 15
X Section 850



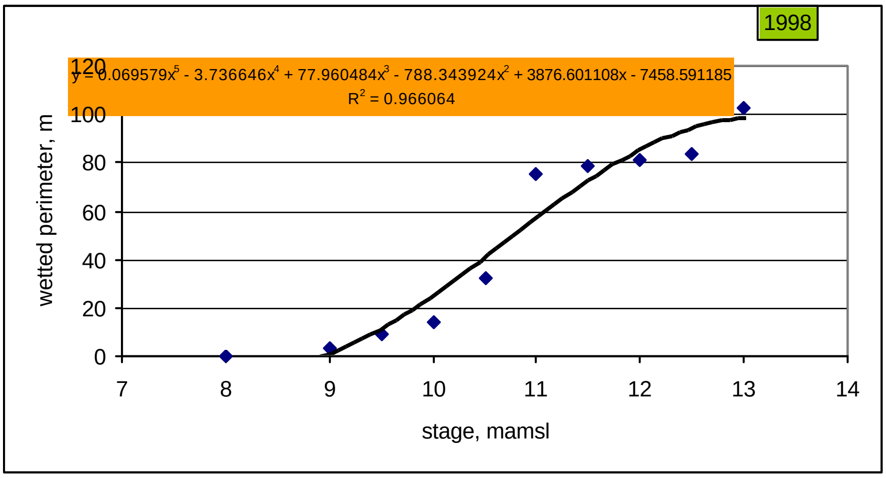

Model Row 16
X Section 830



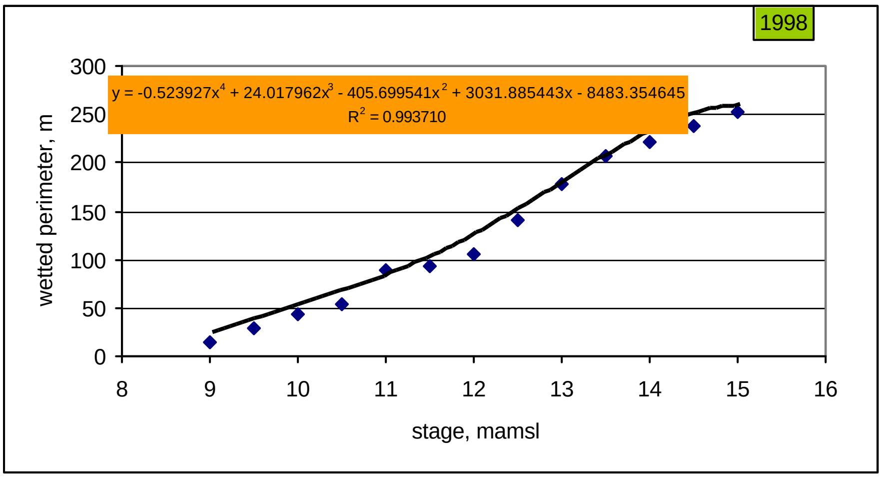

Model Row 17
X Section 810



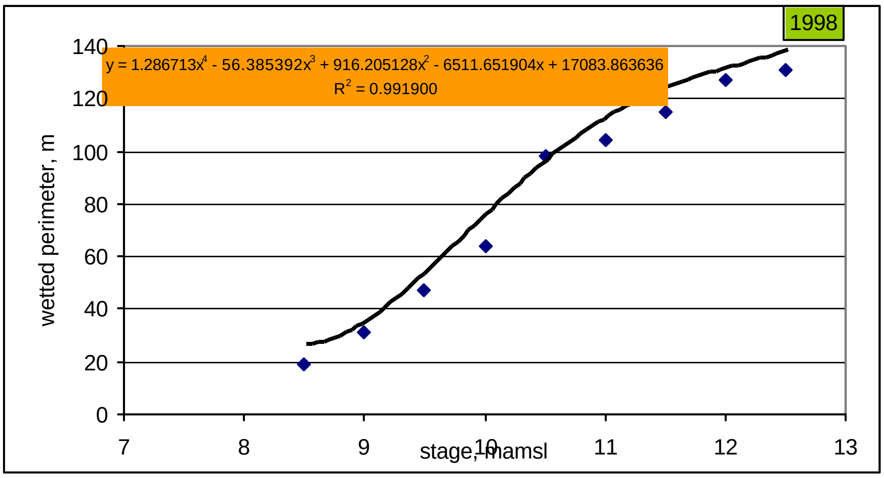

Model Row 18
X Section 790



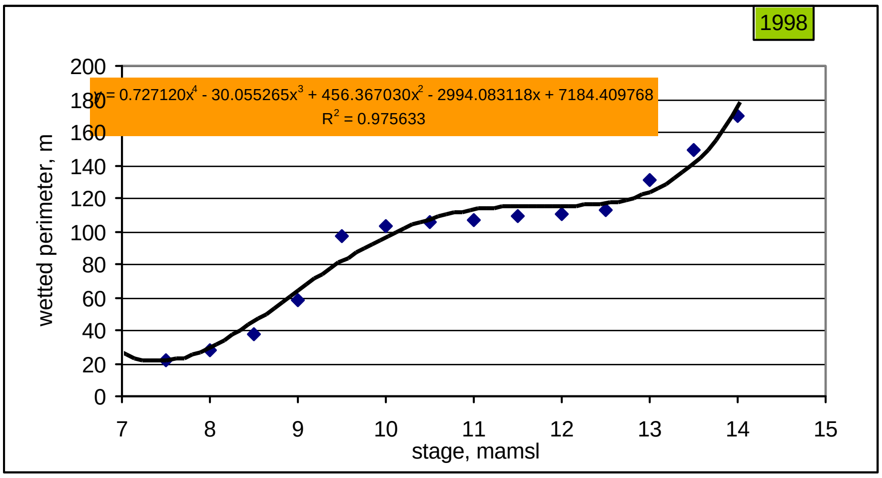

Model Row 19
X Section 770



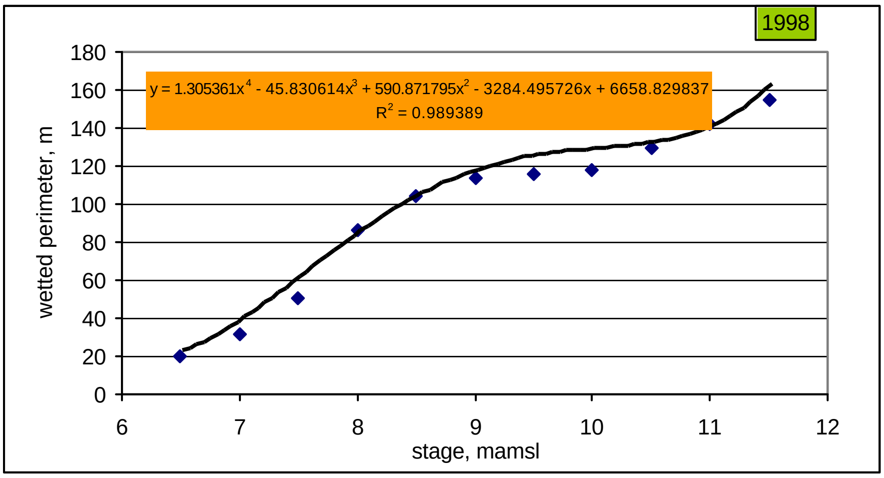

Model Row 20
X Section 760




Model Row 21
X Section 720




Model Row 22
X Section 690




Model Row 23
X Section 640