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CONTENTS

EXECUTIVE SUMMARY

Groundwater investigation in the Upper Motueka catchment is a key end user-driven component of the Integrated Catchment Management (ICM) project, a six year programme which commenced in July 2000. The goal of the ICM project is to conduct multi-disciplinary, multi-stakeholder research to provide information and knowledge that will improve the management of land, freshwater, and near-coastal environments in catchments with multiple, interacting, and potentially conflicting land uses.

The principal aims of the investigations are to understand the hydrogeology of the Upper Motueka valley (including parts of the Motupiko and Tadmor valleys), the aquifer hydraulic properties, the occurrence of groundwater (recharge, storage and discharge), and the connectivity to the rivers. Understanding these will give a conceptual model of the river/groundwater system to constrain computational models.

The study area lies within the Moutere Depression at lower altitude and has moderate rainfall (900-1300 mm). Higher land to the east with rainfall up to 2000 mm feeds the upper reaches of the Motueka River. Comparison of the Motueka River flow at the gorge and upstream of the Wangapeka River confluence shows that much of the flow, and particularly much of the low flow, are generated within the comparatively small gorge headwater area, comprising ultramafics and Maitai Group sediments. Below the gorge, the catchment contains Moutere Gravel. The Motupiko and Tadmor catchments are predominantly Moutere Gravel.

The hydrogeology of the study area is described in Chapter 2. Within the Upper Motueka, Motupiko and Tadmor river valleys, groundwater is abstracted from shallow, thin (<15m), unconfined, alluvial gravel aquifers that receive recharge from river flow loss and local rainfall. Four potentially groundwater-bearing river terrace formations have been identified, which from youngest to oldest are: recent river gravel deposits, Speargrass Formation, Tophouse Formation, and Manuka Formation. The groundwater-bearing formations are underlain by the relatively low permeability Moutere Gravel Formation. At present, groundwater is abstracted from the lower three terrace formations only. The piezometric contours in the valleys are close to being at right angles with the rivers, showing that groundwater flow is primarily along the valleys, but piezometric contours, river flow measurements, and river stage RL heights have identified reaches where river flow is lost to groundwater and reaches where groundwater contributes to river flow. River flow loss occurs from Higgins and Quinneys Bush to Hyatts, river gain from Hyatts to Tapawera Bridge, river loss from Tapawera Bridge to Glenrae, and river gain below Glenrae where the valley narrows. Pump test and groundwater level recorder data have been used to estimate the hydraulic connection between the river and the formations from which groundwater is abstracted.

Rainfall infiltration of 0.33 m/yr (based on annual rainfall of 1.1 m and recharge coefficient of 0.3) is estimated for the Speargrass and modern gravel formations (Section 2.1.2). Based on aquifer volumes and water content, it is estimated that rainfall recharge could replace the

groundwater storage in about 2.5 years. When input from the rivers (the dominant recharge source) is included, it is clear that residence times should generally be substantially less than 2.5 years.

Chapter 3 describes sensitivity analyses undertaken to relate groundwater piezometric levels to river flow rates and rainfall amounts, and identify the relative contributions of river flow and rainfall as sources of aquifer recharge, based on 21 months data and shows that 87% of the recharge to Quinneys Bush groundwater is from the Motupiko River and 13% from rainfall recharge. Recharge is 63% Motueka River and 37% rainfall at North Bridge (WWD4784), and 96% Motueka River and 4% rainfall at Hyatts (WWD4617). These figures will greatly assist the process of setting rational limits for management of the overall river-groundwater system.

Chemical and isotopic results in Chapter 4 show distinct differences between waters sourced from the Upper Motueka valley, and waters sourced from the Motupiko and Tadmor valleys. The former group has relatively high Mg-Ca-HCO_3 concentrations, because of the ultramafics (and sediments derived from them) in the Upper Motueka catchment. Motueka-type waters also have lower $\delta^{18}O$ values than the Motupiko-type waters, because of the higher altitude of the Motueka River headwater catchment. Both ground and river waters display these differences, showing that there is strong interaction between the systems, and emphasising the domination of the groundwater systems by their respective rivers.

The monthly variations of ^{18}O in the groundwaters and rivers give information on the sources and residence times of the waters. Best-fit simulations using the river and rainfall $\delta^{18}O$ variations as inputs yield optimum values of the river/rainfall ratio and mean residence time. The optimum river/rainfall ratios show good agreement with those determined in Chapter 3, and the optimum mean residence times are short and in agreement with the ages indicated by preliminary work on tritium measurements (i.e. 0-12 months) and less precise CFC results

Apart from the rivers and rainfall, a third possible recharge source for the river terrace groundwater was identified in Chapter 2, namely groundwater discharge from underlying Moutere Gravel. Groundwater discharge from Moutere Gravel is likely to have longer residence times and possibly characteristic chemical and oxygen-18 concentrations. However, the residence time results obtained rule out any substantial contribution from Moutere Gravel, since they were 12 months or less. Nor were there any chemical or oxygen-18 indications of input of groundwater from Moutere Gravel. Consequently, we consider that there is no substantial input of groundwater from underlying Moutere Gravel to the terrace groundwaters or rivers.

KEYWORDS

Groundwater/surface water interaction; river terrace gravels; neural network recharge analyses; chemical compositions; isotope tracers; water dating; Upper Motueka River

1. INTRODUCTION

1.1 Background

The area upstream of the Wangapeka River confluence of the Motueka River catchment has a sizeable area of fertile alluvial river terrace land that is suitable for irrigated agriculture. Since the mid 1990s there has been an increasing demand for irrigation water especially from groundwater in these terraces. Very little hydrogeological work had been undertaken in the past in this area to quantify the groundwater availability in these river terraces, their link to the river, the recharge components (river and rainfall), and the groundwater quality. This data is critical in the evaluation of river depletion effects due to groundwater abstraction, as well as to determine holistic and integrated allocation limits for the resource i.e. surface and groundwater. The drought of the summer of 1998/99 added extra pressure in terms of water allocation with the Nelson Marlborough Fish and Game Council seeking minimum flow requirements for the Motueka River and significant tributaries through the National Water Conservation Order Process. Due to the need to manage the water resources in the area in a holistic manner, Tasman District Council initiated investigations into the water resource of the area in late 1999. This report is the stage one output from the studies that have commenced since then.

Groundwater investigation in the upper Motueka River catchment is a key end user-driven component of the ICM project, a 6 year programme which commenced in July 2000. The goal of the ICM project is to conduct multi-disciplinary, multi-stakeholder research to provide information and knowledge that will improve the management of land, freshwater, and near-coastal environments in catchments with multiple, interacting, and potentially conflicting land uses.

Currently, the Tasman District Council has set interim total allocation limits (for surface and groundwater) via its regional water plan where the entire Motueka Catchment above the Motueka Plains has been divided into only two zones. As a result of this study and the surface flow studies within the catchment, the Tasman District Council is hoping to set more defensible surface and groundwater take limits at a more local/subcatchment level accounting for subcatchment flow and groundwater/surface water interactions.

Direct river takes are not in favour due to a combination of the effects of limits set by the Motueka River Water Conservation Order and low flow limits for mainstream Motueka River and tributaries. The principal aims of the investigations are to understand the hydrogeology of the valley, the occurrence of groundwater, aquifer hydraulic properties, and connectivity to river, and storage and recharge sources.

1.2 Study area

The groundwater investigation component of the ICM project focused on the area of the Motueka River catchment upstream of the confluence of the Wangapeka and Motueka rivers, to 3 km upstream of Kohatu on the Motueka River, the lower 3 km of the Tadmor River, and

the lower 4 km of the Motupiko River (Fig 1.1). The boundaries of this study area include almost all of the groundwater abstraction that occurs in the upper Motueka River catchment.

1.3 Hydrological monitoring network

The hydrological monitoring network consists of seven groundwater level and groundwater chemistry monitoring bores, 11 isotope monitoring sites, six river flow recorder sites, and eight rainfall sites (Figure 1.2, Table 1.1).

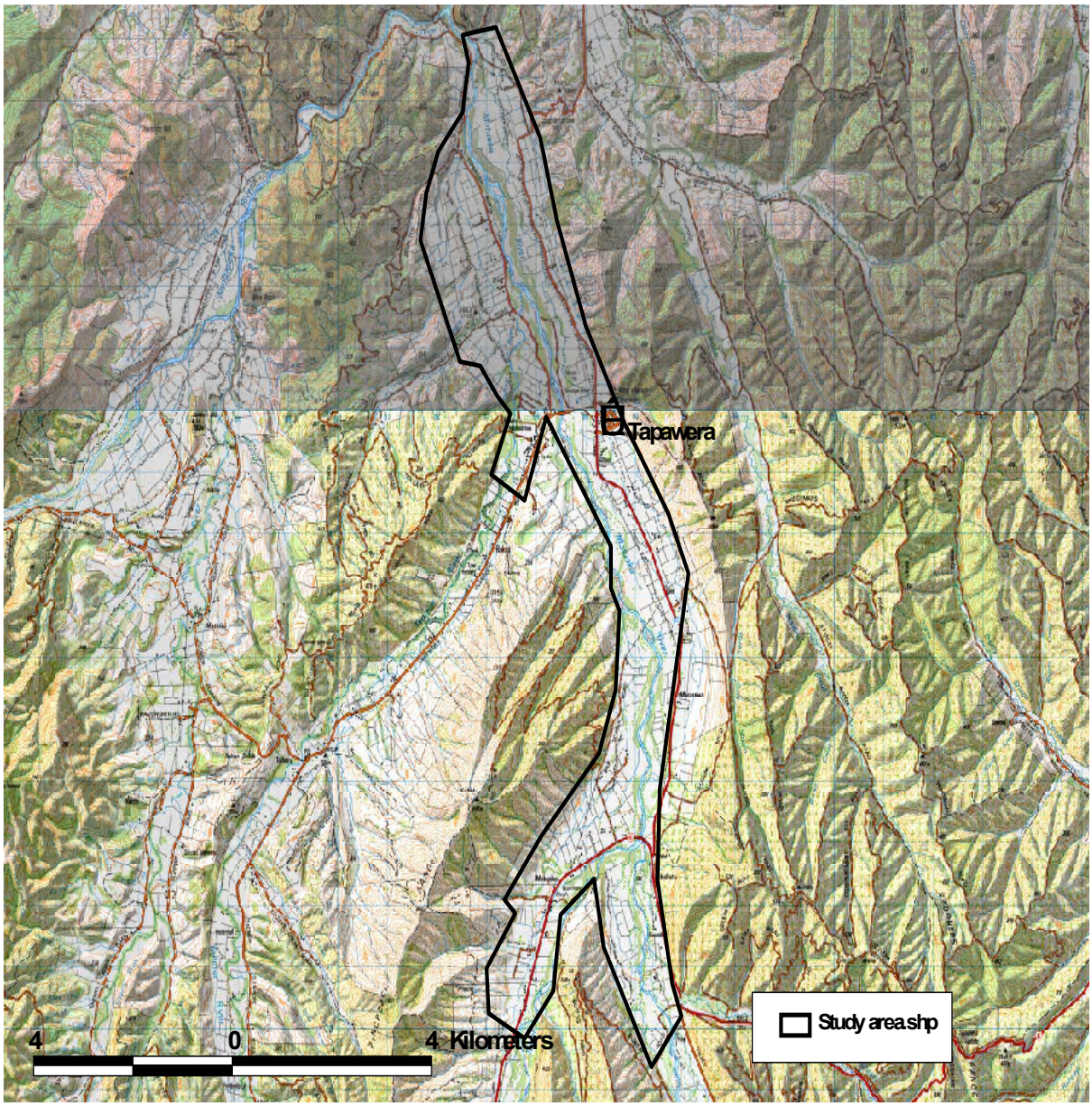

Figure 1.1. Location of groundwater study area

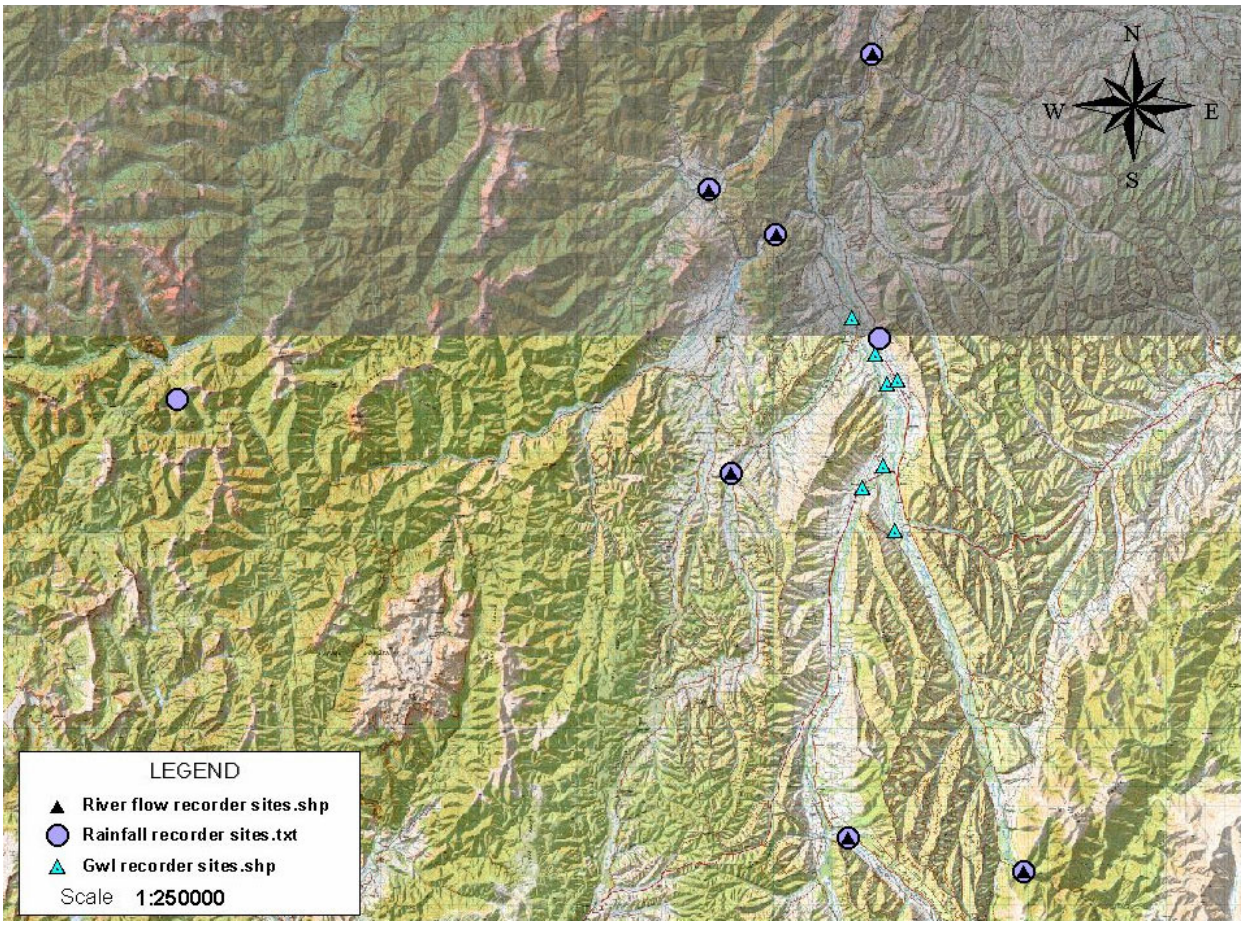

Figure 1.2. Groundwater and surface water monitoring network

Table 1.1 Summary of hydrological monitoring sites

Site ID	Grid Ref	Type	Catchment
Mudstone	M28:876728	River flow & rainfall recorders	Tadmor
Christies Bridge	N28:940542	River flow & rainfall recorders	Motupiko
Baton Flats	M27:868874	River flow & rainfall recorders	Baton
Walter Peak	N27:902851	River flow & rainfall recorders	Wangapeka
Woodstock	N27:951943	River flow & rainfall recorders	Motueka
Motueka Gorge	N28:028526	River flow & rainfall recorders	Motueka
Gravel Pit	N27:04460009	River flow & rainfall recorders	Waiwhero
Woodmans Bend	M27:635915	River flow & rainfall recorders	Motueka
Tapawera Bridge	M27:945799	River flow recorder (engineers)	Motueka
Biggs Tops	M28:598767	Rainfall	Wangapeka
Tapawera		Manual rainfall - daily	Motueka
Higgins	N28:96376996	Groundwater level recorder	Motueka
Quinneys Bush	N28:94637216	Groundwater level recorder	Motupiko
Crimp	N28:95737342	Groundwater level recorder	Motueka
Hyatt	N28:95927750	Groundwater level recorder	Motueka
Campbell	N28:96427776	Groundwater level recorder	Motueka
Oldham	N28:93497894	Groundwater level recorder	Tadmor
Vue-mount	N27:94088087	Groundwater level recorder	Motueka

2. HYDROGEOLOGY

Groundwater in the Upper Motueka catchment is abstracted from shallow unconfined alluvial aquifers that occur in the Quaternary river terrace formations and modern river deposits. Five gravel formations have been identified within the study area upstream of Wangapeka River confluence (Figure. 1.3). These are (from oldest to youngest) the Moutere Gravel, Manuka, Tophouse, Speargrass, and modern river gravel formations. The Quaternary Gravels are underlain by the Moutere Gravel Formation throughout the whole study area.

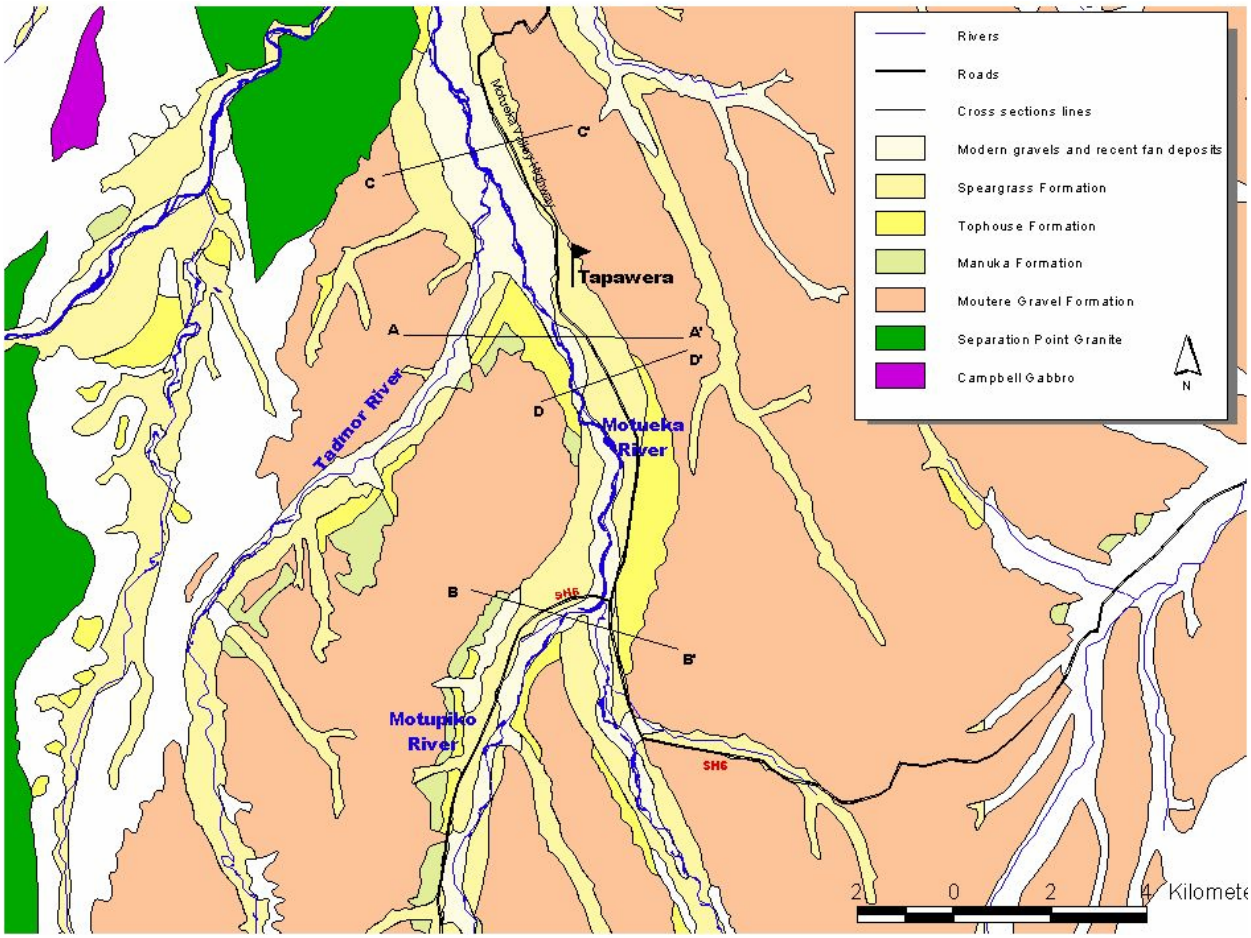

Figure 1.3. Simplified geology map showing locations of cross section lines

The Moutere Gravel Formation consists of rounded greywacke clasts up to 0.6m diameter (most less than 0.2 m diameter) in a yellowish-brown, silty, clay matrix. The formation contains minor clasts of very weathered ultramafics in the Motueka River upstream of the Motupiko River confluence (Johnston, 1983). Moutere gravel is widespread throughout the upper Motueka River catchment and forms the hill country between the valleys of the Motueka, Motupiko, and Tadmor rivers. A good example of the Moutere Gravel Formation is exposed at a road cutting at Stanley Brook Hill (N27: 939 848, Figure 2.1).

A seismic survey centred near Golden Downs (N27: 980590) indicated the Moutere gravel may be up to 550m thick at this locality (Hatherton, 1967; Anderson, 1980 cited in Johnston, 1983). The thickness of the Moutere Gravel Formation is thought to increase eastward

towards the Waimea Fault (Johnston, 1983). The formation has low permeability due to its high clay content and groundwater is not abstracted from the Moutere Gravel in the Tapawera area. However, the formation is groundwater bearing as seepage commonly occurs on exposed Moutere gravel cliff faces (Figure 2.2) and appreciable amounts of groundwater are abstracted from deep levels of the formation in the Moutere catchment, located approximately 25 km to the northeast of Tapawera.

The Quaternary river terrace formations are predominantly composed of reworked greywacke gravel, sand, silt and clay sediment. The formations have been differentiated and formally named on the basis of relative age and clast composition (Suggate 1965, Johnston 1983). Most of the clasts within the gravels are eroded from moraines deposited by glaciers originating in the Spencer Mountains. The higher the gravel above river level the greater the degree of weathering (Suggate, 1965, (Table 2.1, Figure 2.3).

Figure 2.1 Moutere Gravel exposure at Stanley Brooke Hill

Figure 2.2 Seepage from Moutere Gravel cliff face on the Motupiko River

Manuka Formation surfaces lie between approximately 65 m to 70 m above the river level, and terrace remnants are numerous in the Motupiko and Tadmor river valleys. No Manuka Formation surfaces are recognised in the Motueka River valley, except for small remnants at the confluence of the Motupiko and Tadmor rivers. The thickness of the Manuka Formation is estimated to be between 60 to 100m (Figures 2.4, 2.5). No bores have been drilled into the formation to confirm whether it is groundwater bearing but it is likely to be less permeable than the younger lower level Speargrass Formation due to the greater degree of weathering and higher clay content. If the Manuka Formation is groundwater bearing, the saturated thickness is estimated to be between 0 and 20 m, based on extrapolation of groundwater level in geological cross section (Figures 2.4, 2.5). The Manuka Formation is likely to receive a component of groundwater recharge from the Moutere Gravels where they are in direct contact.

The Tophouse Formation is widespread throughout all of the river valleys in the upper Motueka River catchment (Figure 1.3). Tophouse Formation surfaces lie between approximately 17 m to 35 m above river level. The potential saturated thickness of the Tophouse Formation is estimated to be between 0 and 12 m, based on extrapolation of groundwater level in geological cross section (Figures 2.4, 2.5, 2.6. 2.7). Bores drilled into the formation just south of Stanley Brook Hill and just north of Kohatu were abandoned due to insufficient groundwater. This suggests that either the permeability of the formation is very low or the base of the Tophouse Formation is above the groundwater level in these areas.

The top surface of the Tophouse Formation is typically between 10 to 20 m above the top surface of the Speargrass Formation. A good example of the two terrace formations can be seen on the the road between Tapawera and Kohatu at NZMG N28:764-969 (Figure 2.8).

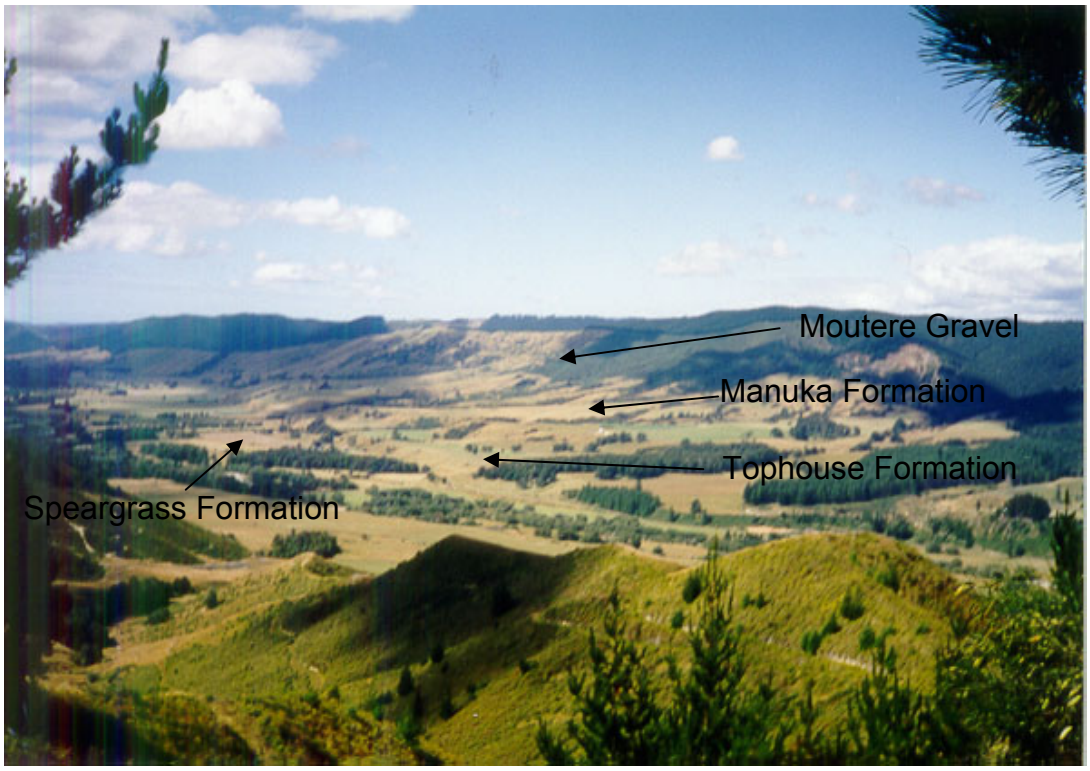

Figure 2.3. Quarternary river terrace formations in the Upper Motueka River (upstream of Motupiko River confluence)

Table 2.1. Summary of Quaternary river terrace formations

Formation	Approximate height above river level (m)	Description	Distribution	Saturated thickness	Groundwater potential
Modern Gravels	0 to 8	Silty sandy greywacke gravel.	Widespread throughout the Tadmor, Motueka, Motupiko valleys	3.5 to 9.0	Good
Speargrass	8	Slightly weathered greywacke gravel with clasts typically 0.2 m diameter in silty clay matrix. Overtopped by minor fans.	Widespread throughout the Tadmor, Motueka, Motupiko valleys	5 to 8.5	Good
Tophouse	25	Partly weathered greywacke gravel with clasts typically 0.2 m diameter in silty clay matrix. Overtopped by fan gravels and covered with loess up to 0.8 m thick.	Moderately widespread throughout the Tadmor, Motueka, Motupiko valleys	estimated 0 to 12 m*	Poor (from few available bore log data)
Manuka	65 to 70	Weathered greywacke gravel with clasts typically 0.2 m diameter in silty clay matrix. Overtopped by fans and covered with widespread loess up to 1.2 m thick.	Isolated distribution in the Tadmor and Motupiko valleys	estimated 0 to 20 m*	Unknown, but suspected poor
Moutere Gravel	0 to >70	Clay-bound gravel containing partly weathered, dominantly greywacke pebbles	Wide spread throughout the Tadmor, Motueka, Motupiko valleys	Unknown	Unknown

* These saturated thicknesses were estimated from extrapolation of groundwater level data in geological cross sections

The Speargrass Formation is widespread in the upper reaches of the valleys but absent in the lower reaches. The formation forms the lowest terrace at approximately 8 m above the river level (Figure 1.3, Suggate, 1988). An aggradation surface occurs on the Speargrass Formation terrace (Fig 2.9) that is approximately one to two meters higher than the degradation surface. Groundwater is abstracted from the formation within the study area. The hydraulic conductivity of the Formation ranges from 54 m/day in the Tadmor River valley to 940 m/day in the Motueka River valley upstream of Kohatu. The average saturated thickness of the Speargrass Formation is between 5 and 8.5 m (Figures 2.4, 2.5, 2.6, 2.7).

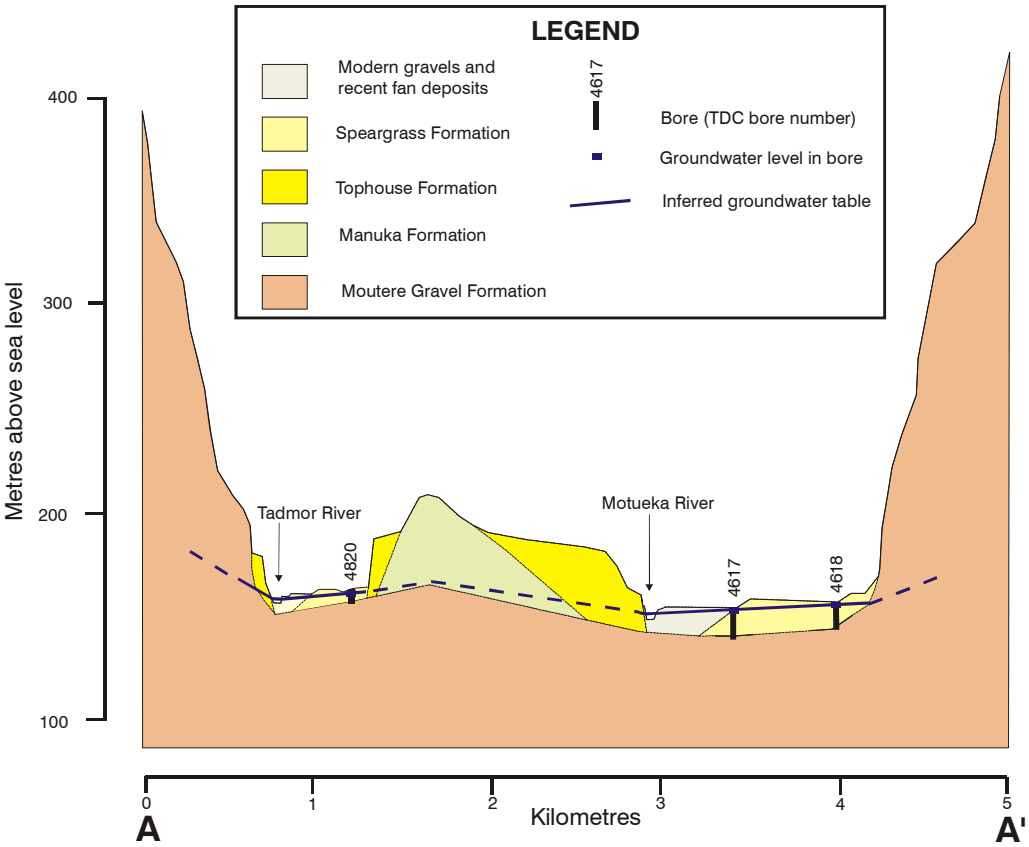

Figure 2.4 Cross section A-A' at Tapawera

Thin modern gravel deposits of Holocene age form the floodplains of the Motueka River and it's tributaries. These deposits are more extensive in the lower reaches of the valleys. The composition is similar to the older quaternary river formations, except the Modern Gravels are better sorted and tend to lack clay (Johnston, 1983). Groundwater is abstracted from these gravels. The hydraulic conductivity of the modern gravels is approximately 640 m/day. The saturated thickness of the Modern Gravels ranges from 5.5 to 9 m (Figures 2.4, 2.5, 2.6, 2.7).

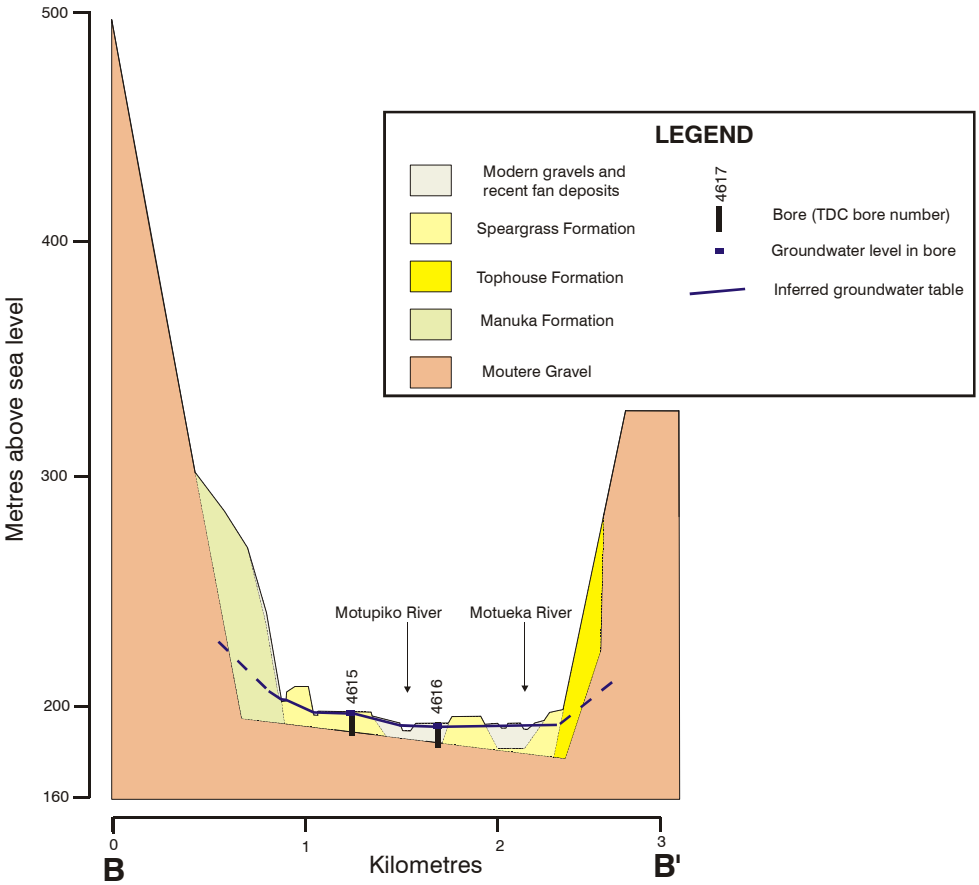

Figure 2.5 Cross section B-B' at Kohatu

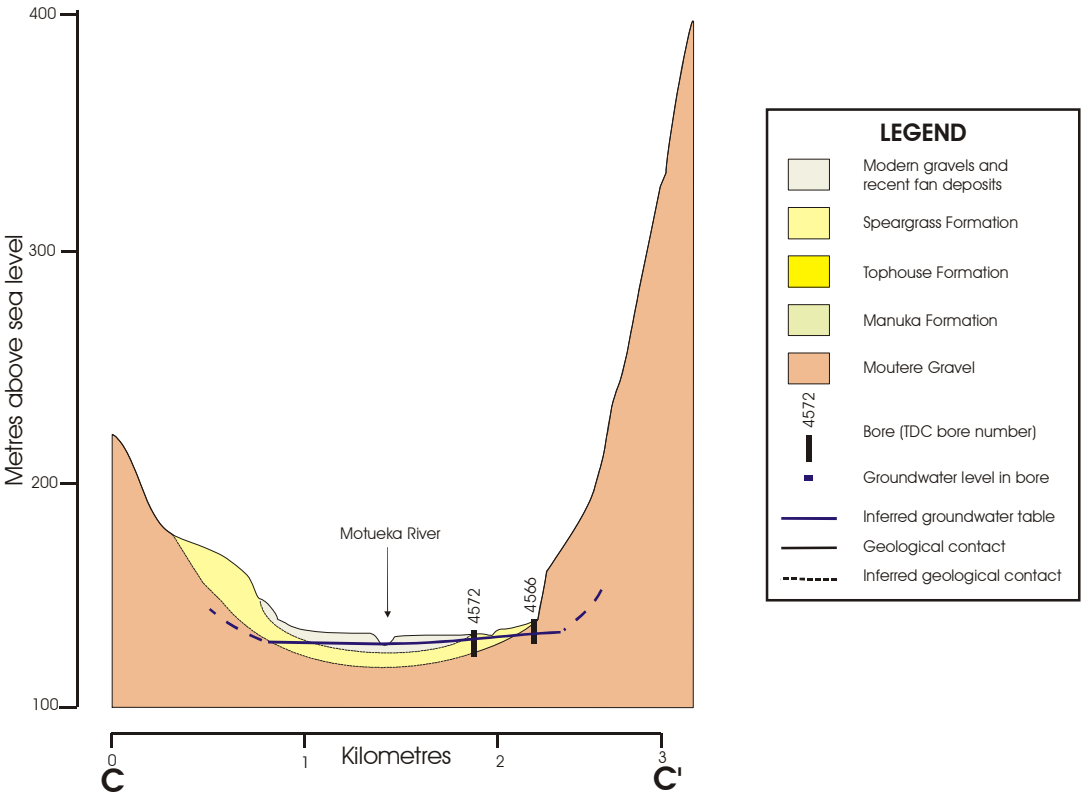

Figure 2.6 Cross section C-C' upstream of Tapawera

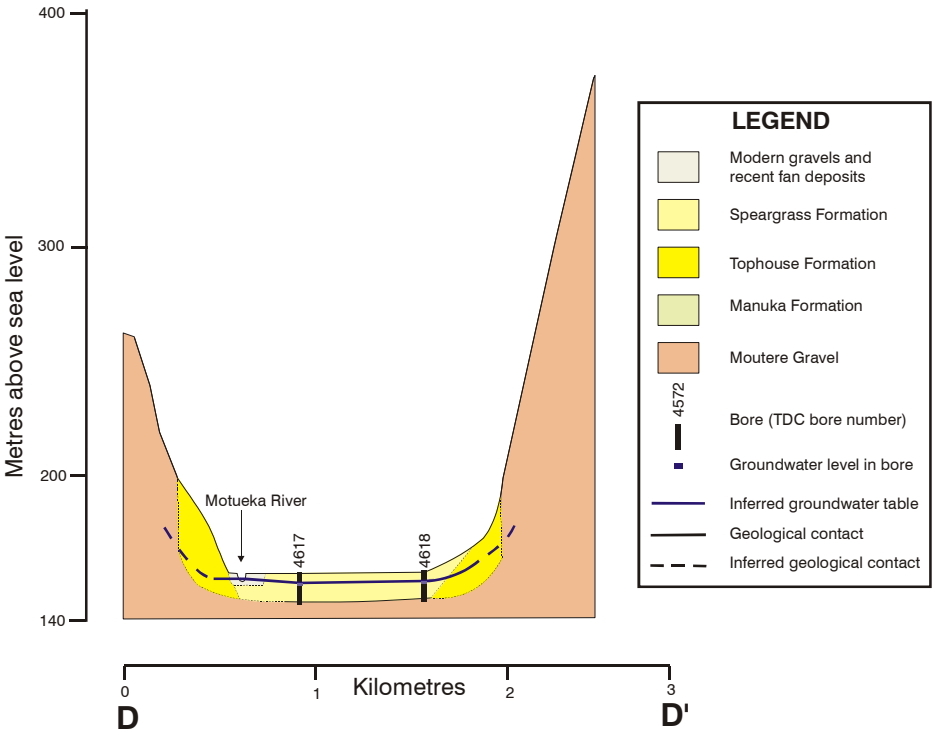

Figure 2.7 Cross section D-D' downstream of Tapawera

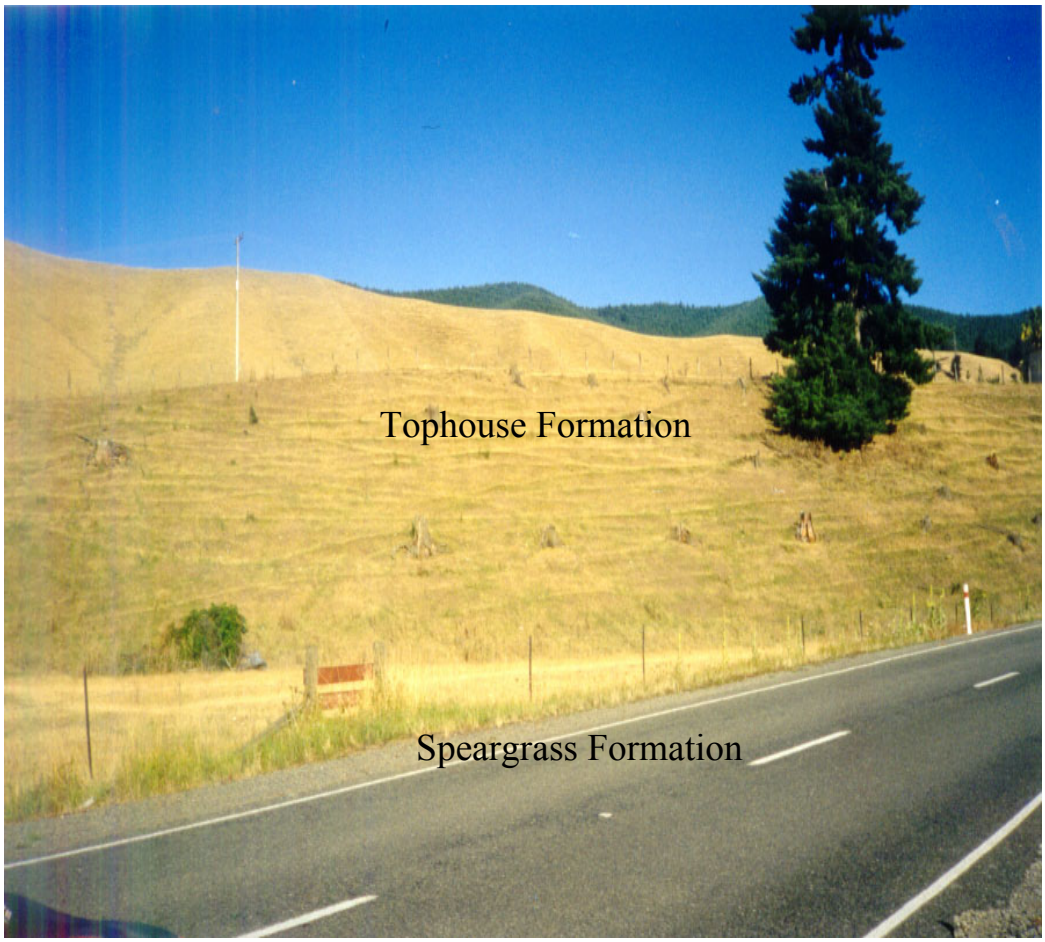

Figure 2.8 Tophouse & Speargrass formation terraces between Tapawera and Kohatu

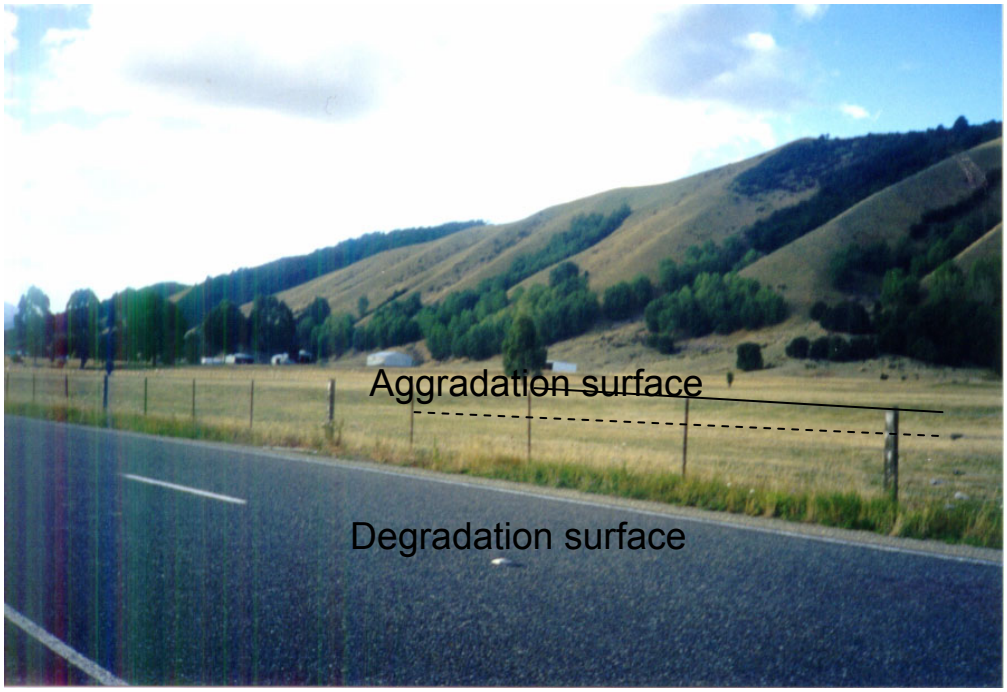

Figure 2.9 Speargrass Formation aggradation and degradation terrace surfaces

2.1 Groundwater recharge

The potential sources of groundwater recharge for the river terrace formations are:

- groundwater discharge from the Moutere Gravel
- rainfall infiltration
- river flow loss

2.1.1 Groundwater discharge from the Moutere Gravel

Groundwater seepage from the Moutere Gravel was observed at some erosion faces in the upper Motueka River catchment (Figure 2.2). Groundwater is also abstracted from deep levels of the Moutere Gravel Formation in the Moutere Valley, located approximately 25 km to the northeast of Tapawera. This indicates that groundwater in the Moutere Gravel potentially discharges into the Quaternary river terrace formations where the formations are in contact with the Moutere Gravel and the piezometric gradient is from the Moutere Gravels towards the river terrace formations. The volume of groundwater recharge from the Moutere Gravel Formation is unknown.

2.1.2 Rainfall infiltration

The mean annual rainfall at Tapawera for the period 1993 to 2001 is 1.11 m/year. The surface area of the Speargrass and modern gravel formations within the study area is approximately 33 million m^2 (3300 ha). The mean annual rainfall recharge to aquifers in the Speargrass and modern gravel formations is estimated at approximately 11 million m^3/year or 350 l/s, based on a recharge coefficient of 0.3. The recharge coefficient is based on measurements of average annual groundwater recharge from rainfall infiltration in areas under grass in the

Canterbury Plains (Thorpe and Scott 1999). A mean annual recharge rate of 350 l/s is approximately 36% of the estimated groundwater through flow rate in the Motueka River Valley downstream of the Tadmor River confluence during dry summer low flow conditions (Table 2.2).

2.1.3 River flow loss

The three main river systems that contribute to flow in the Motueka River upstream of the Wangapeka River confluence are the Motueka, Tadmor, and Motupiko rivers. The reaches of these rivers where flow loss or gain occurs have been identified from river gaugings and a piezometric survey undertaken by TDC on the 09/02/02 (Figure 2.10).

Groundwater levels were measured in 35 bores and river stage and flow at 15 locations. The piezometric and river gauging data show a complex flow pattern occurring between the rivers and the aquifers within the modern gravel and Speargrass formations (Figs 2.10 and 2.11). It appears that river flow is generally lost to groundwater in reaches where the river valley widens and the cross sectional area of the aquifer increases. Conversely, groundwater generally discharges into the river along reaches where the river valley becomes narrower.

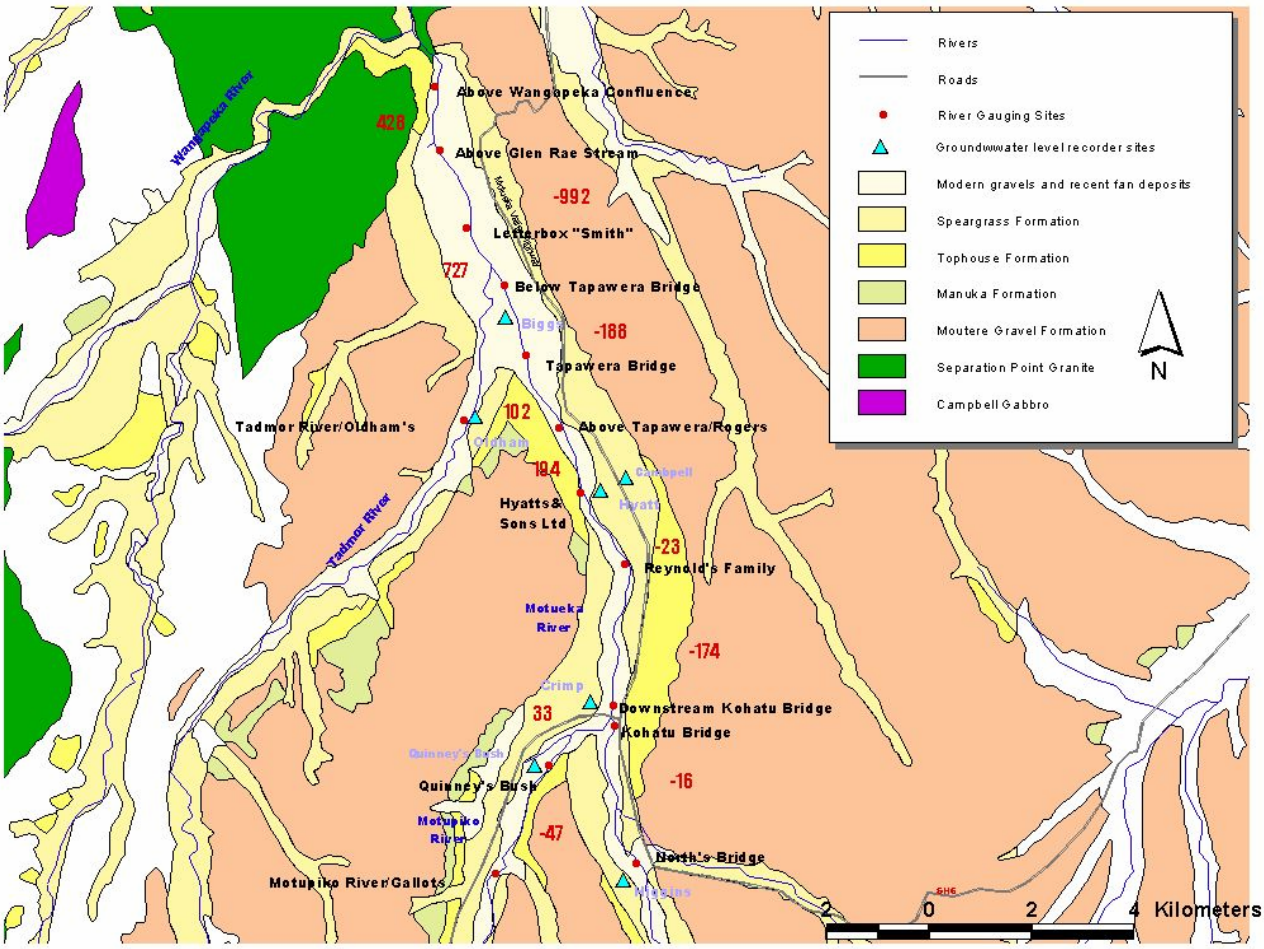

Figure 2.10 River flow loss and gain from concurrent gaugings undertaken on 9 February 2002

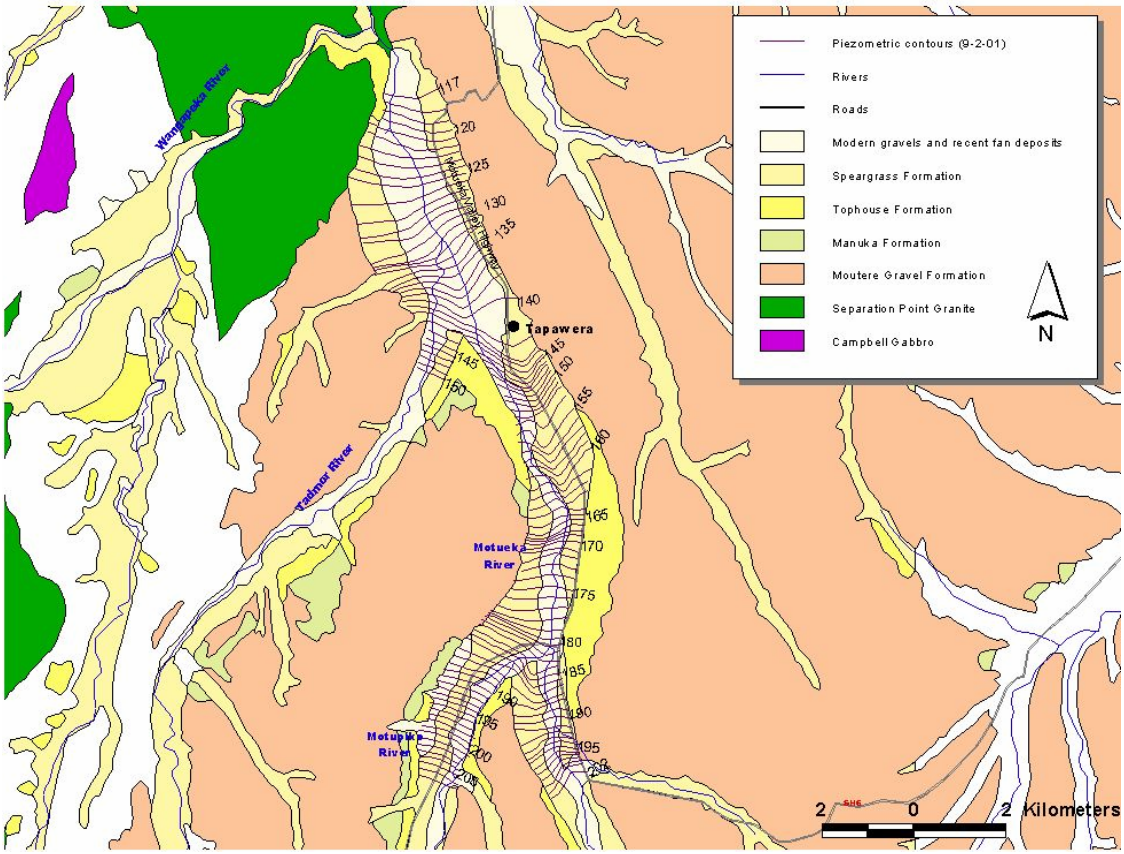

Figure 2.11 Piezometric map (9-2-2002)

The 9/2/01 gauging data show that between Quinneys Bush (on the Motipuko River), Higgins (on the Motueka River) and Hyatts the river system loses approximately 227 l/s to groundwater. Between Hyatts and Tapawera Bridge the river flow increases by approximately 296 l/s. Between Tapawera Bridge and Glenrae the river system loses 664 l/s to the groundwater, when inflow from the Tadmor River is accounted for. Groundwater discharges back into the river downstream of Glenrae due to a narrowing of the valley as the Motueka River enters the gorge above the Wangapeka River confluence.

Surface water and groundwater flow rates through the Modern Gravels and the Speargrass Formation have been calculated at six locations on the Motueka, Tadmor and Motupiko Rivers. (Table 2.2; Fig 2.10). The groundwater flow rates were calculated using Darcy's Law (1, Freeze & Cherry, 1979)

(1) $$Q = K \, {}^{dh}\!/_{dl} \, A$$

The flow rates were based on groundwater levels and surface flow gauging data collected on 9/2/01. The groundwater levels and flow in the Motueka River on 9/2/01 were below mean annual values at all monitoring sites (Fig 2.12). Flow in Motueka River at Woodstock was 11.5 m^3/s on 9/2/01, which is 4 m^3/s more than the lowest mean monthly flow rate at Woodstock for the period of record from 1969 to 2003. The mean monthly flow and the mean monthly flow for March at Woodstock are 57 m^3/s and 30 m^3/s, respectively. Therefore, flow volume calculations are representative of the system during dry summer low flow conditions and are probably close to minimum values. Flow volumes will be greater during non-drought periods .

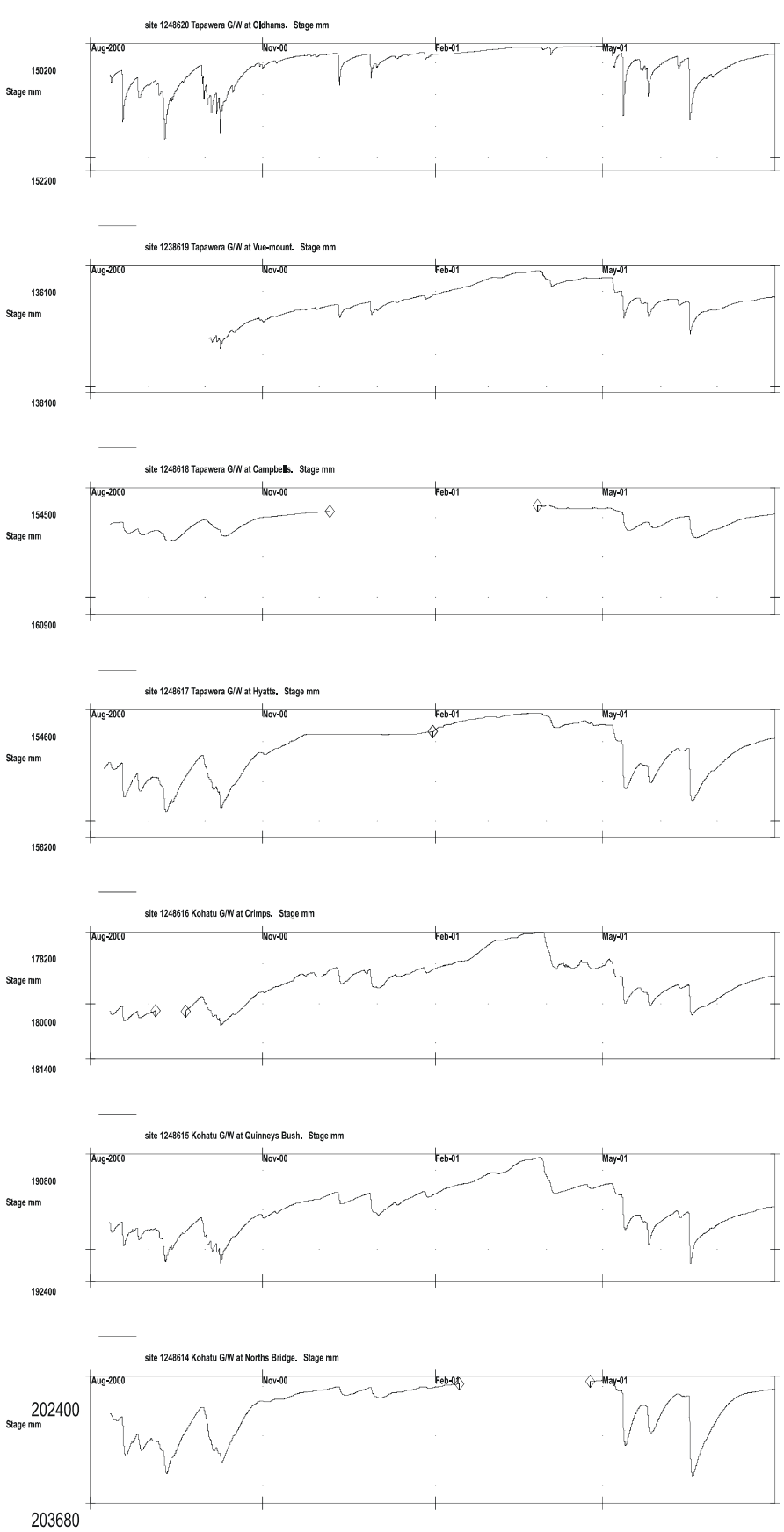

Figure 2.12 Hydrographs of groundwater level in the upper Motueka catchment for the period August 2000 to August 2002.

The flow rate values at Higgins reflect the amount of water that enters the study area via the upper Motueka River valley (Table 2.2, Figure 2.10). Similarly, the flow rates at Quinneys Bush reflect the amount of water that enters the system via the Motupiko River valley. The combined groundwater, surface water, and total flow rates at Higgins and Quinneys Bush correspond closely with flow rates at Crimp, suggesting the flow rate values at Higgin's, Quinneys Bush and Crimp are reasonably accurate. However, the flow rate values at Cambell-Hyatts imply that the combined surface water and groundwater flow rate decreases by approximately 340 l/s between Crimp and Cambell-Hyatts. The possibilities for this apparent water loss from the system are: groundwater recharge into the underlying Moutere Gravels, flow loss due to evaporation, or inaccuracies in the input data used to estimate the groundwater flow rate at Campbell-Hyatt. The input data include:

- Saturated aquifer thickness estimated from cross sections. The cross-sections were constructed from limited bore log data and may not accurately represent the top of the Moutere Gravel Formation, which is considered to be groundwater basement.
- Hydraulic conductivity estimated from slug test and constant rate pump test data. At some localities where no pump tests were undertaken the hydraulic conductivity was assumed to be the same as at the closest pump test sites, or an average thereof. The calculated hydraulic conductivity values from pump test data vary by one order of magnitude, from 54 m/day to 940 m/day.
- Aquifer width. The aquifer width was estimated from 1:250,000 scale geological map data. Any errors in the estimated flow rates caused by inaccuracies in the aquifer width data are considered to be negligible.

The most likely cause of the apparent water flow loss from the system between Crimps and Campbell-Hyatt is considered to be inaccuracies in the estimation of saturated aquifer thickness and variation in hydraulic conductivity from measured sites.

The combined surface water and groundwater flow rate of 2842 l/s downstream of the Tadmor River confluence provides an indication of the total amount of water that is flowing out of system via the Motueka River valley. A flow rate of 2842 l/s corresponds closely with the combined total flow rates at Crimp and Oldham (on the Tadmor River).

2.2 Groundwater storage

Groundwater storage volume for the Modern Gravels and Speargrass Formation aquifers during low flow conditions has been estimated at 9.7 x 10^6 m^3 for the 32.1 x 10^6 m^2 area covered by the piezometric map data. The storage was calculated from the average saturated thickness of 4.7 m based on groundwater levels measured on 2 February 2001. The groundwater level at this time was below mean annual values at all sites (see Section 2.1.3). The storage volume estimate is representative of storage during dry summer conditions and is probably close to minimum value. Storage volume will increase during non-drought periods. An aquifer storage coefficient of 0.065 was assumed, based on results of pump test data from Higgins bore.

2.2.1 Stream Depletion

The abstraction of groundwater from the modern gravels and/or the Speargrass Formation has the potential to cause depletion of upper Motueka River flow. The rate of stream depletion can be estimated using the Hunt Equation (2, Hunt 1999).

(2)
$$\frac{\Delta Q}{Qw} = erfc\left(\sqrt{\frac{SL_2}{4T}}\right) - \exp\left(\frac{\lambda_2 t}{4ST} + \frac{\lambda L}{2T}\right) erfc\left(\sqrt{\frac{\lambda_2 t}{4ST}} + \sqrt{\frac{SL_2}{4Tt}}\right)$$

$$\lambda = \Delta q / L\Delta h = K`W / M$$

where q = the change in flow between gauging sites
L = the length of stream
M = thickness of stream bed

The stream depletion was calculated for six different reaches between gauging sites along the Motueka River and the lower reaches of the Tadmor and Motupiko rivers (Figure 2.13 and Table 2.3). Rates of stream depletion from groundwater pumpage have been estimated using hydraulic conductivity and storage coefficient values from the closest or most reliable pump test data, streambed leakage parameter (λ) values calculated from the 9/2/01 gauging and piezometric data, and a pumping duration of 1 day (Figures 2.14 and 2.15 Table 2.3). For example, the pumping of a bore that draws groundwater from the modern gravels and located 100 m from the river in reach 2 to 4 will cause the Motueka River flow to decrease by approximately 55 % of the pumping rate after 1 day (Figure 2.14).

The rate of stream depletion from groundwater pumpage increases downstream in the Motueka River (Figures 2.14 and 2.15). This is due to the bed conductance increasing down stream (Table 2.4) most likely as a function of stream width increasing downstream. Bed conductance was calculated from Equation 2 and is a function of stream width, bed thickness, and hydraulic conductivity of the bed.

Table 2.2 Estimates of groundwater and surface water flow rates

Location	Aquifer	Hydraulic conductivity (m/d)	Groundwater gradient	Aquifer width (m)	Average saturated thickness in cross section (m)	Cross sectional area (m^2)	Aquifer through-flow		Combined aquifer through-flow (l/s)	River flow (l/s)	Total aquifer and river flow (l/s)
							(m^3/d)	Q (l/s)			
Higgins	Modern	93	0.007	500	9	4500	2790	32	450	1555	2005
	Speargrass	940	0.008	960	5	4800	36096	418			
Quinneys Bush	Modern	93	0.007	450	6	2700	1826	21	323	209	532
	Speargrass	465	0.008	1000	7	7000	26040	301			
Crimp	Modern	93	0.006	560	6	3360	1786	21	753	1781	2534
	Speargrass	465	0.010	1700	8	13600	63240	732			
Campbell-Hyatt	Modern	356	0.004	400	3.5	1400	1812	21	614	1584	2198
	Speargrass	753	0.005	1600	8.5	13600	51204	593			
Oldham	Modern	54	0.008	360	5	1800	778	9	36	211	247
	Speargrass	54	0.010	720	6	4320	2333	27			
Biggs	Modern	620	0.004	1500	3.5	5250	11836	137	962	1880	2842
	Speargrass	753	0.006	1950	8.5	16575	71320	825			

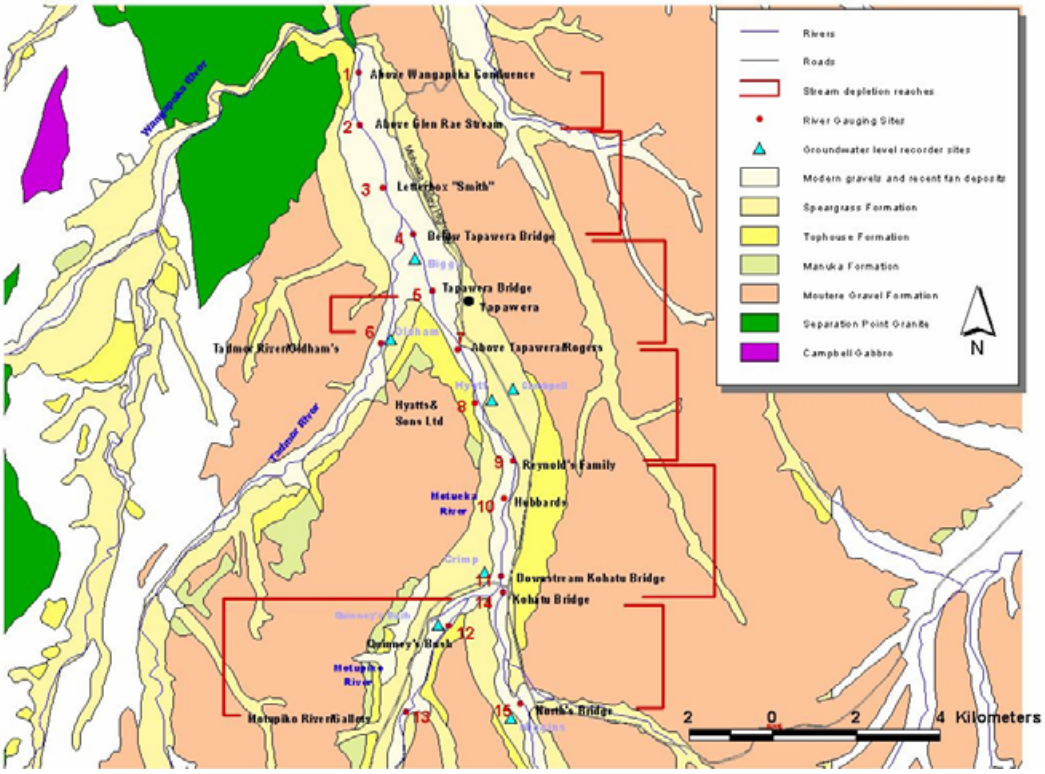

Figure 2.13 Location of stream reaches along the Motueka River used in stream depletion calculations

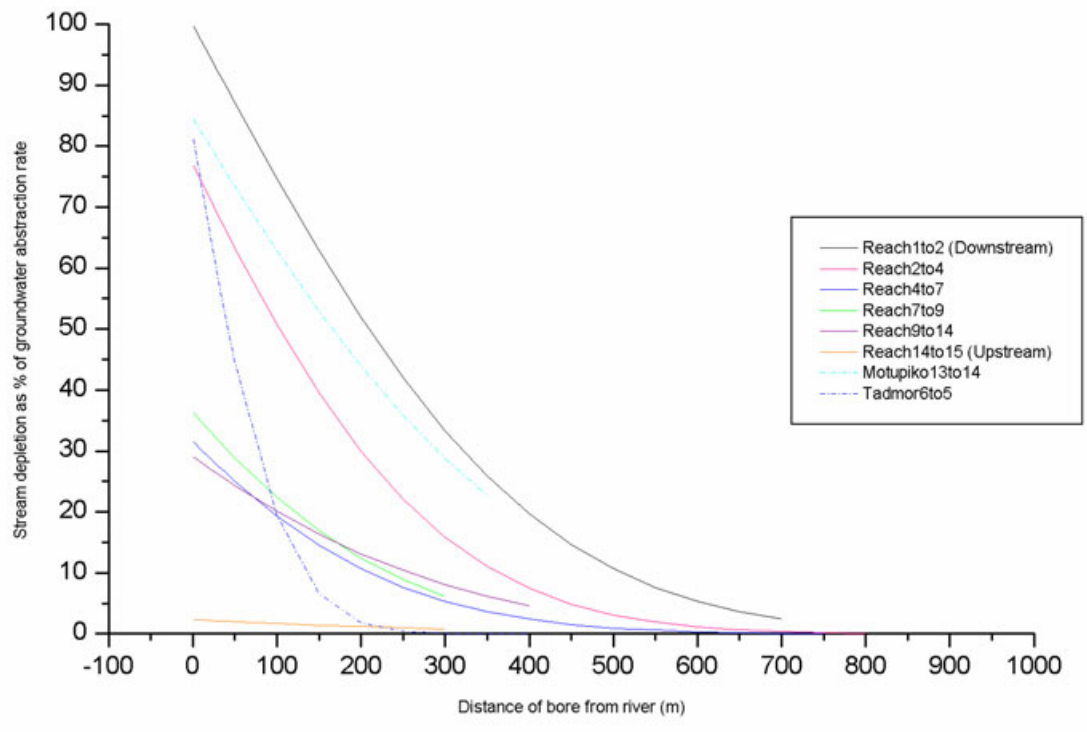

Figure 2.14 Stream depletion when pumping from within the Modern Gravels

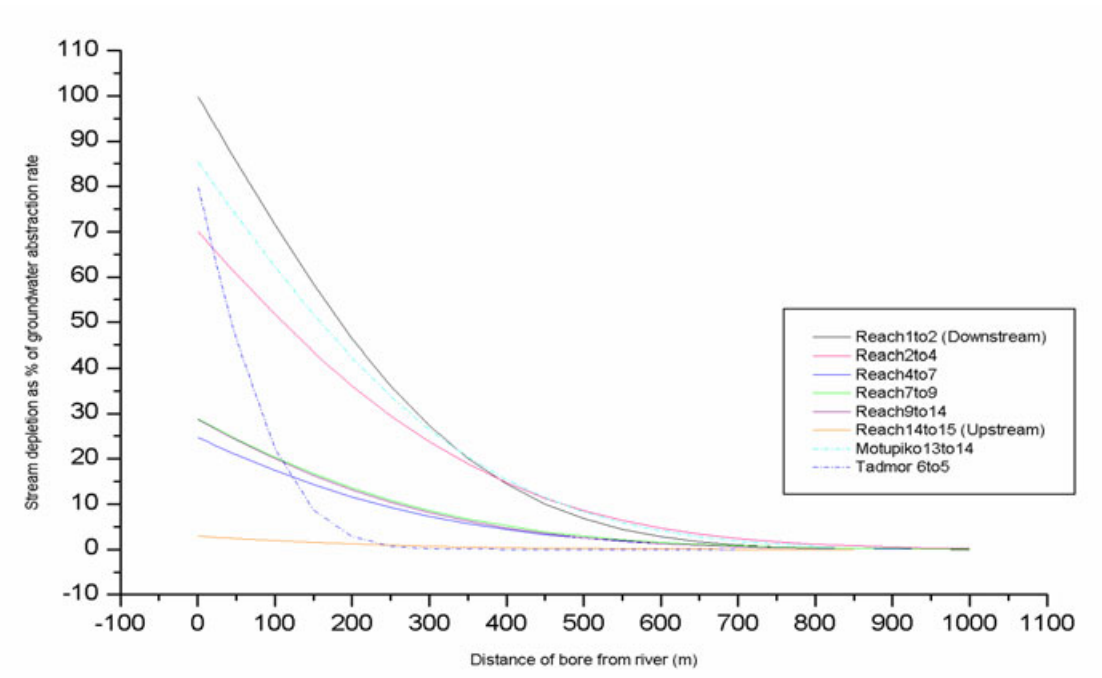

Figure 2.15 Stream depletion when pumping from within the Speargrass Formation

Table 2.3. Input values for stream depletion calculations

Reach	Formation	Storage Coefficient*	Hydraulic Conductivity* K(m/d)	Average saturated thickness of reach** (m)	(λ) Streambed leakage parameter (m/day)
1-2	Speargrass	0.0646	483	5	432.6
	Modern gravels		620	5	
2-4	Speargrass	0.0646	483	8.5	53.8
	Modern gravels		620	3.5	
4-7	Speargrass	0.0646	483	8.5	9.0
	Modern gravels		620	3.5	
7-9	Speargrass	0.0646	483	8.5	10.9
	Modern gravels		620	3.5	
9-14	Speargrass	0.0646	477	8	10.5
	Modern gravels		620	6	
14-15	Speargrass	0.0646	706	5	0.8
	Modern gravels		620	9	
Tadmor 6-5	Speargrass	0.0646	54	6	24.8
	Modern gravels		54	5	
Motupiko 13-14	Speargrass	0.0646	465	7	109.3
	Modern gravels		620	6	

* from pump test data
** from cross sections

3. GROUNDWATER-RIVER-RAINFALL MODELLING

3.1 Study objective

This study aims to identify the recharge condition in Upper Motueka catchment as a function of groundwater level, river flow rate, and rainfall.

The study uses the following methodologies:

A. Identify the correlation among the river flow rate at Motupiko and Motueka, groundwater levels (at Quinneys Bush and North Bridge), rainfall (Tapawera), using *Lipschitz Quotients* method.

B. Develop a predictive model of the relationship of groundwater levels (at Quinneys Bush and North Bridge), the river flow rate (Motupiko and Motueka at George), rainfall in the period 11 September 2000 to 31 July 2002 using a dynamic artificial neural network technique.

C. Investigate the relative strengths of the effects of input variables (river flow at Christie Bridge and rainfall) on the groundwater level (Quinneys Bush and North Bridge) using a Monte Carlo sensitivity analysis on the basis of dynamic artificial neural network model developed.

3.2 Methodology

3.2.1 Dynamic artificial neural network

The artificial neural network (ANN) technique, which is a powerful tool for nonlinear modelling, has recently attracted considerable attention in the modelling and control of engineering systems. ANN offers the distinctive ability to learn complex relationships without requiring the mechanistic knowledge about the underlying systems. Therefore, it has a great potential in areas such as hydrological systems where complex, dynamic, and highly nonlinear mechanisms are the norm. The main advantages of using ANN are: (1) it has the ability to learn a complex nonlinear relationship with limited prior knowledge of the system structure and (2) it can perform inferences for an unknown combination of input variables. The nonlinear state-space model with neural network developed by Hong et al. (1998) was applied in this work. The basic topology of a neural network model used for the prediction of the groundwater level shown in Figure 3.1.

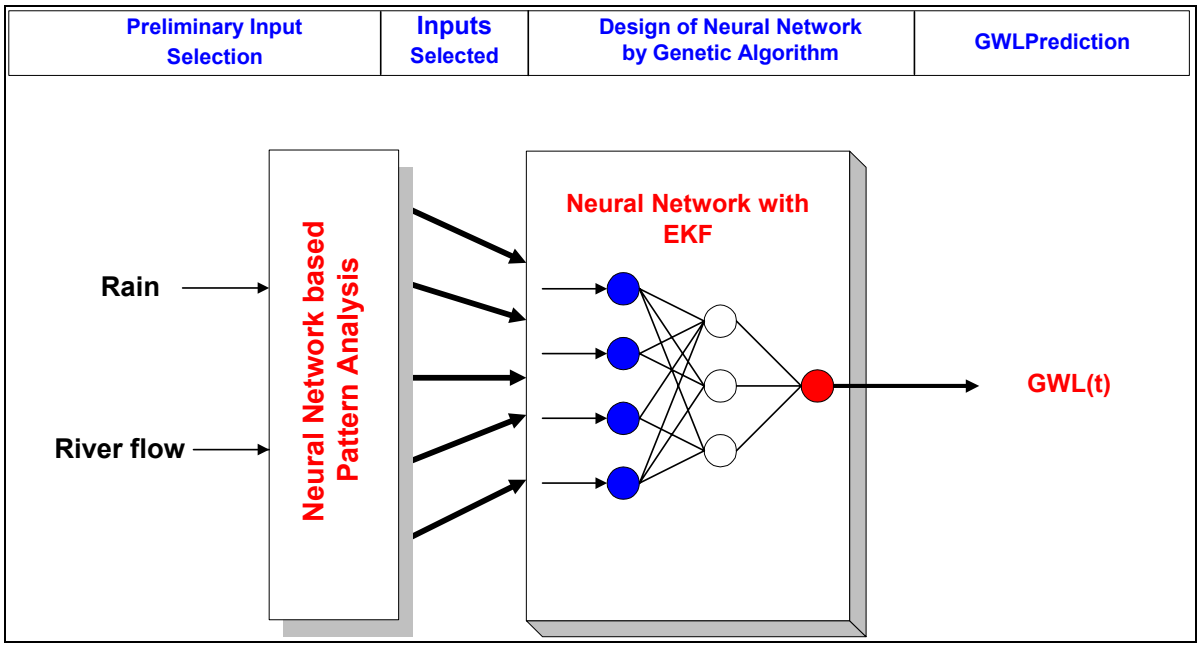

Figure 3.1. Basic model structure of dynamic artificial neural network used in this work

3.2.2 Sensitivity Analysis Procedures

In this work the sensitivity analysis is done to show the relative strengths of the effects that input variables (river flow rate and rainfall) have on the groundwater level dynamics in the artificial neural network developed. The sensitivity analysis is done using the technique of Monte Carlo simulation. The sensitivity analysis is done with the following procedures (see Figure 3.2):

1. Fit rainfall and river flow data to define probability distributions using several probability distribution functions (e.g. normal, log-normal, Gaussian, etc.)

2. Generate a set of possible river flow and rainfall values sampled from a specific probability distribution within each iteration in Monte Carlo simulation.

3. The output of river flow and rainfall from Monte Carlo simulation is fed into dynamic artificial neural network model. The groundwater fluctuation model produced by the dynamic artificial neural network model generates the relative strength of groundwater level fluctuations with respect to the changing river flow and rainfall values generated from Monte Carlo simulation.

3.3 Model development

3.3.1 Data Selection

The training set is the set of points that are used to fit the parameters of the neural network model. Training set selection is done based on the objectives of how the neural network model will be used. The purpose of developing the neural network model is to produce a

formula that captures essential input/output relationships in data. Once developed, this formula is used to interpolate from a new set of inputs to corresponding outputs. In neural nets, this is called generalization. Once the training set is selected, the test set is selected to determine to how well the neural network model generalises or predicts on unseen data not used during training.

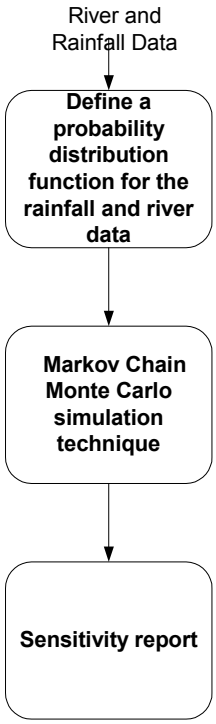

Figure 3.2. Procedures of sensitivity analysis by Monte Carlo simulation.

The data was split into two sets: (1) a training set including 60% of the data, and (2) a test set including the remaining 40%. The training set was used to construct an artificial neural network model. The remaining 40% of the data were used to test the constructed artificial neural network model in order to show how well an artificial neural network model generalises or predicts unseen data not used during the training phase.

3.3.2 Variable selection

In order to construct a suitable neural network topology for the groundwater-river interaction modelling, the appropriate assignment of the neural network input nodes to past values of inputs (rainfall and river flow rate) and output (groundwater level) are required. In other words, this represents the input variable selection of the neural network for the given problem. Basically, the crucial process of developing a predictive model is to identify the selection of input variables among the available variables for each output variable. A model free test proposed by He and Asada (1993) is used in this work. This method is based on the evaluation of the so-called *Lipschitz Quotients*.

3.3.3 Model Performance Criteria

In order to evaluate prediction accuracy of the neural network model, it is necessary to use various model validation techniques. The neural network model can be evaluated only by comparing it's output sequence $[\hat{y}(n),\ t = 1, 2, \ldots, N]$ to the actual data $[y(n),\ t = 1, 2, \ldots, N]$, for the same set of inputs. For a neural network model with a set of estimated parameters ($\hat{\theta}$), the most widely used criterion to evaluate the prediction accuracy of neural network model is the R-squared. The R-squared is calculated between the expected and actual neural network outputs and is averaged across all output neurons, if more than one is employed. R-squared is calculated using the formula:

$$R - squared = \left(1 - \frac{SSE}{SST}\right) \times 100 \tag{3.1}$$

where SSE is a error sum of squares and SST is a total sum of squares.

3.4 Modelling results

In this work two different neural network models are developed for two monitoring sites to simulate the interaction between groundwater and river:

Model 1:

- Groundwater monitoring site: Quinneys Bush (1248615)
- River flow rate monitoring site: Motupiko River at Christie Bridge (57036)
- Rainfall monitoring site: Tapawera
- Data Time interval: daily

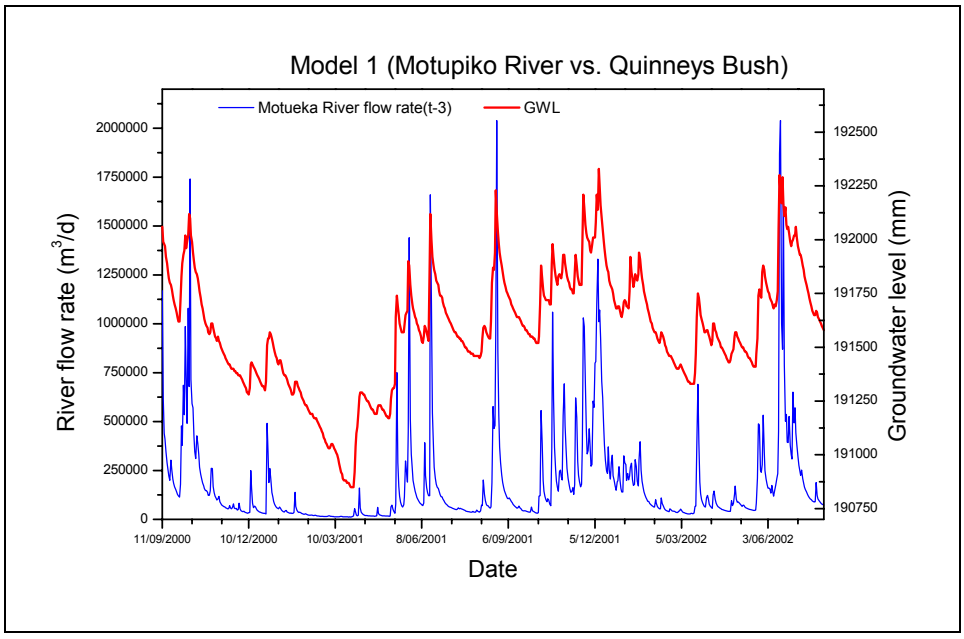

Figure 3.3. Motupiko River vs. groundwater level at Quinneys Bush

Figure 3.3 shows the graphical display of Motupiko River vs. groundwater level at Quinneys Bush. The Lipschitz Quotients method is done to find past input variable (rainfall, Motupiko River flow rate) for the dynamic neural network model construction. The results of the Lipschitz Quotients method are shown in Figure 3.4. It is reasonable that the dynamic artificial neural network model can be modelled by a first order model because the slope of the curve is decreased for model orders ≥ 1. The lag time between change in groundwater level at Quinneys Bush and increase in Motupiko River flow rate is approximately one day. The slope of the curve in Figure 3.4 is nearly flat after 6 days of past input. The time span over which a momentary river change of Motupiko River persists in affecting the groundwater level at Quinneys Bush is 1-6 days. The same procedure of Lipschitz Quotients method as that adopted for Motupiko River flow rate was applied to find past rainfall variables. It is found that previous 1-2 days rainfalls correlate strongly with the current groundwater level at Quenny's Bush. Mathematically, the multi-input, single-output (MISO) dynamic artificial neural network model for the groundwater level dynamics at Quinneys Bush is described by:

$$\hat{GWL}(k) = f\begin{pmatrix} r(t-1), r(t-2), River(t-1), River(t-2), River(t-3), \\ River(t-4), River(t-5), River(k-6) \end{pmatrix} \quad (3.2)$$

where $\hat{GWL}(t)$ is the predicted groundwater level at time *t*. In Eq (3.2) GWL (t) means the groundwater level at time t and River(t-1) represents the river flow rate at past one day . R(t-1) also means the rainfall at past one day.

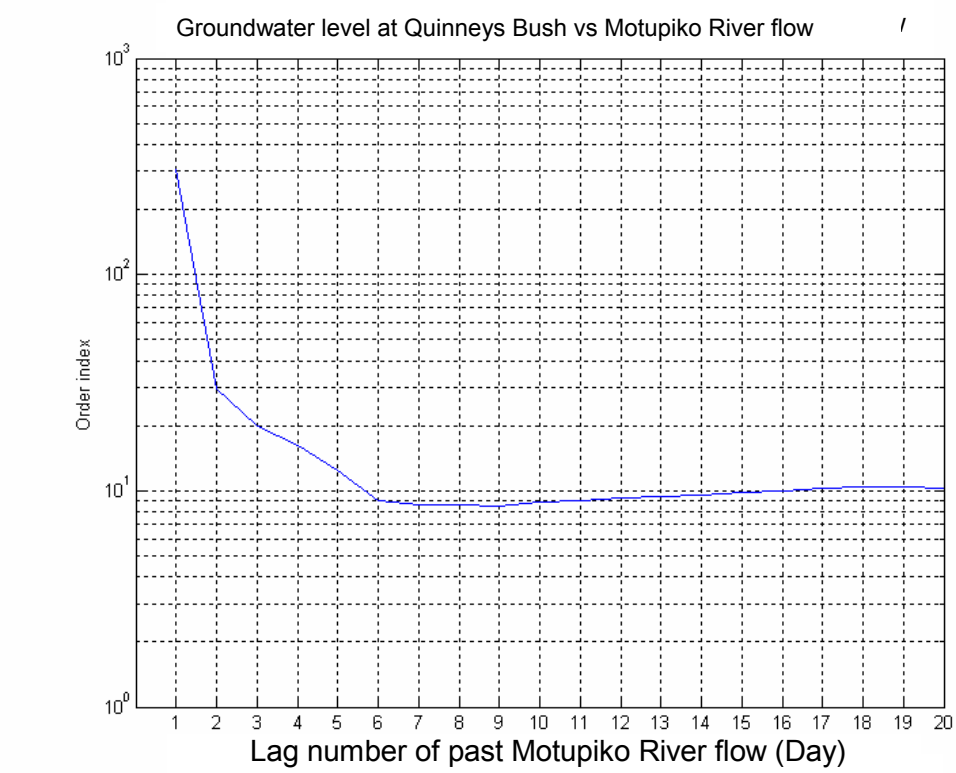

Figure 3.4. Results of lag time selection between Motupiko River flow and groundwater level at Quinneys Bush by *Lipschitz quotients* method

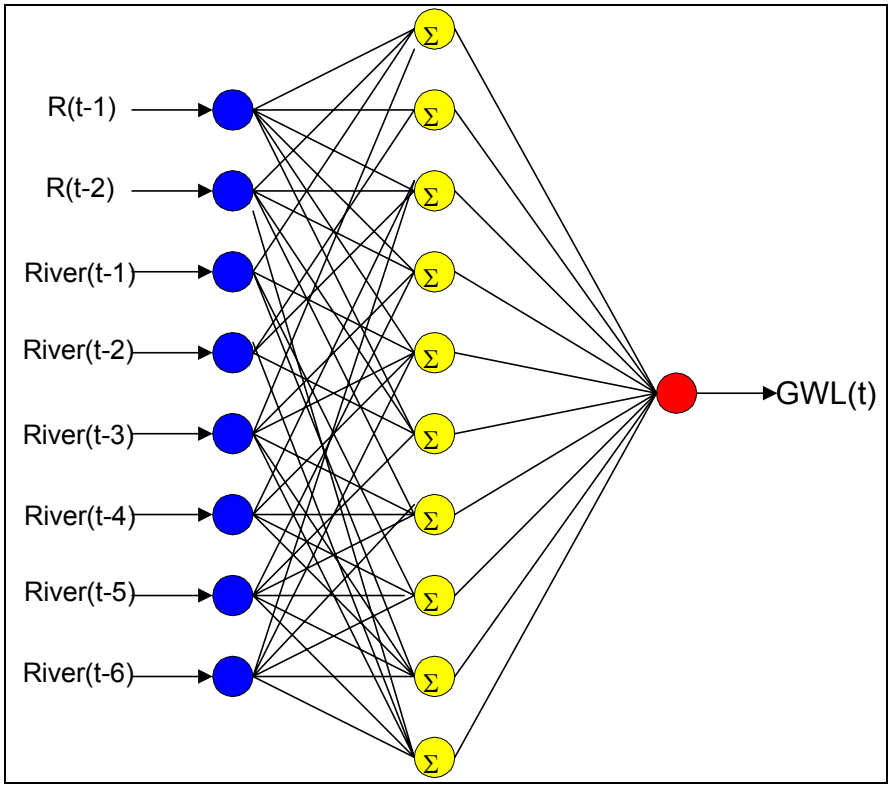

Figure 3.5. Topology of a neural network model to predict the groundwater level at Quinneys Bush.

The topology of a neural network model for the groundwater fluctuation at Quinneys Bush is shown in Figure 3.5. A neural network employed 8 inputs, one hidden layer with 10 neurons, 5 of which use the logistic sigmoid transfer function and 5 of which use hyperbolic tangent transfer function, each hidden neuron has 8 connections back to the input layer, and the network has one outputs with one logistic sigmoid transfer function with 10 connections back to each of the neurons in the hidden layer.

The R-squared of a neural network model, which represents the performance index of the neural network model, was computed as 89.12 % for the training data and 88.03 % for the testing data. The R-squared value of 88.03 % for the testing data indicates very satisfactory performance of the neural network model. According to this R-squared value, the accuracy of a neural network model is extremely good. Results obtained from a neural network model are shown in Figure 3.6. Results obtained from a neural network model on data for the testing set are also plotted in Figure 3.6. Through Figure 3.6, the neural network model has a great generalisation capability for the unseen testing data. It can be seen that predicted results using a neural network model are in good agreement with values of observed groundwater levels and represent the dynamic characteristics of the given system very well.

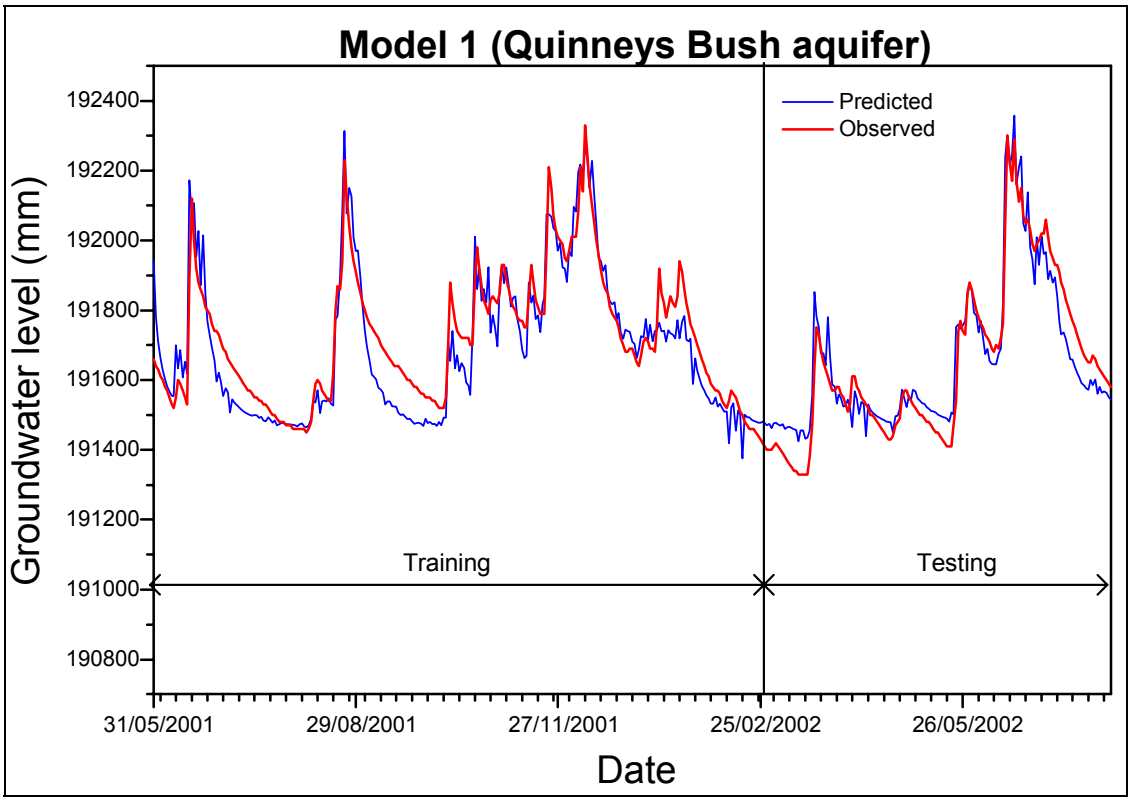

Figure 3.6. Results of a dynamic neural network at Quinneys Bush.

The sensitivity analysis is done to show the relative strengths of the effects that input variables (Motupiko River flow at Christie Bridge and rainfall at Tapawera) have on the groundwater level at Quinneys Bush in the artificial neural network developed.

Table 3.1 shows results of the sensitivity analysis. By comparing the value of Motupiko River flow at Christie Bridge with rainfall, river flow rate (Motupiko River at Christie Bridge) influences the groundwater level at Quinneys Bush significantly. The aquifer at Quinneys Bush is highly sensitive to Motupiko River flow and not sensitive to rainfall, meaning that the groundwater levels at Quinneys Bush are strongly affected by river recharge mechanism rather than rainfall recharge. It is identified that Motupiko River flow is a dominant factor for the recharge mechanism to Quinneys Bush aquifer and is a major recharge source of aquifer at Quinneys Bush through sensitivity analysis.

Table 3.1. Relative variables sensitivity ranking using a Monte Carlo analysis in dynamic artificial neural network model (Model 1)

Inputs	Groundwater level at Quinneys Bush
Rainfall	0.13
Motupiko River flow rate	0.87

Model 2:

- Groundwater monitoring site: North Bridge (1248614)
- River flow rate monitoring site: Motueka River at Motueka George (57008)
- Rainfall monitoring site: Tapawera
- Data Time interval: daily

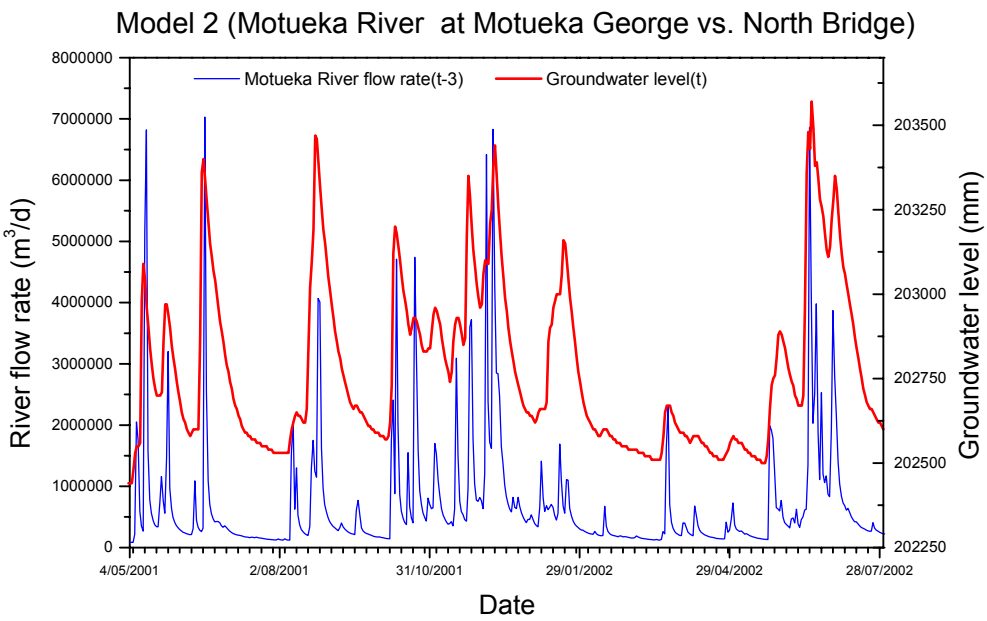

Figure 3.7. Motueka River flow at Motueka Gorge vs. groundwater level at North Bridge

Figure 3.7 shows the graphical display of Motueka River flow at Motueka Gorge vs. groundwater level at North Bridge. The same simulation procedure as that adopted in Model 1 was applied to Model 2.

Figure 3. 8 shows the results of the Lipschitz Quotients method to find optimal past Motueka River flow at Motueka Gorge. It is reasonable that the dynamic artificial neural network model can be modelled by a second order model because the slope of the curve is decreased for model orders ≥ 2. The lag time between change in groundwater level at North Bridge and increase in Motueka River flow at Motueka Gorge is approximately 2 days. The slope of the curve in Figure 3.4 is nearly flat after 7 days of past input. The time span over which a momentary river change of Motueka River flow at Motueka Gorge persists in affecting the groundwater level at Quinneys Bush is 2-7 days. It is also found that previous 1-2-days rainfall correlate strongly with the current groundwater level at North Bridge.

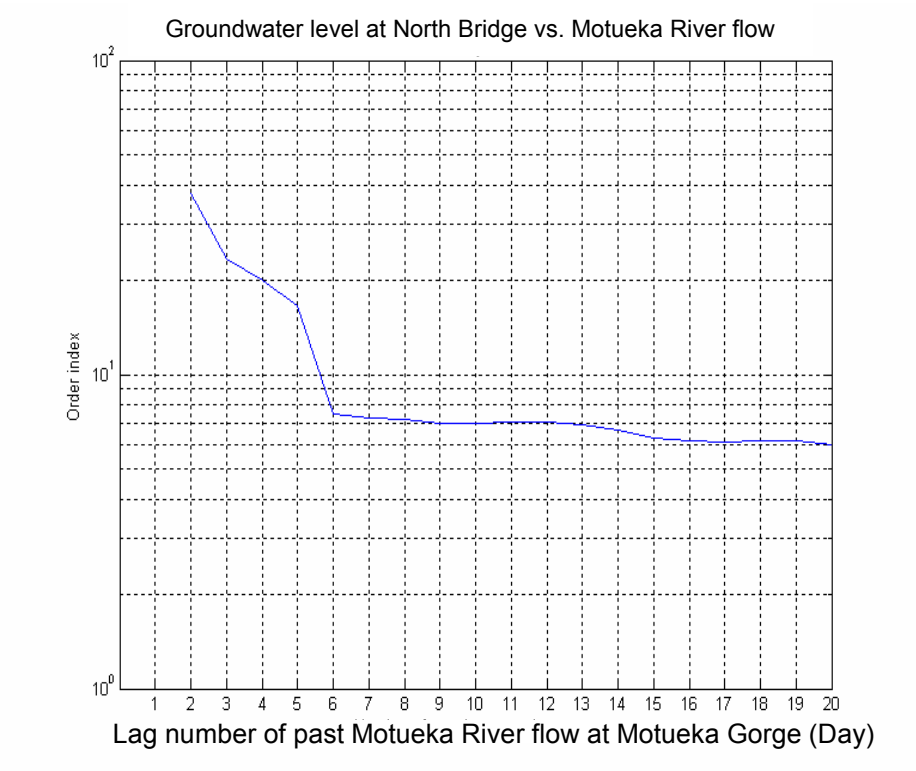

Figure 3.8. Results of lag time selection between Motueka River flow at Motueka Gorge and groundwater level at North Bridge by *Lipschitz quotients* method.

Therefore the multi-input, single-output (MISO) dynamic artificial neural network model for the groundwater level dynamics at North Bridge is constructed by:

$$\hat{GWL}(k) = f\begin{pmatrix} r(t-1), r(t-2), River(t-2), River(t-3), River(t-4) \\ River(t-5), River(k-6), River(t-7), \end{pmatrix} \quad (3.2)$$

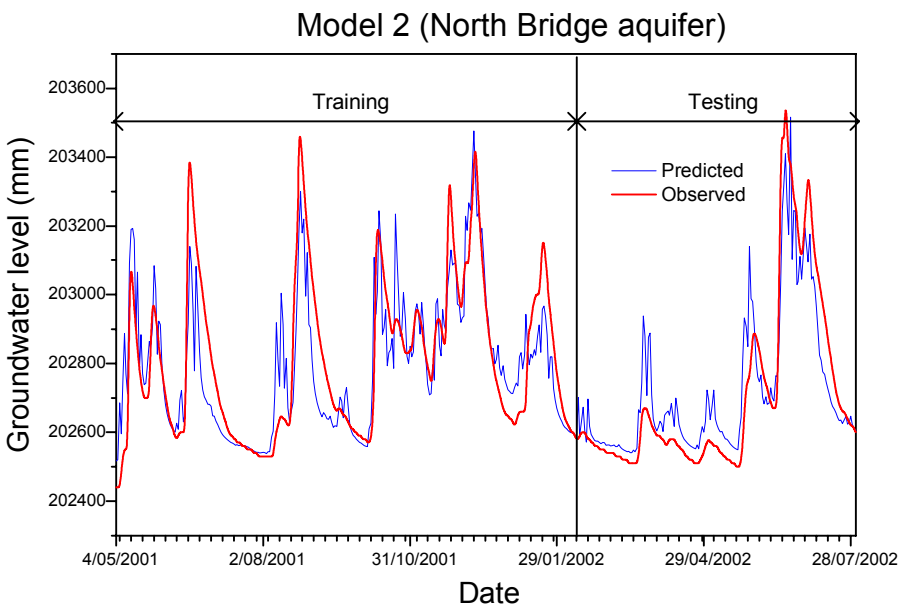

Figure 3.9. Results of a dynamic neural network of groundwater level at North Bridge

Figure 3.9 shows the observed and predicted groundwater level at North Bridge on both the training and testing data set. On the training data set the R-squared was 90.79 % and this only decreased to a value of 87.11% on the testing set. A visual comparison with the measured data indicates that the dynamic neural network of groundwater level at North Bridge has captured the basic dynamic change of the groundwater level during the dry season. The dynamic neural network of groundwater level at North Bridge performs well over the full data range although the magnitude of the lowest value during the dry season in the testing set was significant and gives reasonable generalisation and model accuracy.

The sensitivity analysis is performed to find the relative strengths of the effects that input variables (Motueka River flow at Motueka Gorge and rainfall at Tapawera) have on the groundwater level in the artificial neural network developed. The result of sensitivity analysis is shown in Table 3.2. Compared to the result of sensitivity analysis at Quinneys Bush (see Table 3.1), the aquifer at North Bridge is relatively more sensitive to rainfall recharge than it was at Quinneys Bush. River recharge mechanism is still dominant at North Bridge but the aquifer system at North Bridge is strongly affected by rainfall recharge process as well. Both Motueka River flow at Gorge and rainfall are recharge sources of the aquifer at North Bridge.

Table 3.2. Relative variables sensitivity ranking using a Monte Carlo analysis in dynamic artificial neural network model (Model 2)

Inputs	**Groundwater level at North Bridge**
Rainfall	0.37
Motueka River flow rate at Gorge	0.63

4. GEOCHEMISTRY

4.1 Introduction

The geochemistry of waters in the Upper Motueka Catchment was studied to gain understanding of the sources, flowpaths and residence times of waters in the catchment. Chemical measurements gave information on the major element chemistry in relation to aquifer geology and land use. The chemistry, along with oxygen-18 measurements, can be used to investigate the sources and flowpaths of water in the catchment. Monthly ^{18}O, CFC and preliminary tritium measurements were also made to determine groundwater residence times; further tritium measurements are planned. These measurements contribute to the development of a conceptual model of the groundwater-river water interaction.

4.2 Chemical Compositions

4.2.1 Methods

Sample Locations and Dates

Groundwater samples were collected from eight bores and two natural springs in the Upper Motueka Catchment on 24-25 January 2002 and 14-15 March 2002. Three river samples were also collected from the Motueka River (at Tadmor, Norths Bridge and Hyatts), and one from the Motupiko River.

Sampling and Analytical Methods

Sampling instructions were provided by Cawthron Institute to Tasman District Council, who collected the samples. pH, conductivity and temperature were measured at the time of sampling. Samples for cation analysis were acidified, and samples for anions were stored in a refrigerator before being conveyed to Cawthron Institute in a bin with ice.

Laboratory analyses were made for pH, alkalinity, hardness, HCO_3, NO_3, SO_4 and total concentrations of P, Cl, Ca, Mg, Na, K, Fe and Mn at Cawthron Institute. pH was measured by meter, bicarbonate by titrimetry, and nitrate, sulphate and chloride by ion chromatography. Total phosphorus was measured by persulphate oxidation with flow injection analysis and acid soluble metals by ICP-OES on acid preserved samples. Hardness was calculated.

4.2.2 Results

The analytical results are compiled in Table 4.1 and displayed in the form of a Piper diagram and a Na-Ca-Mg ternary diagram in Figures 4.1 and 4.2 respectively. Notable differences in chemistry are apparent, particularly in the molar ratios of Na to Ca to Mg. Based on these differences in chemistry, the following sample groupings can be made:

Table 4.1. Chemical compositions of waters from the Upper Motueka River Catchment.

Lab. No.	Type	Name	WWD	pH	Alk	HCO_3	NO_3	P	SO_4	Cl	Ca	Mg	K	Na	Fe	Mn	Hardness
					←						g/m^3						→
Upper Motueka River water																	
02W02011	R	Motueka N. Bridge		8	74	90	<0.02	<0.002	2.5	4.6	7.7	10.8	0.8	3.6	0.009	<0.001	63
02W02049	R	Motueka Hyatts		7.2	61	74	0.13	0.003	2.5	4.7	7.2	9.24	1.1	4	0.019	0.001	56
02W02010	R	Motueka Tadmor		7.6	58	71	0.13	0.004	2.5	4.4	6.71	8	1	3.9	0.008	<0.001	50
Median	**R**	**Motueka**		**7.6**	**61**	**74**	**0.13**	**0.004**	**2.5**	**4.6**	**7.2**	**9.24**	**1**	**3.9**	**0.009**	**0.001**	**56**
Upper Motueka Valley groundwaters																	
02W00531	GW	Higgins piezo	4784	6.6	96	96	5.7	0.007	14	5	9.7	25	0.5	3.8	0.07	<0.01	130
02W02048	GW	Hyatts	4617	6.6	48	59	0.53	0.009	2.5	4.5	6.69	8.31	1.4	4.4	1.16	0.003	51
02W00530	GW	Campbells	4618	6.6	58	58	1.2	0.056	4.1	4.4	8	10	0.55	3.6	0.84	<0.01	62
02W00532	GW	Hinetai Hops	4539	6.2	45	45	3.1	0.011	7.8	4	7.7	9	0.94	5.6	0.06	<0.01	56
02W00534	GW	Hinetai Spring		6.8	69	69	2.2	0.007	7.1	4.2	8.4	14	1.2	4.8	0.13	0.01	78
Motupiko & Tadmor Valley groundwaters																	
02W00529	GW	Quinneys piezo	4785	6.3	30	30	0.46	0.082	2	3.7	6.9	1.6	1.2	4.8	0.2	<0.01	24
02W00533	GW	Quinneys Spr.		6.1	21	21	0.86	0.008	4.9	4.2	6.4	1.6	1.3	4.9	0.13	<0.01	23
02W02012	GW	Tadmor Hop Garden	4620	5.8	71	86	3.3	0.044	26	3.9	13.7	2.62	2.2	6.4	2	0.073	45
02W02009	GW	Crimps	4616	6.5	33	40	6	0.019	2	5.7	4.33	2.38	1.2	4.4	3.59	0.006	21
02W02007	GW	Viewmont	4619	6.3	39	47	1.4	0.002	6.7	3.7	7.09	3.61	1.6	5	4.72	0.01	33
Motupiko River water																	
02W02008	R	Motupiko		6.8	21	25	0.022	0.01	1.6	6.7	4.65	1.32	1.3	4.7	0.015	0.001	17

"Alk" is alkalinity as $CaCO_3$ in g/m^3

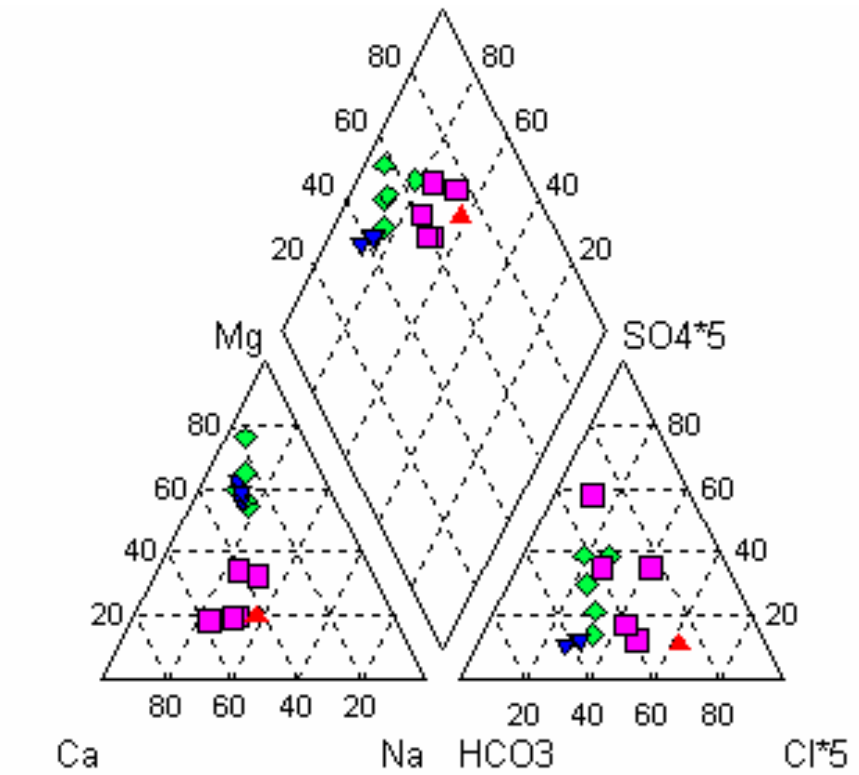

Figure 4.1. Major element chemistry of Upper Motueka valley waters plotted on a Piper Diagram. (Motueka-type waters: blue - Motueka River, green – bores 4539, 4617, 4618, 4784, Stanley Spring. Motupiko-type waters: red - Motupiko River, pink - 4785, 4616, 4619, 4620, Quinneys Spring.

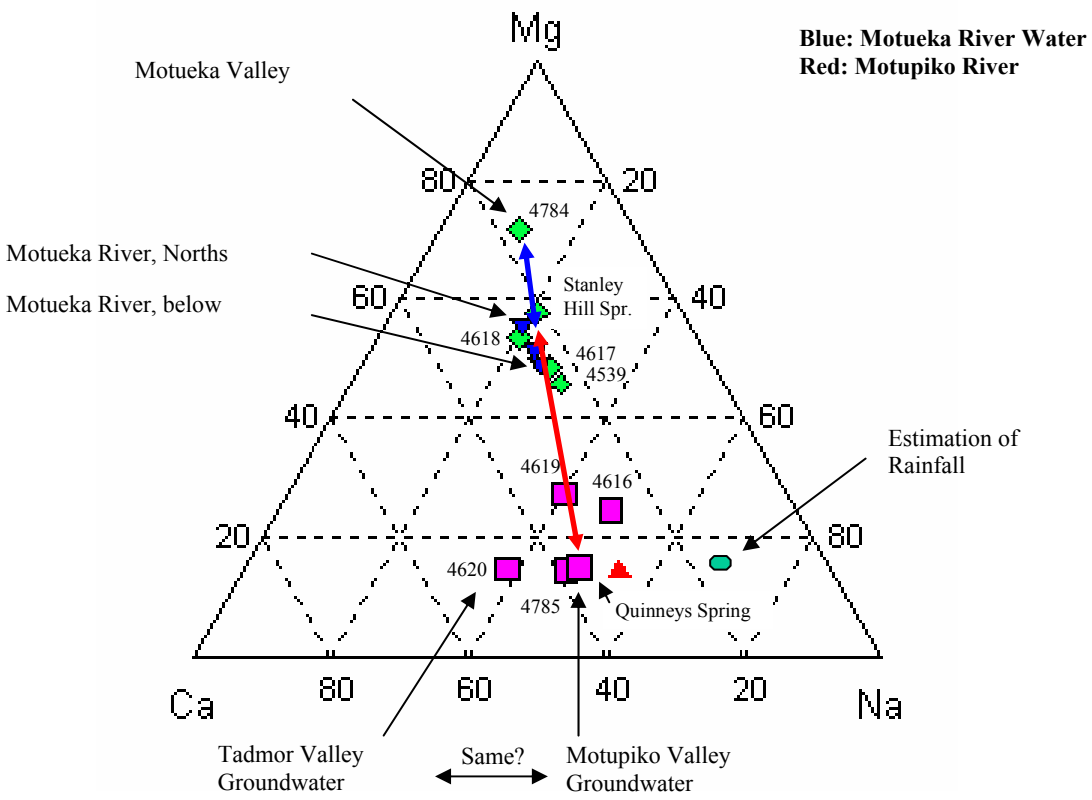

Figure 4.2. Enlargement of the cation triangle of the Piper Diagram (Fig.4.1), showing the relationships between the samples.

Table 4.2. Oxygen-18 and CFC concentrations of waters from the Upper Motueka Valley.

Location/ Well Owner	TDC Well No.	Date Sampled	Grid Reference	Well Depth	Screened Depth	$\delta^{18}O$ ‰	CFC-11 pptv	CFC-11 Model	CFC-12 pptv	CFC-12 Model	Recc'd Age (yr)
Rainfall											
Valley rainfall		16/4/02 - 12/3/03	N28:96437216			-6.67	(weighted 2-year mean				
Valley rainfall		10/4/03 - 9/3/04				-6.38	= -6.52 ± 1.33‰)				
Hilltop rainfall		16/4/02 - 12/3/03	N28:93157410			-7.51	(weighted 2-year mean				
Hilltop rainfall		10/4/03 - 9/3/04				-7.30	= -7.40 ± 1.26‰)				
Motueka River											
Motueka R (u/s Tadmore)		16/4/02 - 13/4/04	N28:94527998			-7.16 ± 0.22					
Motueka R (Woodmans Bend)		16/4/02 - 13/4/04	N27:06350915			-7.01 ± 0.26					
Motueka R (Norths Bridge)		24-Jan-02	N28:96376996			-7.53					
Motueka R (u/s Motupiko)		24-Jan-02				-7.21					
Upper Motueka Valley groundwaters											
Higgin's piezo	4784	10/4/03 - 13/4/04	N28:96376996	7.0		-7.21 ± 0.35					
Higgin's piezo	4784	24-Jan-02	N28:96376996			-6.82					
Higgins	4614	23-Aug-00	N28:9638-7002	7.8	5.2 - 7.2	-6.83	227	1988	535.5	1998	<2
Hyatt	4617	10/4/03 - 14/10/03	N28:95927750	13.1	8.6 - 12.6	-7.29 ± 0.20					
Hyatt	4617	23-Aug-00	N28:95927750			-7.25	238.1	1989	530	1997	<3
Campbell	4618	16/4/02 - 13/4/04	N28:96427726	11.8	8.3 - 11.3	-7.22 ± 0.15					
Campbell	4618	23-Aug-00	N28:96427726			-6.92	281.9	Modern	500.3	1993	<7
Campbell	4618	24-Jan-02	N28:96427726			-7.18					
Hinetai Hops	4539	24-Jan-02	N28:93768341	7.2		-6.68					
Hinetai Spring		24-Jan-02				-6.83					
Motupiko & Tadmor River											
Motupiko R (Quinneys)		15/5/03 - 13/4/04	N28:94887208		23-Aug-00	-6.67 ± 0.29					
Motupiko Quinneys		24-Jan-02	N28:94887208			-6.90					
Tadmor R (Tapawera)		24-Jan-02				-6.65					
Motupiko Valley groundwaters											
Quinney's Bush	4615	16/4/02 - 13/4/04	N28:94637216	8	5.0 - 7.5	-6.63 ± 0.21					
Quinney's Bush	4615	23-Aug-00	N28:94667223			-6.93	265.3	1995	632.2	Excess	<5
Quinney's piezo	4785	24-Jan-02	N28:94657215	7.5		-6.87					
Creek/spring (Quinneys)		24-Jan-02				-6.63					
Crimps	4616	10/4/03 - 13/4/04	N28:95737342			-6.64 ± 0.24					
Viewmount	4619	10/4/03 - 13/4/04	N27:94088087			-6.54 ± 0.18					

4.2.2.1 Motueka-type waters

Motueka River Water

All Motueka River samples are very similar Mg-Ca-HCO_3 type waters. In all three samples, the concentration of Mg is quite high (average 9.2 ppm), and exceeds the concentrations of both Ca (average 7.2 ppm) and Na (average 3.9 ppm). The concentration ratio of Mg to Ca is highest in the sample taken from furthest up-river, near Norths Bridge. Down-river, the ratio of Mg to Ca decreases. It is therefore likely that the Mg is derived from the ultramafic dunites found in the uppermost portion of the Motueka River Valley. Calculation of mineral saturation indices suggests that the concentrations of Mg and Ca in the river water are limited by saturation with respect to carbonate phases such as calcite, aragonite, dolomite and magnesite. Accordingly, alkalinity decreases in the downstream direction.

Groundwater from the Upper Motueka River Valley: Well 4784 (Higgins)

This well is located in the upper Motueka River Valley, upstream of the confluence of the Motueka and Motupiko Rivers (Norths Bridge, near Kohatu). The well is located on the upper river terrace. This is the most Mg-rich sample (a Mg-Ca-HCO_3 type water). Its composition is significantly more Mg-rich than the sample of the Motueka River taken nearby. Observation of the river shingle shows clasts of rapidly-weathering ultramafic rock derived from the Red Hills part of the catchment, which is likely to be present throughout the river terrace gravels. This appears to be the source of the enriched Mg-Ca-HCO_3 (compared to the river) in the groundwater.

The river water has higher molar ratios of Na and Cl than the groundwater, which may indicate a rainfall influence. Although the chemistry of the rainfall in the region is unknown, an estimation of its cation composition is shown on the Na-Ca-Mg ternary diagram. If this estimation is appropriate, it appears that the Motueka River near Norths Bridge is composed of a combination of water from its headwater (Red Hills) area, groundwater probably similar to that from well 4784, and 20-25% rainwater.

Groundwater near Hyatts: Wells 4617 (Hyatts) and 4618 (Campbells)

Wells 4617 and 4618 are located on the east bank of the Motueka near Hyatts. Well 4617 is near the boundary between the lower and upper river terraces; well 4618 is further from the river on the upper terrace. Groundwater from these two wells are virtually identical to Motueka River water collected at Hyatts. The similarity in composition indicates either that the waters are derived by similar leaching processes, or water with higher chemical concentrations (like well 4784) is diluted by rainfall. Note that both the groundwaters and the river water fall on a line between wells 4784 (upper Motueka Valley groundwater) and 4785 (Motupiko Valley groundwater). (4785 is considered to be representative of water which has contacted Moutere Gravel but not ultramafic rock.)

Down-valley Groundwater: Well 4539 (Hinetai Hops)

Well 4539 is located further down the Motueka Valley than any other well sampled. It plots

along the mixing line shown on the Na-Ca-Mg diagram (Figure 4.2), at a position that is almost midway between the Motueka Valley and Motupiko Valley groundwater (and even more towards the Motupiko Valley end than a sample of the Motueka River water taken from nearby). This suggests that the groundwater has had less contact with ultramafics, perhaps because of dilution by water from the adjacent hillslope to the east.

Hinetai Spring

Hinetai Spring is located upstream of the gorge where the narrowing of the valley causes the Motueka River flow to be increased by groundwater emergence. The sample composition is most like that of well 4784 (i.e. enriched in Mg-Ca-HCO_3) reflecting interaction with ultramafic clasts underground. The water source is not apparent.

Summary

The distinctive (Mg-rich) chemistry of this group of samples distinguishes it from the rest of the samples. The river water derives mainly from the Red Hills ultramafic area, and the groundwaters are located in the Upper Motueka Valley and on the east side of the Motueka Valley. Elevated Mg levels in the groundwaters (above that of the Motueka River) are considered to result from weathering of ultramafic clasts from the Red Hills area within the terrace gravels. Figure 4.3 (showing Mg plotted against conductivity) illuminates this process. Points for Higgins and Campbells wells form a trend away from the Motueka River points, showing enrichment in Mg by interaction with ultramafic clasts in the terrace gravels. The groundwater is sourced from the Motueka River and rainfall infiltrating the terraces.

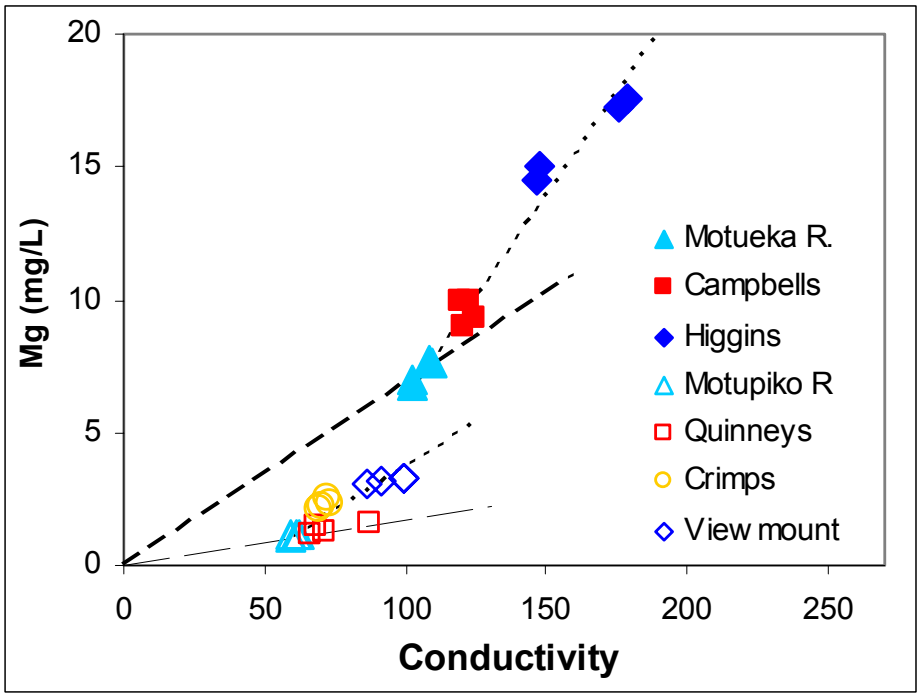

Figure 4.3. Plot of Mg versus conductivity in river and groundwater samples collected monthly from January to April 2004.

4.2.2.2 Motupiko-type waters

Motupiko River Water

The single sample from the Motupiko River is chemically very different from the three Motueka River samples. The Motupiko River sample is a Ca-Na-HCO_3-Cl type water, having much less Mg than the Motueka River. The lack of Mg likely reflects the absence of Mg-rich ultramafic rocks in the Motupiko River catchment and terrace gravels. The river chemistry, then, can be considered more representative of interaction with reworked Moutere Gravel in the valley and with Moutere Gravel on the hills. The presence of Na and Cl in the Motupiko River sample may indicate a rainfall influence (a chemical analysis of local rainfall was not available, but it is likely typical of near-coastal rain, with Na and Cl as the dominant ions in approximately equimolar concentrations).

Groundwater from the Motupiko River Valley: Well 4785 (Quinneys) and Quinneys Spring

These two groundwater samples are very similar to each other (Ca-Na-Mg-HCO_3 type waters) and to the Motupiko River sample collected from the immediate vicinity. The Motupiko River water has slightly higher molar ratios of Na and Cl, which may indicate the influence of rainfall. Comparing the river and groundwater compositions and using the estimation of rainfall chemistry shown on the Na-Ca-Mg diagram, it appears that the Motupiko River is fed by groundwater like that in this vicinity, with groundwater and rainfall representing about 80% and 20% of its discharge, respectively. Quinneys Spring is derived from seepage from the west side of the Motupiko Valley and represents delayed runoff from the Moutere Gravel hillside.

Groundwater below Motupiko confluence: Well 4616 (Crimps)

Well 4616 is located on the west bank of the Motueka River about 1 km downstream of the confluence of the Motueka and Motupiko Rivers. Motupiko valley type groundwater (like Quinneys) dominates, but a slight rise in Mg is discernible because of minor interaction with ultramafic clasts within the terrace gravels, input of Motueka River water, or input of Motueka-type groundwater. Because of the oxygen-18 evidence, the former is considered more likely (see below).

Groundwater from the Tadmor River Valley: Well 4620 (Tadmor Hop Garden)

This well is located in the Tadmor River Valley upstream of the confluence of the Tadmor and the Motueka. The groundwater chemistry is similar to that of Well 4785 and Quinneys Spring, both of which are in the Motupiko River Valley. It is clear that the groundwaters in these two valleys are controlled by interaction with similar rocks (river terrace gravels derived from Moutere Gravel).

Groundwater below Tadmor: Well 4619 (Viewmount)

Well 4619 is located on the west floodplain of the Motueka River below its confluence with

the Tadmor River. Like the well 4616 sample, this sample has slightly increased Mg concentration, which could have resulted from minor interaction with ultramafic clasts, or input of Motueka river or groundwater.

Summary

The Motupiko River water and groundwaters from the Motupiko and Tadmor Valleys, and on the west bank of the Motueka River downstream of the confluences with Motupiko and Tadmor rivers are all very different from the Motueka-type waters (see Figure 4.3). They are considered to have resulted from interaction with Moutere Gravel and terrace gravels derived from it. Crimps and Viewmount plot on a line slightly above that of Motupiko River and Quinneys in Fig. 4.3, indicating they are slightly influenced by input of Motueka River water or Motueka-type groundwater.

4.3 Oxygen-18 Concentrations

Oxygen-18 concentrations have been measured for rainfall, rivers and groundwaters in the study area. Samples were collected at monthly intervals in the period 16 April 2002 to 13 April 2004 (Table 4.2). Sample collection durations of twelve months or multiples of twelve months are preferred, in order to obtain meaningful average values, because the $\delta^{18}O$ values are expected to show approximately seasonal variations. Data was also collected in two surveys on 23/8/00 and 24/1/02.

The rainfall $\delta^{18}O$ values show considerable variation from month to month (the standard deviations are 1.3‰ for both the valley and hilltop sampling sites). The valley site was at Quinneys Bush, and the hilltop site at transmitter by Borlase Forest (N28:93157410). Annual mean values showed less, but still considerable variation, (-6.67 and -6.38‰ for the valley site, and -7.51 and -7.30‰ for the hilltop site). However, there is a relatively constant difference between the two sites from month to month, with the mean difference being 0.88‰. The more negative value is for the hilltop site, which is 500 m higher in altitude than the nearby valley site. The mean rainfall values are given in Figure 4.4, with the mean values for the rivers and groundwaters.

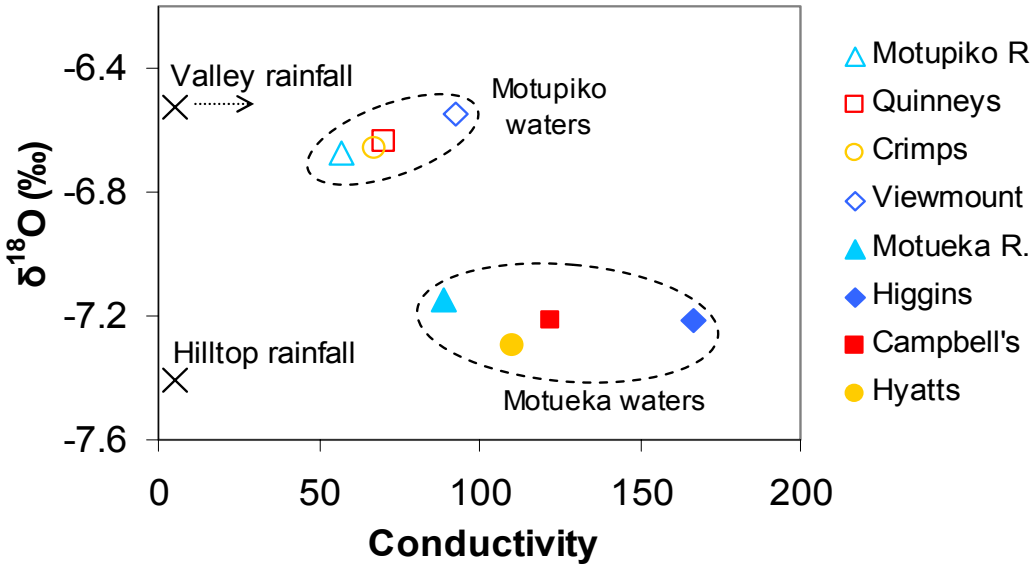

Figure 4.4. Mean $\delta^{18}O$ values of Upper Motueka catchment waters.

There is a marked difference between the average $\delta^{18}O$ values of the two types of water. The Motueka-type waters have values around -7.2‰ (Figure 4.4), which is similar to that observed for Motueka River upstream Wangapeka (-7.16‰), suggesting that the Motueka River dominates the supply of water to these groundwaters. Valley rainfall $\delta^{18}O$ (-6.5‰) is too positive to be a major source of the water. This means that these groundwaters (situated on the east side of the Motueka valley) are mainly sourced from the headwater catchment with supplementation from valley and hillslope rainfall. However, it is probable that the Motueka River $\delta^{18}O$ becomes more positive on average as it traverses the Upper Motueka River valley and gains valley rainfall recharge.

In contrast, the Motupiko-type groundwaters have $\delta^{18}O$ values around -6.6‰, and these match both the Motupiko River and valley rainfall, so the ^{18}O does not show which source predominates. Motupiko and Tadmor Rivers have Moutere Gravel catchments with low to moderate relief; their $\delta^{18}O$ values reflect this moderate altitude range. However, analogy with the Motueka valley, and other evidence, indicates that the Motupiko and Tadmor rivers also dominate the supply of water to groundwater in their respective valleys and probably also to groundwater on the west side of the Motueka valley.

4.4 Groundwater Dating

4.4.1 Monthly δ18O values

The monthly $\delta^{18}O$ values are displayed in Figures 4.5a,b. Figure 4.5a gives the Motueka-type waters, the rainfall and Motueka River water. The range of variation of the rainfall has been reduced by 30% to fit it into the figure. The monthly rainfall amounts are shown at the top. Inspection of the figure shows that there is a moderately good correlation between the $\delta^{18}O$ values of Higgins and Motueka R, that Hyatts and Campbells have almost the same $\delta^{18}O$

values, and that Campbells $\delta^{18}O$ correlates poorly with Motueka R. in the 02/03 year, but rather better in the 03/04 year.

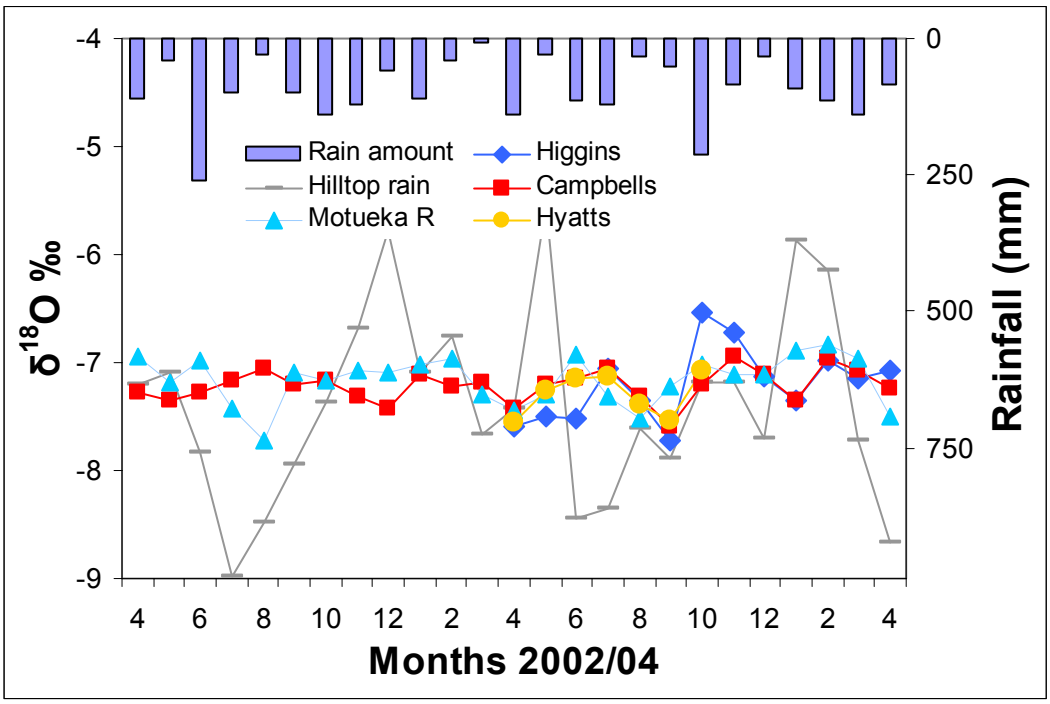

Figure 4.5a. Plot of $\delta^{18}O$ values of rainfall, Motueka R. and Motueka-type groundwaters versus calendar time in the period 4/2002 to 4/2004. Monthly rainfall amounts are given at the top.

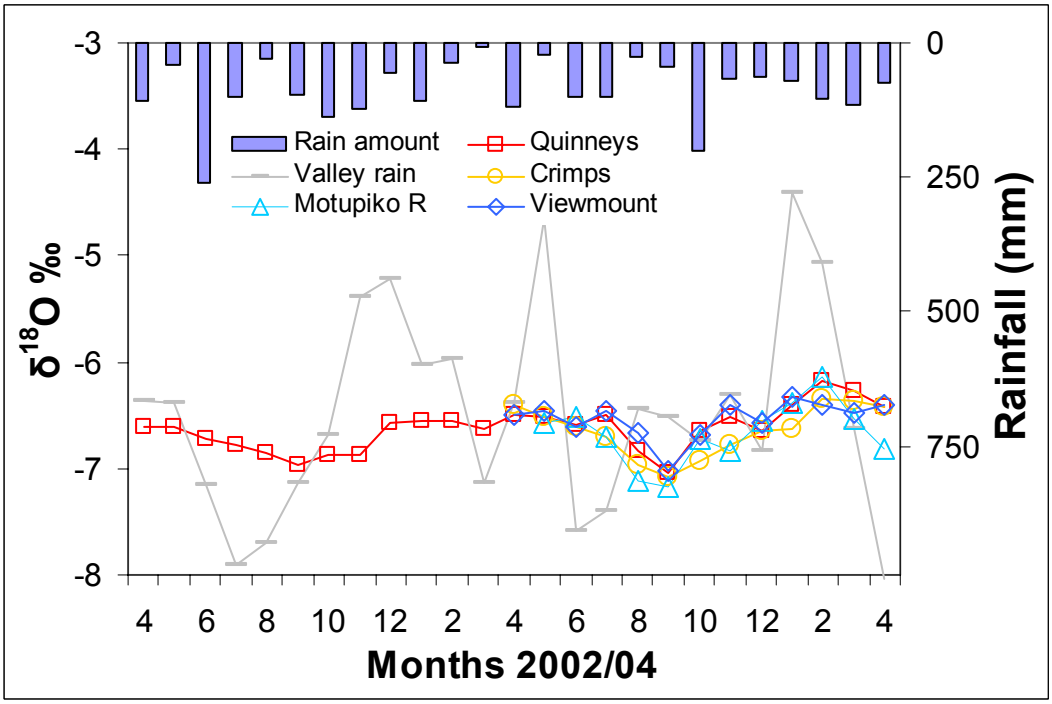

Figure 4.5b. Plot of $\delta^{18}O$ values of rainfall, Motupiko River and Motupiko-type groundwaters versus calendar time in the period 4/2002 to 4/2004. Monthly rainfall amounts are given at the top.

Figure 4.5b gives $\delta^{18}O$ values for the Motupiko-type waters. There is quite a good correlation between the variations observed in the Motupiko River and those of all three bores (Quinneys, Crimps and Viewmount), indicating dominance of the Motupiko River water as a recharge source to the groundwater. There is also a lag of 1-3 months between the rainfall and the river/groundwater ^{18}O variations.

The monthly $\delta^{18}O$ values allow residence times to be estimated. Figures 4.6a-c show $\delta^{18}O$ values for Higgins (4784), Campbell (4618), and Quinneys (4615) bores, for the rivers and for rainfall. The groundwater $\delta^{18}O$ values are simulated by using inputs of river water and delayed rainfall to an exponential mixing model; the simulated curves are shown as heavy lines passing through the measured groundwater data in the figures. The exponential piston-flow mixing model was used to simulate the distribution of residence times, however, in all cases, the best fits to the data were obtained with close to 100% exponential volumes showing that the systems are well-mixed (i.e. water following different flow paths mixes in the discharge so as to appear well-mixed. The parameters of the simulation curves are given in Table 4.3. The goodness of fit is assessed by calculating the standard deviations of the differences from the simulations.

Table 4.3. Simulations based on recharge from Motueka River and rainfall for Higgins and Campbell bores, and from Motupiko River and rainfall for Quinneys bore. The river : rainfall ratios and mean residence times (MRT) giving the best fits are shown.

Bore	Record period (months)	Mean $\delta^{18}O$ (‰)	River : rainfall contributions	MRT (months)	Simulation std dev. (‰)
Higgins	12	-7.17 ± 0.35	53 : 47	4	0.16
Campbell	24	-7.18 ± 0.15	92 : 8	7	0.13
Quinneys	12	-6.55 ± 0.23	88 : 12	2	0.09

Figure 4.6a shows the result for the Higgins bore. The simulation (sd = 0.16‰) fits considerably better than a straight horizontal line (i.e. the variation about the mean, 0.35‰), although not as well as expected from the measurement error (0.10‰). The optimised values show 53% river to 47% rainfall recharge and a mean residence time of four months.

Figure 4.6b shows the result for the Campbell bore. The best fit (sd = 0.13‰) shows only a slight improvement over a straight horizontal line (0.15‰). The optimised values show dominant river recharge (92%) and a mean residence time of seven months.

Figure 4.6c shows the result for Quinneys bore. The best fit (sd = 0.09‰) fits as well as can be expected given the measurement error in the $\delta^{18}O$ values, and is much better than a horizontal line (sd = 0.23‰). The optimised values show dominant river recharge (88%) and a mean residence time of 2 months.

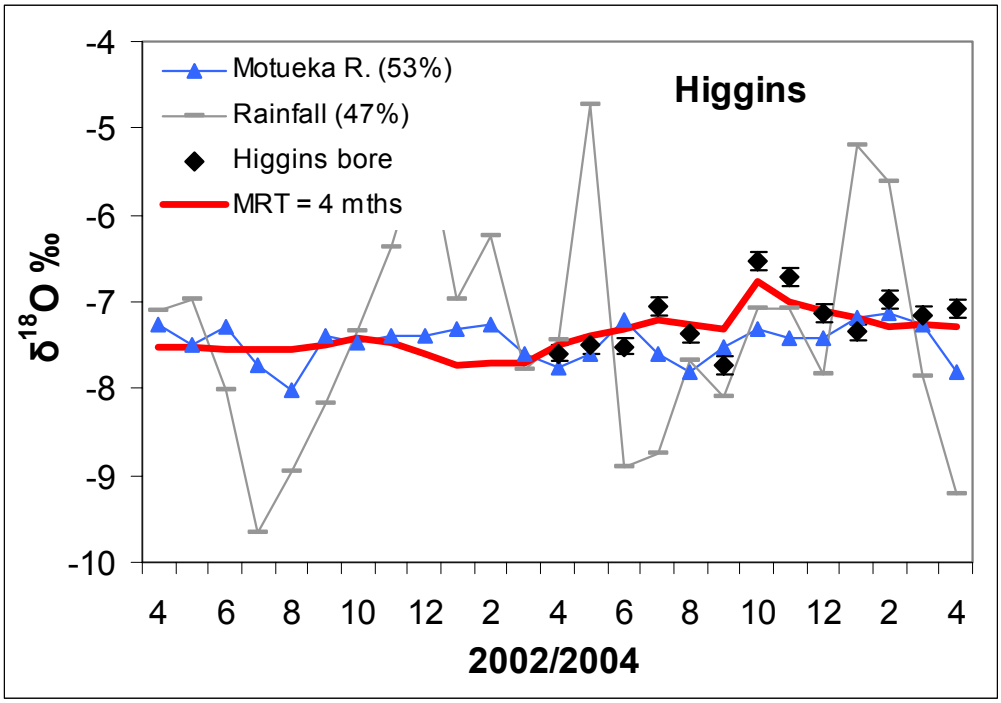

Figure 4.6a. Monthly $\delta^{18}O$ values for Motueka River, rainfall and Higgins bore.

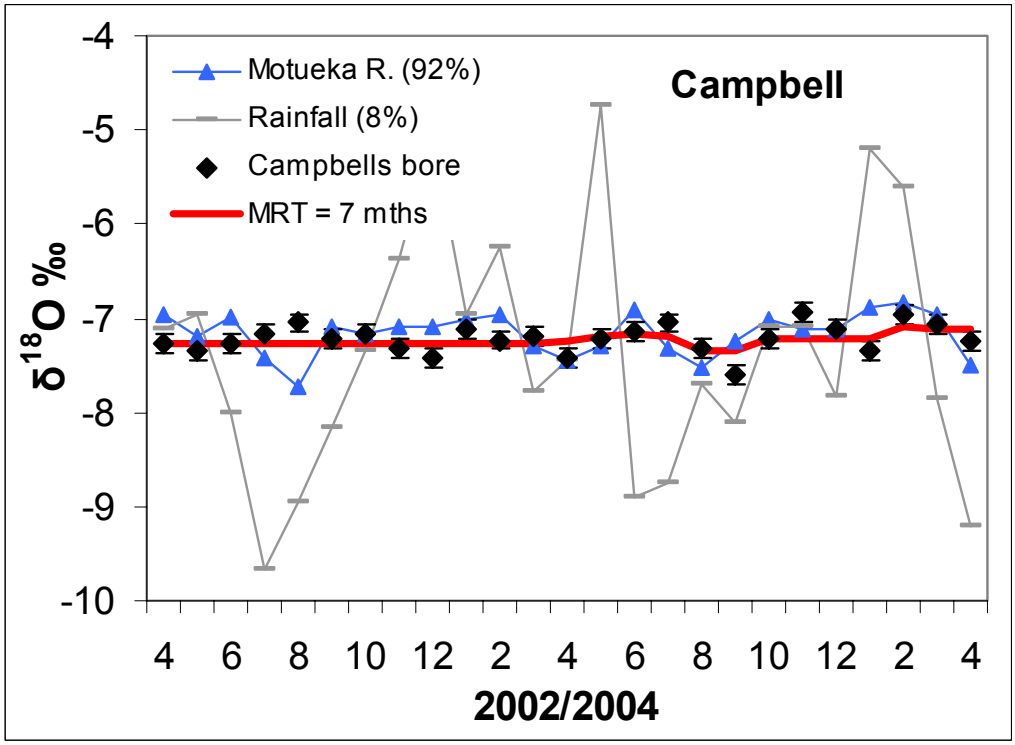

Figure 4.6b. Monthly $\delta^{18}O$ values for Motueka River, rainfall and Campbell bore. The simulated values are shown as the heavy line.

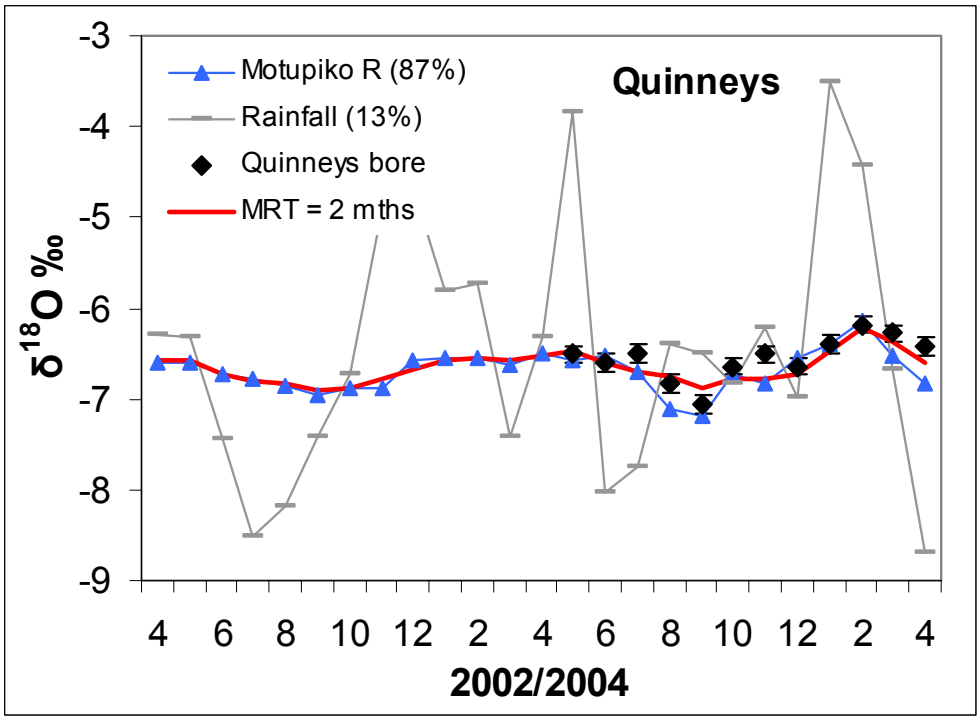

Figure 4.6c. Monthly $\delta^{18}O$ values for Motupiko River, rainfall and Quinneys bore. The simulated values are shown as the heavy line.

4.4.2 CFC and Tritium Dating

CFC samples were collected from four groundwater sites on 23 August 2000 (Table 4.2). The CFC concentrations showed that the residence times of all of the groundwaters were young. Because CFC-11 concentration reached a peak in the Southern Hemisphere atmosphere in 1993, CFC-11 is not very useful for determining ages in this age range. CFC-12 concentrations are still rising slowly and hence can give lower precision ages in this age range. The mean ages obtained from CFC-12 were: Higgins (WWD4614) two years, Hyatt (4617) three years and Campbell (4618) seven years; from which it is concluded that the residence times are between zero and a few years. The CFC-12 concentration did not give an age for Quinneys well; the CFC-11 age was <5 years.

Preliminary tritium measurements have indicated mean residence times of 0 to 12 months for the groundwaters and rivers in the study area, and confirm the relatively short residence times indicated by the O-18 (particularly) and CFC results.

5. DISCUSSION AND CONCLUSIONS

The principal aims of the investigations are to understand the hydrogeology of the Upper Motueka valley (including parts of the Motupiko and Tadmor valleys), the aquifer hydraulic properties, the occurrence of groundwater (recharge, storage and discharge), and the connectivity to the rivers. Understanding these will give a conceptual model of the river/groundwater system to constrain computational models.

The Motueka Catchment has wide variations in geology, relief and rainfall. Steeplands occupy 46%, hill country 41%, fans and high terraces 4%, and floodplains and low terraces 9% of the catchment (Basher 2003). Steeplands on the west (within the Tasman Mountains) provide a large proportion of the river flow because rainfall is very high (up to 3500 mm). The study area lies within the Moutere Depression at lower altitude and has much lower rainfall (900-1300 mm). Higher land to the east with rainfall up to 2000 mm feeds the upper reaches of the Motueka River.

River flows mainly reflect the rainfall with very large variations in specific discharge. Data for rivers in the study area are given in Table 5.1. Comparison of the Motueka River at the gorge and upstream of the Wangapeka confluence shows that much of the flow, and particularly much of the low flow, are generated within the comparatively small gorge headwater area, comprising ultramafics and Maitai Group sediments. The Motupiko and Tadmor catchments are entirely, and mostly on Moutere Gravel respectively.

Table 5.1. Flow characteristics of rivers, and hydrological balances for sites in the Upper Motueka Valley.

	Flow characteristics					Hydrological balance			
Streamflow site	**Area[1] km²**	**Mean flow[1] L/s**	**MALF[1] L/s**	**Specific dis-charge[1] L/s/km²**	**Base flow[2] %**	**Rain fall[3] mm**	**ET[4] mm**	**Run off[5] mm**	**Remain der[6] mm**
Motueka @ gorge	163	7,067	1,550	43.4	36	1,550	620	1,367	-437
Motueka u/s Wangapeka	845	12,030	2,132	14.2		1,250	620	448	182
Motueka @ Woodmans Bend	2,047	82,148	13,318	40.1	42	1,770	620	1,265	-115
Motupiko @ Christies	105	2,173	347	20.6	42	1,300	620	650	30
Motupiko @ Quinneys	344	5,152	488	15.0		1,100	620	472	8
Tadmore @ Mudstone	88	2,347	256	26.0		1,500	620	841	39

[1]Data from Table 4 in Basher 2003. (MALF is mean annual low flow.)
[2]Baseflow calculated by the method of Hewlett & Hibbert 1967 from streamflow measurements supplied by Tasman District Council.
[3]Rainfall estimated from the spatial distribution of mean annual rainfall in the catchment (Figure 14 in Basher 2003).
[4]Evapotranspiration (ET) from Scarf 1972.
[5]Runoff calculated from specific discharge.
[6]Remainder = Rainfall - ET - Runoff.

The hydrological balance at each site is shown in Table 5.1. The rainfall has been estimated from the spatial distribution of the mean annual rainfall (Figure 14 in Basher 2003). Evapotranspiration was estimated to be in the range 540-700 mm/year by Scarf (1972). An

average value of 620 mm has been adopted. Runoff via streamflow was calculated from the specific discharge of the rivers.

The Motueka River at the Gorge site drains the Red Hills and Maitai sections. The land is steep and rainfall high. The hydrological balance at Gorge has a large negative remainder (-437 mm; i.e. the stream output is larger than the nett catchment input), indicating that either the rainfall is higher than expected or the effective catchment is larger than shown by the boundary.

For the Motueka River upstream of the Wangapeka confluence, a positive hydrological balance suggests that there could be subsurface drainage out of the catchment. The other catchments have small remainders, showing that inputs and outputs balance approximately. Baseflow as a proportion of total flow is low where estimated (approximately 40%).

The hydrogeology of the study area is described in Section 2. Within the Upper Motueka, Motupiko and Tadmor river valleys, groundwater is abstracted from shallow, thin (<15m), unconfined, alluvial gravel aquifers that receive recharge from river flow loss and local rainfall. Four potentially groundwater-bearing river terrace formations have been identified, which from youngest to oldest are: recent river gravel deposits, Speargrass Formation, Tophouse Formation, and Manuka Formation. The groundwater-bearing formations are underlain by the relatively low permeability Moutere Gravel Formation. At present, groundwater is abstracted from the lower three terrace formations only. The piezometric contours in the valleys are nearly at right angles to the rivers, showing that groundwater flow is primarily along the valleys. But the piezometric contours, river flow measurements, and river stage elevations have identified reaches where river flow is lost to groundwater and reaches where groundwater contributes to river flow. River flow loss occurs from Higgins and Quinneys Bush to Hyatts, river flow gain from Hyatts to Tapawera Bridge, river flow loss from Tapawera Bridge to Glenrae and river gain below Glenrae where the valley narrows as the Motueka River enters the gorge (Section 2.1.3). Pump test and groundwater level recorder data have been used to estimate the hydraulic connection between the river and the formations from which groundwater is abstracted.

Rainfall infiltration of 0.33 m/yr (based on annual rainfall of 1.1 m and recharge coefficient of 0.3) is estimated for the Speargrass and modern gravel formations (Section 2.1.2). Based on aquifer volumes and water content, it is estimated that rainfall recharge could replace the groundwater storage in about 2.5 years. When input from the rivers, the dominant recharge source, is included, it is clear that residence times should generally be substantially less than 2.5 years.

Section 3 describes sensitivity analyses undertaken to relate groundwater piezometric levels to river flow rates and rainfall amounts, and identify the relative contributions of river flow and rainfall as sources of aquifer recharge, based on 21 months data. The method uses correlation by means of artificial neural network-based pattern analysis. At Quinneys Bush (WWD4785), the method yields 87% Motupiko River and 13% rainfall recharge. Recharge is 63% Motueka

River and 37% rainfall at North Bridge (WWD4784), and 96% Motueka River and 4% rainfall at Hyatts (WWD4617). These figures will greatly assist the process of setting rational limits for management of the overall river-groundwater system.

Chemical and isotopic results in Section 4 show distinct differences between waters sourced from the Upper Motueka valley, and waters sourced from the Motupiko and Tadmor valleys. The former group has relatively high Mg-Ca-HCO_3 concentrations, because of ultramafics (and sediments derived from it) in the Upper Motueka catchment. Motueka-type waters also have lower $\delta^{18}O$ values than the Motupiko-type waters, because of the higher altitude of the Motueka River catchment beyond the gorge site. Both ground and river waters display these differences, showing that there is strong interaction between these systems, and emphasising the domination of the groundwater systems by the respective rivers.

The monthly variations of $\delta^{18}O$ in the groundwaters and rivers give information on the sources and residence times of the waters. $\delta^{18}O$ variations in the groundwater mimic those of the rivers, and best-fit simulations using the river and rainfall variations as input indicate optimum values of the mean residence time and river/rainfall ratio (Table 4.3). The optimum mean residence times are short and in agreement with ages indicated by preliminary work on tritium measurements (i.e. 0-12 months). The optimum river/rainfall ratios agree with those determined by water table sensitivity analyses (Section 3). The CFC measurements also indicated similar short mean residence times with less precision (being between zero and a few years).

Apart from the rivers and rainfall, a third possible recharge source for the river terrace groundwater was identified in Section 2.1, namely groundwater discharge from the underlying Moutere Gravel. Groundwater discharge from Moutere Gravel is likely to have longer residence times and possibly characteristic chemical and oxygen-18 concentrations. However, the residence time results obtained rule out any substantial contribution from Moutere Gravel, being 12 months or less. Neither were there any chemical or oxygen-18 indications of input of groundwater from Moutere Gravel. Consequently, we consider that there is no substantial input of groundwater from underlying Moutere Gravel to the terrace groundwaters or rivers.

6. REFERENCES

Anderson H J, 1980. Geophysics of the Moutere Depression. Geophysics Division report 159. Wellington, New Zealand. Department of Scientific and Industrial Research. 41p.

Basher, L.R. Comp. 2003: The Motueka and Riwaka catchments: a technical report summarising the present state of knowledge of the catchments, management issues and research needs for integrated catchment management. Landcare Research New Zealand, Lincoln, New Zealand. 120 pp.

Freeze, A. R. and Cherry, J. A. 1979: Groundwater. Prentice-Hall, Inc.

Hatherton T, 1967. A geophysical study of Nelson-Cook Strait region, New Zealand. New Zealand journal of geology and geophysics 10(6): 1330-1347.

He, X., Asada, H. 1993: A New Method for Identifying Orders of Input-Output Models for Nonlinear Dynamic Systems. *Proc. of the American Control Conf.*, S.F., California.

Hewlett JD, Hibbert AR. 1967. Factors affecting the response of small watersheds to precipitation in humid areas. *In* Sopper, W.E., Lull, H.W. (Eds.), Forest Hydrology. Oxford, Pergamon. Pp 275-290.

Hong Y.-S., Bhamidimarri S. M. R. and Charleson T. (1998) A genetic adapted neural network analysis of performance of the nutrient removal plant at Rotorua. *Institute of Professional Engineers New Zealand (IPENZ) Conference*, Simulation & Control Section, **2**, 213-217.

Hunt B, 1999. Unsteady stream depletion from groundwater pumping. Groundwater, vol.37, No.1, pp98-102.

Johnston M R, 1983. Geological Map of New Zealand 1:50,000 Sheet N28 AC Motupiko. New Zealand Geological Survey, Department of Scientific and Industrial Research

Scarf, F. 1972: Mapping average annual surface water resources of the hydrological regions of Nelson, New Zealand. *Journal of Hydrology (NZ) 11*, 105-126.

Suggate R P, 1965. Late Pleistocene geology of the northern part of the South Island, New Zealand. New Zealand Geological Survey bulletin (n.s) 77. 91 p

Suggate R.P. 1988: Late Otira Glaciation in the upper Buller valley, Nelson, New Zealand. *In*: Suggate, R.P. *ed.*: Quaternary deposition and deformation in the Buller and tributary valleys. New Zealand Geological Survey record 25:13-25.

Thorpe, H. R., Scott, D. M., 1999. An evaluation of four soil moisture models for estimating natural groundwater recharge. New Zealand Journal of Hydrology 38:179-209.