Moutere Valley Groundwater: Nature and Recharge from Isotopes and Chemistry

M.K. Stewart and J.T. Thomas

Science Report
2002/22

□□□□□□□□□□□□□□□□□□□□2/22□□

July
2002

Institute of
GEOLOGICAL
& NUCLEAR
SCIENCES
Limited

Moutere Valley Groundwater: Nature and Recharge from Isotopes and Chemistry

M.K. Stewart and J.T. Thomas

Institute of Geological & Nuclear Sciences science report 2002/22

Institute of Geological & Nuclear Sciences Limited
Lower Hutt, New Zealand
July 2002

Gracefield Research Centre, 69 Gracefield Road, P O Box 30368, Lower Hutt, New Zealand, Telephone: +64-4-570 1444, Facsimile: +64-4-570 4600

A Crown Research Institute

BIBLIOGRAPHIC REFERENCE

Stewart, M.K. and Thomas, J.T. 2002. Moutere Valley Groundwater: Nature and Recharge from Isotopes and Chemistry. *Institute of Geological & Nuclear Sciences science report* 2002/22. 28p.

M.K. Stewart, Institute of Geological & Nuclear Sciences Limited, Wellington
J.T. Thomas, Tasman District Council, Richmond

ISSN 1171-9184
ISBN 0-478-09773-5

CONTENTS

ABSTRACT

Recharge to the Moutere Gravel aquifer system in the Moutere Valley was investigated by means of isotopic and chemical measurements. Bores up to 500 m deep tap three Moutere Gravel aquifers underlying the area. Shallow bores (50-100 m), tapping the shallowest of the three aquifers, have $\delta^{18}O$ in the range –6.8 ± 0.4‰ as expected for present-day (Holocene) rainfall. Their carbon-14 concentrations are generally 90 ± 10 pmC indicating modern ages, i.e. water residence times of up to hundreds of years.

Deeper bores have more negative $\delta^{18}O$ values and lower ^{14}C concentrations resulting from input of much older water from depth in the western and eastern zones. The old deep water from the deepest of the aquifers is believed to have been recharged in the Pleistocene during the last glaciation. This 'glacial' water has $\delta^{18}O$ of –7.6‰, and ^{14}C concentration of 0 pmC. Mixing of glacial and modern waters gives rise to the variations observed in the oxygen-18, carbon-14 and chemical concentrations in the bore waters. The chemical characteristics of the glacial water have been determined as end members on mixing plots between chemical components and $\delta^{18}O$. Sea level was much lower when the glacial water was recharged, and the sea would have been far from its present position. A large body of glacial age water may be resident in the Moutere Gravel under the sea.

Recharge is provided by modern water penetrating the groundwater system at shallow levels. Measurements on this water give evidence on the patterns and rates of recharge. The distribution of $\delta^{18}O$ and chloride suggest that water has been recharged through both the tm1 and tm2 units of Moutere Gravel in the past few hundred years, but evidently at low rates because of the ages. Young recharge is observed only on the hills west of the valley floor, but observations are lacking in the most probable recharge zone (the tm1 outcrop area in the Rosedale Hills). Under the natural situation, it is believed recharge water flowed at shallow or intermediate levels, leaving an undisturbed body of ice age water at deep levels. This pattern resulted from the present sea level and the expected lack of offshore outlets for water in the deep aquifer. However, groundwater exploitation from deep bores will now be tending to draw shallow water deeper into the system.

KEYWORDS

Groundwater recharge; oxygen-18; carbon-14; tritium; CFCs; chemical compositions

INTRODUCTION

Groundwater in the Moutere Valley is an important resource for horticulture. Deep wells revealed the hitherto unknown water resource in the early 1980s, after shallow wells were found to provide limited and unreliable supplies. The hydrogeology of the groundwater system was investigated by Thomas (1989, 1991, 1992, 2001). The present work uses isotopes and chemistry in conjunction with other data to improve understanding of the nature of the system. This will lead to better understanding of the patterns and rates of recharge to the deep Moutere Aquifers, including its location and recent history. Better understanding of the groundwater system and recharge will contribute to policy on future permitted land uses in the recharge areas.

Hydrogeology

The Moutere Depression is a 30 km-wide system of valleys between the Tasman Mountains and the ranges of east Nelson (Figure 1). Voluminous Plio-Pleistocene gravels (including Moutere Gravel) are preserved in the depression and have been incised by the Motueka, Moutere and Waimea rivers (Rattenbury *et al.* 1998). Geophysical interpretation of seismic data and petroleum wells indicate that the depression reaches depths of 2500 m on the eastern side (Lihou 1992). The depression formed in the Pliocene-Pleistocene during uplift of the Tasman Mountains and the east Nelson Ranges.

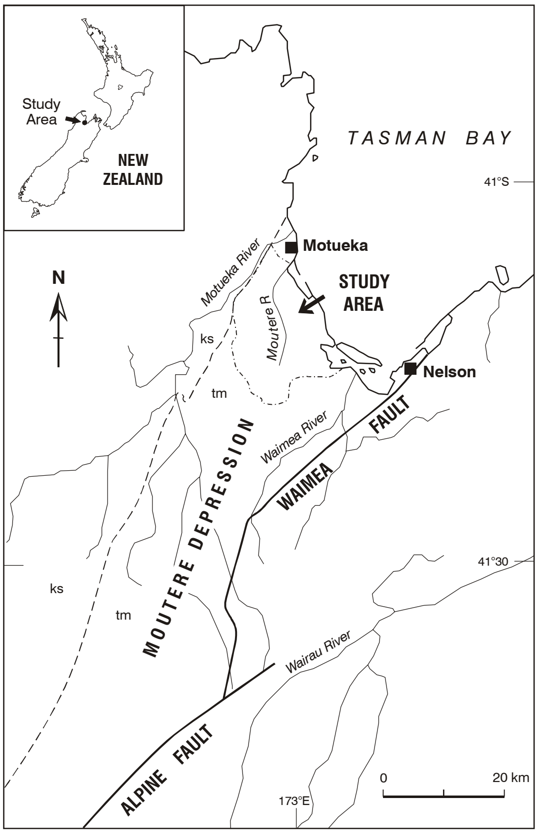

Figure 1. Geology of the Moutere Depression. The contact with Separation Point Granite (ks) defines the western boundary, while the eastern boundary is against the upward-faulted east Nelson Ranges. The depression is mainly filled with Moutere Gravel.

Moutere Gravel is a uniform yellow-brown, clay-bound gravel, with deeply weathered clasts almost entirely of Torlesse-derived sandstone and semi-schist. Well rounded, quartzofeldspathic sandstone clasts in a brown weathered muddy sand matrix comprise the bulk of the gravel.

The Moutere Valley lies south of Motueka (Figure 2). Most of the Moutere River catchment comprises Moutere Gravel (marked tm); some Separation Point Granite (ks) is found in part of Powley Creek catchment (Figure 3). The catchment is underlain by a north-east trending basinal structure in which Moutere Gravel reaches a maximum depth of about 600 m (Figure 4). A basement high running through Ruby Bay forms the southern flank of the basin. Basement granite then descends south of Ruby Bay to the Waimea Fault on the east side of the Waimea Plains. Groundwater in Moutere Gravel south of the Ruby Bay high is largely unexplored.

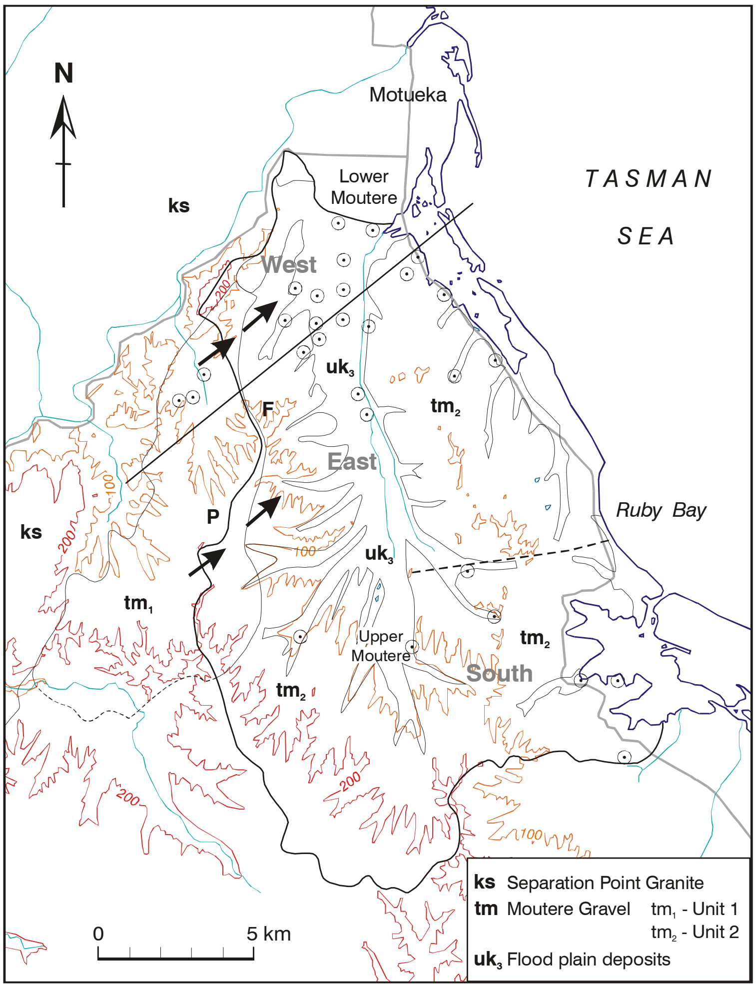

Figure 2. Geological setting of the Moutere Valley, Northwest Nelson. Fine lines show the surface geology comprising Separation Point Granite (ks) to the northwest and Moutere Gravel (units tm_1 and tm_2) to the southeast. The valley floor contains reworked Moutere Gravel (uk_3). The heavy line is the boundary of the Moutere River Catchment. Arrows show inferred directions of groundwater flow from Thomas (1992). The three groundwater zones are shown; west and east zones are separated by the fault (straight line) and east and south zones by the Ruby Bay basement high (dotted). Bore locations are marked by dotted circles. P (pasture) and F (forest) mark sites where soil moisture and streamflow were monitored (see text).

The floor of the Moutere Valley has a Quaternary infilling (uk), which derives from reworked Moutere Gravel (Figure 2). Shallow wells (<20m) draw limited and often unreliable supplies of water from the valley infill, showing that permeabilities are low. Shallow wells on the Moutere Hills also tend to have low yields and unreliable supplies. Rainfall is the main recharge source of these supplies, with variable contributions from local streams (Thomas, 1989).

The hydrogeology has been described by Thomas 1989, 1991, 1992, 2001. Significant groundwater resources are found in deep Moutere Gravel aquifers. The three aquifers in vertical succession are the Shallow Moutere Aquifer (SMA), Middle Moutere Aquifer (MMA), and Deep Moutere Aquifer (DMA) (Figure 4). Intervening leaky clay layers containing carbonacious material constrain the aquifers. Groundwater yields improve significantly with depth, and heads are generally higher at depth. Many deep bores (>50m) are artesian. The deep bores are cased to 30-50 m depth and then are generally screened or open to the bottom, so that they are likely to draw on water from several depths. Thomas (1989) has identified feed zones in several bores from downhole measurements.

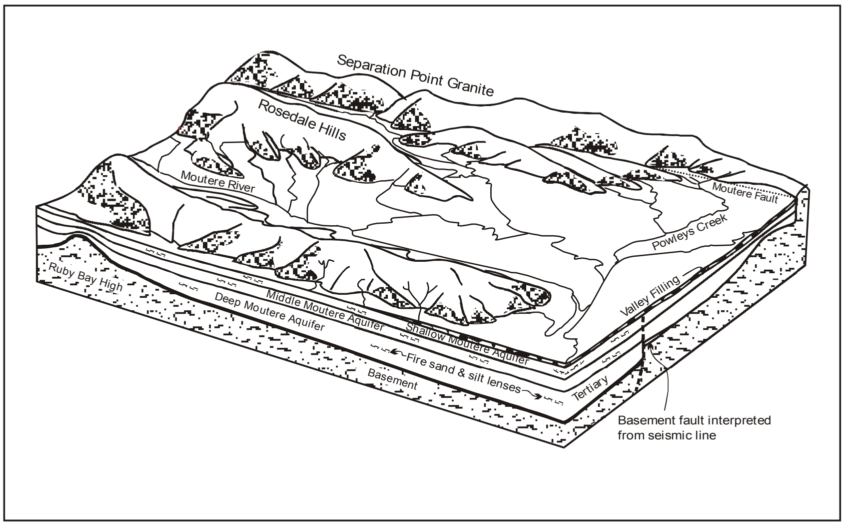

Figure 3. Three-dimensional hydrogeology of the Moutere Valley looking southwest from Tasman Sea (Thomas 2001).

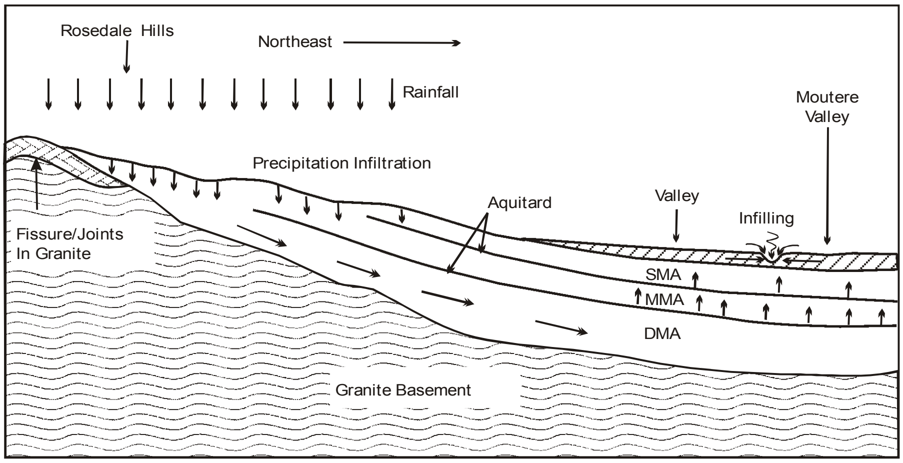

Figure 4. Cross-section showing inferred recharge patterns for the Moutere aquifers (Thomas 2001).

The Moutere groundwater resource north of the Ruby Bay basement high is divided into two zones by a major fault; the western and eastern zones (Figure 2). Pressure communication between wells is limited across this barrier. These zones are used for management of the resource (Thomas 2001). A third groundwater zone (southern) is defined south of the Ruby Bay high for discussion purposes.

Recharge to the aquifers occurs by infiltration of rainfall where Moutere Gravels outcrop. Two units have been identified by geological mapping, a lower unit (tm_1) and an upper unit (tm_2). The lower unit outcrops only in the southwest of the area (Figures 2 and 3), dips gently northeast into the Moutere Valley, and correlates with the DMA and MMA. The upper unit correlates with the SMA. Thomas (1989, 1992) has proposed a recharge model illustrated in Figure 4, in which rainfall infiltrates through the lower unit in the Rosedale Hills area (Figures 3 & 4) and penetrates into the deep and middle Moutere aquifers.

SAMPLING AND METHODS

Sampling and bore details are given in Table 1. The bore locations are shown in Figure 5a.

Isotopic Data

Groundwater wells were purged of at least three casing volumes before samples were taken. Bottles were flushed with the water to be sampled, emptied, and filled with water and allowed to overflow. Care was taken to seal the bottles tightly to prevent evaporation. Samples of water were collected in 28 mL glass bottles for ^{18}O, 500 mL bottles for carbon isotopes, and 1.1 L bottles for tritium.

For ^{18}O measurement, 2 mL of the water is isotopically equilibrated with CO_2 gas at 29^oC for two hours, and then the CO_2 is analysed in a stable isotope mass spectrometer (Hulston et al., 1981). For tritium, samples are distilled, enriched in tritium by electrolysis and then counted in a Quantalus low background liquid scintillation counter for several weeks (Hulston et al., 1981). Carbon isotope measurements are made by quantitatively extracting carbon from an aliquot of the water as CO_2 by adding acid. The total yield of CO_2 is measured. Part of the CO_2 is analysed for ^{13}C, the remainder is turned into a graphite target for accelerator mass spectrometric analysis of ^{14}C.

Chlorofluorocarbons

Water samples for CFC concentration measurements were collected in such a way as to prevent contact of the sample with the atmosphere or with plastic materials, either of which could contaminate the water with excess CFCs. The samples are preserved in the field by sealing them into 62 mL borosilicate glass ampoules at the well site. The sampling apparatus is connected to the well outlet by copper tubing. All other tubing in contact with the water during sampling is stainless steel. The ampoule is attached to the sampling apparatus and flushed with ultra-high-purity nitrogen gas. The well water is then allowed to flow through the tubing and valves and into the bottom of the ampoule, displacing the nitrogen. The ampoule is rinsed with several hundred millilitres of water, then nitrogen is forced into the neck to displace some of the water. The ampoule is then fused shut about 1-2 cm above the water level with an oxy/acetylene gas torch. Nitrogen flows continually across the union to prevent any air contamination. Four ampoules are normally collected at each sampling site. The CFC samples were analysed by gas chromatography.

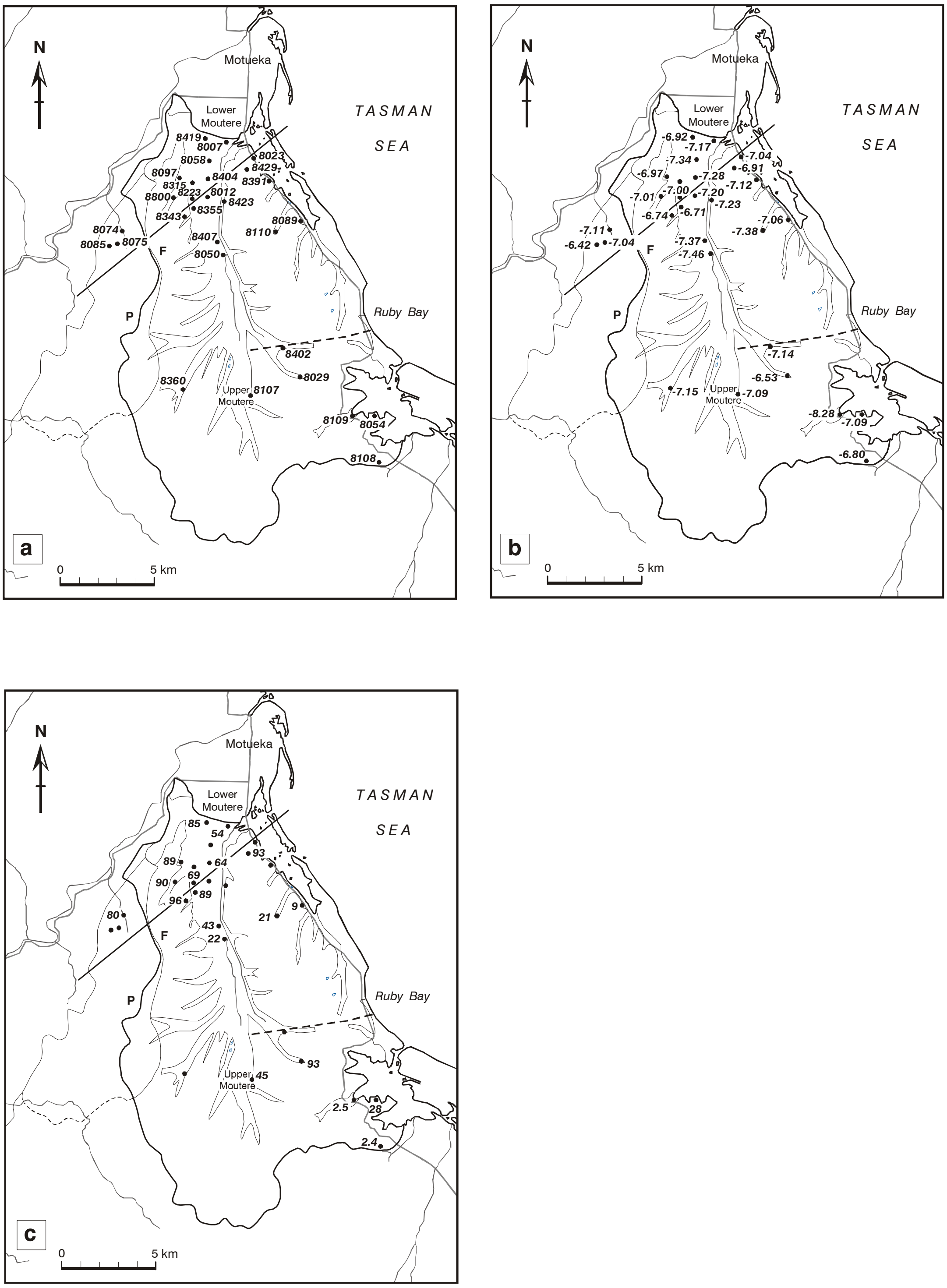

Figure 5. Moutere Valley showing: (a) bore locations, (b) $\delta^{18}O$ values (‰) of bore waters, and (c) ^{14}C concentrations (pmC) of bore waters.

Chemical Data

Water samples have been collected from groundwater wells in the Moutere Valley by Tasman District Council hydrologists for a number of years. Samples for cations were field filtered and acidified with high-purity nitric acid. Samples for anions were field filtered and kept below 4°C until analysed, and bicarbonate samples were collected unfiltered, kept below 4°C, and analysed within 48 hrs of collection. Samples were analysed by the Cawthron Institute in Nelson. Analytical methods have changed for some parameters, but in general the same methods have been used for each collection period. Methods for cation analyses include Atomic Adsorption, ICP-OES, and for anion analyses include auto titrator, auto analyser, and ion chromatography.

RESULTS

Oxygen-18 Concentrations

$\delta^{18}O$ values give information on the source of the groundwater because there is generally a relationship between the location of recharge and its $\delta^{18}O$ value (Stewart and Morgenstern, 2001). ^{18}O concentrations in water are expressed as δ values with respect to a water standard in units of per mil (‰), where

$$\delta^{18}O\ (‰) = [(^{18}O/^{16}O)_{sample} / (^{18}O/^{16}O)_{VSMOW} - 1] \times 1000 \qquad (1)$$

The standard (VSMOW or Vienna Standard Mean Ocean Water) is held at the International Atomic Energy Agency in Vienna. Measurement errors are ±0.1‰ (one standard deviation).

$\delta^{18}O$ in precipitation depends on altitude, latitude, and distance from the sea along prevailing storm tracks. The average relationships between $\delta^{18}O$ and altitude and latitude for New Zealand precipitation are expressed by the equations

$$\delta^{18}O = -0.0021h - 5.51 \qquad (2)$$

$$\delta^{18}O = -0.22L + 3.58 \qquad (3)$$

where h is the altitude in metres, and L the latitude South in degrees. This gives $\delta^{18}O$ of about –5.5‰ for precipitation at sea level and –6.2‰ for precipitation at 300-m altitude for Moutere. However, Moutere is situated east of the Tasman Mountains, which lie at right angles to the prevailing storm tracks from the west, and therefore precipitation at Moutere would be expected to be more negative than the above estimate. The mean $\delta^{18}O$ value of precipitation on the Waimea Plains at Richmond (near sea level) was measured at –6.2‰ (Stewart et al. 1981) and gives a guide to the values to be expected at Moutere. This would indicate values of –6.2‰ at sea level and –6.9‰ at 300-m altitude for the Moutere Valley.

Recent measurements of the mean $\delta^{18}O$ values of groundwater recharge from rainfall in comparison with the rainfall itself suggest that there can be differences between them (work in progress on Canterbury Plains; Stewart et al., 2002). If winter rainfall provides more of the recharge, because more water is lost by evapotranspiration in summer, then the $\delta^{18}O$ of the recharge will be more negative than the $\delta^{18}O$ of the rainfall. Monthly rainfall measurements at Waiwhero (at the pasture site marked “P” on Figure 1) and Rosedale (forest site, marked “F”) had annual mean values of –6.3‰, and winter mean values of –7.1‰. Nearby pasture and forest springs had mean values of –6.4‰ and –6.6‰ respectively. These indicate a probable range for rainfall-recharged groundwater in the region of –6.4 to –7.1‰.

In fact, the $\delta^{18}O$ values of the Moutere Gravel groundwaters are in the range –6.4 to –7.5‰ (Table 2), except for one bore with $\delta^{18}O$ of -8.3‰. (The latter is discussed below).

The $\delta^{18}O$ values show interesting areal patterns (Figure 5b). In the western zone, the shallow bores on the west side of the valley (i.e. the Waiwhero area, bores WWD8074, 8075, 8085) have $\delta^{18}O$ values of –7.0 to –7.1‰. (8085 is an open well, so its value of –6.4‰ is likely to have been affected by evaporation.) On the west side of the valley floor, bores WWD 8419, 8364, 8097, 8800 and 8223 have values of about –6.9 to –7.0‰. These waters are likely to have been recharged in the Waiwhero area. The remaining bores in the valley floor WWD8007, 8058 and 8404 tap deeper waters and have more negative $\delta^{18}O$ values (–7.2 to –7.3‰). (Well 8404 has been sampled since 1988 and has shown no change in $\delta^{18}O$ in that time).

In the eastern zone, shallow bores on the west side of the Moutere Valley (WWD8343 and 8355) have $\delta^{18}O$ values of –6.7 to –6.8‰. The deeper bores within the valley floor (WWD8012, 8423, 8407 and 8050) have $\delta^{18}O$ from –7.2 to –7.5‰. And bores on the east side (WWD8023, 8428, 8429, 8391 and 8089) have $\delta^{18}O$ of –6.9 to –7.1‰. Bore 8110 (501 m depth) has a value matching those of the deep bores 8407 and 8050. Bore 8407 has shown no change in $\delta^{18}O$ from 1988 to 2002.

These results indicate that the ground waters are from at least two sources; shallow waters with $\delta^{18}O$ in the range –6.7 to –7.1‰, which are as expected for present-day rainfall, and deeper waters with more negative $\delta^{18}O$ values (–7.2 to –7.5‰). (Elevation of about 600 m would be required to produce $\delta^{18}O$ values of –7.5‰.) This relationship is shown in Figure 6; deeper bores are found to have more negative $\delta^{18}O$ values than shallow bores. This might suggest that the water at depth is recharged at higher altitude than the shallow water, except that the shallow water has $\delta^{18}O$ values matching what is expected for present-day rainfall including rainfall on the Rosedale Hills. This means that the deep waters cannot easily be accounted for by precipitation at higher elevation.

Hence, the favoured explanation is that there are two types of water in the Moutere aquifers. The first is a body of ‘fossil’ water occupying deeper levels of the Moutere aquifers, which has lower $\delta^{18}O$ values because it was recharged during the last glacial period (in the Pleistocene). Above this is ‘modern’ water, probably recharged in the last few hundred years of the Holocene, with $\delta^{18}O$ values much the same as today. These two end member compositions are shown by the hollow squares in Figure 6; the line connecting them shows the effect of mixing of these waters. Many of the deeper bores are thought to be drawing on both types of water, because they are open for most of their depths (Table 1). The ^{14}C results support the glacial age of the deep water (see below). (Older Holocene water may also be present in the modern component.)

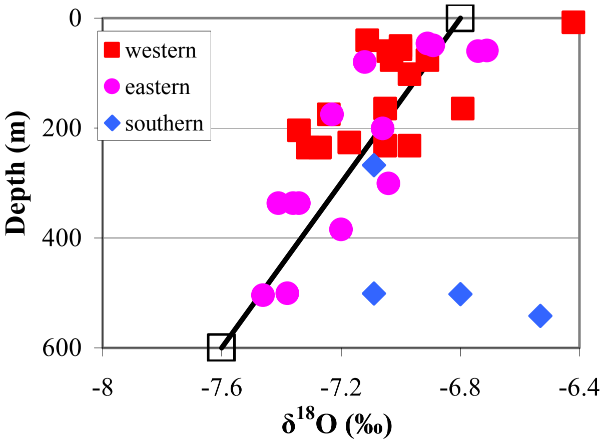

Figure 6. $\delta^{18}O$ values versus bore depths. A line is fitted to the points and connects deep (-7.6‰, 600m) and shallow (-6.8‰, 0m) end-members. (Three southern zone points are excluded from the correlation.)

In the southern zone of the valley, the $\delta^{18}O$ values are more scattered. Bore 8360 is close to the Rosedale Hills, its $\delta^{18}O$ is –7.15‰ (a value expected for local recharge). Also similar are 8107 and 8402 at –7.09 and –7.14‰. Although bore 8029 is deep, the water comes from relatively shallow depth because it contains a trace of tritium. Its $\delta^{18}O$ is –6.53‰. Bore 8109 has an unusually negative $\delta^{18}O$ (–8.28‰), almost certainly indicating glacial age water. Bores 8054 and 8108 have values more typical of present rainfall (–7.09 and –6.80‰). These bores do not draw on a consistent deep component like the deep bores in the western and eastern zones.

Carbon Isotope Compositions

Carbon-14 is the major tool for dating old groundwater. ^{14}C (half-life 5730 years) is generated by cosmic rays in the atmosphere and introduced into living biomass by photosynthesis, and into the hydrosphere by CO_2 exchange reactions. Consequently, any carbon compound derived from atmospheric CO_2 since the late Pleistocene can potentially be dated by ^{14}C.

^{14}C concentration or activity (a) is expressed as percent modern carbon (pmC), where the activity of "modern carbon" is taken as 95% of the activity in 1950 of the NBS oxalic acid standard. Groundwater dating by ^{14}C is complicated by changes in ^{14}C activity in the atmosphere during the late Pleistocene and Holocene, and by dilution of ^{14}C in groundwater by dead carbon derived from soils and rocks when carbon-bearing solutions penetrate underground.

Most of the ^{14}C in groundwater is gained from the soil, where CO_2 accumulates by root respiration and decay of vegetation. The ^{14}C in dissolved inorganic carbon (DIC) is susceptible to reaction and dilution with dead carbon from carbonate, other minerals and organic matter in the soil and groundwater zones. A dilution factor q is used to take account of the resulting dilution of ^{14}C. The age equation is written

$$t = (1/\lambda) . \ln (q . a_o / a_t) \qquad (4)$$

where a_o is the initial ^{14}C activity (q.a_o the diluted initial activity in the groundwater), a_t is the ^{14}C activity in groundwater after time t (i.e. when measured) and λ is the carbon-14 decay constant ($1/\lambda = T_{½} / \ln 2 = 8267$ years). The apparent simplicity of this equation is deceptive. Numerous methods have been proposed for estimating q, based on the chemical and ^{13}C composition of the groundwater.

The carbon-13 concentrations in dissolved inorganic carbon (DIC) from Moutere are shown in Figure 7a (plotted against 1/bicarbonate). The δ^{13}C values are remarkably uniform around the values –20 to -24‰ (except for one sample, see below). This range shows that all of the carbon is sourced from organic matter within the soil or aquifers (Clark and Fritz, 1997). Waters gain dissolved CO_2 by plant respiration and oxidation of organic matter as they pass through the soil, where CO_2 partial pressures are commonly 10 to 100 times those in the atmosphere. The second source is from carbonaceous matter within the aquifers, in this case from the intervening clay layers between the aquifers. Oxidation of such matter produces CO_2 if chemical and/or microbiological conditions are suitable (bacteria are needed to catalyse redox reactions between water and organic matter).

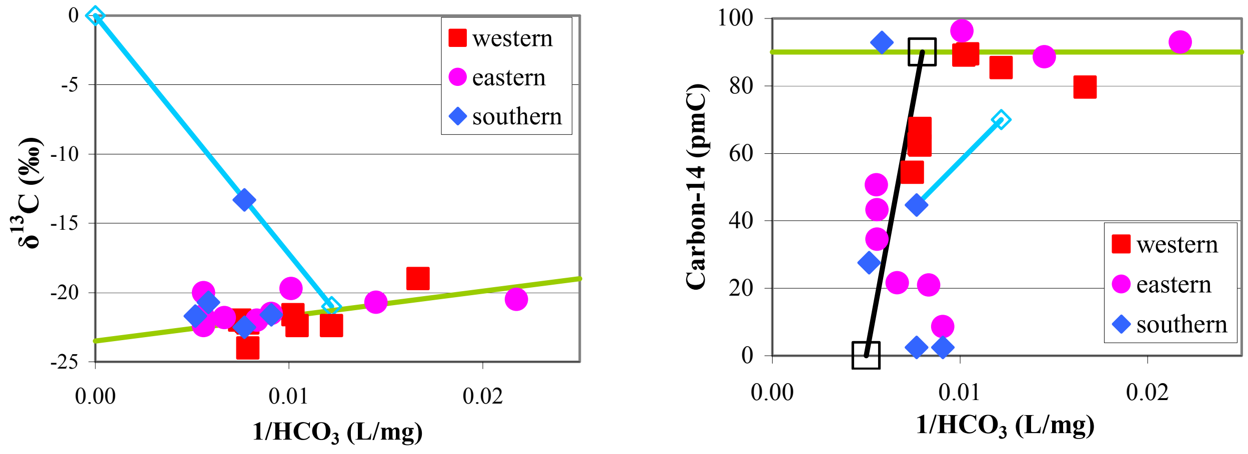

Figure 7a

Figure 7b

Figure 7. (a) δ13C values versus $(HCO3)^{-1}$ for bore waters. All except one southern zone water have δ13C of –20 to -24‰ showing that the carbon is derived from organic matter. (b) 14C values versus $(HCO3)^{-1}$ for bore waters. The line connects the old (zero 14C, 200 mg/L bicarbonate) and young (90 pmC 14C, 125 mg/L bicarbonate) end-members. Addition of modern plant carbon within the soil moves the points to the left along the line at 90 pmC.

Dissolved CO_2 tends to react with soil and aquifer minerals, acting as the main chemical weathering agent. However, many of these waters have had only limited chemical reaction with the aquifer rocks, because they still contain considerable amounts of dissolved CO_2. This is partly because of the unavailability of carbonate minerals, but weathering reactions with silicate minerals such as albite and anorthite also neutralise dissolved CO_2, e.g.,

$NaAlSiO_3 + CO_2 + 5.5H_2O > Na^+ + 0.5Al_2Si_2O_5(OH)_4 + 2H_4SiO_4^o + HCO_3^-$

$CaAl_2Si_2O_8 + 2CO_2 + 3H_2O > Ca^+ + Al_2Si_2O_5(OH)_4 + 2HCO_3^-$

However, these reactions are slow. The green line through the points in Figure 7a traces the evolution of water, which gains bicarbonate by solution of CO_2 and reaction with rock, as it goes underground.

Only one sample has $\delta^{13}C$ outside the range –20 to -24‰, namely WWD8107 with $\delta^{13}C$ of –13.3‰. This sample is likely to have reacted with marine carbonate, which has the effect of moving the sample towards the $\delta^{13}C$ value of such carbonate (approximately 0‰). The blue line in Figure 7a shows the effect of reaction with marine carbonate. Carbon from carbonate rock would have zero ^{14}C, hence it would have a diluting effect on the ^{14}C concentration. The short blue line in Figure 7b shows the effect of reaction with carbonate on this sample.

Figure 7b shows ^{14}C concentrations plotted against $1/HCO_3$. The ^{14}C concentrations show a wide range of values, from almost 0 to 100 pmC. Shallow bores have ^{14}C concentrations in the range 90 ± 10 pmC (Table 2). These values are a little less than 100 pmC, because plant material within or below the soil is likely to have ^{14}C concentrations less than modern (~100 pmC) if soils contain material older than a few hundred years. (None of the waters have concentrations high enough to indicate the presence of carbon-14 from nuclear weapons testing and hence are 'pre-bomb'; i.e. they were all recharged before the early 1960s.) The line at 90 pmC in Figure 7b shows the effect of increasing bicarbonate concentration by solution of CO_2 and reaction with rock within the soil. Points along this line (from right to left) trace the evolution of the modern water component as it goes underground (in the same process as illustrated for evolution of $\delta^{13}C$ in Figure 7a).

The glacial water component has zero ^{14}C. Its bicarbonate concentration is about 200 mg/L. Figure 7b shows the mixing line between the glacial and modern end members (shown by squares). The modern water end member involved in the mixing process has bicarbonate concentration of about 125 mg/L.

The ^{14}C concentrations are plotted against $\delta^{18}O$ in Figure 8. An approximately linear relationship is seen between them for the western and eastern zone samples, showing mixing between the glacial (with composition -7.6‰, 0 pmC) and modern (-6.8‰, 90 pmC) components (again shown by squares).

The areal variations of the ^{14}C concentrations are significant (Figure 5c). In the western zone, ^{14}C was measured in one bore (8074) in the recharge zone. This along with WWD8419, 8097 and 8800 has modern (but pre-bomb) ^{14}C concentrations of 90 ± 10 pmC. 8223 also contains a small amount of tritium although its ^{14}C is relatively low (69 pmC). Two of the remaining three wells in the western zone (8007 and 8404) have ^{14}C measurements, the results are 54 and 64 pmC.

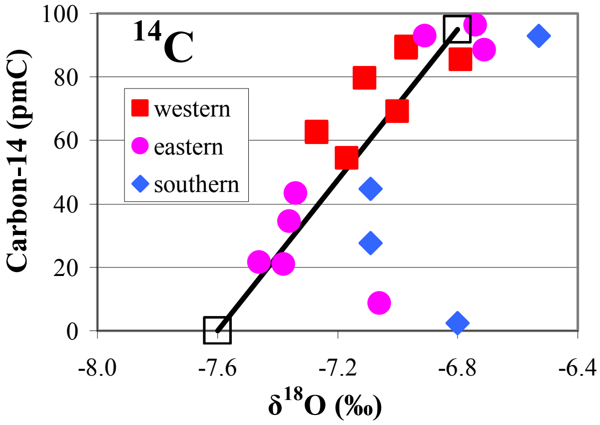

Figure 8. $\delta^{18}O$ versus ^{14}C for bore waters; the older waters (low ^{14}C) have more negative $\delta^{18}O$ values.

In the eastern zone, bores 8343 and 8355 have ^{14}C of 96 and 89 pmC (indicating modern carbon). The deep bores 8407 and 8050 have 43 and 22 pmC respectively. The shallow bore east of the valley floor (8429) has modern carbon (93 pmC), while the deep bores (8110 and 8089) are quite old with 21 and 9 pmC respectively.

In the southern zone, 8029 has modern carbon (93 pmC), 8107 and 8054 have 45 and 28 pmC, and 8108 and 8109 are very old with only 2.4 pmC. Hence there are glacial age waters in the southern zone, but there is not the consistent pattern with $\delta^{18}O$ that is found in the western and eastern zones.

Chemical Compositions

The chemical compositions of the western and eastern zone waters are affected by mixing of the two water types. The glacial water at depth appears to have a nearly uniform composition, whereas the modern water penetrating from the top has a more varied composition.

Chloride concentrations in groundwater often reflect marine influence on rainfall (i.e. rainout of seasalt particles in the atmosphere). For rainfall recharged groundwater, evapotranspiration causes enrichment of chloride while passing through the soil. A third influence is sea water trapped within deep parts of the aquifer during past higher sea level stands, or present-day intrusion of sea water. The plot of chloride versus $\delta^{18}O$ (Figure 9a) shows glacial water (Cl ~ 5.5 mg/L, $\delta^{18}O$ ~ -7.6‰) mixing with modern water containing a range of chloride values (5.5. to 18 mg/L, $\delta^{18}O$ ~ -6.8‰, see Table 3). The graph has two limbs. Most of the western and eastern bores have chloride near 5.5 mg/L. However, bores on the seaward side of the Moutere Valley (WWD8110, 8423, 8391 and 8089) plot on the upper limb with higher chloride concentrations. This is considered to reflect their location nearer the sea where they receive rainfall that has higher chloride concentrations. If so, this shows that the recharge occurred locally. Wells WWD8050, 8007 and 8419 (1988 sample) have markedly higher chloride concentrations because of input of sea water (these points are not plotted in Figure 9a).

Sodium (Figure 9b) has similarities to chloride, but is more affected by interaction with aquifer rocks. Sea water influence is shown by higher sodium concentrations in WWD8050 and 8007 (not plotted). The plot with $\delta^{18}O$ shows two limbs as with chloride, but the upper limb values are more scattered (although it still includes two of the same bores, i.e. 8110 and 8089). Most of the samples lie on the lower limb, forming a trend towards higher sodium at depth because of increased water/rock interaction.

Bicarbonate and calcium (Figures 9c and d) are readily affected by reaction with soil and rock, and the deep component has higher concentrations of these constituents than the shallow component. This is consistent with greater interaction with rock with depth (i.e. residence time).

Sulphate and potassium (Figures 9e and f) are lower in the deep component compared to the shallow component. For sulphate, this is because of chemical reduction in anaerobic environments affecting the deep component. Potassium (like sodium) is affected by interaction with rock, but the rock tends to take up potassium instead of releasing it.

Silica and magnesium (Figure 9g and h) show considerable scatter related to rock/water interaction. For silica, there appears to be a trend towards higher silica with depth, but some high values of silica are not plotted (Table 3). Magnesium shows relatively uniform concentrations in the deep water, but widely varying concentrations in the shallow component. The western (and some eastern) zone bores have the higher magnesium concentrations.

Soluble iron and manganese (Figures 9i and j) show widely varying concentrations. Western zone bores have higher concentrations, while a number of eastern bores have very low concentrations. The deep component has a low concentration. Soluble iron and manganese are affected by the redox conditions of the waters.

The compositions of the end-member waters have been determined from the mixing plots and are given in Table 4.

Tritium and CFCS

Tritium and CFCs can be used to determine the ages of waters too young to be dated by ^{14}C. The minimum age that can be determined by ^{14}C is about a thousand years, unless bomb ^{14}C is present. Tritium and CFCs can give ages in the range of zero to some hundreds of years. The histories of the concentrations of tritium and CFCs in the atmosphere are shown in Figure 10 (Stewart and Morgenstern, 2001). Tritium concentrations passed through a peak in the 1960s and 1970s because of tritium produced by atmospheric nuclear weapons tests. Since then tritium concentrations have declined, reaching the cosmic ray-produced background level of about 2 TU around 1985. Tritium has a radioactive half-life of 12.32 years. CFC-11 and CFC-12 are entirely anthropogenetic in origin and their concentrations in the atmosphere rose from zero in about 1940 to peak in the 1990s. CFC-11 concentration has slowly declined since about 1993, while CFC-12 concentration is still increasing but at a much slower rate than before 1990.

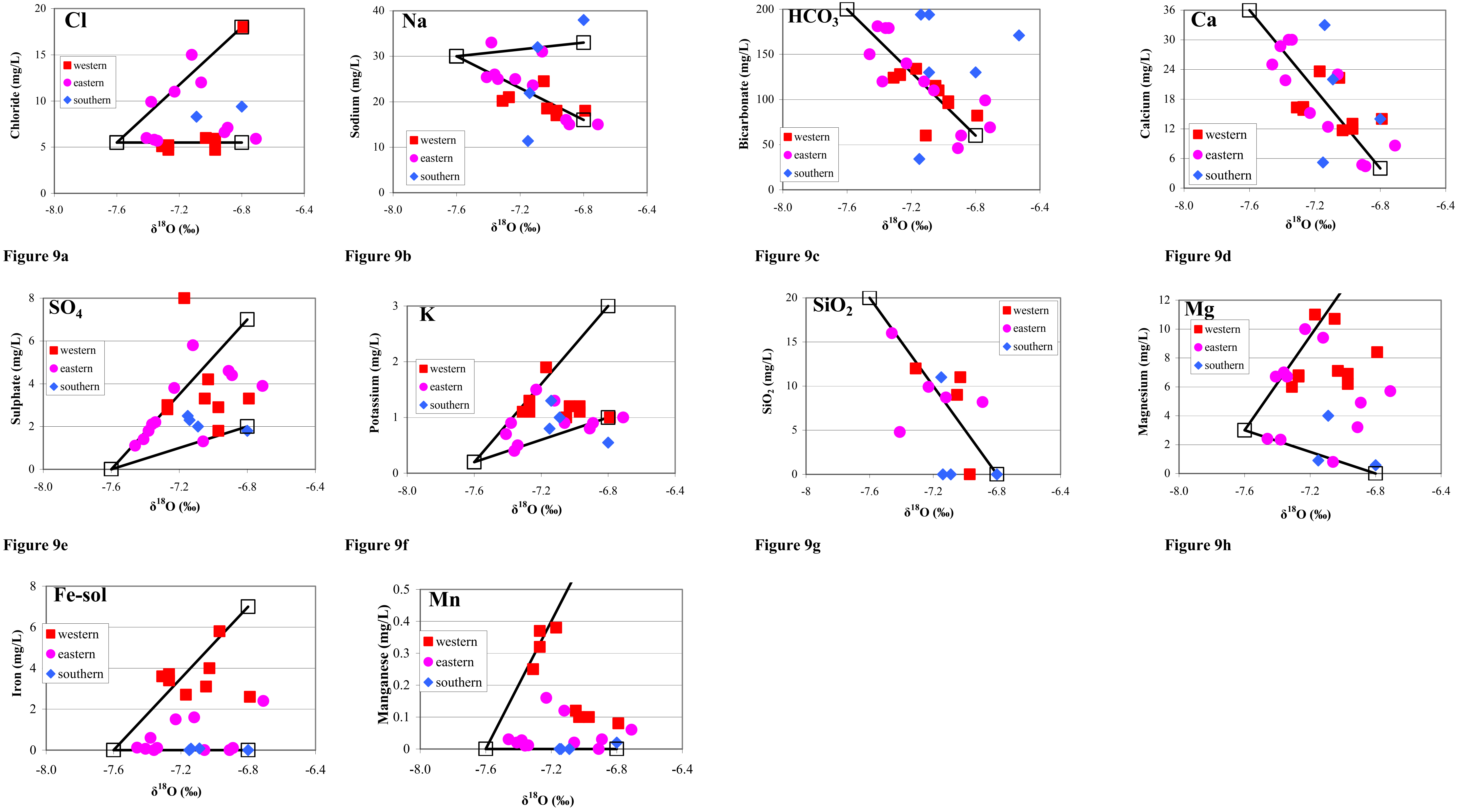

Figure 9a

Figure 9b

Figure 9c

Figure 9d

Figure 9e

Figure 9f

Figure 9g

Figure 9h

Figure 9i

Figure 9j

Figure 9(a-j). $\delta^{18}O$ versus Cl, Na, HCO_3, Ca, SO_4, K, SiO_2, Mg, soluble Fe and Mn concentrations. Lines connect end-members at $\delta^{18}O$ values of –7.6‰ (glacial water) and –6.8‰ (modern water).

Tritium samples were collected from Moutere Valley bores in 1984-1988 and 1998-2002 (Table 4). All but one of the 1984-1988 results had concentrations that were too low to measure (Thomas, 1989, 1992); i.e. their concentrations were zero within the accuracy of measurement. These show that not only were the waters old on average, but that both water components (modern and glacial) are old on the timescale of tritium. The samples contain about 50% of the glacial and 50% of the modern water components (from ^{18}O and ^{14}C results). The glacial component will have zero tritium, therefore the maximum the modern component can have is 0.48 TU. (This is twice the measurement error of ±0.12 TU divided by 50%.) This gives a minimum age of 90 years for the modern component assuming a mixing model with a relatively wide distribution of residence times (namely a dispersion model with a dispersion parameter (DP) of 0.2, which is equivalent to an exponential piston-flow model with 63% mixing,). The only sample of this group which contained tritium (WWD8360), came from a shallow bore on the Rosedale Hills. Its value of 1.21 TU showed influence of bomb tritium and a mean residence time of 57 years for the same mixing model as before (DP = 0.2, 63% mixing).

Measurements during 1998-2002 had smaller measurement errors (±0.02 TU for low tritium concentrations). A number of samples (WWD8404, 8800, 8012, 8050, 8355, 8054) had tritium concentrations below the detection limit; for these the modern component has less than 0.08 TU tritium assuming 50:50 modern/glacial mixtures. The minimum mean age for these is 150 years (for DP = 0.2, 75% mixing).

Bore WWD8407 unexpectedly showed a trace of tritium. The 1988 sample had 0.13 ± 0.05 TU and the 1999 sample 0.050 ± 0.016 TU. Assuming a 30:70 modern/glacial mixture, the modern component has 0.17 TU; this gives a minimum mean age of 120 years (DP = 0.2, 72% mixing). It is more probable however that the tritium is brought in at a shallow depth by a small fraction of much younger water (i.e. with higher tritium concentration).

The shallow bores WWD8223 and 8343, on the west side of the Moutere Valley, contained tritium. 8223 had a trace of tritium with 0.070 ± 0.016 TU and a modern/glacial makeup of between 100/0 and 80/20. Assuming the former, the mean age is 150 years ((DP = 0.2, 75% mixing). Its CFC-11 age was greater than 110 years, in agreement with the tritium age. 8343 had 0.894 ± 0.034 TU giving a mean age of 67 years (DP = 0.2, 55% mixing). Its CFC-11 concentration gave a mean age of 32 years with the same mixing model. The difference (67 and 32 years) shows that the mixing model used must be incorrect. The tritium and CFC-11 ages can be reconciled by using a model with 40% 13 year old water and 60% water old enough to have no tritium or CFC-11. The 40% of younger water shows recent recharge.

Bores WWD8074 and 8085 are in the Waiwhero area. Their tritium concentrations (1.94 ± 0.06 TU, 2.21 ± 0.06 TU) are in the ambiguous range and mean ages could be 13-16 years or 32-37 years (DP = 0.2). However both have CFC measurements with CFC-11 indicating ages of 12-16 years. (CFC-12 ages are younger still at 7-12 years, but the CFC-11 ages are generally preferred.) In either case, the CFCs show that the younger tritium ages are the correct ones.

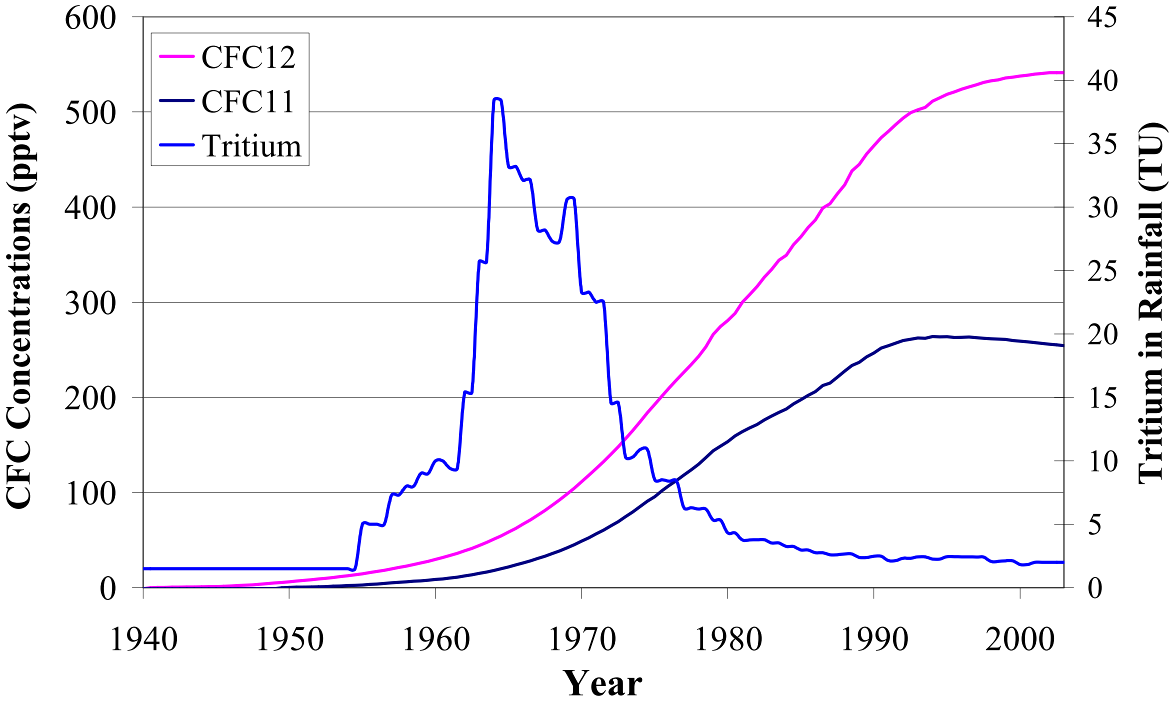

Figure 10. History of tritium concentration in precipitation at Kaitoke (near Wellington) and CFC concentrations in the Southern Hemisphere atmosphere.

Bore WWD8029 had a trace of tritium (0.053 ± 0.019 TU) giving a mean residence time of 165 years (DP = 0.2, 76% mixing).

These results show that the deep waters did not contain detectable tritium or CFC concentrations when first measured (as expected) and continue to show none. (And if anything, carbon-14 concentrations appear to be decreasing rather than increasing since 1988.) On the other hand, groundwater levels, which are drawn down during the summer, generally recover during the subsequent winter and early spring. Thus recharge is occurring, but this new water must be near the surface in the recharge areas and has not yet found its way to the aquifers tapped by the deep bores, or younger water is slowly penetrating into the deep aquifers but dilution with old water has been sufficient to keep concentrations at less than detectable levels up to now.

DISCUSSION

Nature of the System

The δ^{18}O values of the western and eastern zone groundwaters show a linear relationship with depth (Figure 6). This indicates the presence of two types of water, because the δ^{18}O values are not likely to change underground. Consideration of the likely mean δ^{18}O of rainfall in the Moutere Valley indicates that the shallow groundwater derives from present-day rainfall (around –6.8‰). Even water recharged at the highest altitudes in the Rosedale Hills (250-300 masl) would not have δ^{18}O values as negative as the deep water (-7.6‰).

The ^{14}C concentrations show a relationship with the $\delta^{18}O$ values (Figure 8), hence the shallow waters are young and the deep waters old in terms of ^{14}C. These are the modern and glacial water types identified above. The bores discharge either modern or mixtures of modern and glacial water. None of the western or eastern bores discharge pure glacial water. The glacial water is believed to have been recharged during the last glaciation (20-50,000 years ago).

Glacial water body

This water is deep and very old. During the last glacial maximum, the sea level was probably at least 120 m lower than present sea level and therefore was a long way (100s of kms) from its present position. If the aquifer does not connect to the sea, there could be a very large body of freshwater or mainly freshwater underlying part of Tasman Bay.

This body of water was probably recharged over a considerable period during the last glaciation. A minimum mean age can be estimated using equation 4. We assume that the ^{14}C activity of the deep water is less than 1 pmC, and that of the shallow water is 90 pmC. The bicarbonate concentrations in the deep and shallow waters are 200 and 60 mg/L respectively (Table 4), hence the dilution factor (q) is 60/200. These give a mean age of greater than 27,000 years.

This water is being drawn on and presumably the part under Moutere Valley will gradually be replenished by younger water. It is probable that there is very little natural flow through the deep aquifer (i.e. little natural flow towards outlets under the sea). The lack of ^{14}C indicates that no recharge has taken place into this water body since the last glaciation (i.e. during the Holocene). Some of the water is now being extracted by deep bores, causing marked drawdowns in water levels during the late summer. However, levels recover during the winter. Hence recharge is occurring, and there must be a tendency for shallow water to penetrate deeper as deep water is extracted.

Where repeated measurements have been made (WWD8404 and 8407), there appears to be a trend towards ages becoming older due to exploitation. This suggests that more of the deep water is being extracted because permeabilities at depth allow more efficient recovery (i.e. water flows more rapidly in the deep aquifer).

Shallow water body

The shallow water body is modern or pre-industrial Holocene water, and recharge has occurred before the advent of carbon-14 and tritium from nuclear weapons testing (i.e. the 1960s) for the bores sampled. The ages are mostly in the hundreds of years (Table 5). Recharge appears to have been relatively widespread, albeit at a very low rate. The evidence (including $\delta^{18}O$ values and chloride concentrations) suggests that rainfall has infiltrated into the hills both east and west of the Moutere Valley floor (i.e. into both the tm1 and tm2 outcrop units of Moutere Gravel) in the past.

Only sporadic traces of tritium and CFCs have been observed, and these are generally in shallow bores on the western hills and western side of the Moutere Valley floor. Tritium was observed in WWD8074 and 8085 in the Waiwhero area, and in 8223 and 8315 on the west side of the valley floor west of the fault. WWD8343 and 8407 (trace only) are the only eastern zone bores to contain tritium. Tritium was detected in the shallow bore on the Rosedale Hills (WWD8360) and in 8029 (trace) in the southern zone. CFC occurrences are consistent with the tritium detections. Hence in summary, the highest tritium concentrations are found in shallow groundwater in the hills west of the valley floor. This suggests that the most active recharge is in this region and very probably into the tm1 outcrop area (Thomas 1992, Figure 1). However, there is no direct geochemical evidence for the latter, because no such young water has yet reached bores tapping the Deep or Middle Moutere Aquifers.

A revised pattern of recharge and groundwater flow for the Moutere Aquifers is given in Figure 11 in light of this work. Rainfall recharge into the hills both west and east of the Moutere Valley is shown. (There could also be a recharge contribution from Waiwhero Stream on the west side.) But under the natural situation, this recharge is believed to be flowing at shallow or intermediate levels, leaving an undisturbed body of ice age water at deep levels. This pattern results from the present sea level and the expected lack of offshore outlets for water in the deep aquifer. Groundwater exploitation from deep bores will now be tending to draw shallow water deeper into the system.

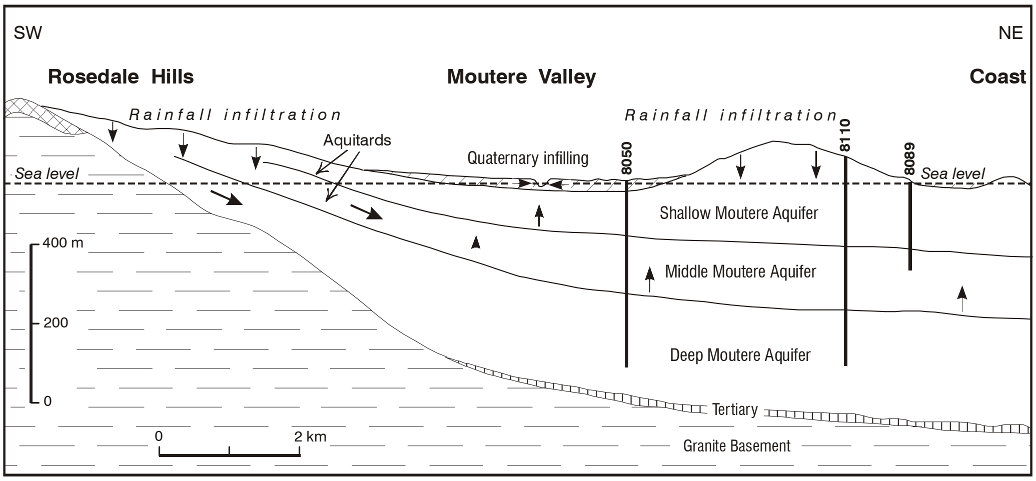

Figure 11. Revised recharge patterns for the Moutere aquifers in light of this work

CONCLUSIONS

Recharge to the Moutere Gravel aquifer system in the Moutere Valley was investigated by means of isotopic and chemical measurements. Bores up to 500 m deep tap three Moutere Gravel aquifers underlying the area. Shallow bores (50-100 m) have $\delta^{18}O$ in the range –6.8 ± 0.4‰ expected for present-day rainfall. Their carbon-14 concentrations are generally 90 ± 10 pmC indicating modern ages, i.e. water residence times of up to hundreds of years.

Deeper bores have more negative $\delta^{18}O$ values and lower ^{14}C concentrations resulting from input of much older water from depth in the western and eastern zones. The old deep water is believed to have been recharged in the Pleistocene during the last glaciation. This 'glacial' water has $\delta^{18}O$ of –7.6‰, and ^{14}C concentration of 0 pmC. Mixing of glacial and modern waters gives rise to the variations observed in the oxygen-18, carbon-14 and chemical concentrations in the bore waters. The chemical characteristics of the glacial water have been determined as end members on mixing plots between chemical components and $\delta^{18}O$. Sea level was much lower when the glacial water was recharged, and the sea would have been far from its present position. A large body of glacial water may be resident in the Moutere Gravel under the sea.

Recharge is provided by modern or pre-industrial water penetrating into the groundwater system at shallow levels. Measurements on this water give evidence on the patterns and rates of recharge. The distribution of $\delta^{18}O$ and chloride suggest that water has been recharged through both the tm1 and tm2 units of Moutere Gravel in the past few hundred years, but evidently at very low rates because of the ages. Young recharge is observed only on the hills west of the valley floor, but observations are lacking in the most probable recharge zone (the tm1 outcrop area in the Rosedale Hills). Under the natural situation, it is believed recharge water flowed at shallow or intermediate levels, leaving an undisturbed body of ice age water at deep levels. This pattern resulted from the present sea level and the expected lack of offshore outlets for water in the deep aquifer. However, groundwater exploitation from deep bores will now be tending to draw shallow water deeper into the system.

ACKNOWLEDGEMENTS

I thank Margaret Norris and Vanessa Trompetter for carbon isotope measurements, Rob van der Raaij for CFC measurements, and Carolyn Hume for draughting figures.

REFERENCES

Clark, I.D.; Fritz, P. 1997: Environmental isotopes in hydrogeology. Lewis Publishers, New York. 328 p.

Hulston, J.R.; Taylor, C.B.; Lyon, G.L.; Stewart, M.K.; Cox, M.A. 1981: Environmental isotopes in New Zealand hydrology. Part 2. Standards, measurement techniques and reporting of measurements for oxygen-18, deuterium and tritium in water. *New Zealand Journal of Science 24,* 313-322.

Lihou, Joanne C. 1992: Reinterpretation of seismic reflection data from the Moutere Depression, Nelson region, South Island, New Zealand. *New Zealand Journal of Geology and Geophysics 35*, 477-490.

Rattenbury, M.S., Cooper, R.A., Johnston, M.R. (compilers) 1998: Geology of the Nelson Area. Institute of Geological and Nuclear Sciences 1:250,000 geological map 9. (1 sheet + 67 p.) Lower Hutt, New Zealand.

Rosen, M.R. 2001: Hydrochemistry of New Zealand's aquifers. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White (*eds*). New Zealand Hydrological Society Inc., Wellington. Pp. 77-110.

Stewart, M.K.; Dicker, M.J.I.; Johnston, M.R. 1981: Environmental isotopes in New Zealand hydrology. Part 4. Oxygen isotope variations in subsurface waters of the Waimea Plains, Nelson. *New Zealand Journal of Science 24,* 339-348.

Stewart, M.K., Morgenstern, U. 2001: Age and source of groundwater from isotope tracers. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White (*eds*). New Zealand Hydrological Society Inc., Wellington. Pp. 161-183.

Stewart, M.K., Trompetter, V., van der Raaij, R 2002: Age and source of Canterbury Plains groundwater. Technical Report, Environment Canterbury. In press.

Thomas, J.T. 1989: Hydrogeology of the Moutere Valley, Nelson, New Zealand. Unpublished MSc Eng. Geol. Thesis. Department of Geology, University of Canterbury, New Zealand.

Thomas, J.T. 1991: Moutere Valley groundwater investigations 1989/1990. Unpublished Nelson Marlborough Regional report, 81 pp.

Thomas, J.T. 1992: Hydrogeology of the Moutere Valley with emphasis on groundwater recharge. Unpublished Tasman District Council report, 8 pp.

Thomas, J.T. 2001: Groundwater resources of the Tasman Region. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White (*eds*). New Zealand Hydrological Society Inc., Wellington. Pp. 411-425.

Table 1. Details of bores sampled in the Moutere Valley

TDC Well No.	Date	Well Owner	Zone	Grid Reference	Well Depth	Screened Depth	Aquifer
Western							
?	Nov-76	Jacksons	W	S14:356-433	175.3		
8007	25-Jan-02	Rowntree	W	N27:09300646	227	41-227	SMA/MMA
8058	17-Jun-99	Urquhart	W	N27: 0857-0535	205	55 - 205	MMA
8074	17-Jun-99	McEwans	W	N27:0419-0225	40.5	9.1 - 40	MMA
8075	01-Feb-98	Hunt	W	N27:0398-0127	60	25 - 57	DMA
8085	16-Jun-99	Meadows	W	N27:0360-0102	8.2	n.a.	MMA
8097	23-Jan-02	Palmers	W	N27:0740-0480	102	49.5 - 102	MMA
8223	24-Aug-00	Clark	W	N27: 0809-0354	51	22 - 42	SMA
8315	14-Jun-84	Fry	W	N27:07840434	61.5	?	SMA
8364	Nov-76	Glenavon F	W	N27:08150430	76.8	?15 -76.8	SMA/MMA
8364	27-May-88	Glenavon F	W	N27:08150430	76.8	?15-76.8	SMA/MMA
8365	Nov-76	Glenavon F (artesian	W	N27:07450460	56.7	21-56	SMA
8404	27-May-88	Wrattens	W	N27:08690455	236	42-236	MMA
8404	17-Nov-88	Wrattens	W	N27:0869-0455	236	42 - 236	MMA
8404	15-Jun-99	Wrattens	W	N27:0869-0455	236	42 - 236	MMA
8404	23-Jan-02	Wrattens	W	N27:0869-0455	236	42 - 236	MMA
8419	27-May-88	Jacksons	W	N27:08400661	165	30 - 143	MMA
8419	25-Jan-02	Jacksons	W	N27:0840-0661	165	30 - 143	SMA/MMA
8800	9-May-84	Edwards Rd	W	N27:07000369	233	42 - 147	MMA
8800	26-May-84	Edwards Rd	W	N27:07000369	233	42 - 197	MMA
8800	11-Jun-84	Edwards Rd	W	N27:07000369	233	200 - 203	n.a.
8800	16-Jun-99	Edwards Road (C & J)	W	N27 0700-0369	232	42 - 197	MMA
8800	23-Jan-02	Edwards Rd	W	N27 0700-0369	233	42 - 197	MMA
Eastern							
8012	24-Aug-00	Wratten/Naylor	E	N27: 0859-0364	385	53 - 385	MMA & DMA
8023	17-Jun-99	Rowling	E	N27:1100-0585	301	54 - 301	MMA & DMA
8050	23-Jan-02	TDC (Wilson Rd)	E	N27:0950-0054	505	50 - 490	MMA/DMA
8089	25-Jan-02	Johnston	E	N27:1376-0254	201	53 - 201	SMA/MMA
8110	1-May-02	Weka Rd	E	N27:1215-0228	501	61-500	MMA/DMA
8343	24-Aug-00	Fisher	E	N27: 0750-0250	60	26 - 56	SMA
8355	23-Jan-02	Hawthorne	E	N27:07980295	59.5	25-55.1	SMA
8391	27-May-88	Burnaby	E	N27:12050490	80	0 - 80?	SMA
8407	27-May-88	Williams	E	N27:09130137	337	40 - 220	DMA
8407	17-Nov-88	Williams	E	N27:0913-0137	337	40 - 220	DMA
8407	15-Jun-99	Williams	E	N27:0913-0137	337	40 - 220	DMA
8407	23-Jan-02	Williams	E	N27:0913-0137	337	40 - 220	DMA
8423	27-May-88	Kirks	E	N27:09400330	175	41 -152	MMA
8428	25-Jan-02	Urquhart	E	N27:1095-0557	50.5	12 - 35	SMA
8429	25-Jan-02	Urquhart	E	N27:1090-0545	47	45 - 75?	SMA
Southern							
8029	24-Aug-00	Evans	S	N27: 1360-9398	542	100 - 532	MMA & DMA
8054	24-Aug-00	Middleton	S	N27: 1755-9219	268	58.5 - 268	MMA & DMA
8107	23-Jan-02	TDC (Upper Moutere)	S	N27:10849303	501	61-500	MMA/DMA
8108	1-May-02	Redwood	S	N27:1656-8940	502	61-501	MMA/DMA
8109	1-May-02	Stringer	S	N27:1644-9220	72	72-512	SMA/MMA/DMA
8360	27-May-88	Hill	E	N27:09259335	55	10 to 45	SMA
8402	1-Dec-86	Tuckers	E	N27:12709620	214	42-214	DMA

Table 2. Isotopic and CFC concentrations of waters from the Moutere Valley

TDC Well	Date	Well	δ18O	14C	δ13C	Tritium	CFC-11	CFC-12
No.		Depth	‰	pmC[1]	‰	TU	pptv	pptv
Western								
?	Nov-76	175.3	-7.24					
8007	25-Jan-02	227	-7.17	54.4 ± 0.4	-22.0			
8058	17-Jun-99	205	-7.34				0.9	0.1
8074	17-Jun-99	40.5	-7.11	79.6 ± 0.6	-19.0	1.94 ± 0.06	156.8	365.8
8075	01-Feb-98	60	-7.04				-0.5	16.6
8085	16-Jun-99	8.2	-6.42			2.21 ± 0.06	200.8	466.8
8097	23-Jan-02	102	-6.97	89.1 ± 0.6	-21.6		0.5	0.1
8223	24-Aug-00	51	-7.00	69.1 ± 0.5	-22.6	0.070 ± 0.016	1.5	57
8315	14-Jun-84	61.5				0.32 ± 0.11		
8364	Nov-76	76.8	-6.91					
8364	27-May-88	76.8	-7.03			0.03 ± 0.08		
8365	Nov-76	56.7	-7.00					
8404	27-May-88	236	-7.31			0.13 ± 0.08		
8404	17-Nov-88	236		67.4 ± 0.8	-24.0			
8404	15-Jun-99	236	-7.27	62.4 ± 0.4	-22.2	0.025 ± 0.019		
8404	23-Jan-02	236	-7.27	62.8 ±0.6	-22.1			
8419	27-May-88	165	-7.05			0.04 ± 0.07		
8419	25-Jan-02	165	-6.79	85.4 ± 0.8	-22.4			
8800	9-May-84	233				0.12 ± 0.12		
8800	26-May-84	233				0.04 ± 0.11		
8800	11-Jun-84	233				0.14 ± 0.12		
8800	16-Jun-99	232	-7.05				0.9	3.7
8800	23-Jan-02	233	-6.97	89.5 ± 0.6	-22.4	-0.016 ± 0.021		
Eastern								
8012	24-Aug-00	385	-7.20			0.016 ± 0.018		
8023	17-Jun-99	301	-7.04				0.6	3.5
8050	23-Jan-02	505	-7.46	21.6 ± 0.2	-21.8	-0.011 ± 0.017		
8089	25-Jan-02	201	-7.06	8.6 ± 0.1	-21.5			
8110	1-May-02	501	-7.38	21.0 ± 0.2	-22.0			
8343	24-Aug-00	60	-6.74	96.3 ± 0.7	-19.7	0.894 ± 0.034	79	348.2
8355	23-Jan-02	59.5	-6.71	88.6 ± 0.7	-20.7	0.008 ± 0.020	0.9	2.3
8391	27-May-88	80	-7.12			0.12 ± 0.06		
8407	27-May-88	337	-7.41			0.13 ± 0.05		
8407	17-Nov-88	337		50.7 ± 0.7	-21.7			
8407	15-Jun-99	337	-7.36	34.5 ± 0.3	-20.0	0.050 ± 0.016	0.3	2.4
8407	23-Jan-02	337	-7.34	43.3 ± 0.3	-22.4			
8423	27-May-88	175	-7.23			0.08 ± 0.08		
8428	25-Jan-02	50.5	-6.89					
8429	25-Jan-02	47	-6.91	93.0 ±	-20.5			
Southern								
8029	24-Aug-00	542	-6.53	92.9 ± 0.7	-20.7	0.053 ± 0.019		
8054	24-Aug-00	268	-7.09	27.6 ± 0.2	-21.7	0.016 ± 0.017		
8107	23-Jan-02	501	-7.09	44.7 ± 0.3	-13.3		1.0	2.4
8108	1-May-02	502	-6.80	2.43 ± 0.07	-22.5			
8109	1-May-02	72	-8.28	2.45 ± 0.07	-21.6			
8360	27-May-88	55	-7.15			1.21 ± 0.10		
8402	1-Dec-86	214	-7.14			0.00 ± 0.08		

Table 3. Chemical compositions of waters from the Moutere Valley

Well No.	Sampling Date	pH	CO_2 mg/L	HCO_3 mg/L	Cl mg/L	SO_4 mg/L	Na mg/L	K mg/L	Ca mg/L	Mg mg/L	NO_3 mg/L	Phos mg/L	Fe mg/L	Mn mg/L	SiO_2 mg/L	DO_2 mg/L	T °C
Western																	
8007	14-May-90	6.5	11	134	53	8	45	1.9	23.6	11	0.028	0.12	2.7	0.38	57	--	14.1
8058																	
8074				60													
8075																	
8085																	
8097	23-Jan-02	6.6	58*	98	5.9	1.8	18	1.2	13	6.9	<.02	0.19	5.8	0.10	--	--	
8223				183													
8315																	
8364																	
8364	27-May-88	6.7	53	110	6	4.2	18.5	1.2	11.7	7.1	<.001	0.18	4.0	0.10	11		
8365																	
8404	27-May-88	7.0	38	124	5.1	8.3	20.2	1.1	16.3	6	0.014	0.13	3.6	0.25	12	0.75	13.0
8404				127													
8404	15-Jun-99	6.7		127	4.7	2.8	21	1.3	16.4	6.8	<.02	--	3.4	0.32	70	--	13.7
8404	20-Jun-01	6.8	32*	128	5.2	3	21	1.1	15.8	6.7	<.02	--	3.7	0.37	66	--	13.6
8419	27-May-88	6.8	43	115	42	3.3	24.5	1	22.3	10.7	0.004	0.086	3.1	0.12	9.0	4.8	12.8
8419	25-Jan-02	6.8	59*	82	18	3.3	18	1	14	8.4	<.02	0.096	2.6	0.08			
8800	7-May-84	6.3	74	105	4.7	2.9					0.01						
8800	7-May-84	6.3	54	96	4.7	2.9	17	1.1	12	6.2	0.01	0.18	3.3	0.11	--		
8800	7-May-84	6.3	27	139	4.2	0.1	33	2.5	17	3.9	<.001						
8800																	
8800	7-May-84	6.3	54	96	4.7	2.9	17	1.1	12	6.2	0.01						
Eastern																	
8012																	
8023																	
8050	30-Nov-93	8.4	<1	150	130	1.1	73	8	25	2.4	0.1	0.14	0.12	0.03	16	--	--
8089	25-Jan-02	8.0	18*	110	12	1.3	31	0.9	23	0.8	<.02	0.010	<0.05	0.02			
8110	22-Mar-02	8.4	<1.0	120	9.9	1.8	33	0.9	21.8	2.34	0.003	0.072	0.596	0.027			15.0
8343				99													
8355	23-Jan-02	6.7	48*	69	5.9	3.9	15	1	8.6	5.7	<.02	0.11	2.4	0.06			
8391	27-Mar-88	6.8	48	120	15	5.8	23.6	1.3	12.4	9.4	0.008	0.042	1.6	0.12	8.7		
8407	27-May-88	7.2	3	181	6	1.4	25.4	0.7	28.7	6.7	0.002	0.023	0.06	0.02	4.8	3.8	11.5
8407				180													
8407	15-Jun-99	7.9		179	5.8	2.1	26	0.4	30	7	<.02		<.02	0.01			13.3
8407	20-Jun-01	7.7	0*	179	5.7	2.2	25	0.5	30	6.7	<.02		0.1	0.01			
8423	27-May-88	6.9	34	140	11	3.8	25	1.5	15.2	10	0.008	0.053	1.5	0.16	9.9	2.6	12.8
8428	30-May-88	6.8	19	60	7.1	4.4	15	0.9	4.4	4.9	0.14	0.042	0.10	0.03	8.2	7.2	13.5
8429	25-Jan-02	6.2	61*	46	6.6	4.6	16	0.8	4.7	3.2	0.11	0.012	<0.05	<0.01			
Southern																	
8029				171													
8054				194													
8107	4-Sep-01	7.8	3.9	130	8.3	2	32	1	22	4	0.025	0.13	0.08	<0.01	--	--	
8108	6-Nov-01	8.3	<1.0	130	9.4	1.8	38	0.55	14	0.58	0.003	0.082	<0.05	0.02	--	--	14.8
8109	2-Jan-00	8.1	1.7	110	6.2	2.3	31	1.2	15.1	2.68	0.009	0.14	0.3	0.02	--	--	16.9
8360	27-May-88	6.5	52	34	7.8	2.5	11.4	0.8	5.2	0.9	0.56	0.25	<0.05	<0.01	11		12.9
8402	14-Oct-86	7.1	26	194	11	2.3	21.9	1.3	33	20	0.055	0.022	0.07	<0.04	--		13.7

Table 4. Characteristics of the modern and glacial end member waters.

Quantity	**Modern Water**	**Glacial Water**
Age	Holocene	Pleistocene
Approximate depth	0 - 100 m	500 - 600 m
$\delta^{18}O$	-6.8 ‰	-7.6 ‰
Carbon-14	90 pmC	0 pmC
Chloride	5.5 - 18 mg/L	5.5 mg/L
Bicarbonate	60 mg/L	200 mg/L
Sulphate	2 - 7 mg/L	0 mg/L
Sodium	16 - 33 mg/L	30 mg/L
Potassium	1 - 3 mg/L	0.2 mg/L
Calcium	4 mg/L	36 mg/L
Silica	0 mg/L	20 mg/L
Magnesium	0 - 18 mg/L	3 mg/L
Iron	0 - 7 mg/L	0 mg/L
Manganese	0 - 0.8 mg/L	0 mg/L
Tritium	0 - 2.2 TU	0 TU
CFC-11	0 - 200 pptv	0 pptv
CFC-12	0 - 467 pptv	0 pptv

Table 5. Interpretation of tritium and CFC residence times for the modern water component

Table 5: Interpretation of tritium and CFC residence times for the modern water component using the dispersion mixing model (DP = 0.2

TDC Well	Date	Well	Well	Screened	Aquifer	$\delta^{18}O$	Ratio*	Tritium		CFC-11		CFC-12		Mean
No.		Owner	Depth	Depth		‰		TU	Model	pptv	Model	pptv	Model	Age
									Year		Year		Year	Year
Western														
8058	17-Jun-99	Urquhart	205	55 - 205	MMA	-7.34	30/70			0.9	>110	0.1	>110	>110
8074	17-Jun-99	McEwans	40.5	9.1 - 40	MMA	-7.11	100/0	1.94 ± 0.06	13 or 37	156.8	16	365.8	12	14
8075	01-Feb-98	Hunt	60	25 - 57	DMA	-7.04	100/0			-0.5	>110	16.6	77	>110
8085	16-Jun-99	Meadows	8.2	n.a.	MMA	-6.42	100/0	2.21 ± 0.06	16 or 32	200.8	12	466.8	7	14
8097	23-Jan-02	Palmers	102	49.5 - 102	MMA	-6.97	100/0			0.5	>110	0.1	>110	>110
8223	24-Aug-00	Clark	51	22 - 42	SMA	-7.00	80/20	0.070 ± 0.016	153	1.5	>110	57	53	153
8315	14-Jun-84	Fry	61.5	?	SMA			0.32 ± 0.11	>90					>90
8364	27-May-88	Glenavon F	76.8	?15-76.8	SMA/MMA	-7.03	90/10	0.03 ± 0.08	>90					>90
8404	27-May-88	Wrattens	236	42-236	MMA	-7.31	50/50	0.13 ± 0.08	>90					>90
8404	15-Jun-99	Wrattens	236	42 - 236	MMA	-7.27	50/50	0.025 ± 0.019	>150					>150
8419	27-May-88	Jacksons	165	30 - 143	MMA	-7.05	70/30	0.04 ± 0.07	>90					>90
8800	9-May-84	Edwards Rd	233	42 - 147	MMA			0.12 ± 0.12	>90					>90
8800	26-May-84	Edwards Rd	233	42 - 197	MMA			0.04 ± 0.11	>90					>90
8800	11-Jun-84	Edwards Rd	233	200 - 203	n.a.			0.14 ± 0.12	>90					>90
8800	16-Jun-99	Edwards Road (C & J)	232	42 - 197	MMA	-7.05	70/30			0.9	>110	3.7	>110	>110
8800	23-Jan-02	Edwards Rd	233	42 - 197	MMA	-6.97	80/20	-0.016 ± 0.021	>150					>150
Eastern														
8012	24-Aug-00	Wratten/Naylor	385	53 - 385	MMA & DMA	-7.20	50/50	0.016 ± 0.018	>150					>150
8023	17-Jun-99	Rowling	301	54 - 301	MMA & DMA	-7.04	70/30			0.6	>110	3.5	>110	>110
8050	23-Jan-02	TDC (Wilson Rd)	505	50 - 490	MMA/DMA	-7.46	20/80	-0.011 ± 0.017	>150					>150
8343	24-Aug-00	Fisher	60	26 - 56	SMA	-6.74	100/0	0.894 ± 0.034	67	79	32	348.2	15	?
8355	23-Jan-02	Hawthorne	59.5	25-55.1	SMA	-6.71	100/0	0.008 ± 0.020	>150	0.9	>110	2.3	>110	>150
8391	27-May-88	Burnaby	80	0 - 80?	SMA	-7.12	60/40	0.12 ± 0.06	>90					>90
8407	15-Jun-99	Williams	337	40 - 220	DMA	-7.36	30/70	0.050 ± 0.016	120	0.3	>110	2.4	>110	120
8423	27-May-88	Kirks	175	41 -152	MMA	-7.23	50/50	0.08 ± 0.08	>90					>90
Southern														
8029	24-Aug-00	Evans	542	100 - 532	MMA & DMA	-6.53	100/0	0.053 ± 0.019	165					165
8054	24-Aug-00	Middleton	268	58.5 - 268	MMA & DMA	-7.09		0.016 ± 0.017	>150					>150
8107	23-Jan-02	TDC (Upper Moutere)	501	61-500	MMA/DMA	-7.09				1.0	>110	2.4	>110	>110
8360	27-May-88	Hill	55	10 to 45	SMA	-7.15		1.21 ± 0.10	57					57
8402	1-Dec-86	Tuckers	214	42-214	DMA	-7.14		0.00 ± 0.08	>90					>90

* Ratio of modern to glacial water