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Environmental isotopes in New Zealand hydrology
4 Oxygen isotope variations in subsurface waters of the Waimea Plains, Nelson

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Abstract Oxygen isotope measurements of ground and surface waters of the Waimea Plains, Nelson, have been used to identify sources of water in aquifers beneath the plains. Major rivers flowing onto the plains are from higher-altitude catchments (maximum altitude 2000 m) and have $\delta^{18}O \simeq -7.2‰$, whereas rainfall on the plains and adjacent low-altitude catchment streams have $\delta^{18}O \simeq -6.2‰$. The $\delta^{18}O$ measurements indicate that the 3 major aquifer units, the "Lower Confined Aquifers" and the "Upper Confined Aquifers" in the Hope Gravel (Late Pleistocene) and the "Unconfined Aquifers" in the Appleby Gravel (Holocene) are recharged from different sources. The "Lower Confined Aquifers" probably receive slow recharge in the south near Brightwater. The "Upper Confined Aquifers" are recharged, in the south, from the Wairoa River and locally in the north are connected with the unconfined aquifers. The "Unconfined Aquifers" are recharged from the Waimea River and, away from the river, from rainfall. Intermixing of water, via multiple screened wells, between the various aquifers is also indicated.

Keywords Stable isotopes; hydrology; rainfall; aquifers; groundwater; surface waters; oxygen-18; deuterium; Waimea Plains, Nelson.

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INTRODUCTION

The Waimea Plains, an area of intensive farming and horticulture of some 60 km², lies to the southwest of Nelson city and was formed in the Late Quaternary by terrestrial gravel deposition by the Waimea River and its tributaries the Wairoa and Wai-iti rivers (Fig. 1, 2). Underlying the plains there are two major confined aquifer units, and, adjacent to the rivers, there are important unconfined aquifers. As part of the Nelson Catchment Board's investigation into the groundwater resource of the plains, oxygen isotope measurements of water samples, collected regularly from wells, rivers, streams, and rainfall, on and adjacent to the plains, are used in an attempt to identify the sources of the groundwater.

Although the watershed of the Waimea River is relatively small (800 km²), there is a considerable topographic contrast between the Wairoa and the upper part of the Wai-iti catchments compared to the Waimea Plains and the area to the west (Fig. 1). Consequently rainfall precipitated on and adjacent to the Waimea Plains has greater oxygen-18 content than rain (and snow) precipitated at altitudes of up to 2000 m, and this is reflected in the isotope ratios in the various tributaries of the Waimea River.

BASIS FOR THE OXYGEN ISOTOPE MEASUREMENTS

The decrease in ^{18}O content of precipitation with altitude results from the difference in physical properties between the water containing the heavy isotope ($H_2{}^{18}O$) and the predominant water species ($H_2{}^{16}O$). Sea water has an almost constant oxygen-18 composition of about $^{18}O/^{16}O = 2000 \times 10^{-6}$. Marine vapour produced by evaporation from sea water has less ^{18}O than sea water because $H_2{}^{18}O$ has lower vapour pressure than $H_2{}^{16}O$. Condensation from this vapour produces rain which initially has an ^{18}O content close to that of sea water, but as vapour is removed from the air by condensation (as the air passes over land), precipitation is formed at increasingly lower temperatures, and its ^{18}O content also decreases (Stewart & Taylor 1981). In addition there is superimposed on this an effect due to seasonal variations of temperature.

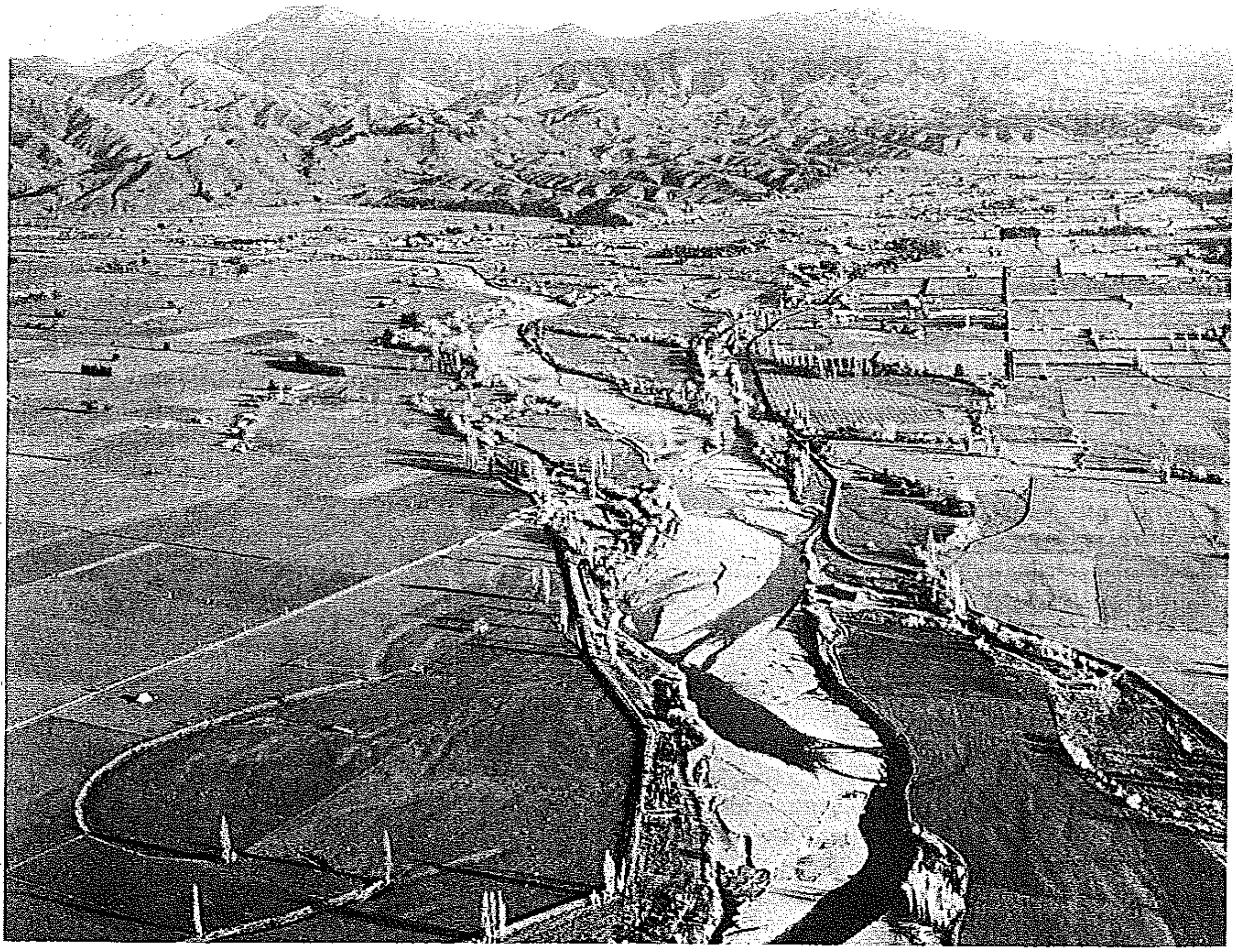

Fig. 1 The Waimea Plains looking south towards the junction, near Brightwater, of the Wai-iti (right distance) and Wairoa rivers (left distance) draining the mountains in the distance. The boundary between the Appleby Gravel (Holocene), adjacent to the river, and the Hope Gravel (late Pleistocene) is the easternmost (left centre) terrace riser (Burkes Bank) on which is built a number of houses.

The oxygen-18 abundance is expressed as a δ value relative to a standard (in parts per thousand, ‰),

$$\delta^{18}O‰ = \left(\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{standard}} - 1 \right) \times 1000$$

The standard is V-SMOW (Vienna-Standard Mean Ocean Water) and the measurement error is ±0.15‰.

HYDROGEOLOGY

The Late Quaternary terrestrial gravel, up to 60 m thick beneath the Waimea Plains, has been divided, largely on information obtained by exploratory drilling, into several formations (Johnston 1979, 1981). These unconformably overlie clay-bound Moutere Gravel (Fig. 2, 3) of late Pliocene or Early Pleistocene age. Neither the Moutere Gravel or older formations beneath the gravel are likely to yield appreciable quantities of groundwater. Within the Late Quaternary only the Hope Gravel (late Pleistocene) and Appleby Gravel (Holocene) are important as a source of groundwater.

The Hope Gravel, up to 55 m thick, occupies most of the valley cut in the Moutere Gravel by the Waimea River and is dominantly a tight, poorly sorted, clay-bound gravel. However, at 2 levels beneath the plains it contains large lenses of sorted, less clay-bound gravel which, along with minor lenses elsewhere in the formation, contain confined aquifers. In the east the Hope Gravel interdigitates with, and is partly overlain by, Stoke Fan Gravel derived from the Barnicoat Range (500 m) in the east of the plains (Fig. 2, 3).

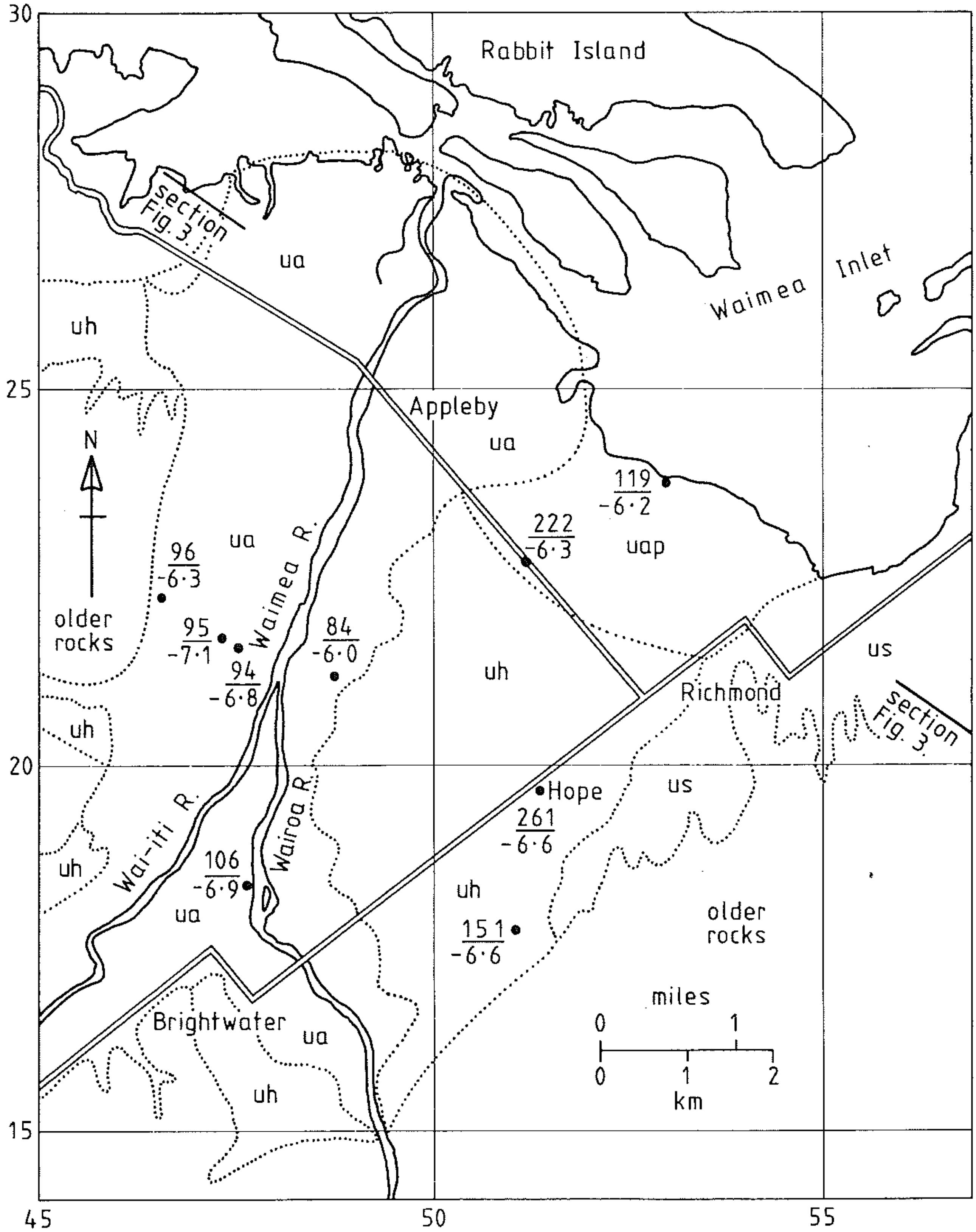

Fig. 2 Map of the Waimea Plains showing gravel units exposed at the surface (ua—Appleby Gravel, uap—Pugh Gravel Member, us—Stoke Fan Gravel, uh—Hope Gravel; after Johnston 1979). The $\delta^{18}O$ values (‰) of water from unconfined aquifers in these gravels are shown.

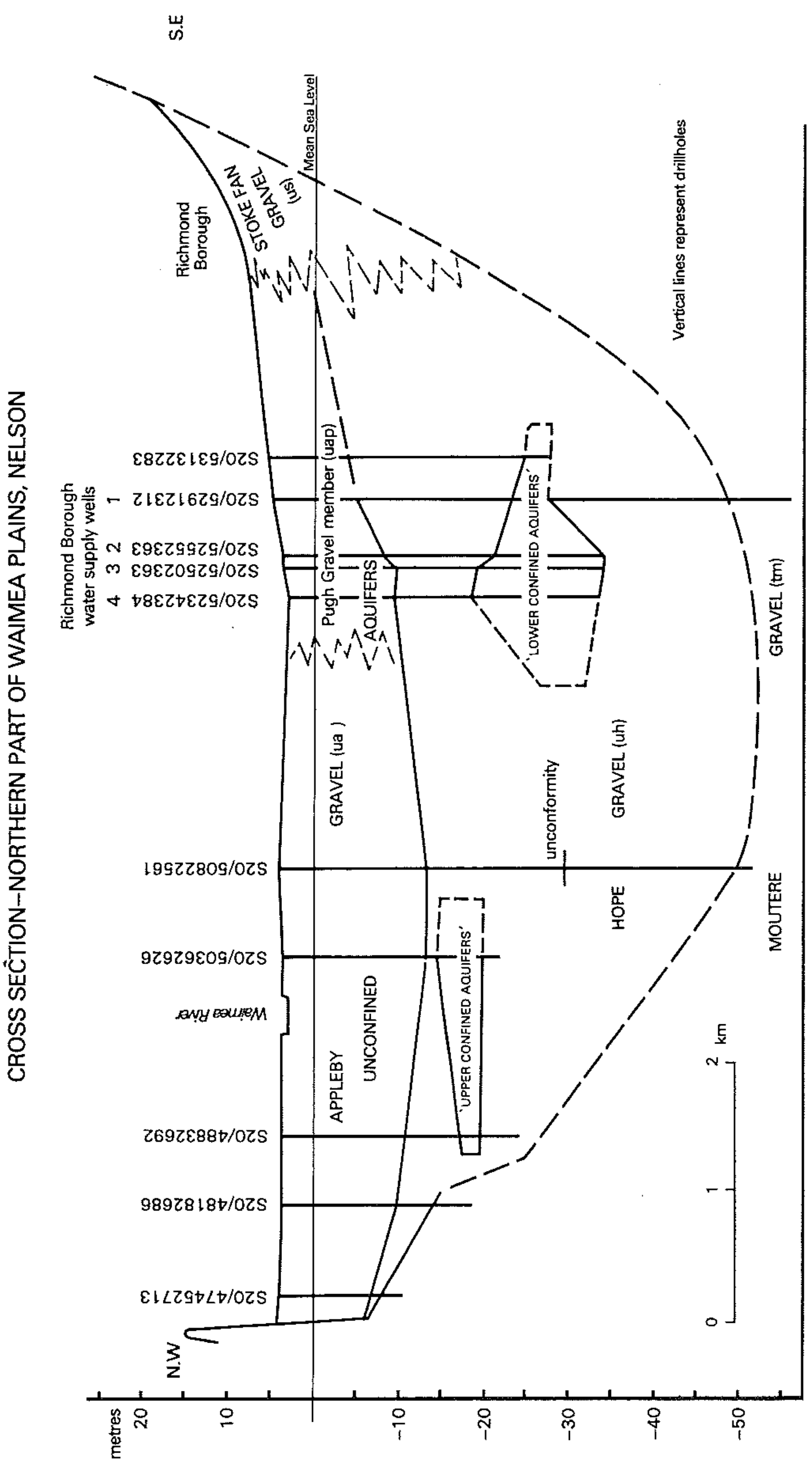

Fig. 3 Diagramatic cross-section across the northern part of the Waimea Plains (from Johnston 1979). For line of section see Fig. 2.

After deposition of the Hope Gravel, the rivers cut down into and reworked the surface gravel and deposited the well-sorted Appleby Gravel in the delta of the Waimea River. Adjacent to the coast the sea removed the upper part of the Hope Gravel to form a sea cliff, up to 12 m high, that extends eastward from the Waimea River near Appleby towards Richmond (Fig. 2). On the seaward side of this cliff, while the Appleby Gravel was being deposited, small streams draining the eastern part of the Waimea Plains deposited relatively poorly sorted gravel mapped as the Pugh Gravel Member of the Appleby Gravel. The Appleby Gravel is generally highly permeable and forms unconfined aquifers.

Confined aquifers

The large lenses of sorted gravel within the Hope Gravel are, on the basis of their depth beneath the surface, divided into 2 major units: the "Lower Confined Aquifers" and the "Upper Confined Aquifers" (Johnston 1979) and have been described more fully by Dicker (1980). Each unit consists of a number of aquifers separated by less permeable, commonly sandy gravel.

The unit embracing the "Lower Confined Aquifers" at a depth of about 30–40 m below the surface at the coast (Fig. 3) extends southwest almost to the mouth of the Wairoa Gorge (Fig. 4) where it is at a depth of 26 m. The unit has not been located in holes drilled in the Wai-iti Valley or in the Waimea Inlet. In the north the unit is 1.8 km wide, and it decreases to 0.9 km near the gorge. Water in the unit is artesian at the coast with a tidal influence of 1.5 m, reducing to 10 mm inland (well 105 near Brightwater). The static levels are very low indicating that there is little recharge from the Wairoa River. Water quality is generally good, although near Hope (Fig. 2) nitrate levels are as high as 28 mg/L, and in the north levels of 10 mg/L have been recorded. The aquifers provide all the water for Richmond Borough in the northeast of the plains, and are used extensively for irrigation on the plains.

The "Upper Confined Aquifers" extend south from beneath the Waimea Inlet at a depth of about 18–32 m (Fig. 3) to the mouth of the Wairoa Gorge (Fig. 5) where the unit is within a few metres of the surface. Like the "Lower Confined Aquifers", the unit has not been located in the Wai-iti Valley. Beneath the plains the unit is of similar dimension to the "Lower Confined Aquifers", but beneath the Waimea Inlet it widens considerably into a now buried delta of the Waimea River. Between Appleby and the coast, much of the clay-bound Hope Gravel capping the unit has been removed so that the Appleby Gravel rests on the "Upper Confined Aquifers" and all the aquifers become one hydraulic unit. Further north where Holocene marine sediments overlie the buried delta, infiltration of salt water to the aquifers has occurred. As a result the aquifers contain up to 6000 mg/L of chloride, are not artesian, and show a large tidal fluctuation in static level. Beneath the Waimea Plains the aquifers contain fresh water with a nitrate content similar to the water in the "Lower Confined Aquifers". Static level measurements indicate recharge from the Wairoa River at the mouth of the gorge where the capping gravels are absent and the Appleby Gravel overlies the unit (Dicker 1980).

At other levels within the Hope Gravel, particularly within 15 m of the surface, and in the Stoke Fan Gravel, water-bearing gravels no more than 0.4 m thick, form minor confined aquifers. The aquifers are not likely to be continuous, and their distribution is not well-defined or predictable. In the Hope Gravel in the southeast and in the Stoke Fan Gravel they commonly fail during periods of prolonged dry weather. Northeast of the state highway near Appleby the now buried sea cliff separating the Hope Gravel and the Pugh Gravel Member of the Appleby Gravel truncates some of these minor aquifers. Water from the aquifers rises to the surface and partly recharges the unconfined aquifers in the Pugh Gravel. Geological data and water analyses suggest that some of these aquifers in the Hope area are connected to the deeper confined aquifer units.

Unconfined aquifers

The unconfined aquifers are within the Appleby Gravel and, adjacent to the coast between the Waimea River delta and Richmond, the Pugh Gravel Member (Fig. 2, 3). The gravel is up to 14 m thick on the coast but thins inland to 6 m thick in the lower Wai-iti valley and 3 m thick at the Brightwater Bridge over the Wairoa River. Except near the mouth of the Wairoa Gorge and near Appleby the unconfined aquifers rest unconformably on clay-bound gravel with no appreciable loss of water into the Hope Gravel. Water yield from the aquifers is generally high, but in the Pugh Gravel Member permeability and consequently water yield decreases rapidly in an easterly direction.

ISOTOPE RESULTS AND DISCUSSION

Results of oxygen-18 measurements of samples collected between November 1974 and January 1977 are given in Table 1. Some of the results are average values (with standard deviations) over a number of samples collected at monthly intervals, while others are from 1 or 2 samplings.

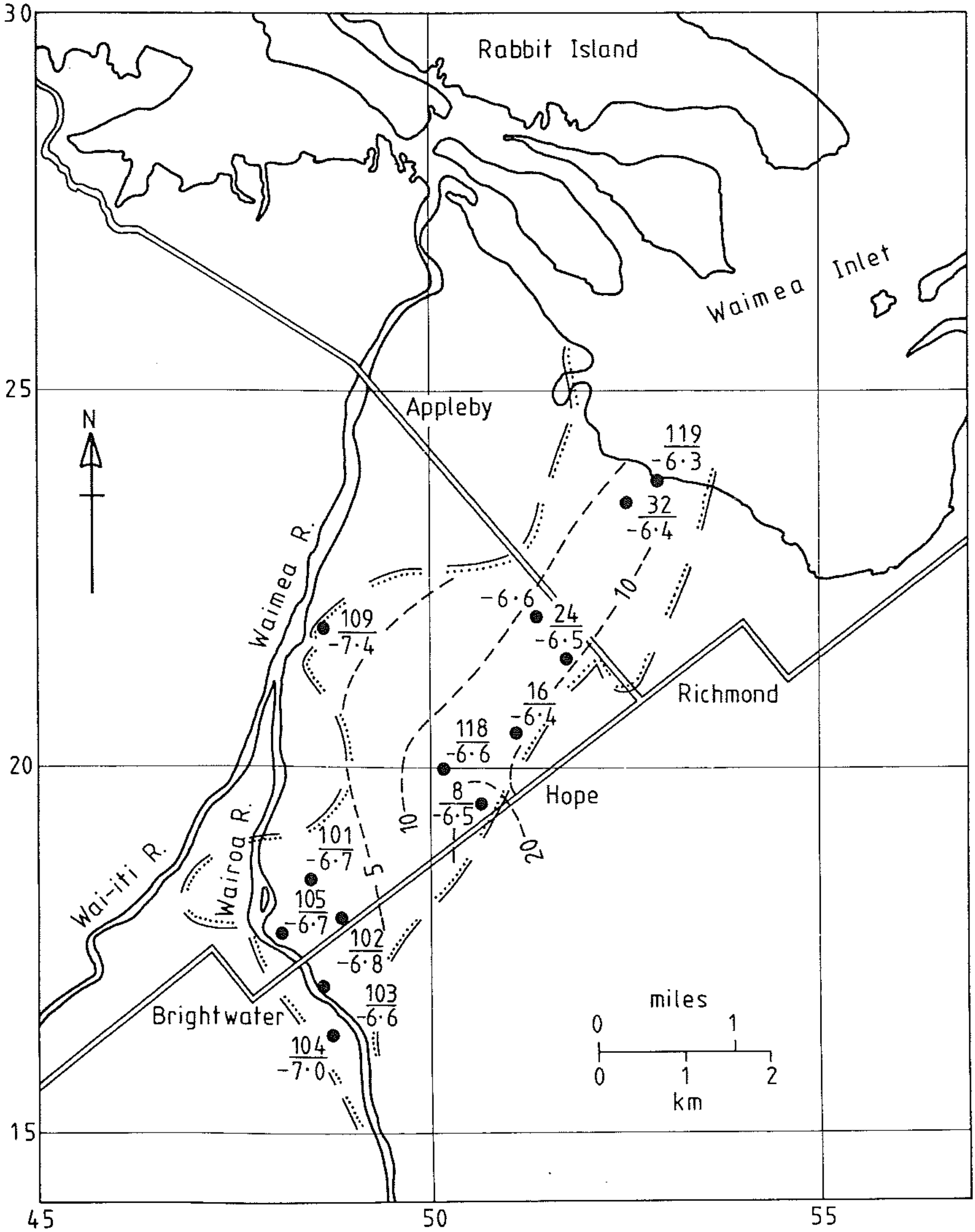

Fig. 4 Map showing $\delta^{18}O$ values (‰) of water in wells penetrating the "Lower Confined Aquifers" (lca). Contours of NO_3-N content (mg/L) are from Dicker (1980).

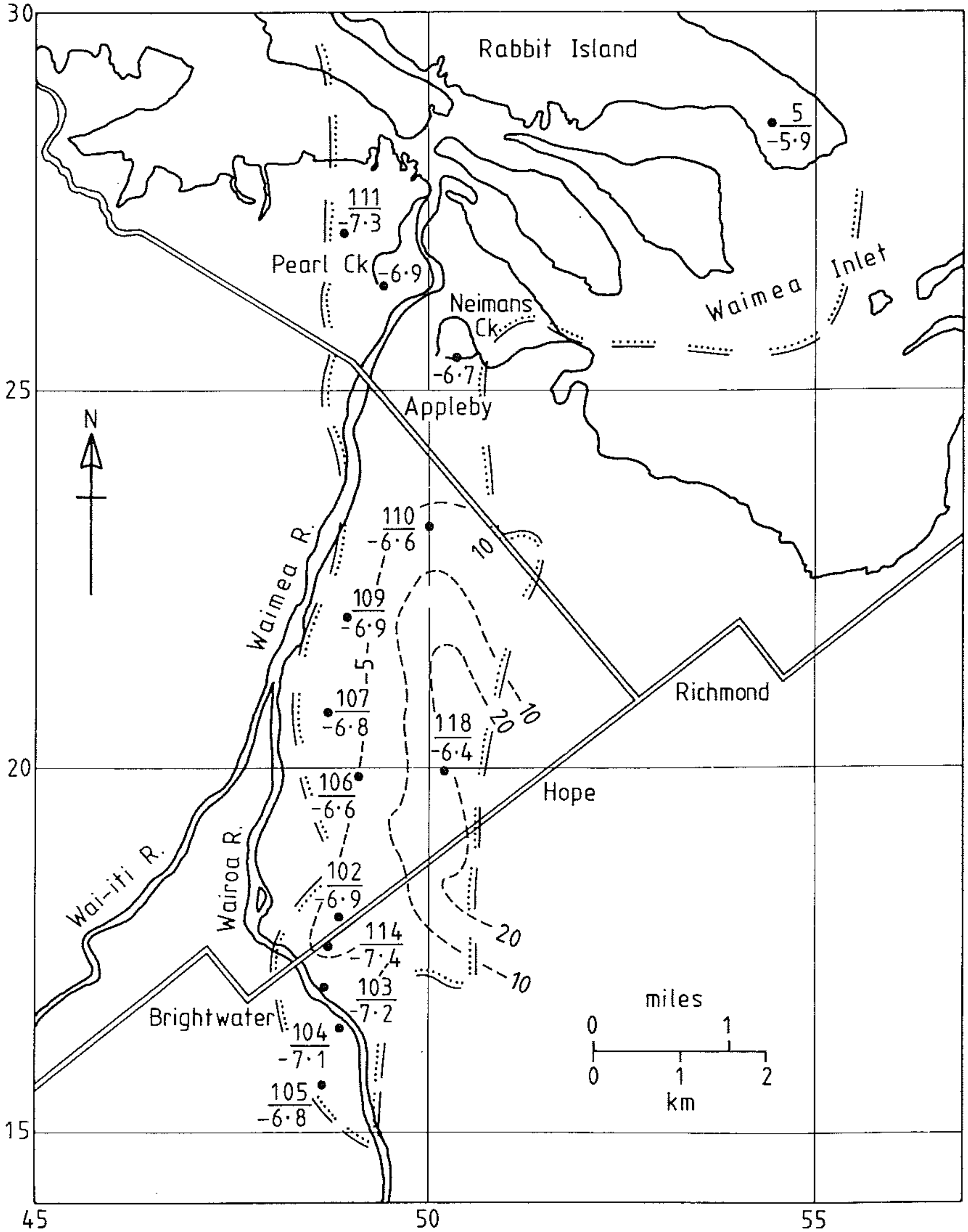

Fig. 5 Map showing $\delta^{18}O$ values (‰) of water in wells penetrating the "Upper Confined Aquifers" (uca). Contours of NO_3-N (mg/L) are from Dicker (1980).

Table 1 Sample description and oxygen isotope content of waters from the Waimea Plains.

Description	Well no.	Location Ref.NZGS Map S20	Sampling period	No. of samples	$\delta^{18}O$ ‰	Comment
Rainfall						
Rain gauge at Roding Dam		-	1975	12	-6.18 ± 1.37	Monthly samples weighted average
Rain gauge at N.C.B. Richmond		528210	1976	12	-6.28 ± 0.70	Monthly samples unweighted average
Rivers and streams						
Wai-iti River		364112	Nov 74-Nov 75	13	-7.22 ± 0.23	Monthly samples
Wairoa River		492149	"	13	-7.21 ± 0.72	" "
Waimea River		491236	Jan 75-Nov 76	21	-7.20 ± 0.35	" "
Jimmy Lee Creek		548202	June 75	1	-6.3	)
Malcolm Creek		534192	June 75	1	-6.1	) Streams from east of
Creek		525184	June 75	1	-6.2	) Waimea Plains
88 Valley Stream		-	Dec 74	1	-7.5	South of Waimea Plains
Ground waters						
Springs						
Pearl Creek		488259	Sept 75	1	-6.9	) Springs on Waimea Plains
Nieumanns Creek		502254	Sept 75	1	-6.7	)
Unconfined Aquifers						
E3	84	487211	July 75-Jan 76	2	-6.0, -6.8	
EW1	94	474215	"	3	-6.9	
EW2	95	472216	"	3	-7.0	
EW3	96	464222	July 75-Nov 76	2	-6.3, -6.8	
Bryants Lane	106	476184	Mar 75	1	-6.9	
Richmond Observation	119	530237	Dec 76	1	-6.2	
Minor confined Aquifers						
Ivory	222	510226	July 75-Jan 76	7	-6.23 ± 0.13	
Constable	216	513196	July 75-Dec 76	15	-6.42 ± 0.25	
Webby	151	509177	"	14	-6.46 ± 0.25	
Upper confined Aquifers						
Mt Heslington Rd	108	486157	Mar 75	1	-6.5	
Baigents	104	489159	Feb 75	1	-7.1	
Waimea Council	103	486169	Feb 75-May 76	8	-7.21 ± 0.38	
Roadside	114	485172	June-Dec 76	6	-7.37 ± 0.18	
Sowman	102	478177	Feb 75	1	-6.9	
Berketts	66	491198	July 75-Dec 76	15	-6.55 ± 0.15	
Buschls	118	502198	Dec 76	1	-6.4	
Edens Rd	107	486205	Mar 75	1	-6.8	
Bartletts Rd	109	489218	"	1	-6.9	
Harfords	110	488269	May 75-Dec 76	15	-6.60 ± 0.13	
Coterell Rd	111	489269	May'75	1	-7.3	
Rabbit Island	5	542285	July 75-Dec 75	6	-5.92 ± 0.15	
Nichols	8	505194	July 75	1	-6.5	
Lower confined Aquifers						
Baigents	104	489159	Feb 75	1	-7.0	
Waimea County	103	486169	"	1	-6.6	
Railway Reserve	105	480176	Feb 75-July 76	7	-6.69 ± 0.11	
Sowman no. 1	101	483186	Feb 75	1	-6.7	
" no. 2	102	487177	"	1	-6.8	
Buschls	118	502198	Dec 76-Jan 77	2	-6.6	
Johnston's	16	511203	Nov 74-Nov 76	25	-6.37 ± 0.18	
Bartletts Rd	109	489218	May 75	1	-7.4	
Bests	24	519215	July-Oct 75	4	-6.53 ± 0.22	Next to double screened well
Richmond Borough no. 2	32	525235	May 75-Dec 76	16	-6.43 ± 0.09	
Richmond Observation		530237	Jan 77	1	-6.3	
Chipmill	119	529237	"	1	-6.2	

Surface waters

Rainfall on the plains had mean $\delta^{18}O$ values of −6.2‰ (1975) and −6.3‰ (1976). The samples are monthly cumulates, and the 1975 mean value is weighted by the amount of monthly precipitation. The 1976 mean value is unweighted but, since rainfall is distributed fairly evenly throughout the year, is not expected to differ significantly from the weighted average. Similar values are also shown by small creeks, such as Jimmy Lee and Malcolm creeks (Table 1) draining lower parts of the Barnicoat Range on the eastern side of the plains (Fig. 2). Eighty-eight Valley stream, a southeastern tributary of the upper Wai-iti River, derives water from high altitudes (900 m) and has a $\delta^{18}O$ value of −7.5‰. The Wai-iti and Wairoa rivers, sampled at monthly intervals over 1 year, have slightly less negative $\delta^{18}O$ values ($\delta^{18}O$ = −7.2‰) indicating dilution by rainfall falling at lower altitudes, with only a small seasonal variation. The Waimea River, sampled over a period of 2 years, also has $\delta^{18}O$ = −7.2‰.

Groundwaters

Water in the unconfined and minor confined aquifers (Fig. 2) has variable $\delta^{18}O$ values lying between those of the Waimea and Wairoa rivers (−7.2‰) and the low-altitude streams and rainfall (−6.2‰). In the Appleby Gravel, in the vicinity of the Waimea River (e.g., wells 84, 94, 106, Table 1; Fig. 2), groundwater has $\delta^{18}O$ values of −7.0‰, indicating recharge from the river. At greater distances from the river (e.g., wells 95, 96) the $\delta^{18}O$ values are less negative, suggesting rainfall infiltration from the surface. Wells in the confined aquifers in the Stoke Fan Gravel to the northeast have less negative $\delta^{18}O$ values indicating rainfall infiltration (e.g., wells 222, 119), and wells near Hope probably also have stream infiltration from the east (e.g., wells 216, 157).

Wells penetrating the "Upper Confined Aquifers" (Fig. 5) are listed in order of decreasing distance from the Waimea Inlet (Table 1). Well 108, south of the Wairoa River, has $\delta^{18}O$ values of −6.5 and −6.6‰, which indicates a rainfall or low-altitude stream flow recharge. $\delta^{18}O$ values in wells 104, 103, 114, and 118 indicate Wairoa River recharge to the aquifer. The aquifer lies just to the east of the Waimea River and the $\delta^{18}O$ values indicate water flow to the north, but with admixture of water from the eastern side (well 8). Nieuman's Spring, in the delta of the Waimea River northeast of Appleby, has a $\delta^{18}O$ value of −6.7‰ indicating that it is derived from the "Upper Confined Aquifers", and it is known from exploratory drilling that the cap to the unit is broken in this vicinity. On the west side of the Waimea River (well 111) $\delta^{18}O$ = −7.3‰, indicating only direct river water contribution. Thus most recharge to the "Upper Confined Aquifers" is from the Wairoa River. However, in the Hope area some recharge through the Stoke Fan Gravel from the overlying minor confined aquifers or ephemeral streams draining the Barnicoat Range is probable.

$\delta^{18}O$ values in wells in the "Lower Confined Aquifers" are generally less negative than those in the "Upper Confined Aquifers". Well 104, close to the Wairoa River, is the only southern well to show a distinct river water influence. Wells 103, 105, 101, and 102 have $\delta^{18}O$ values of −6.7‰, suggesting that water is derived from overlying confined aquifers. Wells (e.g., 8, 118, 16, 24) on the east side of the "Lower Confined Aquifers" near Hope have less negative $\delta^{18}O$ values (−6.4 to −6.6‰), suggesting that there is no river water recharge in this vicinity. Instead the $\delta^{18}O$ values suggest recharge from small streams on the east of the plains through the Stoke Fan Gravel. Intermixing of water, through multiple screened wells, between the "Upper" and "Lower Confined Aquifers" or with minor confined aquifers is also probable. Some wells (e.g., 109) near the Waimea River show river water infiltration. Near the coast the wells 32 and 119 have $\delta^{18}O$ = −6.4 to −6.3‰, similar to, or less negative than ^{18}O values from wells near Hope, perhaps indicating addition of further water with a high (less negative) ^{18}O value. Some wells (e.g., well 16) show a $\delta^{18}O$ variation from −6.7 to −6.3‰ from March to July 1975, confirming that a gradual recharge from an eastern source took place as the aquifers recovered after summer drawdown.

COMPARISON WITH NITRATE MEASUREMENTS

Nitrate measurements on samples from the confined aquifers show a high concentration (up to 40 mg/L NO_3-N) in the east of the plains near Hope (Stanton & Martin 1975, Dicker 1980; Fig. 4, 5). The Wai-iti, Wairoa, and Waimea rivers have relatively low nitrate levels, and the nitrate level is also low in the aquifers where oxygen isotope measurements and hydrogeology indicate there is river recharge. Sources of nitrate are therefore from infiltrating rain water and probably assisted by wells screened to connect 2 or more aquifers. $\delta^{18}O$ values in wells in the Hope area are low, indicating recharge from rainfall and/or from small streams to the east.

CONCLUSIONS

Despite the relatively low contrast in ^{18}O content between the plains' rainfall and the rivers, the ^{18}O variations clearly indicate the sources of the groundwater. The unconfined aquifers derive water from the Wairoa River and rainfall on the plains. The minor confined aquifers are recharged also by rainfall and by the small streams draining the Barnicoat Range to the east of the plains. The "Upper Confined Aquifers" unit is largely recharged by the Wairoa river, but also receives water from the eastern side, probably via minor aquifers within the Stoke Fan Gravels. The "Lower

Confined Aquifers" unit is not directly connected to either the Wairoa or Wai-iti rivers in the south but probably receives slow recharge from near Brightwater. Some artificial connection between the confined aquifers, via multiple screened wells, is indicated.

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