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Environmental isotopes in New Zealand hydrology

3 Isotope hydrology of the Waikoropupu Springs and Takaka River, northwest Nelson

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Abstract Measurements of oxygen-18, deuterium, and tritium have been made to aid interpretation of the groundwater hydrology of the Takaka Valley, including the Waikoropupu Springs. Isotope and temperature data confirmed 3 main aquifers to exist in the region: firstly, a large (~1.5 km^3) artesian aquifer in karstified Ordovician marble; secondly, a smaller artesian aquifer in overlying karstified Oligocene limestones; and thirdly, a very extensive and unconfined aquifer in Quaternary sands and gravels. The first, which supports an average annual outflow of 14 m^3/s at the Waikoropupu Springs, derives a third of its annual recharge from influent flow of isotopically relatively light water from the upper Takaka River, the remainder coming from runoff and infiltration in the middle valley. The second is recharged by local low-altitude rainfall, while the third is largely recharged by seepage from the main rivers but also from local rainfall. A significant difference exists in $\delta^{18}O$ values in different parts of the Waikoropupu Springs, the Upper Fish Spring being isotopically distinct from the Main Spring, indicating a different provenance. Water at the springs is several years old, probably covering a spectrum of ages, whereas water in the upper karstic aquifer is less than 1–2 years old. The flow-through time of recharge waves in the sand and gravel aquifer is of the order of months.

Keywords Stable isotopes; hydrology; aquifers; springs (water); groundwater; surface waters; oxygen-18; deuterium; tritium; Takaka; Pupu Springs.

INTRODUCTION

The Waikoropupu Springs, usually known simply as the Pupu Springs, are the largest springs in New Zealand. They are artesian, karstic, and tidal in character, and are located 4.4 km inland from Golden Bay, near Takaka, in northwest Nelson (Fig. 1). As both an impressive natural phenomenon and a potential water resource, the springs have attracted scientific interest since the end of the last century (Park 1890; Bell et al. 1907; Henderson 1928, 1941), but the speculation surrounding the origin of the springs' waters and the general lack of substantive factual information have prompted more intensive investigations in recent years.

In 1966 the Nelson Catchment Board sent a water sample from the main spring (Fig. 2) to the Institute of Nuclear Sciences, DSIR, for tritium analysis. This was found to have a concentration of 14 T.U. and was interpreted at the time as 3–4 years old, if it had all precipitated at the same time, assuming a straight-through system. Meanwhile, a series of river gaugings was initiated in the Takaka Valley by the Hydrological Survey of the Ministry of Works and Development to establish the components of flow in the district, and particularly the losses and gains of flow in the karstic terrain associated with marble outcrops. Several samples of Pupu Springs' water were analysed for chemical characteristics by the Cawthron Institute, Nelson, the results being incorporated in research on the ecology of the springs by Michaelis (1974, 1976, 1977). These analyses and subsequent work showed the waters of the springs to contain a much greater concentration of dissolved solids than other freshwaters in the district, although the saltiness is greatest in the Main spring and least in the Fish Springs (Fig. 2). The possibility of marine contamination was therefore recognised to exist, particularly since freshwater upwellings were found 1–5 km offshore in nearby Golden Bay by an oceanographic survey in 1957.

The general lack of information on the source of the springs' waters and on the nature of the groundwater system in the Takaka Valley led to the initiation of a more detailed hydrogeological investigation in the district in 1973 (Williams 1977, in press). This demonstrated by pulse-train analysis that the main source of the springs' outflow is the upper Takaka River which loses water into its bed

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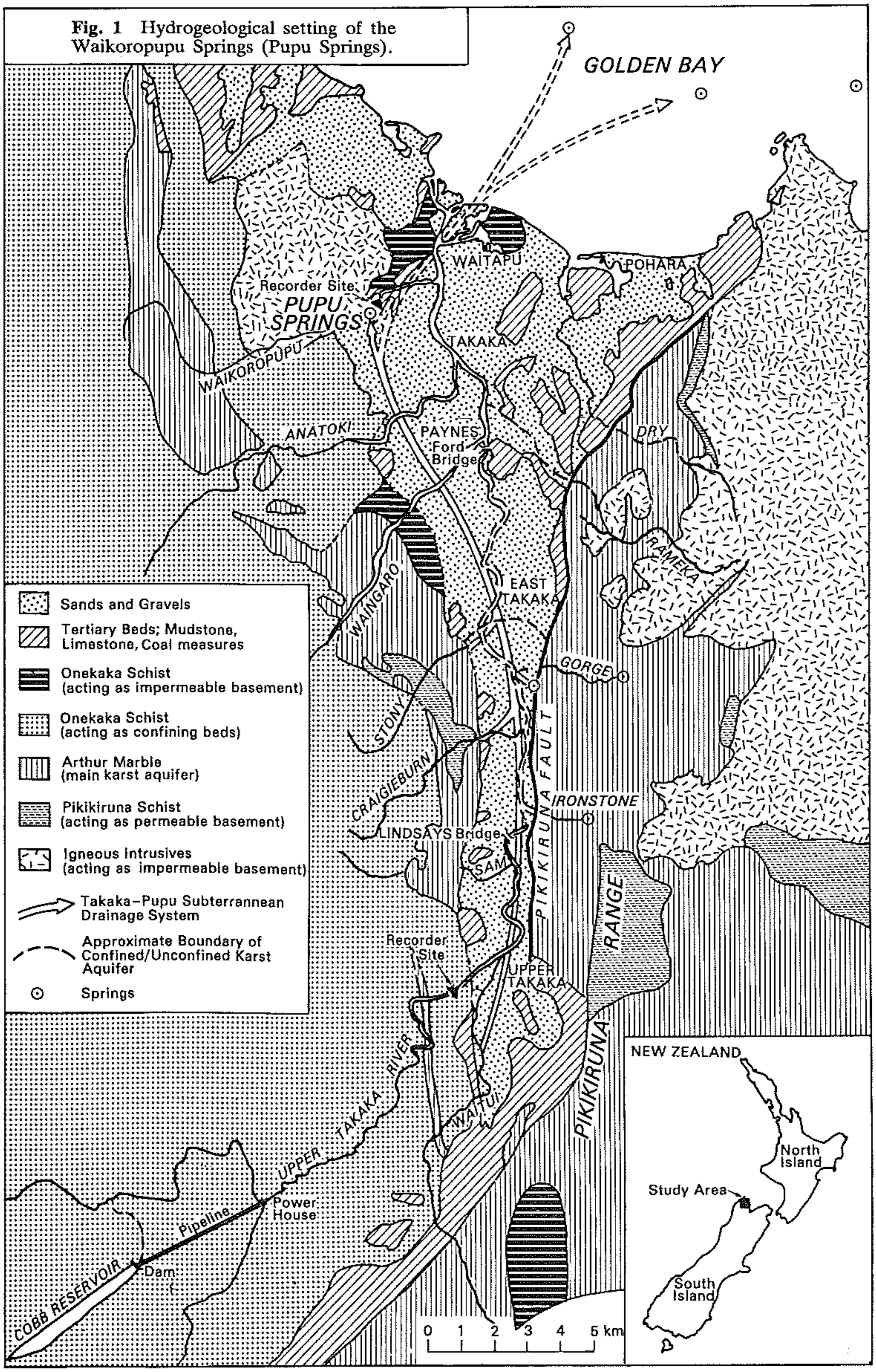


Fig. 1 Hydrogeological setting of the Waikoropupu Springs (Pupu Springs).

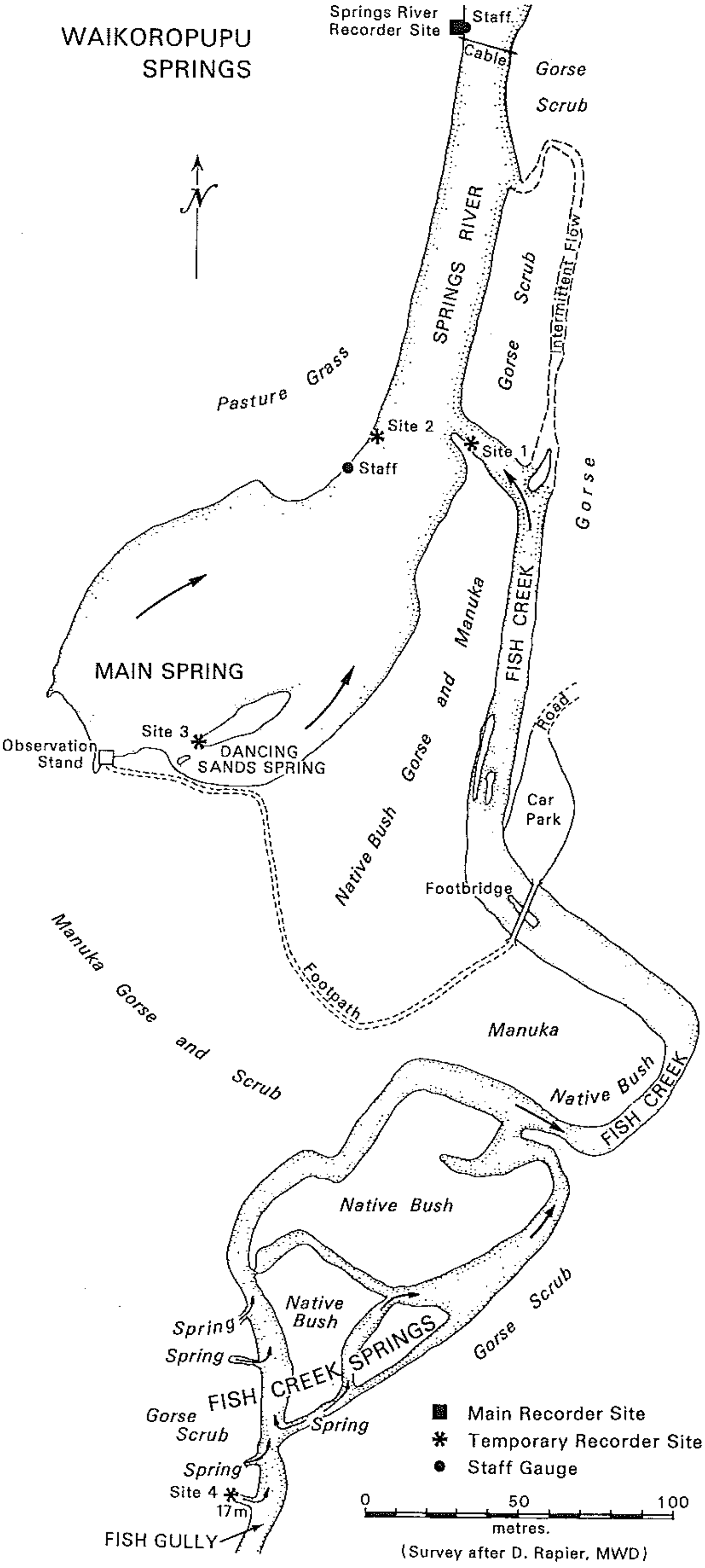


Fig. 2 Plan of the Waikoropupu Springs (Williams 1977).

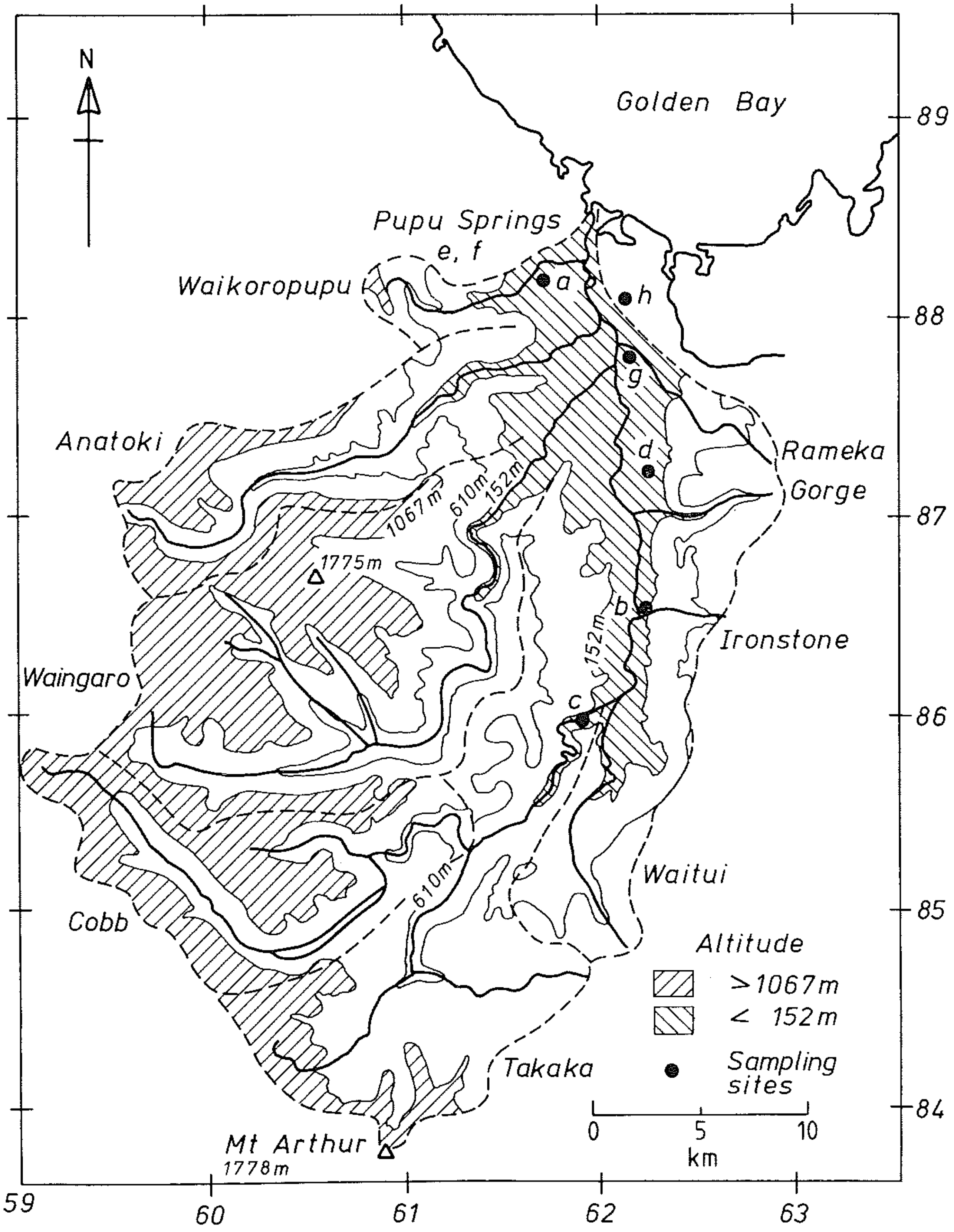


Fig. 3 Takaka River catchment showing sampling sites (a–h).

16–18 km inland. The springs were also found to be tidal, the evidence favouring an earth-tides mechanism rather than a marine-tides effect (Rapier pers. comm.). Nevertheless, the slightly brackish water of the springs is most simply explained by sea water intrusion and venturi mixing, especially since no halites are known in the local geological sequence. Three main aquifers were also recognised in the Takaka Valley: the principal karstic artesian aquifer in the Ordovician marble, an upper secondary karstic artesian aquifer in Oligocene limestone, and a large unconfined aquifer in overlying Quaternary gravels, the last being particularly important in the upper valley.

Measurements of environmental isotopes, particularly oxygen-18, have been made to shed light on the provenance and age of natural waters in the Takaka region (Stewart & Taylor 1980). This paper reports the oxygen-18 measurements from several years of sampling, together with some deuterium, tritium, chloride, and temperature measurements. Further work on tritium and chemical contents is in progress.

HYDROLOGY OF THE TAKAKA RIVER CATCHMENT

The Takaka Valley (Fig. 1) occupies a narrow fault-angle depression between two eastward-tilted blocks that moved differentially during the Kaikoura orogeny in the Upper Tertiary period (Grindley 1971). In the north the blocks are separated by the narrow trough of the lower Takaka Valley; in the south they are in contact. To the west the valley is bounded by the deeply dissected block of the Tasman Mountains, composed dominantly of Palaeozoic schists. To the east the valley terminates abruptly against the straight, steeply rising Pikikiruna fault-scarp that separates the lowland from a karstic plateau at around 850 m developed in Ordovician Arthur Marble (Williams & Dowling 1979; Williams in press). The marble is at least 1000 m thick, and downfaulted segments of it underlie the Takaka Valley.

The Takaka River follows the depression between the tilted blocks during its middle and lower course. It receives only a small proportion of its water from the Pikikiruna Range, but several large tributaries flow down from the west (Fig. 3); the geological structure explaining the asymmetrical catchment. The main western tributaries are (from south to north) the Cobb, Waingaro, Anatoki, and Waikoropupu Rivers. These tributaries drain country of up to 1800 m in altitude (in the Waingaro catchment), and a good fraction of the area is at elevations in excess of 1000 m (Fig. 3). The greatest rainfall occurs in the highest areas and ranges from 3000 to 5600 mm per year. Westerly airflows predominate. The western area comprises 630 km^2 of the total catchment of 890 km^2.

Eastern tributaries are the Waitui, Ironstone, Gorge, and Rameka streams, the last two of which have intermittent surface flows. They drain marble and granite and are partially spring fed. A considerable amount of water drains underground. Elevations rise to 900 m and annual rainfall is 2500–3000 mm. The eastern catchment area is about 145 km^2, the balance lying in the lower valley.

Much rainfall within the Takaka Valley disappears underground, penetrating into Arthur Marble and overlying gravels in the upper valley and into Tertiary sediments, particularly in the mid-valley region. Several creeks (Stony, Craigieburn, and Sam) drain basement schist up to 600 m altitude on the western side of the valley in a region with 2000–2500 mm of rainfall. But their creek beds are usually dry after crossing onto marble bedrock in their lower reaches.

SAMPLING AND ANALYSIS

Initial surveys of the oxygen-18 and deuterium contents of the Takaka Valley waters were made in September 1975 and February 1976 to gain an idea of the isotope variation in the district. Since February 1976 regular 4-weekly sampling has been carried out for oxygen-18 measurements from 8 sites. These sites were chosen to sample:

(1) the outflow of the Waikoropupu artesian system (the Main Spring and Upper Fish Spring—e, f, Fig. 3; Fig. 2);
(2) water from within marble in the main body of the artesian system underlying a cap of gravel and Tertiary sediments in the mid-valley region where the Takaka River loses much of its flow (Low's bore—d, Fig. 3);
(3) the Takaka River at Harwoods (gauging station south of Upper Takaka—c, Fig. 3), being the principal input to the artesian system;
(4) eastern block runoff (Ironstone Creek—b, Fig. 3);
(5) rainfall (sampled at a rain gauge at the Pupu Springs—a, Fig. 3);
(6) water from the upper artesian karstic aquifer in the Tertiary limestone (Hodgkinson's bore—g, Fig. 3); and
(7) water from the Quaternary gravel aquifer in the lower valley (Dairy Factory bore—h, Fig. 3).

Table 1 Sampling details, isotopic results, and some chloride results for initial survey samples from the Takaka valley and surroundings.

Sample description	Sampling date	Temperature (^{o}C)	Oxygen-18 ($\delta^{18}O$ ‰)	Deuterium (δD ‰)	Tritium TR	Chloride (ppm)	Location	Comment
Pupu Springs								
Main Spring	4/ 9/75	11.5	- 7.0	- 45	-	128	S8/172820	Springs River flow 16.0m^3/s
	5/ 2/76	11.5	- 7.1	-	12.6±0.9	98	"	"""" " " 14.3m^3/s
Dancing Sands Springs	4/ 9/75	11.5	- 7.1	- 44	-	79	S8/172820	
	5/ 2/76	11.6	- 7.2	- 45	11.5	70	"	
Upper Fish Spring	4/ 9/75	11.5	- 7.5	- 46	-	32	S8/171817	
	5/ 2/76	11.6	- 7.7	- 48	11.1	23	"	
Traverse across Pupu Springs)Largest DS spring	5/ 2/76	11.6	- 7.1	-	-	79	S8/172820	
)E side isl.	"	11.6	- 7.1	-	-	87	"	
)W side isl.	"	11.6	- 7.0	-	-	110	"	
)Largest main side spring	"	11.4	- 7.2	-	-	117	"	
Ground Waters (bores and other Springs)								
Riwaka South Branch Spring	1/ 9/75	8.5	- 9.2	- 57	-	-	S13/262535	Not in Takaka Catchment
Motupipi Springs	1/ 9/75	14.0	- 7.8	- 53	-	-		
Dairy Factory bore	30/9/75	13.7	- 8.0	- 53	-	-	S8/213812	
	5/ 9/76	13.5	- 8.2	- 53	12.8	6	"	
Hodgkinson's bore	6/ 9/75	13.5	- 6.0	- 36	-	21	S8/215785	
	5/ 2/76	13.8	- 6.1	- 38	9.0	14	"	
J C Low's bore	5/ 2/76	11.6	- 7.8	- 50	12.6	5	S8/220734	

Table 1 (continued)

Sample description	Sampling date	Temperature (^{o}C)	Oxygen-18 (δ^{18}O ‰)	Deuterium (δD ‰)	Tritium TR	Chloride (ppm)	Location	Comment
Precipitation								
Rain (Pupu rain gauge)	28/11/75 - 5/ 2/76	-	- 6.5	-43.5	8.1*	-	S8/172820	Rainfall 62 cm(annual rainfall(1976)272.7 cm
Snow (Mt Owen)	8/ 1/77		-10.2		-	-	S13	
Snow (Owen Chasm) 1400 m	9/ 1/77	-	- 9.6		-	-		
Snow (Mt Arthur) 1600 m	22/ 1/77	-	- 8.6	-	-	-		
Snow melt pool (Mt Arthur) 1600 m	22/ 1/77	-	- 6.2	-	-	-		^{18}O content probably enriched by evaporation
Snow melt pool (Mt Arthur) 1700 m	23/ 1/77	-	- 7.5	-	-	-		" " "
Stream (Mt Arthur) 1500 m	23/ 1/77	-	- 9.9	-	-	-		
Streams from west								
Fish Creek	5/ 2/76	-	- 5.7	-34	-	-	S8/169815	
Anatoki River	5/ 2/76	10.6	- 7.0	-	-	-		
Takaka River	3/ 9/75	7.5	- 9.0	-57	-	17	S8/198600	
	5/ 2/76	15.4	- 8.3	-53	-	8		
Waingaro River	5/ 2/76	11.6	- 8.0	-	-	-		
Streams from east								
Rameka Creek	5/ 2/76	15	- 6.5	-41	-	-	S8/246744	
Gorge Creek	4/ 9/75	9.5	- 8.0	-51	-	-	S8/225703	
	5/ 2/76	17.4	- 7.1	-	-	-	"	
Ironstone Creek	4/ 9/75	8.5	- 7.8	-50	-	-	S8/220653	
	5/ 2/76	14.2	- 7.5	-45	-	7	"	
Waitui Stream	3/ 9/75	10.0	- 7.6	-51	-	-	S8/213610	
	5/ 2/76	15.0	- 7.3	-	-	-		

* Tritium in Hutt River at Kaitoke (February 1976).

Table 2 Climatic parameters and mean annual $\delta^{18}O$ values for the Takaka valley.

	Year	1974	1975	1976	1977	1978	Mean
Mean temperature °C		12.9	12.6	11.8	11.9	12.8	12.3
Rainfall (Pupu Springs) cm		163	151	172	132	108	137
Rainfall " "	$\delta^{18}O$‰			-5.62	-5.98	-6.10	-5.90
Ironstone Creek	"	-	-	-7.68	-7.85	-7.88	-7.80
Takaka River	"	-	-	-8.87	-9.21	-8.61	-8.90
Low's Bore	"	-	-	-7.88	-7.97	-7.99	-7.95
Main Spring	"	-	-	-7.24	-7.31	-7.48	-7.34
Fish Spring	"	-	-	-7.53	-7.67	-7.69	-7.62
Hodgkinson's Bore	"	-	-	-6.15	-6.24	-6.32	-6.24
Dairy Company Bore	"	-	-	-8.13	-8.28	-8.33	-8.24

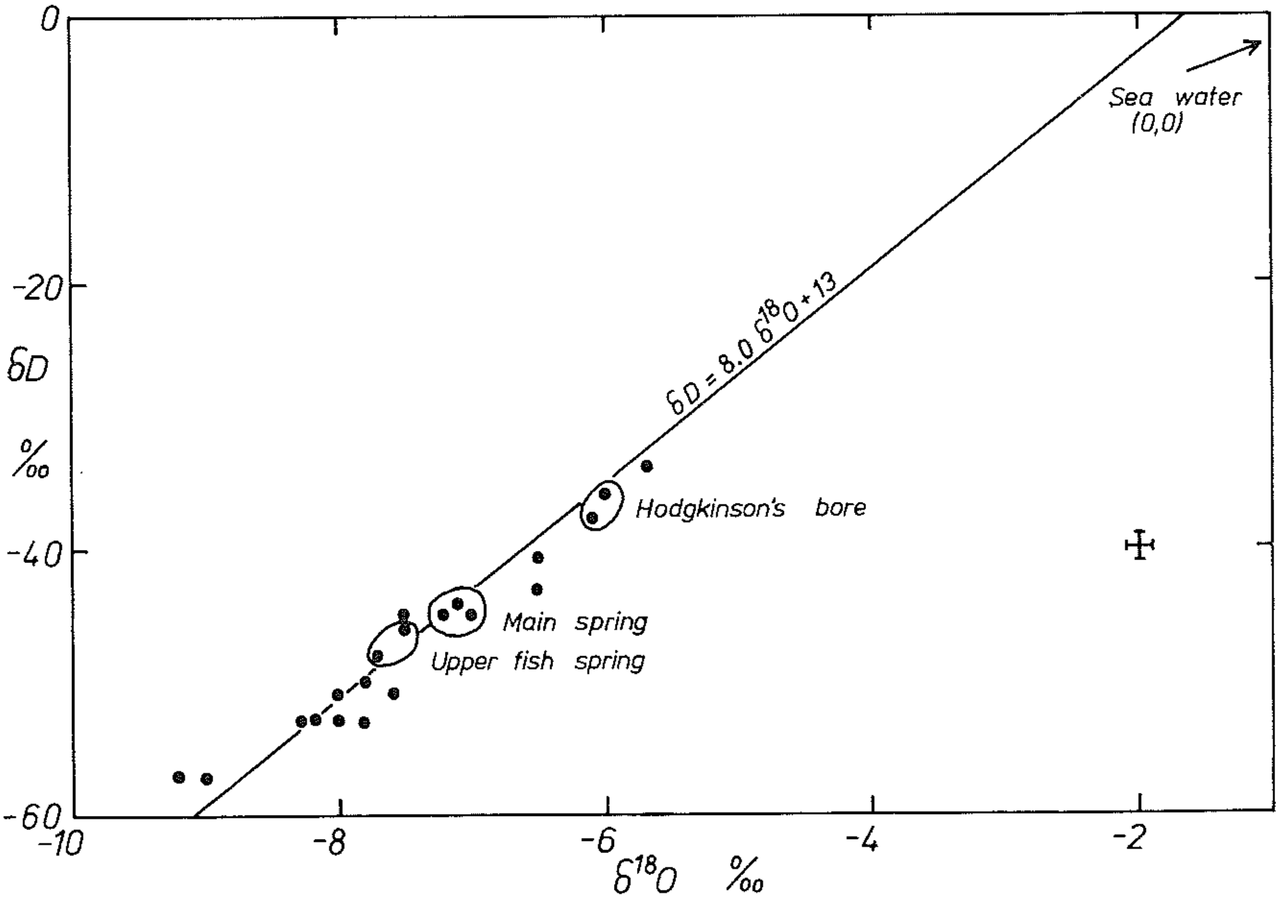


Fig. 4 Plot of $\delta^{18}O$ (‰) against δD (‰) for Takaka Valley samples.

Some of these samples were also analysed for tritium content.

The samples were collected and temperatures measured in flowing parts of streams and after allowing bores to flow for 15 min or so to clear the bores and storage tanks of standing water.

The isotopic measurements were made by techniques described in Hulston et al. (1981). Oxygen-18 and deuterium contents are expressed as δ values relative to a standard (V-SMOW or Vienna-standard mean ocean water) in parts per thousand,

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

Measurement errors are ±0.15‰ for $\delta^{18}O$ and ±1.0‰ for δD. Tritium contents are in TR where TR = 1 is $T/H = 1 \times 10^{-18}$.

RESULTS

Initial survey

Results of measurements on samples from the initial surveys are given in Table 1 which shows oxygen-18 content, sampling temperatures and dates, and locations of a number of springs, bores, rivers, and rainfall gauges in the Takaka area. The sampling points are also shown on Fig. 3. Deuterium, tritium, and chloride contents are given for some of the samples.

Rainfall from the Pupu rain gauge has mean $\delta^{18}O = -6.5‰$ over the period 28 November 1975 to 5 February 1976. Snow from high altitudes (1400–1500 m) which fell during the winter of 1976 and was sampled in January 1977 had $\delta^{18}O \sim -10‰$, showing the variation of $\delta^{18}O$ with altitude. Rivers had $\delta^{18}O$ varying between −9.0‰ (Takaka River) and −5.7‰ (Fish Creek). The mountain streams had $\delta^{18}O$ between −7 and −9‰, and foothills streams (low-altitude catchment) had $\delta^{18}O$ values between −5 and −7‰. Water temperatures measured were between 7 and 17°C, and three chloride contents ranged from 7 to 17 ppm.

The Main Spring and Dancing Sands Spring had $\delta^{18}O = -7.1 \pm 0.1‰$ and showed no variations in different parts of the Pupu Springs apart from measurement error (see the results of the traverse, Table 1). However, the Upper Fish Spring, which discharges water at 3 m higher altitude, has a more negative $\delta^{18}O$ of −7.6‰. This difference from the Main Spring water is confirmed by a more negative δD value for Upper Fish Spring water. The temperatures measured were identical for all vents of the Pupu Springs, including Upper Fish Spring, at 11.4–11.5°C, which agrees reasonably well with the constant value of 11.7°C found by Michaelis (1976). The chloride contents show a decrease from the Main Spring to the Dancing Sands Spring from about 110 to 75 ppm, which is of the same order as found by Michaelis (1976). Upper Fish Spring contains even less chloride (28 ppm), although this is greater than observed in the few measurements on rivers. There is an indication that the chloride content of the waters from the Main Spring and Dancing Sands Spring is discharge-related, with higher flows (e.g., on 4 September 1975) correlating with higher chloride contents in the water.

Other groundwaters were sampled from various wells and springs in the area. Low's bore water is drawn from Arthur Marble below sea level in the mid-valley region and had $\delta^{18}O = -7.8‰$ (similar to Ironstone Creek and more positive than Takaka River water). Its temperature of 11.6°C was the same as that for Pupu Springs and colder than other ground waters in the area, strongly suggesting that the bore draws from the same groundwater system that feeds the Pupu Springs. The water has a low chloride content, similar to that for Ironstone Creek.

Hodgkinson's bore discharges water from Tertiary limestone with $\delta^{18}O \sim -6.1‰$ and a temperature of about 13.6°C. The $\delta^{18}O$ value shows that the water is derived from local low altitude rain. The temperature is 2°C above the mean annual air temperature at the nearest low altitude meteorological station (Riwaka, Motueka) and is very close to the mean annual soil temperatures at 1 m depth at Riwaka. The water thus derives from infiltration of rain on local low-altitude country, and its temperature is determined by the country rock it passes through.

The Dairy Factory bore ($\delta^{18}O = -8.1‰$) draws water from gravel, which probably originates from the (lower) Takaka River below its confluence with the Waingaro River. The Waingaro ($\delta^{18}O = -8.2‰$) and Anatoki rivers (Fig. 1) contribute almost all of the flow, especially in summer. The temperature is similar to that of Hodgkinson's bore and Motupipi Springs. The latter springs ($\delta^{18}O = -7.8‰$) probably derive water from karst at higher altitudes on the eastern side of the valley. Riwaka South Branch Spring (Table 1; Williams & Dowling 1979) derives water from the marble plateau on the eastern side of the Takaka Valley, and the water probably has a short residence time in the underground system and variable $\delta^{18}O$ and temperature.

Fig. 4 shows a plot of $\delta^{18}O$ versus δD. The samples fit well to the line

$$\delta D = 8.0\ \delta^{18}O + 13$$

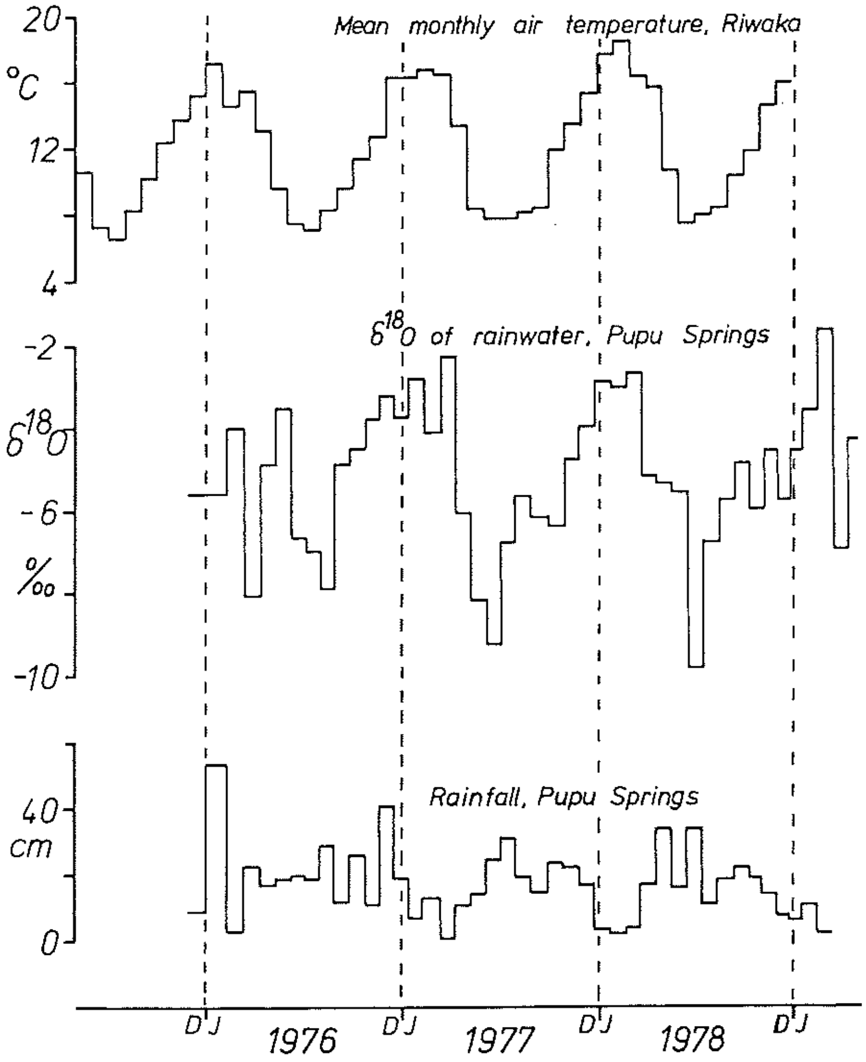


Fig. 5 Monthly $\delta^{18}O$ (‰) and rainfall amount (cm) at the Pupu springs (Slackline) rain gauge for the years 1976–8. The mean monthly air temperature at Riwaka is also shown.

found for other New Zealand waters, showing that the variations in $\delta^{18}O$ and δD are essentially parallel.

Tritium contents of the Pupu Springs waters were 11±1 TR in February–May 1976. In comparison, tritium in rainfall at Pupu Springs in February was 8 TR. Rainfall at higher altitudes will tend to contain a little more tritium. Furthermore, water from Low's bore and the upper Takaka River also contained 11±1 TR. These results suggest that there was a considerable fraction of older water (several years in age) present in upper Takaka River, Low's bore, and Pupu Springs' discharge. Hodgkinson's bore discharges water with 9 TR, indicating young water (less than 1–2 years).

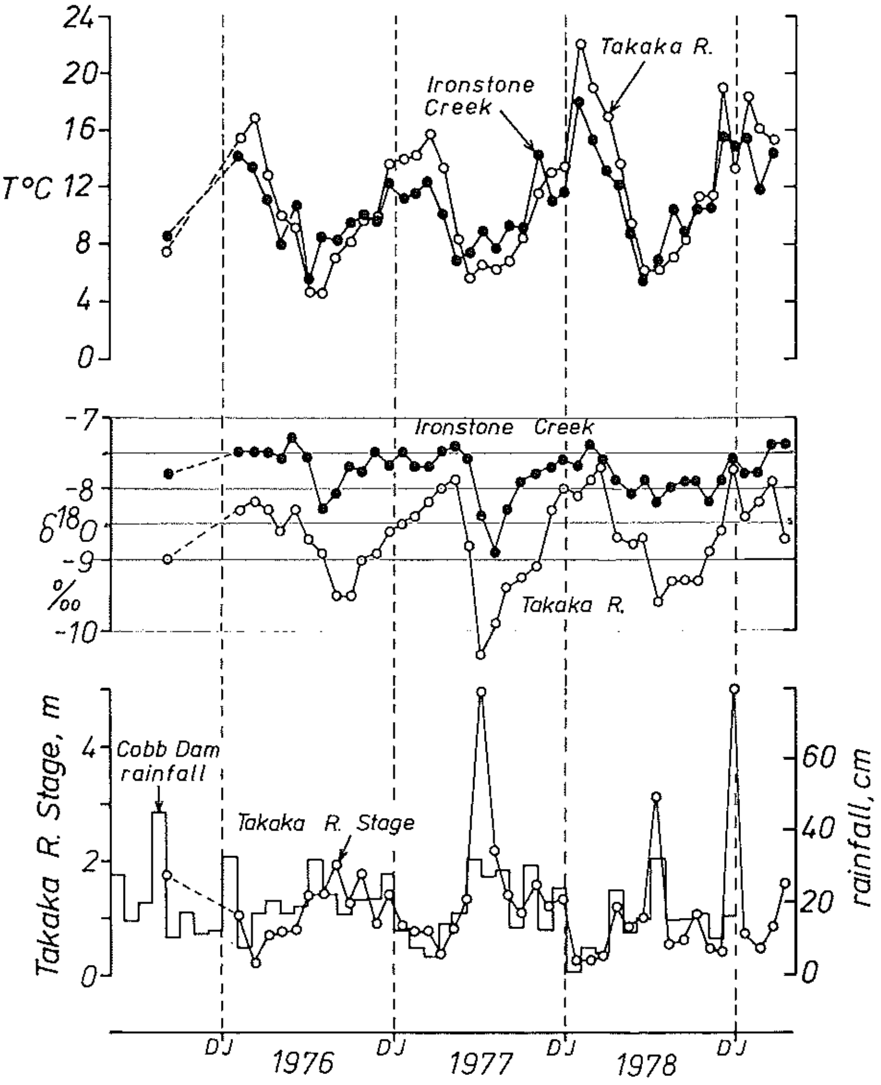
Monthly sampling programme

Monthly oxygen-18 contents, rainfall totals or flow data, and sampling temperatures are plotted in Fig. 5–8 for the 8 features sampled. Mean annual $\delta^{18}O$ values are given in Table 2, with mean annual temperature (Riwaka Meteorological Station) and annual rainfall totals at the Pupu Springs.

Rainfall sampled at Pupu Springs shows a regular seasonal pattern in $\delta^{18}O$ (Fig. 5), with high $\delta^{18}O$ in summer and low $\delta^{18}O$ in winter, except for early 1976 when the pattern was disturbed by storms producing low ^{18}O water in late summer. Although rain falls in every month of the year, it shows a seasonal pattern with relatively dry summers and wet winters. January–May 1977 and January–March 1978 were dry months (Fig. 5). The average difference between summer and winter $\delta^{18}O$ is 4–6‰, which gives a good "signal" to use in tracing water underground. The monthly mean air temperatures for Riwaka, near Motueka, are also plotted.

The upper Takaka River (Fig. 6) shows a regular seasonal variation in $\delta^{18}O$ with an amplitude of about 2‰. The $\delta^{18}O$ varies smoothly, probably because of 2 factors: hold-up of precipitation in the

Fig. 6 Monthly $\delta^{18}O$ (‰) and sampling temperatures (°C) for the Takaka River (at Harwoods) and Ironstone Creek (at bridge) for 1976–8. Also shown are the stage heights (m) at times of sampling for the Takaka River at Harwoods and monthly rainfall totals (cm) at the Cobb Dam Meteorological Station.



catchment (as soil and groundwater) and storage of water in the Cobb Reservoir. Melting of snow in spring contributes low ^{18}O water. All 3 of these factors cause the winter ^{18}O minimum to be delayed. The most pronounced ^{18}O minimum occurred in 1977 and coincided with high precipitation (at Cobb Dam, Fig. 6) and flood flows (Fig. 6).

Ironstone Creek (Fig. 6) derives water from the eastern block, but unlike the Waitui, Gorge, and Rameka creeks, it usually maintains a surface flow to its confluence with the Takaka River. There is only a minor seasonal effect in $\delta^{18}O$. In base-flow conditions $\delta^{18}O$ is about −7.6‰, but this value is changed if quick runoff following rainfall occurs. The mean difference between the $\delta^{18}O$ in summer and winter flows is about 1‰, and the ^{18}O minimum in winter is of relatively short duration. As noted above for the Takaka River, the 1977 ^{18}O minimum was much more pronounced than the ^{18}O minima in 1976 and 1978.

Low's bore $\delta^{18}O$ values (Fig. 7) show a small minimum in August–October 1977 (maximum − minimum difference is 0.5‰) and barely detectable differences in 1976 and 1978 (about 0.2‰). The $\delta^{18}O$ values show a downward trend and a mean value of −7.95‰. Temperatures are also shown. They have a (small) seasonal trend and fluctuate between 11.2 and 12.4°C.

Pupu Main Spring $\delta^{18}O$ values (Fig. 7) are relatively constant, varying between −7.1 and −7.4‰ except for one period in January–March 1978, when $\delta^{18}O$ values of −7.6‰ were measured. The $\delta^{18}O$ values show a downward trend and a mean value of −7.3‰. The February 1978 ^{18}O dip follows the ^{18}O minimum observed in June 1977 in upper Takaka River water by 8 months and the September 1977 ^{18}O minimum observed in Low's bore water by 3 months. If this is the cause of the ^{18}O dip in Pupu Main Spring water, it indicates that part of the input water travels quite rapidly (about 8 months) through

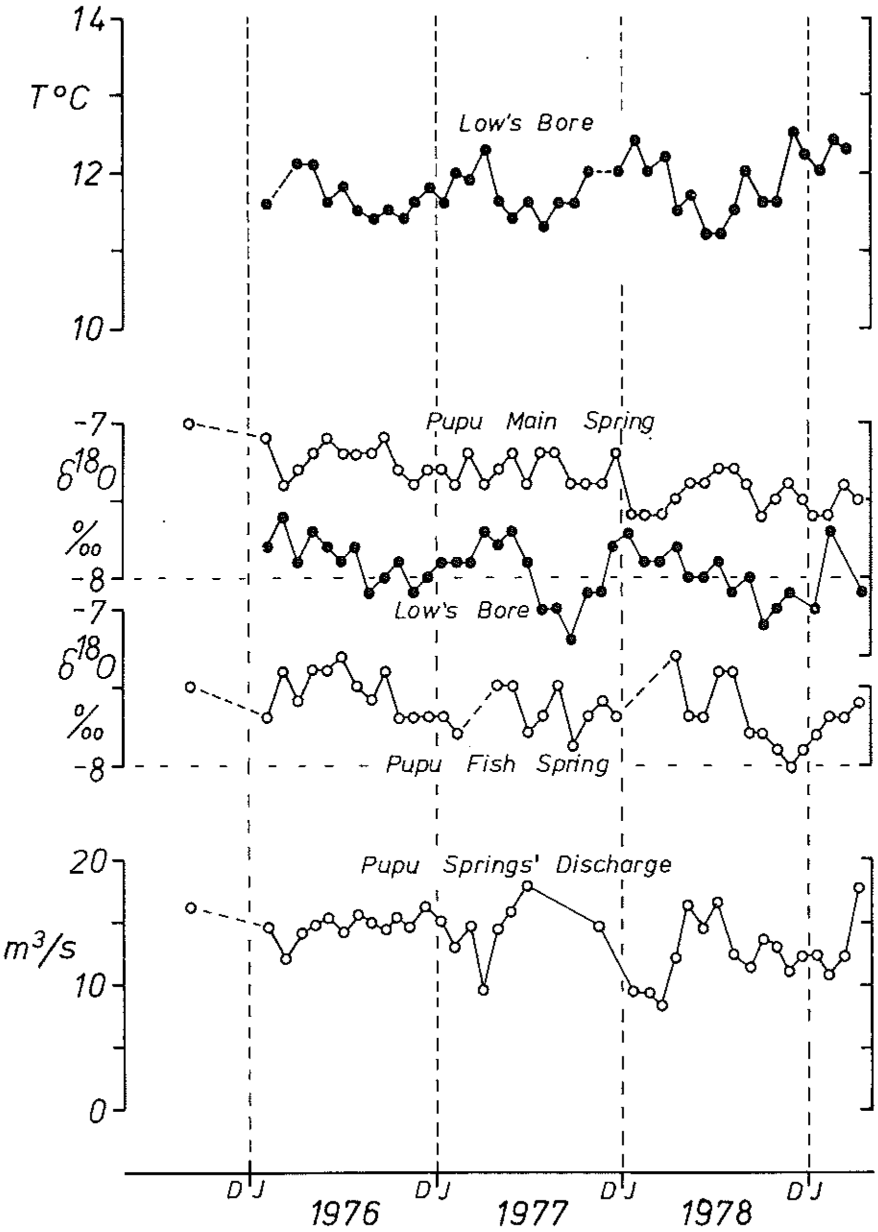


Fig. 7 Monthly $\delta^{18}O$ (‰) and sampling temperatures (°C) for Pupu Main Spring, Upper Fish Spring, and Low's bore. The discharge (m^3/s) for the Waikoropupu Springs area is also given for sampling times. (Note the offset $\delta^{18}O$ scale for the Upper Fish Spring results.)

channels in the marble between the upper valley and Pupu Springs, although it is likely that deeper water travels more slowly. However, it is also possible that the $\delta^{18}O$ dip in Pupu Main Springs water resulted from low flow conditions in the Springs (the Pupu Springs discharge is shown in Fig. 7 in m^3/s). It can be seen from Fig. 7 that January–March 1978 was a period of very low flow (when Upper Fish Spring ceased to flow). This is the preferred interpretation.

^{18}O results for Upper Fish Spring (Fig. 7) show a variation between −7.4 and −7.9‰. There appears to be a downward trend in $\delta^{18}O$ during 1976 and 1977 and possibly an increase in 1978. No seasonal variation is distinguishable. The spring ceases to flow during dry conditions in summer (this happened in March–April 1977 and January–March 1978, but not in 1976). In both 1977 and 1978 the spring water $\delta^{18}O$ showed an increase in value of 0.4‰ between just before and just after drying up. Except for the general trend, there is no obvious correspondence between $\delta^{18}O$ variation of Upper Fish Spring and Main Spring; and the $\delta^{18}O$ of Upper Fish Spring is significantly different from that of the Main Spring (by 0.4‰).

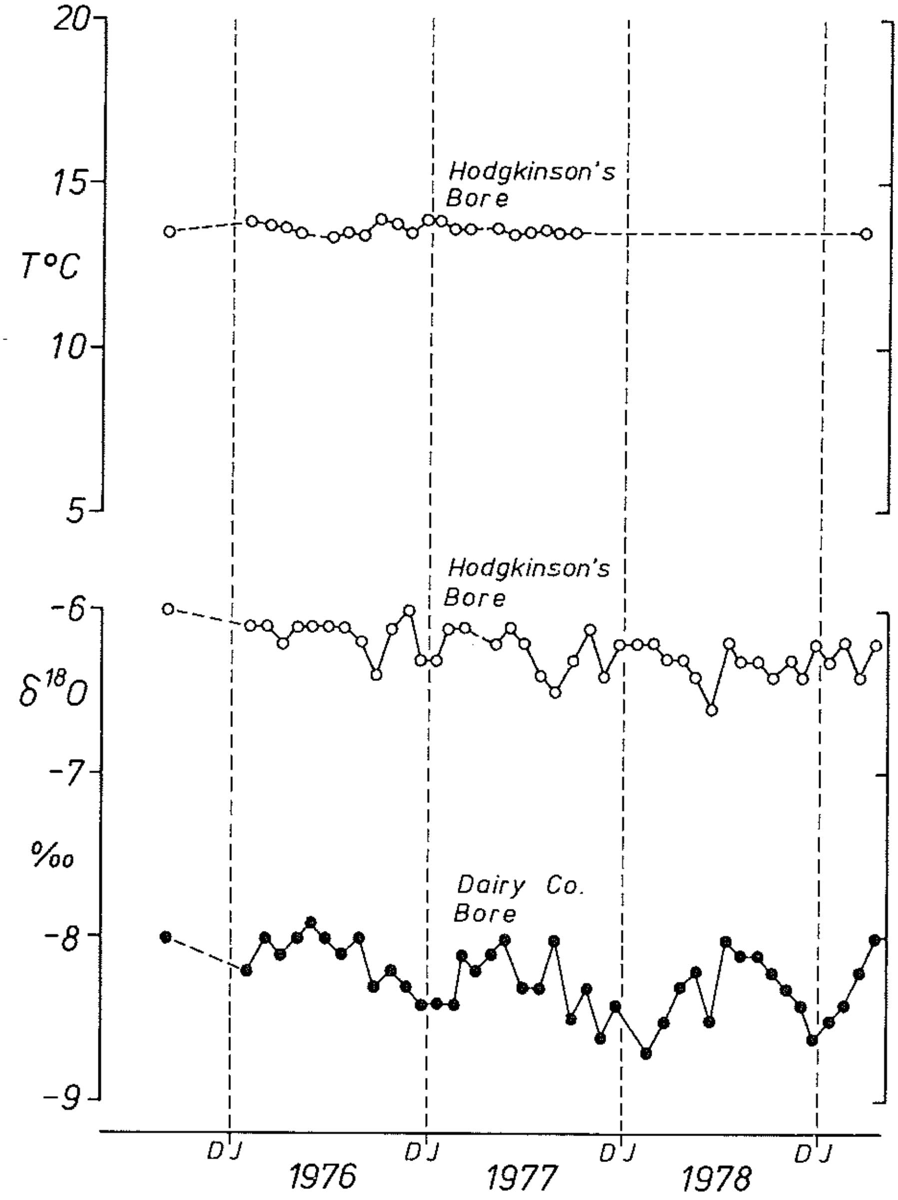


Fig. 8 Monthly $\delta^{18}O$ (‰) and sampling temperatures (°C) for Hodgkinson's bore and Dairy Co. bore.

The $\delta^{18}O$ values of water from Hodgkinson's bore (Fig. 8) show little variation, lying between −6.0 and −6.6‰, the δ values indicating recharge by low-altitude rainfall. There may be a slight seasonal variation with an amplitude of about 0.3‰ between summer and winter samples, the temperature data also showing a very small variation of about 0.4°C between summer and winter and a mean temperature of about 13.7°C. This is higher than water temperature at Pupu Springs, Low's bore, and average temperatures of Takaka River and Ironstone Creek.

The Dairy Factory bore (Fig. 8) had $\delta^{18}O$ between −8 and −9‰. These $\delta^{18}O$ values are more negative than those of water from Takaka Valley rain or eastern block runoff or the marble underlying the valley. Instead, the water must be infiltration from the lower Takaka River, which in this part of the valley obtains almost all of its flow from the Waingaro and Anatoki rivers. A probable seasonal oscillation is shown by the $\delta^{18}O$ values, with the ^{18}O minima occurring about November to February. This suggests a travel time through the valley gravels of several months. The water has a mean temperature of about 13.7°C, which is the same as in Hodgkinson's bore.

DISCUSSION

Source and dynamics of Pupu Springs

Williams (1977) suggested that water from 4 main sources is discharged from the Pupu Springs: (a) conduit flow from the Takaka River; (b) conduit flow from sinking streams including the Waitui, Gorge, and Craigieburn creeks; (c) diffuse percolation through a network of minor fissures in the karstified marble; and (d) diffuse flow from storage in sands and gravels directly overlying the marble. There may also be a small contribution (up to 0.5%) of sea water to account for the salt content of the discharge.

Monthly water samples from the Main Spring during the period 1976–78 had an average $\delta^{18}O$ value of $-7.3\pm0.16‰$, whereas water from the upper Takaka River over the same period had an average $\delta^{18}O$ of $-8.6\pm0.48‰$. Assuming the latter value to be representative of previous input conditions, it is apparent that only part of the water from the Main Spring can be derived from the upper Takaka River.

Eastern streams from the Pikikiruna–Canaan marble uplands, for which losses to groundwater have been gauged, had a $\delta^{18}O$ value of about $-7.7‰$ (the mean value for Ironstone Creek), while rainfall in the mid and upper Takaka Valley which contributes to diffuse percolation through minor fissures in the marble and through terrace gravels had $\delta^{18}O$ values of about $-6.0‰$. A mass balance of the oxygen isotopes thus indicates an input to the Pupu groundwater system of roughly equal quantities of upper Takaka River water and mid to upper valley rainfall, with indeterminate quantities of water from other streams.

Another calculation can be made by considering the quantity of lower valley low altitude rainfall that must be added to Low's bore water ($\delta^{18}O = -7.8‰$) to give the quality determined at Pupu Springs. Addition of approximately 30% of low-altitude rainwater is required in this case—but it should be noted that not much lower valley recharge can occur because of the capping of the aquifer by impermeable beds.

It is also clear from the isotope evidence that the waters issuing at various sites within the Pupu Springs complex (Fig. 2) do not all have precisely the same admixtures of source waters. Indeed, different sources may be involved. It has already been noted that the outflow from the Upper Fish Springs is less saline than that from the Dancing Sands and Main Spring. The Upper Fish waters are also significantly different with respect to $\delta^{18}O$ (Fig. 4 and 7); a difference that is more than can be accounted for by the previously suggested varying proportions of seawater contamination (about 1:200 in the Main Spring compared to 1:450 in the Upper Fish Spring on the basis of Cl^- values). Hence, it appears that the Fish Spring has a larger proportion of water from higher altitude sources than the Main Spring, possibly inflow from marble outcrops to the west and southwest, and conceivably including leakage from the Waingaro River (Fig. 1).

The implications of the significantly different $\delta^{18}O$ values at 2 sites in the springs for the dynamics of the Pupu artesian system is that separate currents must exist within the aquifer, in part drawing water from different sources. However, the flow-through time from these sources is unknown.

The pulse-time through the system of a recharge wave from the upper Takaka River has been shown by Williams (1977) to be about 10 hours, but the time the new input water requires to travel through the system is much longer. The 1966 tritium analysis referred to earlier suggested 3–4 years. The present series of tritium measurements also indicates the age spectrum of the springs' waters to extend back several years, although the currently low levels of tritium in precipitation make greater precision impossible. Large seasonal variations in $\delta^{18}O$ values in the recharge zones diminish to within experimental error at the springs due to diffusion in the very large (1.5 km^3) groundwater reservoir; thus little information on the rate of groundwater flow can be obtained from these data also. However, it may be observed from Fig. 6 that after heavy rain in winter (June and July) 1977 after a previous dry summer and autumn, there was a large negative deviation in $\delta^{18}O$ values in the upper Takaka River (June/July) and Ironstone Creek (July/August). This was followed 2–3 months later by a large negative deviation in Low's bore (Fig. 7), which is located just downstream of the artesian boundary near the exit of Gorge Creek (Fig. 1 and 3) in the mid valley region. This event gives a measure of the rate of flow down valley to the upstream end of the confined aquifer, and is essentially confined in order of magnitude by the lag in seasonal oscillation between water temperatures in the upper Takaka River (Fig. 6) and water temperatures in Low's bore (Fig. 7). However, within the main body of the artesian system, evidence for the flow-through time is more equivocal, because no clear counterpart to the large variations in $\delta^{18}O$ and temperatures at Low's bore could be identified at either Pupu Main Spring or Pupu Upper Fish Spring (Fig. 7).

Sources and dynamics of other groundwaters

The stable isotope data confirm the existence of the 2 other main aquifers in the valley: the upper secondary karst artesian aquifer in the Oligocene limestones, and the large unconfined aquifer in Quaternary gravels. Furthermore, the considerable contrast in oxygen isotope values indicates entirely different source areas for their waters; a conclusion that is also supported by the different temperature characteristics.

The upper karst aquifer is recharged by local low-altitude rainfall over the Oligocene limestone outcrops at the foot of the Pikikiruna fault scarp southwest ad east of Takaka (Fig. 1). Both temperature and $\delta^{18}O$ values suggest a slight seasonal variation in response to recharge (Fig. 8), tritium data from Hodgkinson's bore indicating a throughput of less than 1–2 years.

The unconfined sand and gravel aquifer is very extensive, covering most of the valley from Upper Takaka to the sea. It consists mainly of large low-angle coalescing fans, extending into the fault-angle depression from its various tributary valleys. It is of variable thickness and must be recharged both by infiltration from inflowing streams and by valley rainfall. Evidence from the Dairy Factory bore at Takaka indicates that the water there has mostly a river water origin, the main flow in the area being from the Waingaro and Anatoki Rivers. Seasonal oscillations in $\delta^{18}O$ suggest that recharge waves pass down valley through the gravels, with a lag of up to 4 or 5 months, even though the pressure wave may affect groundwater levels much sooner.

CONCLUSIONS

The significant differences in isotopic values of water from various sources confirm earlier conclusions regarding the multiple nature of aquifers in the Takaka Valley. Recharge areas for these aquifers are clearly indicated by the $\delta^{18}O$ values, the seasonal variations of which sometimes also give evidence of the lag time between rainfall event and recharge response. Significant differences in mean groundwater temperatures in the aquifers support the isotopic evidence as to provenance of the waters, but seasonal variations in groundwater temperatures are usually so small as to shed little further light on recharge lags. Low's bore is the main exception to this with a seasonal temperature variation of 0.8–1.3°C, the temperature swings usually being 1–2 months later than those in the upper Takaka River.

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