NATURAL GEOTHERMAL INFLOWS TO THE WAIKATO RIVER

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SUMMARY - Data collected from two monitoring programmes conducted by Environment Waikato have been used to estimate the mass flows of chloride, boron, lithium and total arsenic down the Waikato River, the mass inflows of these elements from the river's tributaries and by difference, the mass inflows from unmeasured sources which are mostly direct inflows of geothermal fluids through the bed of the river. For two sections of the river, between Lake Taupo and the dam on Lake Ohakuri and between the dams on Lakes Ohakuri and Whakamaru, the total inflows of chloride, the major anion in most geothermal waters, were respectively, 2680 g/s of which 15% was unmeasured and 325 g/s of which 40 % was unmeasured. These estimates at the detail of individual tributaries, are the most reliable that have been done to date and are timely information, particularly for boron and arsenic, not only because the World Health Organisation has recently recommended reduced drinking water standards for both these metals but also because over the next few years the resource consents for the Wairakei geothermal power station discharges to the Waikato River will be reviewed and development of the geothermal fields at Mokai and Rotokawa is likely.

1.0 INTRODUCTION

The Waikato River (catchment area 14,258 km^2) is the longest river (450 km) in New Zealand and is the region's most significant and utilised water resource. Originating in the snow-covered mountains of the Volcanic Plateau, it passes through Lake Taupo into the upper and middle reaches of the river with its chain of eight hydroelectric reservoirs. From Lake Taupo to the Tasman Sea, the river decends over 365 m and increases its flow 2.5-3 fold to about 450 m^3 at its mouth. The Wairakei geothermal power station discharges separated geothermal water and condensed steam into the first reservoir, Lake Aratiatia, and geothermal fluids from active fields enter the following four reservoirs, Ohakuri, Atiamuri, Whakamaru and Maraetai (Fig. 1.) The majority of these natural inflows originate in tributary catchments and can be identified and measured but significant sub-surface inflows to the river occur from active systems drowned by the formation of the reservoirs.

Environment Waikato, the authority responsible for managing the water resources of the Waikato River catchment has conducted a monitoring programme (the GMP) specifically designed to identify the sources of geothermal fluids, determine the mass flows of their constituents and assess the relative chemical significance of these in the Waikato River and its tributaries (Timperley, 1994). A larger, long-term monitoring programme (the WRMP) also operated on the Waikato River by Environment Waikato, records the water quality of the river.

In the study reported here the mass flows of geothermal fluid constituents entering the Waikato River from its tributaries were calculated from the results of the GMP and the mass flows passing specific locations in the river were calculated from the results of the WRMP. The differences between the mass flows estimated from the two monitoring programmes were estimates of the unmeasured inflows to the river of geothermal fluid constituents from the few catchments not monitored in the GMP and also through the bed of the river. The GMP is the most detailed programme ever directed at the geothermal fluids of the Waikato River catchment and consequently, the estimates made in this study of the unmeasured chemical contributions to the river from geothermal fluid inflows are the most accurate that have been made. It is particularly important at this time to know both the origins of these chemicals in the Waikato River water and the relative contributions from the various sources because over the next few years the resource consents for the Wairakei geothermal power station will be reviewed and development of the Mokai and Rotokawa fields is likely. Furthermore, the World Health Organisation recently reduced their drinking water guidelines for boron from 0.5 to 0.3 mg/l and for arsenic from 0.050 to 0.010 mg/l. These guidelines will be adopted by New Zealand.

2. MONITORING AND DATA ANALYSIS

Regular water quality monitoring of the Waikato River began in the late 1970's with data recorded for up to 34 variables at 16 sites. In 1988 the programme was changed slightly and the current programme (the WRMP) collects data for 31 variables at monthly or quarterly intervals from 14 sites (Fig. 1). Some of these sites are located in the tailraces of the hydroelectric power stations on the river and so give well-mixed samples of the whole river flow as well as reliable estimates of the water flow. The three sites from this monitoring programme used in this study for estimating the unmeasured geothermal salt inflows were those at the outlets of Lakes Taupo, Ohakuri and Whakamaru.

The monitoring programme (the GMP) specifically targeted at the inflows of geothermal fluids from tributaries to the Waikato River operated over the years 1986 to 1992. Water flow and quality data from 70 sites covering all 15 major geothennal areas were regularly collected at least twice annually at baseflow conditions.

In the study described here, chemical data for chloride, lithium, boron and arsenic are used. Chloride was analysed hy the mercury thiocyanate colorimetric method, lithium by atomic absorption spectrophotometry, boron by the azomethine-H colorimetric method and arsenic (total) by digestion, hydride generation and atomic absorption spectrophotometry. All methods followed APHA (e.g. APHA, 1989) standard methods.

The mass flows of dissolved salts in the tributary flows consist of salts from non-geothermal near-surface weathering (called the "baseline" contribution) and salts from geothermal fluids. The chemical compositions of the waters of the Waikato River catchment are determined by the variable proportions of surface and shallow groundwater (the baseline water), geothermal water after its separation from geothermal steam and condensed geothermal steam. Geothermal water is characterised by high chloride ion concentrations and the presence of this anion above a certain concentration in a freshwater indicates the probable influence of geothermal water. Geothermal steam contains hydrogen sulphide and carbon dioxide which appear in condensed steam as sulphate and bicarbonate. In some situations the hydrogen sulphide is lost to the atmosphere before oxidation and the condensed steam contains only elevated bicarbonate concentrations. Conversely the carbon dioxide can be lost after oxidation and only sulphate appears in the condensed steam. These three anions, chloride, sulphate and bicarbonate, can be used to distinquish and quantify the proportions of the three geothermal waters in a particular water sample (Timperley and Vigor-Brown, 1986). To estimate these proportions it is necessary to firstly separate the geothermal contribution from the baseline contribution.

In this study the average composition of the baseline water was estimated from the water quality data collected in the GMP by examining proportional plots of the three anions. The proportional plots of chloride, sulphate and bicarbonate concentrations all showed two distinct populations and the waters with ion concentrations falling in the lower of these populations for all three anions were considered to be baseline waters. The median concentrations for the different variables over all the samples in baseline data set were considered to be an adequate estimation of the baseline water composition. The samples remaining in the database after separation of the baseline waters were all considered to be influenced by geothermal fluids.

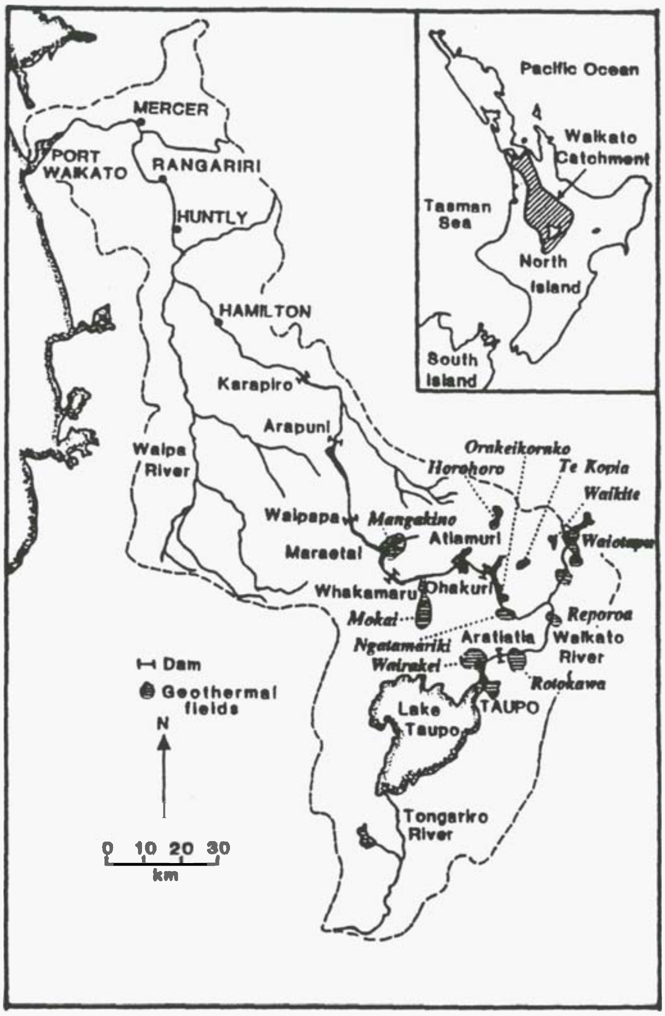

Figure 1. The Waikato River catchment showing the hydroelectric dams and the geothermal fields.

The mass flows of Cl, As, B, and Li at each site affected by geothennal fluids were calculated from the mean water flow at the site (all sampling was done under low flow conditions) and the mean concentrations of the variables. To estimate the total mass flows to the Waikato River from each tributary catchment, selected site mass flows were summed. For some tributaries, this *sum* included only one site on the main stem of the tributary immediately upstream of its confluence with the Waikato River but for other tributaries, several sites on different stems of the tributary were summed. This process required summing the mass flows for 31 sites fiom 15 different tributary catchments.

The mass flows from the Waiotapu Stream catchment, the largest in the study, were estimated by *summing* the mass flows over 11 out of a total of 19 sites. For the three sites on the Waikato River, the outlets of Lakes Taupo, Ohakuri and Whakamaru, the mass flows of the geothermal salts were calculated from the mean annual water flows and the mean annual concentrations. These data were extracted from several sources. Monitoring results for As and B in the Waikato River for the 1980 to 1986 period were summarised by Boswell (1986) and river flow data is available from Mulholland (1987) for the period 1980 to 1985.

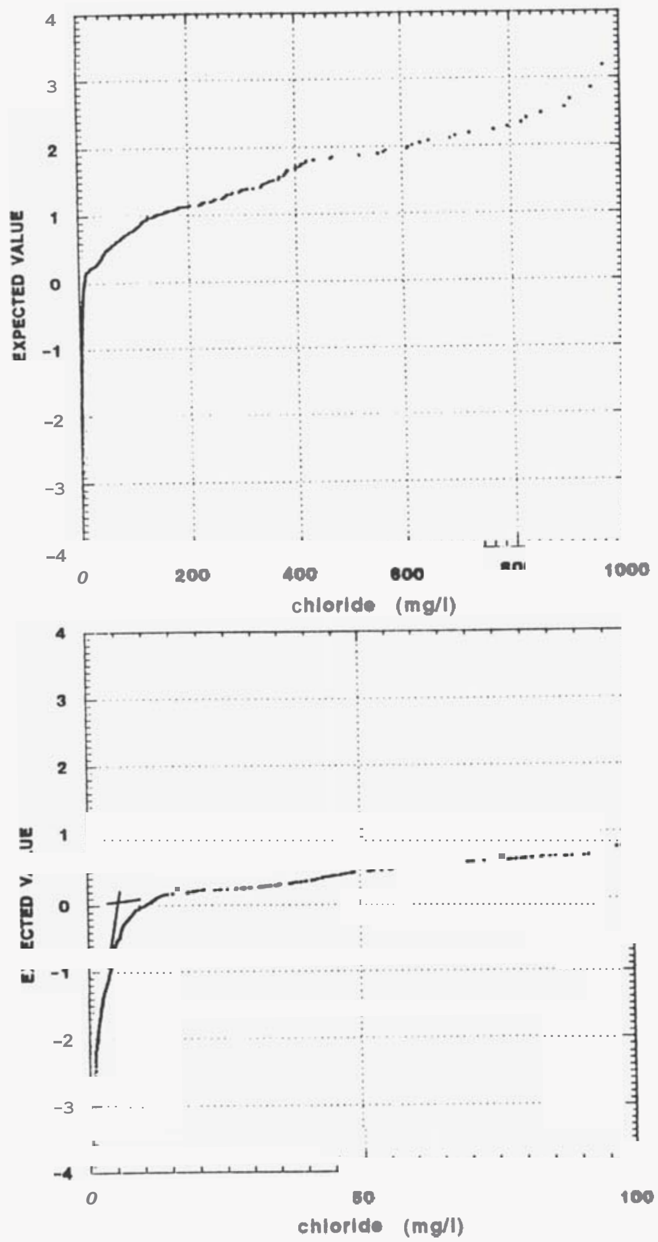

Figure 2. Proportional plot of chloride concentrations in water samples. The solid lines show the intersection of the lines fitted to the two data populations.

Monitoring data for 1988 were reported by Zuur (1989) and those for 1989 were reported by Huser (1990). From April 1988 to May 1989 the flow through the drain carrying separated geothermal water from the Wairakei field was reduced from about 4000 t/h to about 3400 t/h for reinjection trials.

Only two samples from the drain were collected over this period and these do not give an adequate measure of the mass flows to the river over this period. From 1990 to 1994, data for Cl, B, Li and total As were collected in the Waikato River monitoring programme (Huser, 1991, Huser and Prouse, 1994). Daily mean flows for the dam sites are available for these years.

3. RESULTS AND DISCUSSION

Fig. 2 shows a proportional plot of chloride concentrations in the samples. Data which are normally distributed appear as a single straight line in proportional plots but the chloride concentrations plot as two straight lines implying two independent normal populations.

Table 1. Chemical composition (mg/l) of baseline water.

	n	min	max	mean	median
ALKT	164	11.3	39.9	27.5	27.1
AsT	93	0.001	0.074	0.005	0.002
B	113	0.006	0.910	0.063	0.015
Ca	106	1.32	14.0	3.62	3.30
Cl	164	1.30	6.0	4.43	4.43
K	108	1.00	5.30	2.50	2.50
Li	162	0.001	0.050	0.012	0.010
Mg	106	0.880	5.80	1.59	1.50
Na	106	3.30	14.8	8.60	8.70
SO_4	164	0.50	6.0	4.03	4.00
NNN	83	0.010	1.50	0.372	0.310
NH_4	109	0.002	0.094	0.017	0.013

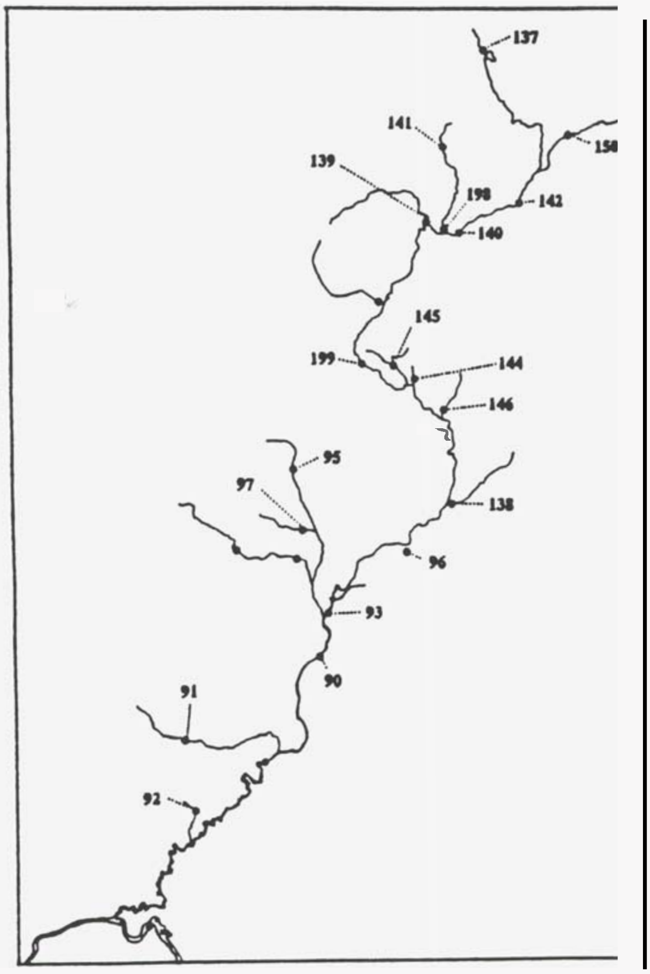

Figure 3. Sample sites in the Waiotapu catchment.

The population with the lower concentrations is comprised mostly of surface and shallow ground waters whereas the samples in the other population are mostly influenced by chloride-containing geothermal water. The inflexion point between the two lines is the boundary between the two water types although there is some overlap. The inflexion point occurs at 6 mg/l Cl. The subset of samples with Cl < = 6.0 mg/l was then subjected to the same procedure for SO_4 (plot not shown) The inflexion point for SO_4 also occurs at 6.0 **mg/l.** The proportional plot for ALKT for the subset with both Cl and SO_4 < = 6.0 **mg/l** gave an inflexion point at 40 mg/l which is quivalent to 49 **mg/l** of HCO_3 (plot not shown).

The subset from this analysis contained 164 samples. These samples were from waters which have not been significantly affected by Cl from geothermal water, or from SO_4 or HCO_3 from geothermal steam. The statistics for this baseline water are given in Table 1. The calculation of mass flows within the tributary catchments is illustrated for the Waiotapu Stream catchment. The sample sites are shown in Fig. 3 and the mass flows for the sites are given in Table 2. It can be seen from this table that despite the large number of sample sites in this catchment, the mass flows are consistent, i.e. increasing downstream towards the confluence with the Waikato River. Furthermore, all four elements are sufficiently conservative to ensure that the sum of the site mass flows within the catchment gives reliable total mass flows to the Waikato River.

Table 2. Mass flows (g/s) for the Waiotapu catchment.

TRIBUTARIES					MAIN STREAM CHANNEL				
site	As	Li	B	Cl	site	As	Li	B	Cl
					137	0.000	0.001	0.004	0.415
150	0.001	0.002	0.008	1.84		0.001	0.003	0.012	2.256
					142	0.035	0.196	0.319	28.80
					140	0.207	0.570	1.019	101.3
198	0.060	0.155	0.218	26.4		0.267	0.725	1.237	127.7
139	0.017	0.052	0.090	8.88		0.274	0.777	1.327	136.6
					199	0.345	1.025	1.725	157.9
145	0.003	0.012	0.021	1.94		0.348	1.037	1.746	159.9
144	0.057	0.228	0.519	48.2		0.405	1.265	2.265	208.0
146	0.001	0.004	0.010	0.78		0.406	1.269	2.270	208.0
138	0.003	0.011	0.035	3.40		0.409	1.280	2.305	212.2
96	0.008	0.026	0.053	1.69		0.417	1.306	2.358	213.9
93	0.009	0.049	0.101	7.30		0.426	1.355	2.259	221.2
95	0.000	0.002	0.004	0.90					
97	0.001	0.007	0.013	1.28		0.427	1.364	2.476	223.4
					90'	NA	1.131	1.950	130.7
91	NA	0.005	0.027	0.50		0.427	1.369	2.503	223.9
92	0.003	0.019	0.019	1.23		0.430	1.388	2.522	225.2
total	0.163	0.572	1.118	104.		0.430	1.388	2.522	225.2

* site 90 is unreliable because of too few water flow measurements

Table 3. Total mass flows (g/s) of chemical constituents from each section

Section	Cl	Li	As	B
Wairakei	2090	11.6	3.62	26.2
Waiotapu	225	1.388	0.430	2.52
Upper Lake Ohakuri	16.1	0.091	0.012	0.21
Whirinaki	38.5	0.438	0.078	0.35
Whangapoa	9.9	0.048	0.058	0.21
Waipapa/Mokai	137	0.918	0.153	1.40

The mass flows calculated for selected groups of tributary catchments are presented in Table 3. These flows include contributions from baseline waters as well as geothermal fluids. The actual geothermal contribution can be estimated by assuming that the flow of undiluted geothermal waters is a negligible fraction of the total tributary water flow and that the waters effectively comprise surface and ground water of baseline composition plus added geothermal salts. Table 4 shows the baseline mass flows for each section calculated from the total water flows and the baseline concentrations from Table 1. Table 5 gives the differences between the mass flows in Tables 3 and 4. These differences are the estimates of the mass flows of geothermal salts.

Several conclusions can be drawn from the data in Table 5. The first is that the Wairakei field contributes the major proportion of Cl, a fact which is well known. Lithium, B and As, follow Cl with the largest loads coming from the Wairakei field.

Table 4. Estimated baseline mass flows (g/s) from each section assuming total water flow is surface/ground water except for the Wairakei section for which 1.1 m^3/s, the known geothermal water flow, has been subtracted.

Section	Cl	Li	As	B
Wairakei	1.08	0.002	0.001	0.008
Waiotapu	11.2	0.023	0.008	0.079
Upper Lake Ohakuri	4.43	0.009	0.003	0.031
Whirinaki	4.89	0.010	0.003	0.034
Whangapoa	10.4	0.021	0.077	0.073
Waipapa/Mokai	15.3	0.031	0.010	0.108

Table 6 presents the mean Li mass flows and concentrations for the sites included in the Waikato River monitoring programme. The mean mass flow for this site can be accurately estimated as the mean for the four years, i.e. 6.84 g/s. Concentrations at the Ohakuri dam apparently increased over the 1989 to 1991 period and the mass flow of Li also increased. This is likely to have occurred because of the reduced geothermal water flow from the Wairakei field during the reinjection trial of 1988 to 1989. The long term mean mass flow of Li at the Ohakuri dam should therefore, be close to the mean of the 1990 to 1993 period.

Table 5. Mass flows (g/s) of geothermal fluid constituents estimated as the total mass flows minus the estimated baseline mass flows.

Section	Cl	Li	As	B
Wairakei	2059	11.6	3.62	26.2
Waiotapu	214	1.365	0.422	2.44
Upper Lake Ohakuri	11.7	0.082	0.009	0.179
Whirinaki	33.6	0.428	0.075	0.316
Whangapoa	-0.5	0.027	-0.02	0.137
Waipapa/Mokai	122	0.887	0.143	1.29

Table 6. Average mass flows (g/s) of Li in the Waikato River. Values in parenthesis are the concentrations in mg/kg.

	1989	1990	1991	1992	1993
Taupo gates	7.21(0.041)	7.23 (0.041)	6.56(0.042)	6.72(0.042)	(0.042)
Ohakuri	21.3(0.110)	22.3(0.115)	23.4(0.137)	23.6(0.134)	(0.137)
Whakamaru	21.7(0.100)	28.9(0.113)	25.3(0.134)	26.0(0.132)	(0.134)

Table 7. Li mass inflows (g/s) to the Waikato River and Li mass flow differences between locations.

site	WRMP*	within section inflow	GMP*	unmeasured inflow
Taupo gates	6.84			
		16.3	13.9	2.36
Ohakuri dam	23.1			
		3.63	0.966	2.67
Whakamaru dam	26.7			
		-4.17	not measured	-4.17

* WRMP = Waikato river monitoring programme
GMP = Geothermal monitoring programme

This same situation applies to the Whakamaru site but because the geothermal mass inflows within the sections Ohakuri to Whakamaru are likely to be reasonably constant over time, the differences between the two sites should also be constant over time. Table 7 summarises these mass flow differences and also the measured mass inflows between the sections. The same analysis was made for boron and chloride and the corresponding data are presented in Tables 8, 9, 10 and 11.

Table 8. Average mass flows (g/s) of B in the Waikato River. Values in parenthesis are the concentrations in mg/kg.

	1980-86	1988	1990	1991	1992	1993
Taupo gates	29.4(0.19)	29.1(0.18)	33.4(0.19)	28.1(0.18)	28.8(0.18)	(0.17)
Ohakuri dam	67.4(0.41)	61.4(0.35)	65.2(0.34)	68.4(0.40)	65.1(0.37)	(0.44)
Whakamaru dam			70.3(0.33)	73.7(0.39)	70.9(0.36)	(0.42)

Table 9. B mass inflows (g/s) to the Waikato River and B mass flow differences between locations.

site	WRMP*	within section inflow	GMP'	unmeasured inflow
Taupo gates	29.9			
		35.1	29.3	5.8
Ohakuri dam	65.0			
		6.60	1.61	5.0
Whakamaru dam	71.6			
		-5.20	not measured	-5.2

* WRMP = Waikato river monitoring programme
GMP = Geothermal monitoring programme

Table 10. Average mass flows (g/s) of Cl in the Waikato River. Values in parenthesis are the concentrations in mg/kg.

	1988	1990	1991	1992	1993
Taupo gates	1570(9.7)	1620(9.2)	1410(9.04)	1530(9.55)	(9.23)
Ohakuri dam	4070(23.2)	4290(22.2)	4170(24.4)	4280(24.3.)	(30.4)
Whakamaru dam		4330(20.5)	4730(25.0.)	4730(24.0)	(29.4)

Table 11. Cl mass inflows (g/s) to the Waikato River and Cl mass flow differences between locations.

site	WRMP*	within section inflow	GMP'	unmeasured inflow
Taupo gates	1520			
		2730	2370	360
Ohakuri dam	4250			
		350	147	203
Whakamaru dam	4600			
		0	not measured	0

* WRMP = Waikato river monitoring programme
GMP = Geothermal monitoring programme

The differences in Li, B and Cl mass flows between the two sections, Taupo to Ohakuri and Ohakuri to Whakamaru, are summarised in Table 12 as mass flows and as ratios of Cl and B to Li. Also given in this table are the average ratios of Cl and B to Li for geothermal fluids in the two sections. These geothermal ratios were calculated by fitting linear regressions to all data for the sections excluding samples classified as baseline, steam SO_4 and steam HCO_3. If the estimated mass flow differences accurately represent the unmeasured inflows of geothermal water then the element ratios for the unmeasured mass flows should be similar to those for the measured flows of geothermal waters.

Considering that the ratios estimated from the regression equations include all the various geothermal waters within each section, the data in Table 12 show that the composition of the unmeasured inflows is quite similar to that of the measured inflows. The apparent deficiency of Cl or surplus of B and Li in the unmeasured inflows for the Ohakuri to Whakamaru section does not have an obvious explanation. A comparison of the results in Tables 5 and 11 shows that the estimates of unmeasured geothermal fluid inflows between Taupo gates and Ohakuri are small, about 15% of the measured inflows.

Table 12. Unmeasured mass flows and element ratios for both the mass flows and the measured geothermal water inflows for two sections of the Waikato River.

Section	element	mass flow g/s	mass flow ratio	geothermal water ratio
Taupo to Ohakuri	Cl	360	150	162
	B	5.8	2.5	2.0
	Li	2.4	1.0	1.0
	As	0.72		
Ohakuri to Whakamaru	Cl	203	76	106
	B	5.0	1.9	2.2
	Li	2.7	1.0	1.0
	AS	0.54		

Between Ohakuri and Whakamaru, however, about 40% of the total geothermal inflow was not measured in the monitoring programme. Also included in the table are the unmeasured inflows of As estimated from the unmeasured Li mass flows and the ratios of As to Li obtained from the regression equations.

4.0 CONCLUSIONS

This monitoring programme has provided the first direct measure of the load of geothermal fluid constituents on the Waikato River. Such information places the various geothermal sources into perspective and also allows the relative impacts on the river of different activities to be assessed. The chemical influence of geothermal fluids within the sub-catchments is useful knowledge for deciding on the need for management of the catchments in terms of water use and also, from a scientific point of view, for identifying the sites under the most stress from geothermal fluids.

The major deficiency in the mass flow estimates is the lack of adequate water flow measurements for some sites and the missing mass flow data for geothermal inputs through the Fed of the river and hydrolakes. The attempt to estimate the unmeasured geothermal fluid inflows from the mass flow differences between river cross sections gave estimates which were consistent with the known Cl, B and Li concentrations in geothermal fluids. These results provide reasonably convincing evidence that the unmeasured inflows are about 15% of the measured inflows between Lake Taupo gates and the Lake Ohakuri dam and about 40% between the Lakes Ohakuri and Whakamaru dams. The absolute quantities are about the same in the two sections.

5. ACKNOWLEDGEMENTS

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