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Taihoro Nukurangi

Effects of the cold, spring-fed, inlet streams on rainbow trout distribution in Lake Rotorua

NIWA Client Report: HAM2006-121
September 2006

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Executive Summary

The Hamurana Stream is the largest stream flowing into Lake Rotorua and contributes a major proportion of the total input of nutrients (N and P) into the lake. As consequence, its diversion is being considered as part of a range of measures to reduce nutrient inputs into Lake Rotorua. Extensive use of this and other cold-water, spring-fed streams is made by anglers in summer and its diversion may have an adverse effect on the trout fishery.

To determine the effects of the proposed diversion of the Hamurana Stream on the trout fishery, we implanted 30 trout with acoustic transmitters that relayed the depth and temperature of the trout to receivers placed by the mouths of spring-fed streams as well as throughout the lake. Signals received from the trout were collected over a seven month period covering both the hot summer months and the cooler spring and autumn months. The results indicated that most trout moved large distances on a daily basis and utilised the entire lake. When lake water temperatures were cool (less than about 18ºC), the trout were distributed throughout the lake. However, when water temperatures were warm (more than about 18°C), trout aggregated in the north-western region of the lake where the majority of spring-fed, cold-water tributary streams are located. Maximum use of the cold-water tributaries occurred when lake temperatures exceeded 20ºC. At this time, some trout used the thermal refugia intermittently, but others entered the streams and remained there for periods of days to months.

Overall, the results indicated that diversion of the entire Hamurana Stream could be expected to affect trout distribution in the lake and hence the fishery during summer months. Complete diversion would result in the summer fishery at the outlet of the Hamurana Stream being lost. The Hamurana Stream is the largest of the cold-water inflows to the lake and its total diversion will reduce the overall attraction of the north-western region of the lake to trout. This can be expected to reduce trout numbers here and, although this effect cannot be quantified, a reduction in trout numbers may reduce catch rates in the north-western region. Although the attraction of the north-western region is likely to be because these streams provide a thermal refuge for trout during hot spells, it may also be related to an increase in trout food supply caused by a localised increase in lake productivity from the nutrients in these streams and/or the aggregations of other fish (e.g., smelt). Such uncertainties about the mechanisms of attraction and the overall effects of diversion on trout numbers warrant a precautionary approach. We therefore recommend that full diversion of the Hamurana Stream should be avoided during summer months.

1. Introduction

The Hamurana Stream is the largest stream flowing into Lake Rotorua and it contributes a major proportion of the total input of plant nutrients (N and P) into the lake (Rowe et al. 2005). It has been estimated that its diversion would reduce the total nitrogen loading into Lake Rotorua by 12.3% and the phosphorus loading by 18.5%. As a consequence, its diversion is being considered as part of a range of measures to reduce nutrient inputs into Lake Rotorua.

Many of the streams that enter Lake Rotorua are spring fed. As such, their temperatures vary less than in the others and in mid-summer (January-March) these streams are much colder (Table 1) than the lake, which prior to 1980 averaged 21 ºC (Mosley 1982).

Table 1: Mean flows, summer water temperatures and relative amounts of thermal refuge for trout provided by the main streams entering Lake Rotorua (based on Rowe 2004, (* smallest, ***** largest).

Streams	Flow ($x10^3$ m^3/d)	Mean summer temperature (Jan-Mar) and its range (^oC)	Relative ranking based on the amount of trout thermal refuge
Hamurana Spring	256.2	12 ± 2	*****
Ngongotaha Stream	197.4	16 ± 9	***
Utuhina Stream	191.4	16 ± 9	**
Puarenga Stream	165.8	22 ± 5	
Awahou Stream	155.2	13 ± 2	***
Waiteti Stream	129.6	15 ± 5	***
Waiohewa Stream	42.2	18 ± 7	
Waingaehe Stream	25.6	18 ± 5	
Waiowhero Stream	----	15 ± 3	*

Angling pressure around the mouths of the larger and colder streams (particularly the Hamurana, Awahou and Waiteti streams) increases during summer months (Rowe et al. 2005) because trout are attracted to the cooler waters when temperatures in the lake exceed their preferred temperature. As these streams occur mainly in the north-western sector of the lake, their collective value to trout during summer months may result in a changed distribution, with a generalised movement of trout to the north-western sector of the lake. If so, then a reduction in the size of the cold-water inflows may have repercussions for trout distribution in Lake Rotorua over summer months and hence for the trout fishery.

In an earlier study (Rowe et al. 2005), the consequences of diversion of the Hamurana Stream on the rainbow trout population of the lake (and hence its fishery) were considered. The amount of cold-water refuge habitat provided by the plume of this stream during the warmer summer months was estimated to be up to 40-50% of the total cold-water refuge habitat available. Although this is relatively high, there was no evidence that the presence of cold-water refugia in this lake was essential for trout growth dynamics and hence for trout survival during summer months. This aside, the increase in shore-based angling, which occurs around the mouths of certain spring-fed streams during summer months, combined with the decrease in trolling in the lake at this time, could indicate that trout distribution in the lake changes during summer. If so, the diversion of the largest spring-fed stream from the lake may well reduce the attraction of the north-western region of the lake to trout over summer months and result in reduced catch rates by stream-based anglers. Data on the distribution of rainbow trout in Lake Rotorua in summer months are required to test this hypothesis.

In this report, we describe the results of an acoustic tagging study that was designed to firstly determine the distribution of rainbow trout before, during and after the hottest months in the lake over the 2005/2006 summer, and secondly to determine whether the trout utilise the cold-water plumes provided at the mouths of spring-fed streams, in particular that provided by the Hamurana Stream. The tags implanted within the trout were individually coded and designed to transmit details of their body temperature and depth to receivers placed strategically throughout the lake. The receivers recorded the information transmitted by the transmitters whenever a tagged trout occurred within their detection range estimated to be from 10’s of meters to a kilometer or more depending on local conditions and interference. The data collected allowed us to record large changes in the distribution of trout within the lake over time as well as data on the water temperature and depth range utilised by the trout when within receiver transmitting range.

2. Methods

2.1 Trout capture tagging and release

Rainbow trout used in the study were caught by fishing guides and anglers trolling or fly fishing around the lake. Barbless hooks were used and fish were held in dark holding bins or bags for transport to the tagging site. The capture location of each fish was recorded according to the grid shown in Fig. 1. As far as possible, fishing was spread over the entire lake and 30 trout from different regions of the lake were retained for tagging (Table 2).

Capture and tagging was undertaken over three periods: 8 November 2005 (13 fish), 10 November 2005 (10 fish) and 17 November 2005 (7 fish). Only healthy trout over 1.1 kg were used and all tagging was done by experienced personnel in accordance with the requirements of the NIWA Animal Ethics Committee.

The 30 trout retained for tagging were implanted with VEMCO V16-TP-4H acoustic transmitters. Each tag was capable of sending two coded pulses transmitting depth (±0.5 m) and temperature (± 0.2 ^{o}C) information from each fish. To minimise the risk of collision between the signals, transmission of signals from the tags was set to occur at a random time within an interval ranging from 60 to 180 seconds. The transmitters, which were about 80 mm long, 16 mm in diameter and weighed about 12 g in water, have a life expectancy of about 450 days.

To implant the transmitters, trout were placed individually into a 50 L bin containing 0.09 ml/L clove oil. Once sedated, their fork length (mm), weight (g) and sex were measured. The trout were then placed ventral side up in a foam mattress soaked in anaesthetic. Anaesthetic was run over the gills for the entire operation (Fig. 2). A 20 mm incision was made in the body wall on the mid-ventral line, anterior to the pelvic girdle. The transmitter was then inserted into the body cavity and positioned forward of the incision. The incision was closed with three to four sterile synthetic absorbable sutures (Ethicon model BH4667). To provide external identification, a numbered T-bar external tag was also inserted just below the dorsal fin (Fig. 3).

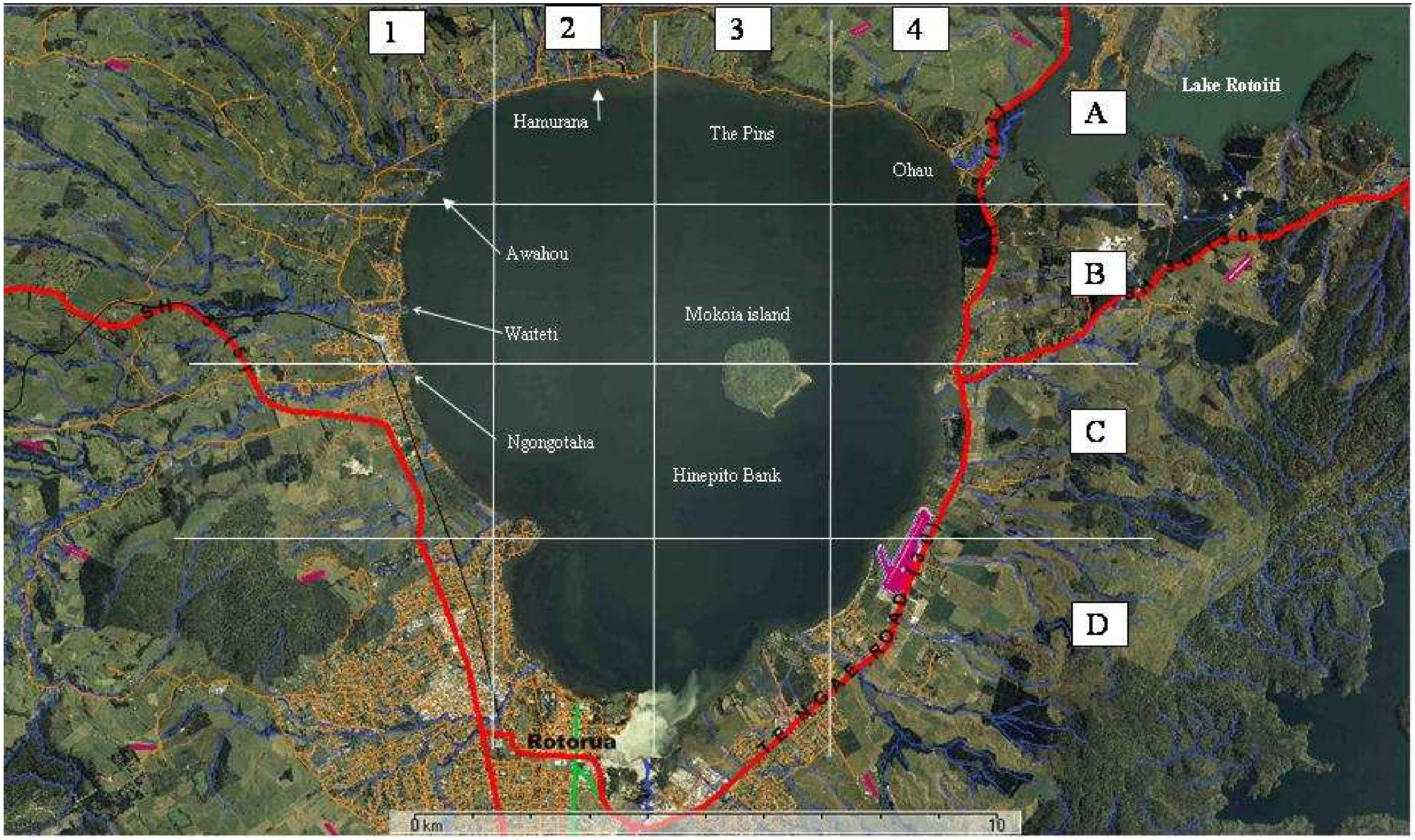

Figure 1: Grid used to assign capture and release location. Common locality names used in the text are also shown.

Table 2: Characteristics, tagging records and tracking summary of the 30 rainbow trout implanted with acoustic transmitters in Lake Rotorua in 2005/06. (M = male, F = female, L = Lake Rotorua, S = stream, O = Ohau Channel, R = Lake Rotoiti).

Fish statistics and tagging records							Last detection		Travel history	Fate	Notes
Fish No.	Length (mm)	Weight (kg)	Catch/release location	Sex	State	Date released	Date	Location			
101	47	1.14	A3	M	Prev. spawn	8/11/05	26/02/06	Pins	L	Caught	Caught 5/04/06 off the Ohau Channel. (May have expelled transmitter.)
103	49	1.26	B4	F	Prev. spawn	8/11/05	26/01/06	Ohau delta	L/S/L/O/R	Caught	Caught 18/2/06 in L. Rotoiti.
105	52	1.9	A3	F	Maiden	8/11/05	23/05/06	Hamurana	L/S/L	Rotorua	Entered Ngongotaha Stm 24/12/05. Returned to lake 16/3/06. In lake at last download.
107	49	1.24	C2			8/11/05	17/05/06	Ngongotaha		Dead	Appear to have died 14/11/05. Tag lying in 10 m water at last download
109	53	1.82	A4	F		8/11/05	28/01/06	Mokaia West	L	Caught	Caught 28/01/06 at the Pins
111	63	2.48	B3	F	Prev. spawn	8/11/05	10/02/06	Hamurana	L	Caught	Caught Hamurana Stm mouth 10/02/05
113	48	1.45	D2			8/11/05	15/12/05	Ngongotaha	L/S/L/S	Caught	Caught 22/02/06, Ngongotaha Stm. 7.68 km from lake
115	51	1.37	C4	M	Kelt	8/11/05	18/05/06	Ohau	L	Rotorua	In lake at last download
117	51	1.76	A3	F	Maiden	8/11/05	28/02/06	Waiteti	L/S/L/S/L/?	?	Entered Ngongotaha Stm 19/11/05. Returned to lake 12/2/06. Entered the Awahou 18/2/06. Returned to lake 26/2/06. Last Recorded Waititi Stm mouth.
119	47	1.17	C2			8/11/05	28/01/06	Ohau delta	L/O/R	Rotoiti	Appears to be in Rotoiti at last download
121	48	1.58	C4	M	Kelt	8/11/05	22/12/05	Awahou	L/S/L/?	?	
123	47	1.44	C2			8/11/05	01/06/06	Awahou		Dead	Appears to have died around 21/11/05. Tag Lying in about 2 m of water at last download.
125	56	1.62	Awahou mouth	M	Prev. spawn	10/11/05	02/06/06	Awahou	L/S/L/S/L	Rotorua	Moved into the Awahou soon after tagging. Returned briefly to lake 10-13 December 2005. Move up the Awahou again but returned to lake on 16/12/05. From then until 25/4/06 appears to have spend most of the
127	57	2.16	C3	F	Prev. spawn	8/11/05	09/11/05	Mokoia West	?	?	Only recorded for one day after release
129	50	1.38	C1	F	Prev. spawn	10/11/05	25/05/06	Waiteti	L	Rotorua	Remained in close proximity to the Ngongotaha Stream mouth most of the time. In lake at last download
131	48	1.28	C1	F	Prev. spawn	10/11/05	17/01/06	Hamurana	L/O/R/O/L	Caught	Was in Rotoiti from 7/1/06 to 11/1/06. Caught 17/1/06 in the Hamurana Stm.
133	52	1.5	C4	F	Prev. spawn	10/11/05	07/05/06	Ohau	L/S/L/S/L/O	Caught	Spend 12 to 14 Dec 2005 and 28 Jan to 25 Feb 2006 up the Awahou Stm. Rest of time in lake. Travelled to Ohau Channel and Caught there 21/05/06.
135	51	1.76	C4	m	Maiden	10/11/05	25/01/06	Waiteti	L/S	Caught	Reported caught 21/04/06 Awahou Stm
137	54	1.72	A2	F	Prev. spawn	10/11/05	25/01/06	Mokaia East	L	?	Travelled around the lake when records available
139	53	1.44	C4	F	Prev. spawn	10/11/05	02/06/06	Hamurana		Dead	Appear to have died in early Dec 2005. Tag now lies in 9-10 m water
141	48	1.48	A3	M	Maiden	10/11/05	02/06/06	Awahou	L/S/L	Rotorua	Appears to have been up the Ngongotaha Stm from 22/11/05 to 16/4/06. In lake at last download.
143	49	1.28	C4	F	Prev. spawn	10/11/05	19/11/05	Ngongotaha	L/S	Caught	Caught 21/11/05 in the Ngongotaha Stm.
145	54	1.74	Awahou mouth	F	Maiden	10/11/05	14/12/05	Ngongotaha	L	?	May have moved up the Awahou 26-29 Nov 2006 before returning to the lake. Last recorded moving into the
147	51	-	B4	F	Prev. spawn	17/11/05	11/05/06	Waiohewa	L	Rotorua	Disappeared from 17/1205 to 8/3/0. In lake at last download
149	53	-	B4	M	Kelt	17/11/05	04/01/06	Awahou	L	?	
151	55	-	A4	F	Prev. spawn	17/11/05	02/06/06	Hamurana	L/S/L	Rotorua	Moved numerous times in and out of the Waititi Stm. between 26/106 and 22/3/03. May have gone up the Awahou from 6-12 Feb 2006. In lake at last download
153	52	-	B4	F	Maiden	17/11/05	02/06/06	Kawaha Point	L/S/L	Rotorua	May have moved into the Awahou, Waiteti, & Ngongotaha and other cold stream periodically from 11 Dec 05 to 26 Mar 06. In lake at last download
155	55	-	B4	F	Prev. spawn	17/11/05	02/06/06	Kawaha Point	L/S/L	Rotorua	May have moved into the Awahou, Waiteti, & Ngongotaha periodically from 12 Dec 05 to 28 Feb 06. In lake
157	48	-	B4	F	Maiden	17/11/05	02/06/06	Awahou	L/S	Dead	May have move up the Awahou from 8/12/06 to 16/1/06. Appear to have died or been caught around 16-19 Jan 06. Tag in 4-5 m at last download
159	52	-	A2	F	Maiden	17/11/05	28/12/05	Ngongotaha	L/S	?	Appears to have dissapeared up the Ngongotaha Stm.

Figure 2: Tag implantation procedure. (Photo Mark Sherburn, Eastern F&G).

Figure 3: Tagged fished on their way to their respective released site. Note highly visible T-bar tag on fish back.

Each implantation took about two minutes and after surgery fish were placed in a holding bag in the lake for recovery (Fig. 4). Once fully recovered, the fish were transferred to an aerated holding bin on a boat (Fig. 3) and released at the place of capture.

Figure 4: Holding bags used prior to and after surgery. (Photo Mark Sherburn, Eastern F&G.)

2.2 Disposition of the acoustic receivers

Detection trials were undertaken on 3 October 2005 by positioning VEMCO VR2 receivers at fixed locations near one of the stream mouths and progressively moving a transmitter away from the receivers. Results indicated that when the lake was calm, a 500 m detection range was easily obtained (a maximum detection range of 4 km was occasionally recorded). The detection range reduced progressively as wind and wave size increased throughout the day. The presence of weed beds and lake bed structures (e.g., sand-banks, holes, rocks), which limit or reduce acoustic transmission through water was also found to affect detection range.

On the basis of this trial and after discussing options with the Lake Rotorua Harbour Master, we concluded that with the limited number of receivers available the best option was to deploy one receiver on each side of each of the main stream mouths (at the 200 m mark where yellow vessel speed restriction markers are located) and one offshore from each stream mouth in the drop-off zone where the lake bed begins to shelve more steeply. The remainder was deployed in the drop-off zone around the rest of the lake (Fig. 4, Table 3). One receiver was added later at the Ohau Channel mouth. With this array, the potential for detecting a trout moving around the lake was maximized, but times when it could be recorded simultaneously from more than one location were minimized and only likely to occur on calm days. Except in very rough conditions, the receivers positioned close to each stream mouth were expected to detect fish present in the cold water plumes.

Table 3: Location of the receivers deployed during the study.

Receiver number	Location & Code	Coordinates South	Coordinates East	Map Ref. (NZMS 260)
1	Ngongotaha Deep	38 04 860	176 13 482	U15 930 418
1A	Ngongotaha A	38 04 758	176 13 246	U15 927 420
1B	Ngongotaha B	38 04 934	176 13 298	U15 927 417
2	Waiteti Deep	38 04 378	176 13 475	U15 930 427
2A	Waiteti A	38 04 524	176 13 149	U15 924 430
2B	Waiteti B	38 04 235	176 13 031	U15 924 427
3	Awahou Deep	38 03 160	176 13 644	U15 933 449
3A	Awahou A	38 03 001	176 13 591	U15 933 452
3B	Awahou B	38 03 201	176 13 385	U15 930 449
4	Hamurana Deep	38 02 699	176 15 587	U15 962 457
4A	Hamurana A	38 02 129	176 15 833	U15 966 467
4B	Hamurana B	38 02 206	176 15 617	U15 963 466
4C	Hamurana C	38 02 183	176 15 501	U15 961 467
5	Pins Deep	38 02 536	176 17 232	U15 986 459
6	Ohau Channel Deep	38 02 910	176 19 094	U15 013 451
7	Ohau Delta	38 02 175	176 20 083	U15:029 462
8	Waiohewa Deep	38 04 704	176 18 956	U15 010 418
9	Mokaia East	38 04 986	176 17 703	U15 992 414
10	Mokaia West	38 04 467	176 16 837	U15 979 424
11	Hinepito Bank	38 06 264	176 16 638	U16 975 390
12	Kawaha Deep	38 06 214	176 14 914	U16 950 392

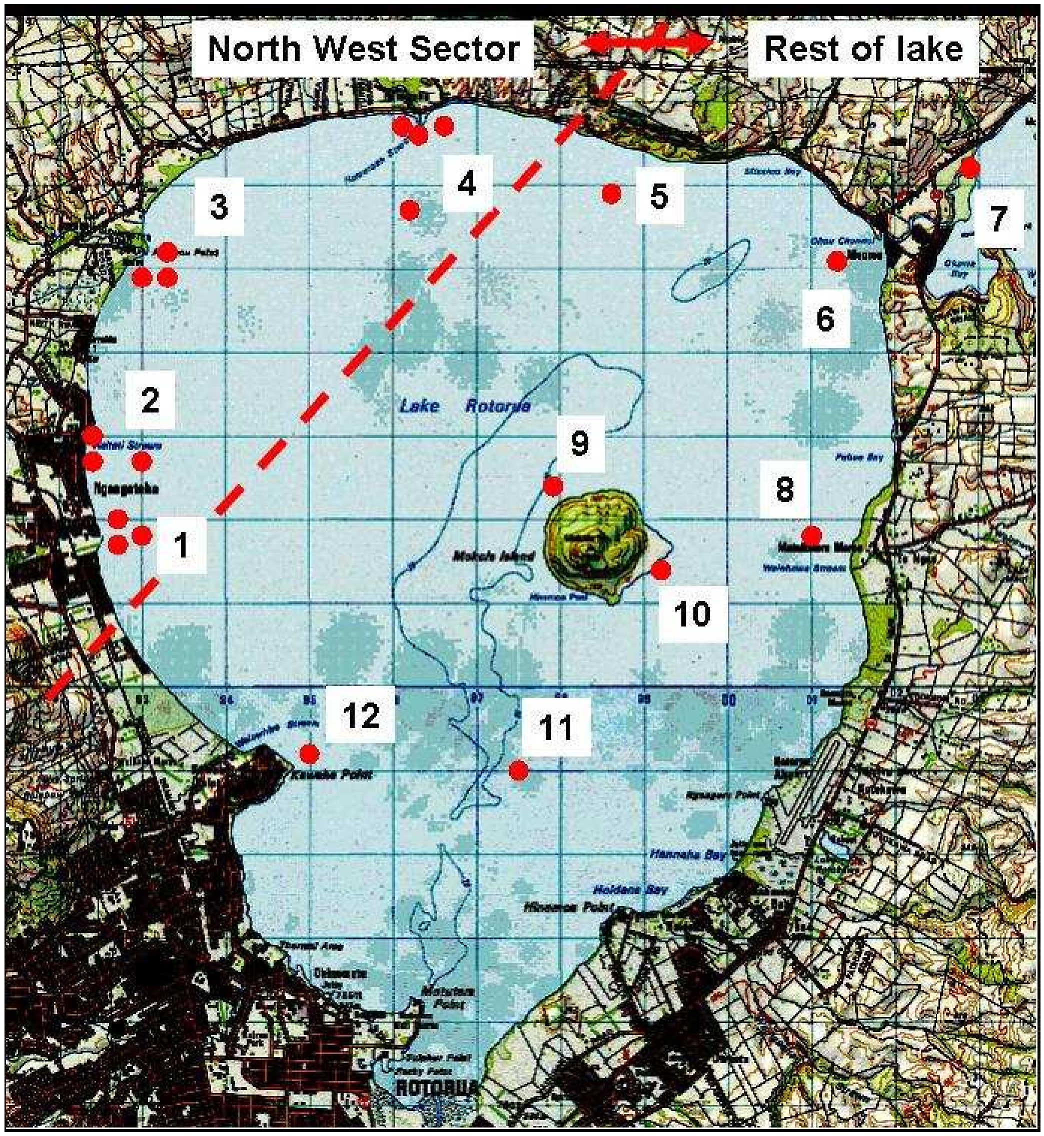

Figure 4: Position of the receivers and the separation line between the north-west region and the rest of Lake Rotorua. (Refer to Table 3 for location names and exact positions of the receivers).

2.3 Water temperatures in the lake

HOBO® temperature loggers were deployed at most of the receiver locations to provide background water temperature. Historical water temperature records were also obtained from NIWA and Environment Bay of Plenty databases.

2.4 Data analysis

Data were downloaded between 18 May and 2 June 2006. The receiver located at the mouth of the Ohau Channel was last downloaded on 30 June 2006. Unfortunately, Receiver 11 on the Hinepito Bank lost its marker buoy after February 2006 and despite extensive searches by divers was not recovered.

Raw data downloaded from each receiver included the tag code identifying individual trout, the date and time when a recording occurred, and the temperature and depth of the trout. To facilitate analysis, all the data collected by the three (or in the case of the Hamurana, four) receivers positioned around each of the spring-fed stream mouths were later pooled to provide a comprehensive data set for each site. Any fish whose signal from a given receiver remained at a consistent depth for an extended period (> 2 days) was deemed to be dead or its transmitter expelled. Data from these fish were excluded from further analysis from the time their signals stopped varying.

Temporal changes in the spatial distribution of each trout were determined to identify their likely movements over time. This was possible only for trout that were sequentially detected by receivers at different sites over short (hours to days) time intervals. Some trout were not detected for extended periods of time (weeks to months) in Lake Rotorua. Three of these fish moved into Lake Rotoiti. However, others are thought to have ascended one or more of the streams for extended periods before moving back downstream to the lake where they were then detected again. Although it is theoretically possible that some trout could swim within the lake and fail to be detected by any receiver because their path avoided the minimum detection range for any receiver, this would only be possible for short time intervals (e.g., hours to days). It is highly unlikely that trout would be able to avoid all receivers over longer periods (e.g., weeks to months). In order to confirm that the extended disappearance of some trout was because of movement into streams, the depth and temperature records prior to signal loss and on regaining it were closely examined. We determined whether fish moved into shallower and colder water (consistent with stream entry) before disappearance and to warmer and deeper waters (consistent with return to the lake) after reappearance (e.g., Fig. 5). The date and time of each stream entry and exit was established for fish exhibiting this behaviour and the time spent in each stream established.

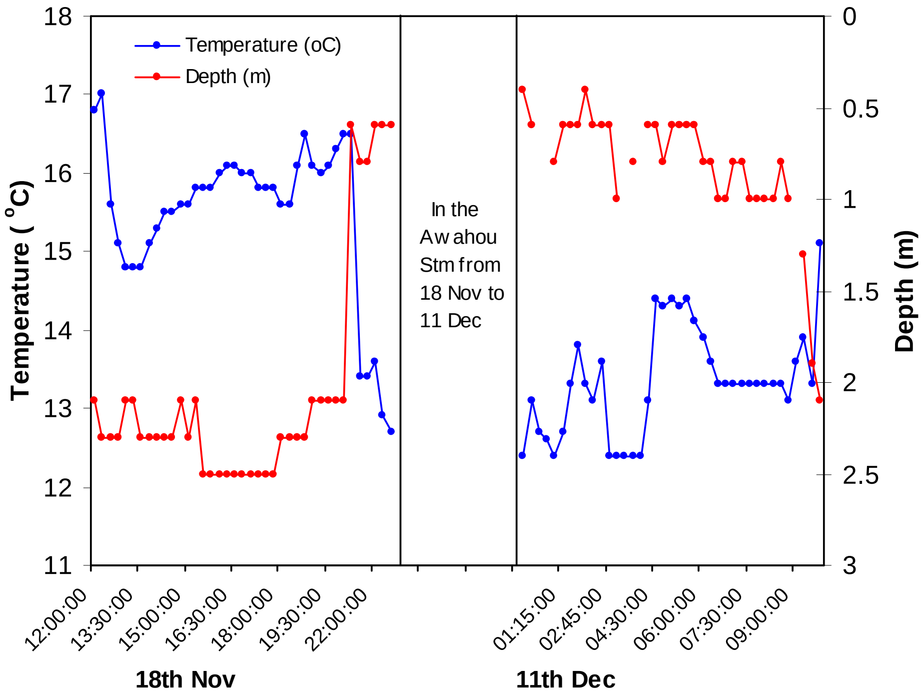

Figure 5: Temperature and depth record for Trout 125 at it entered the Awahou Stream on 18 November and returned to the lake on 11 December 2006.

For each fish, the time of release, time of capture and/or time of last record was used to establish the total length of time record available ($\mathbf{T_t}$) in multiples of 15 minute intervals for both the hottest months (December, January and February) and the cooler months (remainder of records). The occurrence of each trout up tributary streams (or in Lake Rotoiti) ($\mathbf{T_s}$) was subtracted from these data to obtain a measure of the total time each fish was present in the lake. The occurrence of each trout within each 15 minute interval (T_i) of this period, was then determined for each receiver site over the period for which records were available. Where a trout was recorded by more than one receiver within a given 15 minute interval, the previous and future records were examined to determine which receiver to assign its occurrence to. Thus, no trout was assigned to more than one site within a given 15 minute time interval. The frequency of occurrence (F) of each trout at each site was then calculated from:

$$F = \sum T_i / (\mathbf{T_t} - \sum \mathbf{T_s})$$

The frequency of occurrence of each trout was summed for all sites within the north-western region of the lake versus sites in the remainder of the lake for both the cooler and hot months, respectively. As differences in the occurrence of each trout between the north-western region of the lake and the rest of the lake will reflect preferential use of the north-western region (i.e., where the spring-fed streams occur), we determined differences in the occurrence of each trout between these regions in both the hot and cooler periods using chi-square tests of independence (Sokal & Rohlf 1973). Our hypothesis was that there would be no difference in the occurrence of each trout between either the two regions (i.e., areas with and without cold-water streams) or between the cool and hot periods. The frequency of occurrence for each trout at each of the cold-water stream sites was also determined to indicate preferences among these.

To determine whether the acoustically tagged trout as a group preferred the north-western region of the lake in summer months (i.e., the hot period) we counted the total number of tagged fish exhibiting a clear preference for the north-western region in both the hot and cooler periods, respectively. A clear preference was defined as occurring when the frequencies differed statistically (i.e., $P > 0.05$) and when the difference between two frequencies was greater then 33% (i.e., a trout was present in one region for two-thirds more time than in the other). Differences in the proportions of tagged trout between the two regions were then tested using a chi-square test of independence, again assuming no difference in distribution between the two regions or between the hot and cool periods.

3. Results & discussion

Rowe & Chisnall (1995) found that after acclimation to warmer waters, the preferred temperature of adult rainbow trout in three of the deeper (> 50 m) Rotorua lakes was about 16°C and that the depth distribution of these fish was affected by water temperatures over 20ºC. When the surface waters of the deep lakes exceeded 20°C, most trout occupied the cooler waters present below about 20 m. Consequently, water temperatures over 20°C can be expected to have a major effect on trout distribution and movement in a comparatively shallow lake such as Rotorua. Water temperatures in this range occur in Lake Rotorua from December to March (Fig. 6) with the hottest months generally being January and February.

3.1 Lake and stream water temperatures

Seasonal water temperatures in Lake Rotorua during the study period were close to the historical average for the lake (Fig. 6).

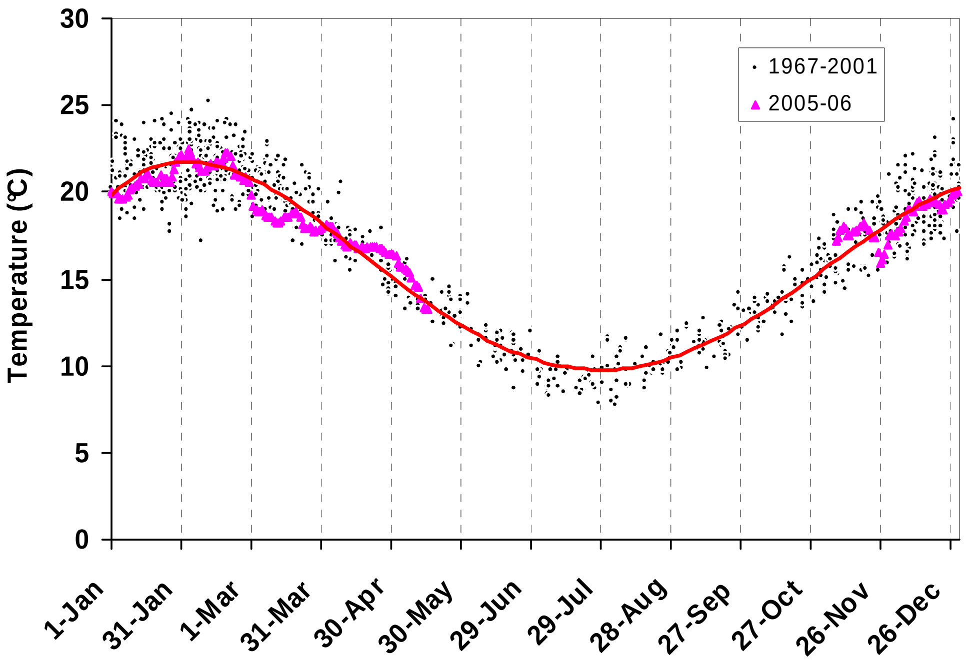

Figure 6: Comparison of the average daily water temperature of Lake Rotorua during the study period with historical records. The trend line shown is for the 1967-2001 period.

Water temperatures increased from about 17^{o}C in early December to a peak of about 22^{o}C in late January and they remained high during February before declining.

Therefore, the warmest period during the 2005/2006 summer included the latter part of December, all of January and February, but not March. This is the period within which the tagged trout would be expected to respond to the hot water temperatures and show a greater affinity with the north-western region of the lake where most of the cold spring-fed streams inflows are located. For this reason, the period 1 December through to 28 February was chosen to represent the hot period and the rest of the study period was designated as the cold period.

In general, Lake Rotorua does not stratify because it is a relatively shallow and exposed lake, prone to wind-mixing. Thus, the water temperature near the bottom (at 18 m) is usually close to that at the surface (Fig. 7). A temperature differential between surface and bottom waters can occur for brief periods when the lake is calm, but the largest differential recorded between 1967-2001 was 5°C and this only occurred during the summer of 1980. This means that in most summers there is no thermal refuge for trout provided by deep waters in this lake as occurs in the much deeper lakes such as Rotoiti and Rotoma. It also indicates that surface water temperatures in Lake Rotorua provide an adequate description of seasonal changes in the temperature of the main body of the lake.

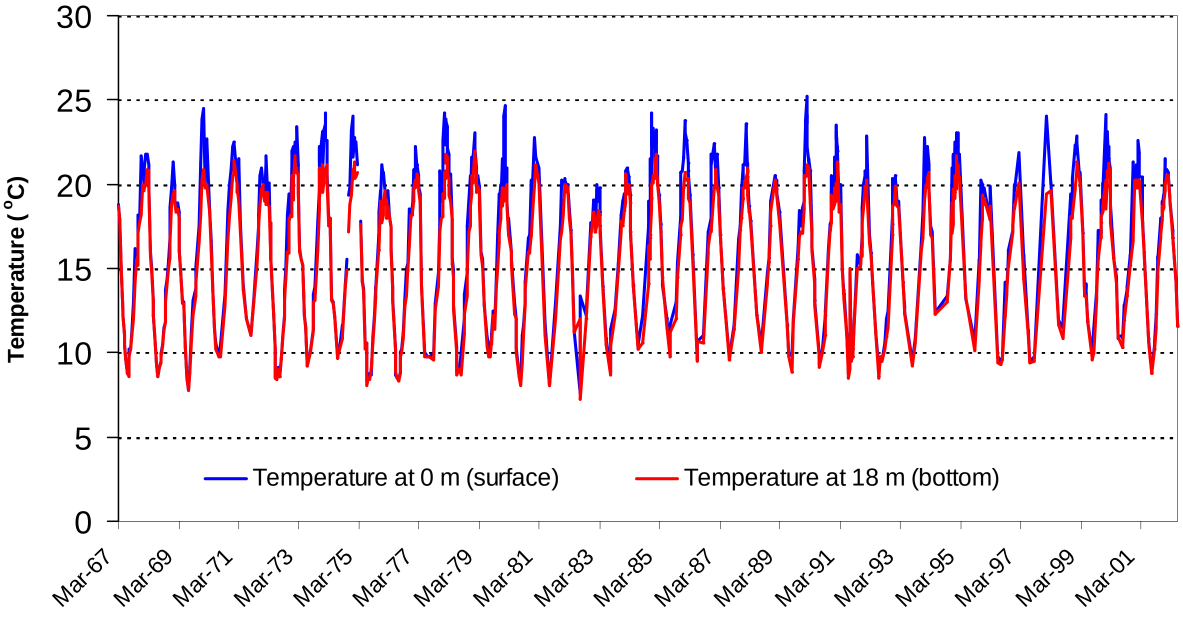

Figure 7: Surface and bottom water temperatures of Lake Rotorua 1967 to 2001 (source NIWA records).

Although surface and bottom water temperatures in the main body of the lake are usually similar, temperatures at the stream mouths are usually colder and show diurnal variation (Fig. 8A). Large differences in temperatures can also occur in shallow waters along the shoreline at times (Fig. 8B). These differences are probably caused by atmospheric heating (during the day) and cooling (at night) along the shallow sheltered lake margins.

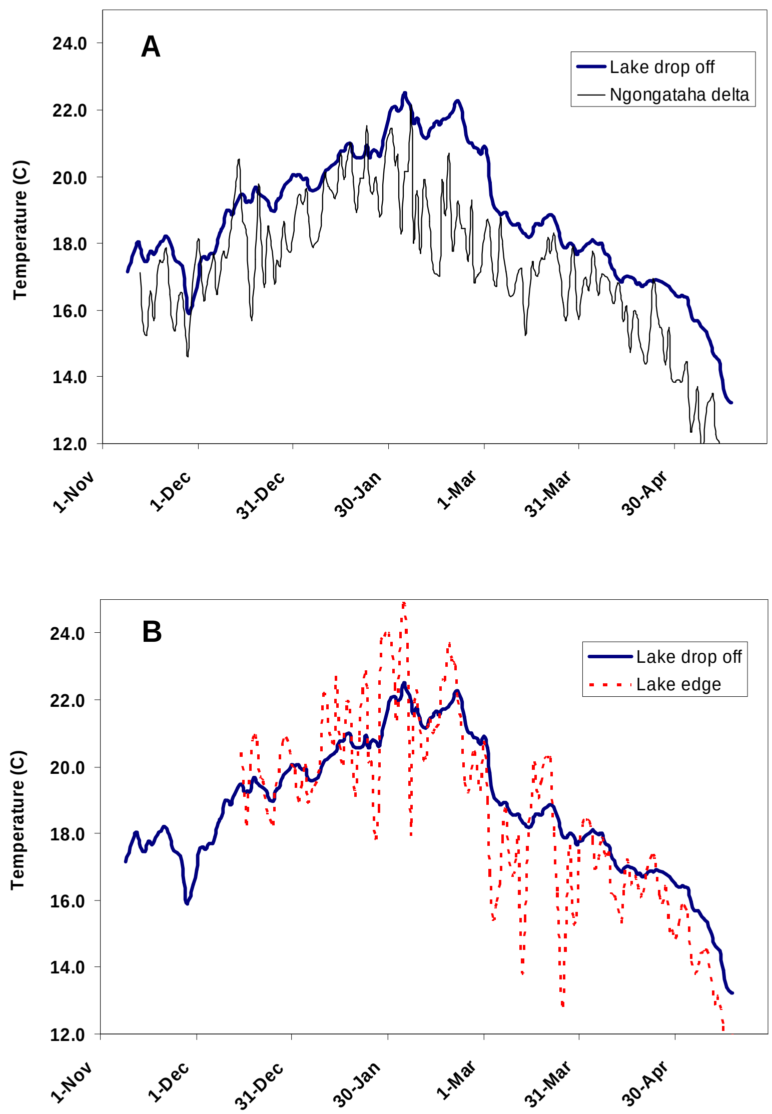

Figure 8: Average daily water temperatures from the middle of Lake Rotorua (i.e., Mokoia Island), between November 2005 and May 2006 compared with temperatures at: (A) the Ngongotaha Stream mouth, and (B) the lake shoreline north of the Awahou Stream mouth.

3.2 Tracking results and fate of tagged trout

The surgical wounds of all the fish recaptured were well healed (Fig. 10), but based on records provided by anglers, some appear to have lost weight and/or condition.

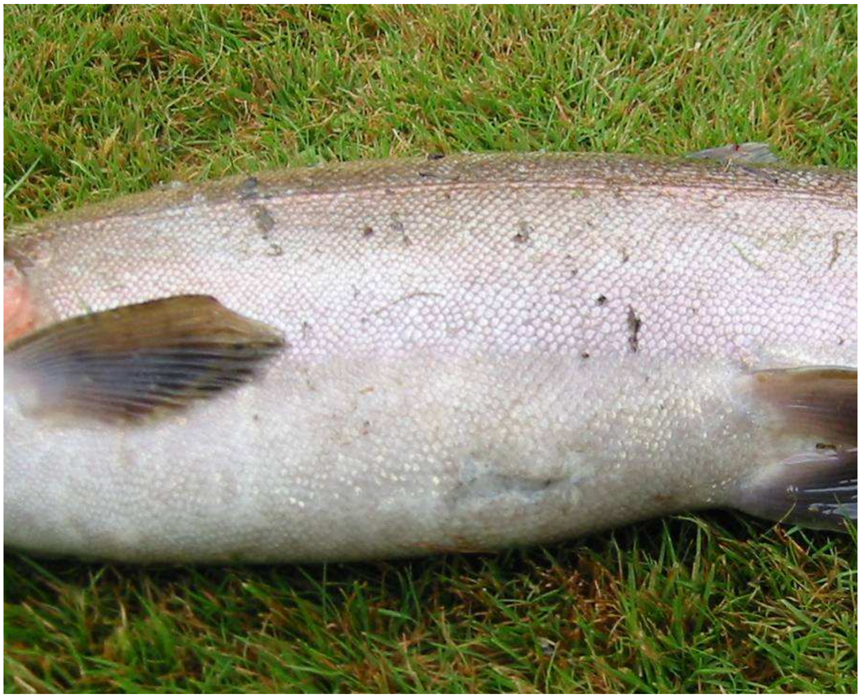

Figure 10: Surgical wound from Trout 113 caught on 22/2/2006, 106 days after surgery. (Note the excellent condition of this fish.)

Of the 30 trout implanted with acoustic transponders, nine are known to have been caught by anglers (one 9 days after release) and four either died or expelled their tags. Nine trout were still in Lake Rotorua when the receivers were last downloaded and one fish is presumed to still be in Lake Rotoiti. The fate of the seven remaining fish is unknown. They may be in tributary streams (e.g., spawning), in which case they may re-occur in the lake in spring, or they may now be dead. Apart from one fish, for which there is only one day of records, the 29 remaining tagged trout were tracked for more than six days with 18 fish providing records in both the cool and warm months.

Most of the fish that were monitored exhibited extensive and sometimes rapid movements over the entire lake, with three travelling down the Ohau Channel to Lake Rotoiti (Table 2). One of these subsequently returned to Lake Rotorua. Such large and rapid movements are consistent with the behaviour of adult rainbow trout in both Lake Coleridge (James & Kelso 1995) and Lake Taupo (Dedual 2005).

3.3 Spatial distribution of trout in Lake Rotorua

A total of 18 trout were recorded in the vicinity of one or more of the receiver sites throughout both the hot and cooler months (Table 4). During the cooler months, five trout demonstrated a clear preference for the north-western region of the lake whereas nine preferred the rest of the lake. Four fish (Nos. 105, 113, 137, 153) showed no clear preference for either region. The smaller number of tagged trout preferring the north-western region of the lake during the cooler period may be a consequence of its smaller area compared with the remainder of the lake.

Table 4: Frequency of occurrence (as a percentage of all the 15 minute time intervals for which each fish was in the lake) for each tagged trout at all locations within the north-western region of Lake Rotorua (cold springs present) compared with all locations within the rest of the lake (cold springs absent), during warm and cool months, respectively. Bold figures indicate predominant use of a lake region by individual tagged fish.

Fish No.	Cool months				Hot months			
	Total time intervals	Missing (%)	Lake region: North west	Lake region: Rest of lake	Total time intervals	Missing (%)	Lake region: North west	Lake region: Rest of lake
101	2064	65.5	1.9	**32.6**	8414	70.3	2.7	**27.0**
105	6548	60.6	17.4	22.0	2301	53.2	**41.7**	5.2
109	2065	76.0	2.9	**21.1**	5610	81.0	3.9	**15.1**
111	944	15.7	33.1	**51.3**	6046	75.5	13.0	10.6
113	1284	37.5	35.5	27.2	429	36.6	**63.4**	0.0
115	6619	31.8	3.3	**64.9**	8640	65.6	18.9	15.5
119	2063	53.5	**30.5**	16.0	3146	65.2	12.8	**22.0**
129	7844	21.6	**78.3**	0.2	8640	38.2	**54.2**	7.5
131	1976	60.0	6.8	**33.2**	4149	71.4	17.1	11.5
133	7833	65.2	10.3	**24.5**	4714	64.0	**34.4**	1.7
135	1978	65.6	6.2	**28.2**	3195	59.7	**33.1**	7.2
137	1987	48.3	22.4	29.3	5354	55.0	**32.0**	13.0
145	1732	26.8	**73.2**	0.0	1284	41.4	**58.6**	0.0
149	1309	80.7	1.1	**18.1**	3314	83.9	**14.4**	1.8
151	7158	69.6	**26.3**	4.0	8640	75.3	**20.6**	4.1
153	6740	65.2	19.1	15.7	1328	72.7	16.0	11.2
155	7153	53.0	7.7	**39.3**	6642	59.9	**30.1**	10.0
159	1298	39.7	**48.7**	11.6	2688	55.3	**37.1**	7.6
Trout preferring each region			**5**	**9**			**11**	**3**

In the hot months, 11 of the trout showed a clear preference for the north-western region of the lake and only three for the rest of the lake. Again, four fish (Nos. 111, 115, 131,153) showed no clear preference for either region in the hot months. Trout 153 was the only fish not showing a clear preference in either the cool and hot months.

Seven trout showed no change in their preference for lake region between the cool and hot months, but seven others switched preference between these two periods, with six of these occurring more frequently in the north-western region of the lake during the hot months. The overall proportion of tagged fish preferring the north-western region of the lake differed significantly between the hot and cool periods ($P = 0.017$), with a majority of the tagged trout (61%) preferring the north-western region to the rest of the lake, despite its smaller area.

Frequencies of occurrence of trout at the various stream mouths varied for individual fish between hot and cool months as well as among the various stream mouths (Table 5). Most of the trout spent some time at most stream mouths in both the hot and cool months. Only Trout 101 demonstrated site fidelity throughout, occurring mainly in the vicinity of the Hamurana Stream in both the hot and cooler months. Overall, the Ngongotaha Stream attracted more tagged trout than the other stream mouths in both the hot and cooler months, and trout spent longer there than at the other streams. The Awahou was the next most popular stream, followed by the Hamurana and Waiteti streams.

At least 15 of the 26 tagged trout which were tracked entered one of the cold tributary streams over the study period, some on more than one occasion (Table 2). Nine of the tagged fish were classified as lake fish as they did not appear to enter any stream over the study period or did not travel to the Ohau Channel. A close examination of the temperature records of these fish revealed that all spent at least some time near one or more of the stream mouths at the peak of the summer. For example, Trout 115 used the Waiteti, Awahou and Hamurana Stream mouths as thermal refugia during January 2005 and February 2006 when its body temperature was 3-5°C below the temperature of lake water (Fig. 11). Even the three fish that appeared to spend most of the summer in the lake spent some time at the peak of the summer within one of the cold water plumes.

Table 5: Frequency of occurrence (as a percentage of all the 15 minute time intervals for which each fish was in the lake) for each tagged trout at the mouths of the cold, spring-fed streams during warm and cool months, respectively. Bold figures indicate predominant use of a stream mouth by individual tagged fish.

Fish	Hot months				Cool months			
No.	Hamurana	Awahou	Waiteti	Ngongotaha	Hamurana	Awahou	Waiteti	Ngongotaha
101	**2.7**	0.0	0.0	0.0	**1.7**	0.2	0.0	0.0
105	0.1	12.6	9.4	**19.6**	3.3	**10.4**	0.8	2.9
109	1.8	1.0	0.3	0.8	1.0	0.4	1.2	0.3
111	4.8	1.6	1.8	5.7	1.6	4.2	8.7	**18.5**
113	0.0	0.2	6.1	**57.1**	3.9	1.6	3.3	**26.6**
115	1.9	6.8	1.7	**8.5**	0.0	0.1	0.1	**3.1**
119	1.4	3.1	2.5	**5.9**	0.9	**19.3**	8.9	1.4
129	0.0	15.6	1.8	**36.9**	0.0	3.0	3.9	**71.3**
131	5.5	7.0	0.9	3.7	1.9	0.7	1.3	3.0
133	0.3	**25.2**	3.6	5.2	0.5	**4.8**	2.3	2.6
135	5.4	9.4	4.8	**13.5**	3.0	2.2	0.1	1.0
137	2.1	12.1	7.0	10.9	0.5	0.8	**16.0**	5.3
145	0.0	**38.1**	16.4	4.2	0.0	**46.2**	22.2	4.7
149	6.3	5.7	0.0	2.4	0.3	0.1	0.0	0.8
151	**11.1**	4.7	2.0	2.8	7.7	2.8	**11.1**	4.8
153	5.1	1.3	6.6	3.0	0.5	9.7	4.9	4.0
155	1.9	10.3	4.6	13.3	4.7	1.3	0.6	1.1
159	2.8	15.5	4.1	14.7	11.2	3.6	6.1	**27.8**

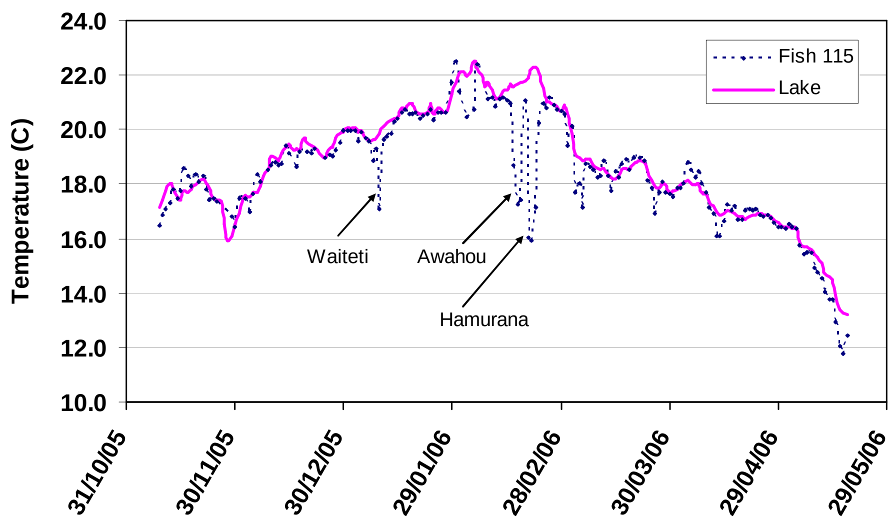

Figure 11: Distribution of temperature records for the main body of Lake Rotorua and for Trout 115 showing periodic occupation of thermal refugia, with much lower water temperatures than the lake in January and especially February. Arrows indicate which stream mouth Trout 115 used as a thermal refuge during this period.

3.4 Temperature preferences for trout

Comparison of the body temperature distribution for all tagged trout throughout the study period with the records for the lake indicated that in both the warm and cooler months, trout utilised areas of the lake where temperatures were lower than in the main body of the lake (Fig. 12). These colder areas are provided primarily by the waters of the spring-fed streams.

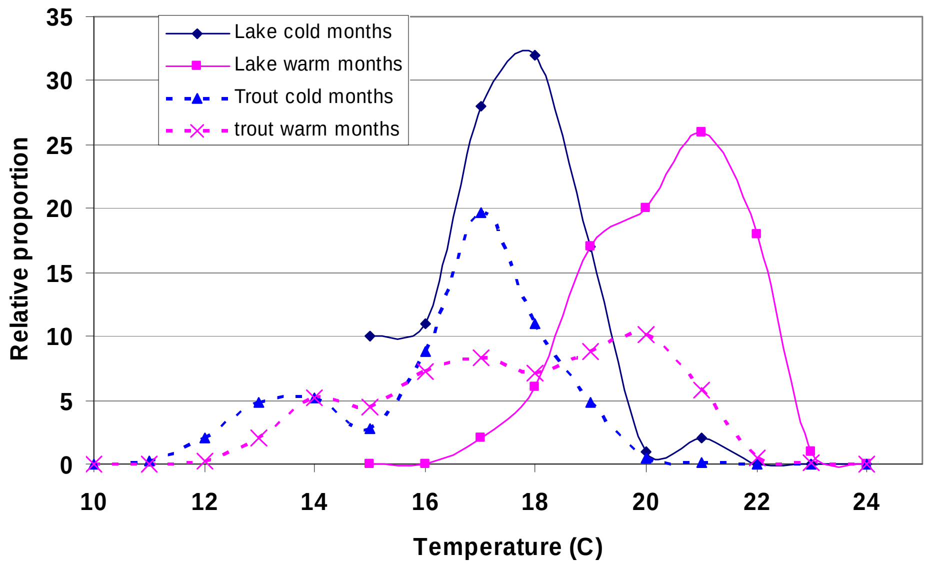

Figure 12: Distribution of temperature records for the main body of Lake Rotorua and of all the trout temperature records during warm months (Dec-Feb) and cool months (Nov, Mar-May).

During the cooler months, the main modal body temperature for the tagged trout was 17°C whereas the modal lake temperature over this period was 18°C (Fig. 12). Thus, the body temperature of trout was close to that of the lake water in these cooler months. However, a secondary mode for trout body temperature occurred at 14°C in the cooler months. This indicates that some of the tagged fish also utilised colder waters associated with the spring-fed streams for short periods during this time. This bimodal pattern of body temperatures agrees well with that for rainbow trout in Lake Taupo over winter months (Dedual 2006).

Temperatures utilised by trout during the hot months in Lake Rotorua were more variable. The main mode for trout occurred at 20°C, but no trout entered water at or above 22^{o}C. This indicates that trout can tolerate temperatures of 20-21°C during summer months, but not 22°C. During the hot months, the body temperatures of the tagged trout in Lake Rotorua exhibited secondary modes at 17ºC and 14ºC, respectively (Fig. 12). Such temperatures rarely occurred in the main body of the lake at this time, so trout were utilising the cold-water plumes of the spring-fed streams as thermal refugia during this period.

Studies of trout temperature preferences in deeper lakes (Rotoiti, Rotoma and Lake Taupo) all indicate that, during summer, trout tend to avoid temperatures over 20°C in surface waters by moving into the deeper, colder waters (Rowe & Chisnall 1995; Dedual 2006). This is not possible in Lake Rotorua, and it is apparent that, *in lieu* of moving into deeper waters, most trout in this lake move laterally to the north-western region of the lake where they utilise the thermal refugia provided by the spring-fed streams.

Of the 30 trout that were tagged, at least three (10%) entered Lake Rotoiti and one returned to Rotorua. This supports the view that some movement of trout between the two lakes occurs, and that for some fish, the two lakes can be regarded as a single habitat. However, the number of trout migrating from Rotorua to Rotoiti and *vice versa* is unknown.

4. Conclusions

In late-winter, when water temperatures in Lake Rotorua are cold and close to 10°C, many adult rainbow trout will be spawning and hence in the tributary streams. However, in spring and autumn when water temperatures in the lake ranged from 13-17°C, trout made use of the entire water body of the lake. This contrasts with the situation in summer when water temperatures exceeded 20ºC. Trout then occurred much more frequently in the north-western region of the lake where the cold, spring-fed streams are located and the body temperature data showed that, at this time, they utilised the cold water plumes of the spring-fed streams as thermal refugia. Some trout even entered the colder streams for extended periods.

These results confirm the conclusions of Rowe and Chisnall (1995) that the preferred temperature of acclimated, adult rainbow trout in the Rotorua lakes is close to 16°C, and that where possible trout avoid water temperatures over 20ºC. They also confirm the suspected ability of trout to periodically forage in the warmer waters of the lake even though water temperatures may be over 20ºC (but less than 22ºC). These results are also in good agreement with data on trout distribution in relation to water temperatures in Lake Taupo (Dedual 2006). The preferred temperature of rainbow trout in this lake during January and February was 15.5°C. The variation in preferred temperature of adult trout among these studies (± 1.5ºC) is negligible and could easily be accounted for by variations in preferred temperature among individual fish because of differences in sex, size and the extent of acclimation (i.e., thermal history).

It is apparent that the summer use of cold water refugia by trout is intermittent in Lake Rotorua, with trout remaining in the cold plume of one spring-fed stream for a time before moving back out to the lake and then utilising the same or another spring-fed stream later. Overall, the Ngongotaha Stream appeared to be the most attractive stream for trout, with the Awahou being the second most popular stream. The Hamurana and Waiteti Streams were less popular. The reasons for these differences in stream attraction are at present unknown and may relate to either the morphology of the lake-bed at the stream mouth and hence the shape of the cold water plume (c.f. Rowe et al. 2005) or the fact that many trout in Lake Rotorua originate from the Ngongotaha Stream, whereas comparatively few originate from other spring-fed streams.

A large proportion of the tagged fish (30%) was caught by anglers. This proportion is much higher than the maximum value (15%) for tagged fish caught in annual fishing competitions (pers. comm. R. Pitkethley) and indicates a potential difference in behaviour between the acoustic-tagged and un-tagged trout. Several of the tagged trout that were recaptured had lost weight (based on angler reports) and this indicates that the tags may have reduced their feeding and hence growth. If so, this may explain their greater vulnerability to anglers. At present it is not known whether the tags have affected trout feeding or not, nor whether all tagged trout could be affected as against just those captured by anglers. If the latter has occurred, then the data from some of the captured trout may be skewed and over-emphasize use of cold-water refugia by trout in Lake Rotorua. This is because starvation reduces the preferred temperature of rainbow trout (Javaid & Anderson 1967). The results from some of the tagged trout may therefore not reflect the behaviour of the population at large, and interpretation of the results needs to bear this possibility in mind.

The results on trout body temperatures and on trout use of the cold-water plumes when lake water temperatures approach or exceed 20°C indicate that the spring-fed streams provide a thermal refuge for many trout in Lake Rotorua during summer months. Furthermore, the difference in trout distribution between the hot and cool months indicates that these thermal refugia result in the aggregation of trout in the north-western region of Lake Rotorua during summer. This shift in trout distribution helps explain the summer decline in trolling in the main lake and the subsequent increase in fishing around the mouths of the spring-fed streams described in Rowe et al. (1002).

Although the Hamurana Stream is the largest of the spring-fed streams in this region of the lake (Table 1), it was not the most attractive stream to the tagged trout. Reasons for this are speculative. Nevertheless, its diversion can be expected to reduce, but not eliminate, the attraction of the north-western region of the lake to trout during summer months. If the summer shift in trout distribution to the north-western region of Lake Rotorua was less pronounced because of diversion of the Hamurana Stream, catch rates in the north-western region could be expected to decline. Thus, its diversion can be expected to impact on the overall fishery, but the extent of this cannot be quantified because of the many other factors likely to affect trout distribution and behaviour in this lake.

A major reason for the overall attraction of the north-western region of Lake Rotorua to rainbow trout in summer months is clearly its provision of cold water refugia. However, the colder, spring-fed waters entering this region of the lake also contain high levels of nutrients (N and P) which are important to phytoplankton growth in the lake. Thus, it is possible that the north-western region of the lake is also a summer ‘hot-spot’ for plankton production and hence for smelt aggregations in summer months. If so, its attraction to trout may be related to an aggregation of food there as well as to the provision of cold water refugia.

The role of such biotic factors is currently unknown and speculative, but cannot be excluded. Given these uncertainties and the likelihood that full diversion will have some impact on trout distribution in the lake as well as result in the loss of the localised fishery at the Hamurana Stream mouth, we advocate a precautionary approach. We recommend that full diversion of the Hamurana Stream only be contemplated during the cooler nine months of the year and not during the three hottest months. This recommendation assumes that the contribution of nutrients to the lake from the Hamurana Stream during the three summer months will not have a significant detrimental effect on lake water quality as this would lead to a long term reduction in trout habitat in this lake and hence compromise the long term viability of the entire lake fishery.

5. Acknowledgements

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