ISSN 2463-6029 (Print)

ISSN 2350-3432 (Online)

Estimation of potential contribution of brown bullhead catfish to the nutrient budgets of lakes Rotorua and Rotoiti

2018

ERI report number 115

Client report prepared for the

Bay of Plenty Regional Council

by

Brendan J. Hicks and Mathew G. Allan

Environmental Research Institute

School of Science

Faculty of Science and Engineering

The University of Waikato, Private Bag 3105

Hamilton 3240, New Zealand

Citation:

Hicks, B.J. and M.G. Allan. 2018. Estimation of potential contributions of brown bullhead catfish to the nutrient budgets of lakes Rotorua and Rotoiti. *Environmental Research Institute Report No. 115.* Client report prepared for the Bay of Plenty Regional Council. Environmental Research Institute, The University of Waikato, Hamilton. 19 pp. ISSN 2463-6029 (print), ISSN 2350-3432 (online).

Cover picture: Adult brown bullhead catfish guarding a school of juveniles. Photo credit: Jim Bannon.

Reviewed by:

Moritz Lehman

Environmental Research Institute

University of Waikato

Hamilton, New Zealand

Approved for release by:

John Tyrrell

Environmental Research Institute

University of Waikato

Hamilton, New Zealand

Table of contents

Tables

Figures

Executive summary

The aim of this research is to apply measured nutrient excretion rates to estimate the potential for catfish to contribute to lake nutrient budgets for lakes Rotorua and Rotoiti. We have assumed that brown bullhead catfish will primarily occupy depths of ≤6m in summer, when water temperatures are highest. This assumption is based on acoustic tracking of catfish in Lake Taupo. Lake Rotorua has about 23.5 km^2 of habitat ≤6m deep (29.1% of its area) that is spread almost completely around the lake, whereas Lake Rotoiti has about 6.7 km^2 of habitat ≤6m deep (19.9% of its area). The shallow areas of Lake Rotoiti are mainly at the western end (Okere Arm, Okawa Bay, and Te Weta Bay) with only a few shallow bays in the eastern basin (Te Karaka Bay, Te Arero Bay, and Wharetata Bay).

Potential annual contributions of nutrients by catfish excretion to lakes Rotorua and Rotoiti are highly dependent on water temperature and the biomass and size of catfish. In July 2018, catfish were at low densities in Lake Rotoiti relative to densities in shallow Waikato lakes and are not known to be present in Lake Rotorua. However, due to the recent prolific successful breeding of catfish in Lake Rotoiti, as shown by the large number of young of the year caught between Nov 2017 and May 2018, we can be certain that the biomass of catfish will increase.

In addition, juvenile catfish have now been found in the Ohau Channel, which increases the chance that catfish will enter Rotorua if they have not already done so. Fyke nets set in Te Weta Bay, Lake Rotoiti, up to July 2017 had a mean catch rate of about 3.5 catfish net^{-1} $night^{-1}$ (0.19 kg net^{-1} $night^{-1}$). Waikato lakes with a high abundance of catfish, for instance, Lake Milicich, which is a 2-ha peat lake, had mean catch rates of 14.8 catfish net^{-1} $night^{-1}$ (3.23 kg net^{-1} $night^{-1}$) during the marking phase of a mark-recapture population estimation. We conclude that catfish in Lake Rotoiti are likely to expand in size, range, and density and are likely to reach Lake Rotorua. While it is uncertain what biomass will eventually establish in the lakes, we can predict that for Lake Rotorua, catfish could contribute 0.4 to 10.9% of the total annual load of N and 0.5 to 10.7% of the total annual load of P. For Lake Rotoiti, catfish could contribute 0.4 to 11.2% of the total annual N load and 0.4 to 8.0% of the total annual P load.

Given that the presence of catfish will not change the external nutrient loads, we can look instead at the potential contribution of catfish nutrient excretion to the internal nutrient loads, and here the potential impact is more concerning. For Rotorua, catfish could contribute 1.1 to 27.7% of the internal N load and 1.1 to 22.3% of the internal P load. For Rotoiti, catfish could contribute 2.3 to 58.9% of the internal N load and 0.6 to 11.7% of the internal P load. Uncertainties around these predictions include whether catfish would add to existing nutrient recycling or would to some extent replace an existing source, such as excretion from goldfish (*Carassius auratus* or morihana), which also thrive in the littoral zones of the Rotorua lakes. In our opinion, nutrient recycling by catfish would be in addition to other internal sources because goldfish and catfish frequently coexist in Waikato lakes at high biomasses and have dietary differences that reduce competition. Of the range of scenarios that we evaluated, based on the current size and abundance of catfish in Te Weta Bay where fish had a mean weight of 53 g in 2016 before extensive removal, we suggest that the most likely scenario should catfish establish widely is that they could add 7.09-31.42 t N and 0.57-2.52 of t P to Lake Rotorua and 2.02-8.96 t N and 0.16-0.72 of t P to Lake Rotoiti. Note that this is in effect not

a new source of nutrients, but is an enhancement of nutrient recycling from the benthos, which is ultimately is derived from external loading.

One constraint on catfish expansion in the Rotorua lakes, which has probably restricted the expansion of catfish in Lake Rotoiti up to this point, is the higher elevation (about 300 m) and thus slightly cooler temperatures (annual mean air temperature 12.5^{o}C, Rotorua Airport 1981-2011) than for lakes in the Waikato region (40-60 m elevation; annual mean air temperature 13.6^{o}C, Hamilton Airport 2000-2016), where catfish thrive. Te Weta Bay, where the majority of catfish have been found, is a sheltered, shallow bay with abundant macrophytes and rocky habitats in the deeper areas. The prolific breeding that was seen as a pulse of juveniles in Lake Rotoiti in January-May 2018 was almost certainly a result of a 2-5^{o}C temperature anomaly of warmer-than-average surface water in Lake Rotoiti in December 2017 that is likely to have stimulated catfish breeding. Future temperature increases may bring more of these warm anomalies that could promote catfish breeding.

Another source of uncertainty is the suitability of different habitats within the littoral zones of both lakes. Rocky habitats were the most suitable for catfish in Lake Taupo, weedy habitats were next most suitable, and sandy habitats were least suitable. Thus the distribution of rocky, weedy and sandy habitats within the littoral zones of lakes Rotoiti and Rotorua may further constrain catfish abundance. While precise lake-wide predictions of nutrient additions from catfish to lakes Rotoiti and Rotorua are problematic because of lack of knowledge of detailed habitat, but this research represents an initial step in understanding the implications of the catfish incursion in the Rotorua lakes. We can conclude with some certainty that catfish abundance is likely to increase in shallow, sheltered bays with macrophytes and is likely to increase internal nutrient recycling there.

1 Introduction

Invasive fish can contribute significantly to ecosystem processes that release nutrients (Holmlund and Hammer 1999), which can increase lake nutrient inputs and primary production and ultimately stimulate algal blooms. Prey consumption and nutrient excretion by fish is a form of nutrient recycling (Villéger et al. 2012), and benthic (bottom) foraging fish can transfer nutrients from the sediments and macroinvertebrates to the water column, further stimulating new primary productivity (Vanni 2002). Fish metabolism produces wastes that are excreted in the form of ammonia, phosphate, total nitrogen and total phosphorus (Morgan and Hicks 2013), which becomes directly or indirectly available to primary producers (Vanni 2002; Schaus et al. 1997). Excretion rates from fish are controlled by water temperature, individual body size, and biomass (Morgan and Hicks 2013).

The North American brown bullhead catfish (*Ameiurus nebulosus*) was introduced to NZ in 1877 and is recognised internationally as an invasive species. This catfish species is commonly 200–300 mm in length in New Zealand but can grow to 480 mm and more than 2 kg in weight (McDowall 1990). Catfish in NZ present potential adverse ecological impacts on lakes due to their benthic feeding, which can add to nutrients and sediment in the water column. They also prey on and compete with native freshwater crayfish (koura) and other fish. Catfish are tolerant of turbid and eutrophic water quality, low dissolved oxygen concentrations, and a wide range of water temperatures, but their preferred and optimum growth temperature 29^{o}C and their minimum spawning temperature is 14^{o}C (Collier et al. 2015). They are sexually mature at 2 years of age (about 180 mm long) and produce a few hundred to 6,000 eggs per female (McDowall 1990).

Catfish have most likely been in Lake Rotoiti for more than 20 years because in 1995 a juvenile catfish was observed to fall out of a hollow-framed boat trailer after a boat launching. This boat had been parked on its trailer overnight in Lake Taupo at Motuapa, where catfish are abundant, some hours before the boat was driven to and launched in Lake Rotoiti. There were no further confirmed sightings of catfish in Lake Rotoiti until January 2009 when a dead adult catfish 450-500 mm long was found on the shore (Blair and Hicks 2009). In March 2016, catfish were caught first by a weed harvester and then by fyke netting in Te Weta Bay, Lake Rotoiti.

Since then, catfish have been found more widely in Lake Rotoiti (in Okere Arm and Okawa Bay) and recently in the Ohau Channel (January-May 2018). Catfish densities are relatively low in Lake Rotoiti (mean catch rate 3.5 catfish net^{-1} night^{-1} in Te Weta Bay May 2016 to July 2017) compared to a mean of 14.8 catfish net^{-1} night^{-1} in Lake Milicich in the Waikato Region (Hicks et al. 2017); no catfish have yet been found in Lake Rotorua. However, recent catches of juvenile catfish in Lake Rotoiti and the Ohau Channel show that recruitment was successful in the summer of 2017/2018, so expansion of the catfish population can be expected. The discovery of catfish in the Ohau Channel suggests that without containment they will eventually move into Lake Rotorua.

The aim of this work is to use measured nutrient excretion rates to estimate the potential for catfish to contribute to lake nutrient budgets for lakes Rotorua and Rotoiti. The area of suitable catfish habitat in lakes Rotorua and Rotoiti was estimated using existing bathymetry, assuming that catfish occupy primarily littoral habitats. These areas of suitable habitat were then be used to estimate nutrient release from excretion based on potential catfish biomass estimates derived from mark-recapture population estimates from the Waikato Region (e.g., Hicks et al. 2015, 2017, Tempero and Hicks 2017).

2 Study sites

2.1 Lake Rotorua

Lake Rotorua is polymictic, eutrophic lake 80.8 km^2 in surface area with a 500.5 km^2 catchment, a mean depth of 10.3 m, and a maximum depth of 52.9 m (Figure 1). Lake Rotorua drains into Lake Rotoiti through the Ohau Channel (Figure 1). Bathymetry was plotted using data from a 2006 side-scan sonar survey with a 120˚-wide fan perpendicular to the vessel by the Coastal Marine Group University of Waikato. The lake is relatively shallow, and the area of depth greater than 26 m comprises only 0.14 km^2 or 0.2 % of the total lake area, 80.8 km^2. This area is a steep-sided crater at the southern end of the lake but there is a broad littoral zone that surrounds much of the rest of the lake (Figure 1).

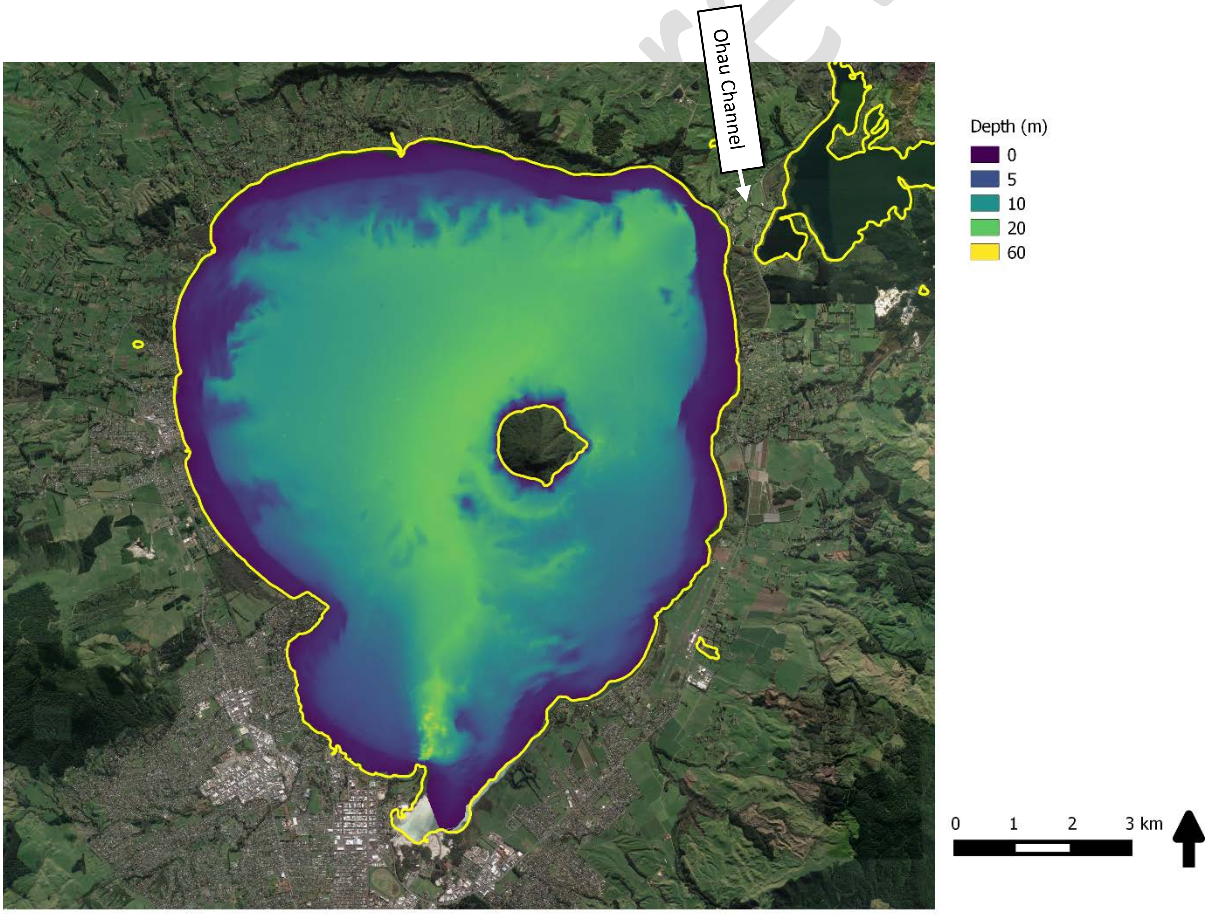

Figure 1: Bathymetry of Lake Rotorua. Source: Coastal Marine Group side-scan sonar survey, University of Waikato.

2.2 Lake Rotoiti

Lake Rotoiti is a monomictic, mesotrophic lake 33.8 km^2 in area with an average depth of 30.3 m and maximum depth 125 m in its explosion crater (Figure 2). The local catchment area comprises 123.7 km^2, excluding that of Lake Rotorua, which is connected to Lake Rotoiti by the Ohau Channel at the western end of the lake (Figure 2). Bathymetry was plotted using data from a side-scan sonar survey by the Coastal Marine Group University of Waikato using methods similar to those described in Hamilton et al. (2005), and shows that the western end is far shallower than the extensive eastern basin (Figure 2).

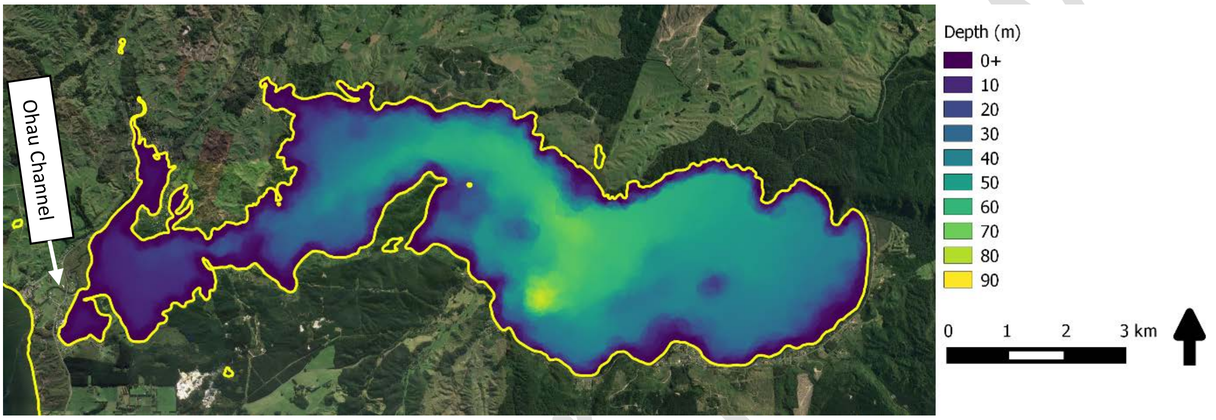

Figure 2. Bathymetry of Lake Rotoiti. Source: Coastal Marine Group side-scan sonar survey, University of Waikato; Hamilton et al. (2005).

3 Methods

3.1 Daily water temperature modelling

Because temperature controls metabolic rate in ectothermic (cold-blooded) organisms such fish, information on water temperature is essential for estimating rates nutrient excretion (Morgan and Hicks 2013). We used the Dynamics Reservoir Simulation Model (DYRESM), a 1-dimensional hydrodynamic lake model that was developed at the Centre for Water Research, University of Western Australia (Hamilton and Schladow 1997). DYRESM simulates vertical distribution of temperature, salinity and density based on a horizontal Lagrangian layer approach. The horizontal Lagrangian layers are free to move vertically and can contract and expand based on changes in inflows, outflows and surface mass fluxes. The layer thicknesses also adjust during model simulations in order to more effectively represent vertical density gradients than with fixed grids. DYRESM is based on an assumption of one dimensionality, where variations in the vertical dimension are assumed to be greater than variations in the horizontal dimension (Imerito, 2007). Lake morphometry was specified within the 1-D model using an ASCII text file that contained lake height and area; volume was calculated by the model. Water temperature of the littoral zones simulated by the lake models is summarised in Table 1.

Table 1. Water temperatures of the littoral zones used in nutrient excretion modelling.

Statistic	Temperature	
	^{o}C	^{o}K
Annual daily mean	16.1	289.1
Annual daily median	16.7	289.7
Annual daily minimum	2.0	275.0
Annual daily maximum	28.0	301.0

3.2 Estimation of excretion

Excretion was estimated from allometric scaling models (Morgan and Hicks 2013, Hicks unpublished data) using daily lake water temperature in degrees Kelvin simulated by lake models (Table 1). For the allometric scaling, body size was determined from catches of catfish in Lake Rotoiti and Waikato lakes with mark-recapture fish biomass estimates (Table 2). To predict whole-fish nutrient excretion, we used the following relationship:

$$\ln(P) = \ln(P_0) + b\ \ln(M) - E/kT \qquad \text{Equation 1,}$$

where P is whole-body metabolic rate for total phosphorus (TP), total nitrogen (TN), NH_4-N, or PO_4-P, M is the mean wet mass of individual fish in g, b is the slope and P_o is a normalisation constant for temperature-corrected excretion rates, k is the Boltzmann constant (8.62 x 10^{-5}), and E is the average activation energy (0.65 eV) of metabolic reactions (Morgan and Hicks 2013). The parameters for Equation 1 for brown bullhead catfish for each nutrient are given in Table 2. These results were scaled up to the area of appropriate habitat in lake by multiplying by the projected areal biomasses of catfish within each lake.

Table 2. Parameters established for scaling nutrient excretion by brown bullhead catfish in New Zealand by wet mass and water temperature. Source: Hicks, unpublished data.

Nutrient	$\ln(P_0)$	b
NH_4-N	30.30	0.634
PO_4-P	25.43	1.135
Total nitrogen	30.81	0.619
Total phosphorus	27.78	0.747

3.3 Scaling for available habitat, catfish size and biomasses

Excretion for projected catfish biomasses was compared to existing nutrient budgets of external and internal loads (e.g., Hamilton et al. 2004, Beyá et al. 2005) to determine potential nutrient contribution from catfish. We estimated the available habitat for each lake from its bathymetry and the assumption that catfish primarily occupy depths ≤6 m in summer (Dedual et al. 2002; Figure 3), when water temperatures are warmest and thus nutrient excretion rates are greatest. Catfish may occupy depth down to14 m in winter, but cooler temperatures will restrict excretion rates then. We projected nutrient excretion for six scenarios. These six scenarios were chosen to reflect two fish sizes (53 g, the mean weight of catfish in Te Weta Bay, Rotoiti, and 231 g, the mean weight for Lake Milicich in the Waikato Region; Table 3) and three catfish biomasses (12, 53, and 169 kg ha^{-1}, which are the minimum, mean and maximum of the biomasses in Table 3).

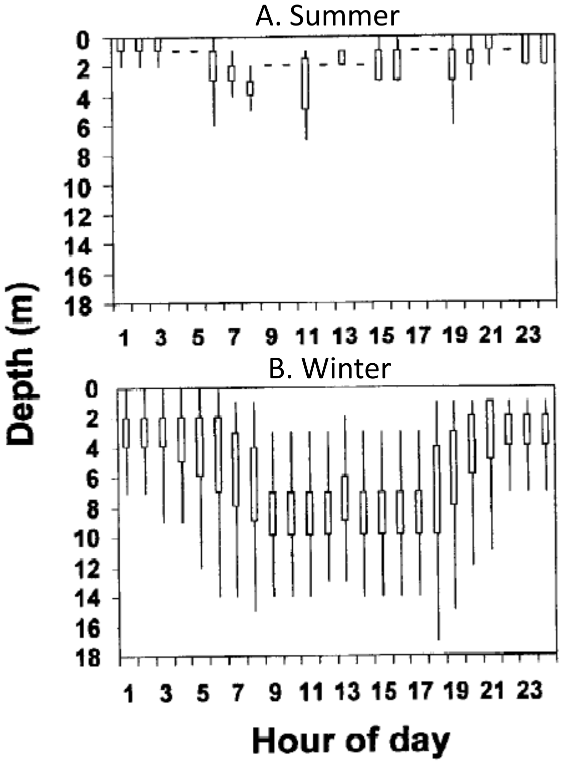

Figure 3. Depths occupied by brown bullhead catfish in Lake Taupo in A. summer and B. winter as recorded by acoustic tracking. The boxes give the 25th and 75th percentiles of the values around the medians. Whiskers indicate the 10th and 90th percentiles of the observations. Source: Modified from Dedual (2002).

Table 3. Mean weights and biomasses determined from mark-recapture for brown bullhead catfish in Waikato shallow lakes.

Lake	Lake area (ha)	Mean weight (g)	Catfish biomass (kg ha^{-1})	Source of data
Kaituna	15	201	12	Hicks et al. (2015), p121
Ohinewai 2011	16	128	12	Tempero and Hicks (2017)
Ohinewai 2016	16	153	37	Tempero and Hicks (2017)
Oranga	0.69	303	51	Hicks et al. (2015), p121
Mangahia	10	136	66	Hicks et al. (2015), p121
Milicich	2	231	169	Hicks et al. (2017)

4 Results

4.1 Potential catfish habitat in Lake Rotorua

We estimated the amount of littoral habitat ≤6m deep in Lake Rotorua, i.e., within the summer depth range of catfish in Lake Taupo, to be 23.5 km^2 out of a total lake area of 80.8 km^2, or 29.1% (Figure 4). This littoral zone ranges from about 500 m to >1 km wide around most of the lake margin.

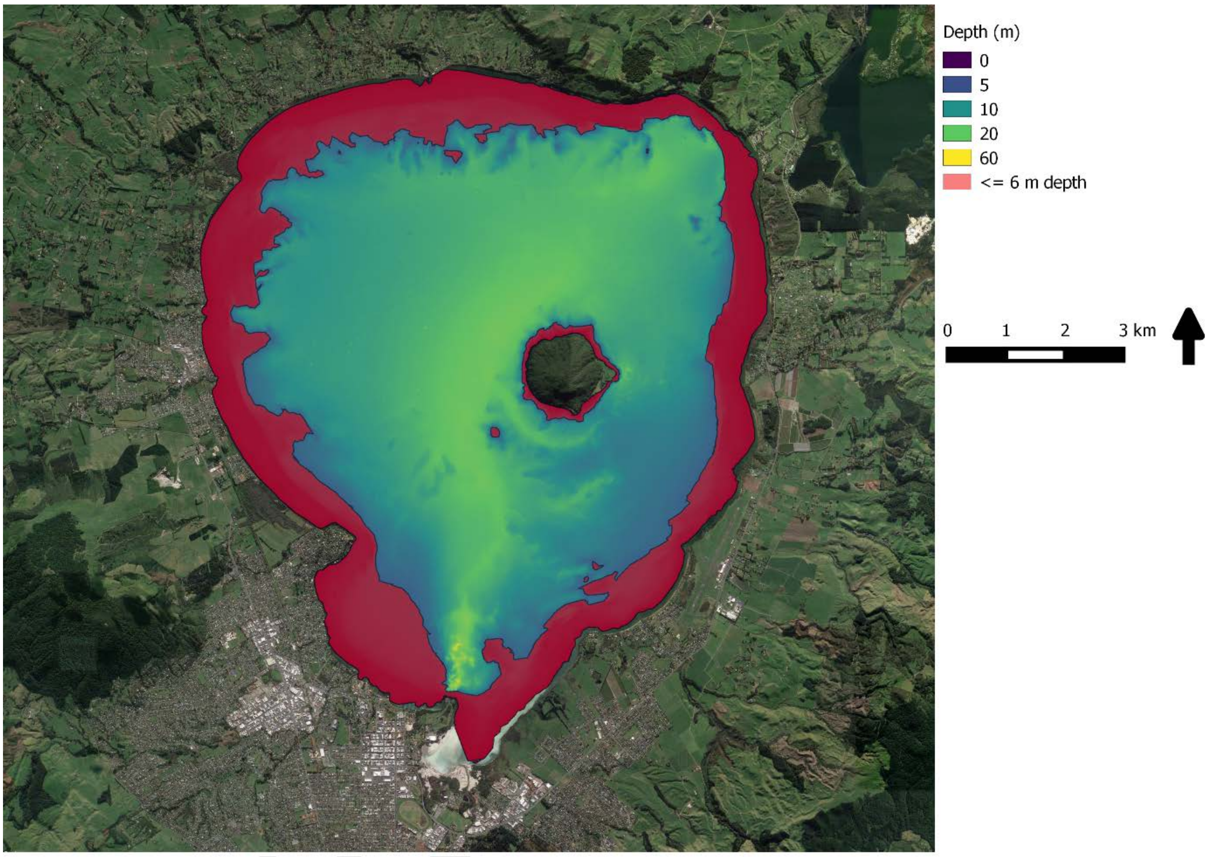

Figure 4. Potential catfish habitat (red polygon) in Lake Rotorua. Source: Coastal Marine Group side-scan sonar survey, University of Waikato.

4.2 Potential catfish habitat in Lake Rotoiti

We estimated that Lake Rotoiti has about 6.72 km^2 (19.9%) of habitat ≤6m deep out of the total lake area of 33.8 km^2 (Figure 5). Most of the suitable littoral habitat is at the western end of the lake closest to the Ohau Channel. In the eastern basin, littoral habitat ≤6m deep is relatively restricted, but bays such as Okawa Bay, Te Weta Bay, Te Karaka Bay, Te Arero Bay, and Wharetata Bay and the Okere Arm (Figure 6) have extensive areas of shallow water.

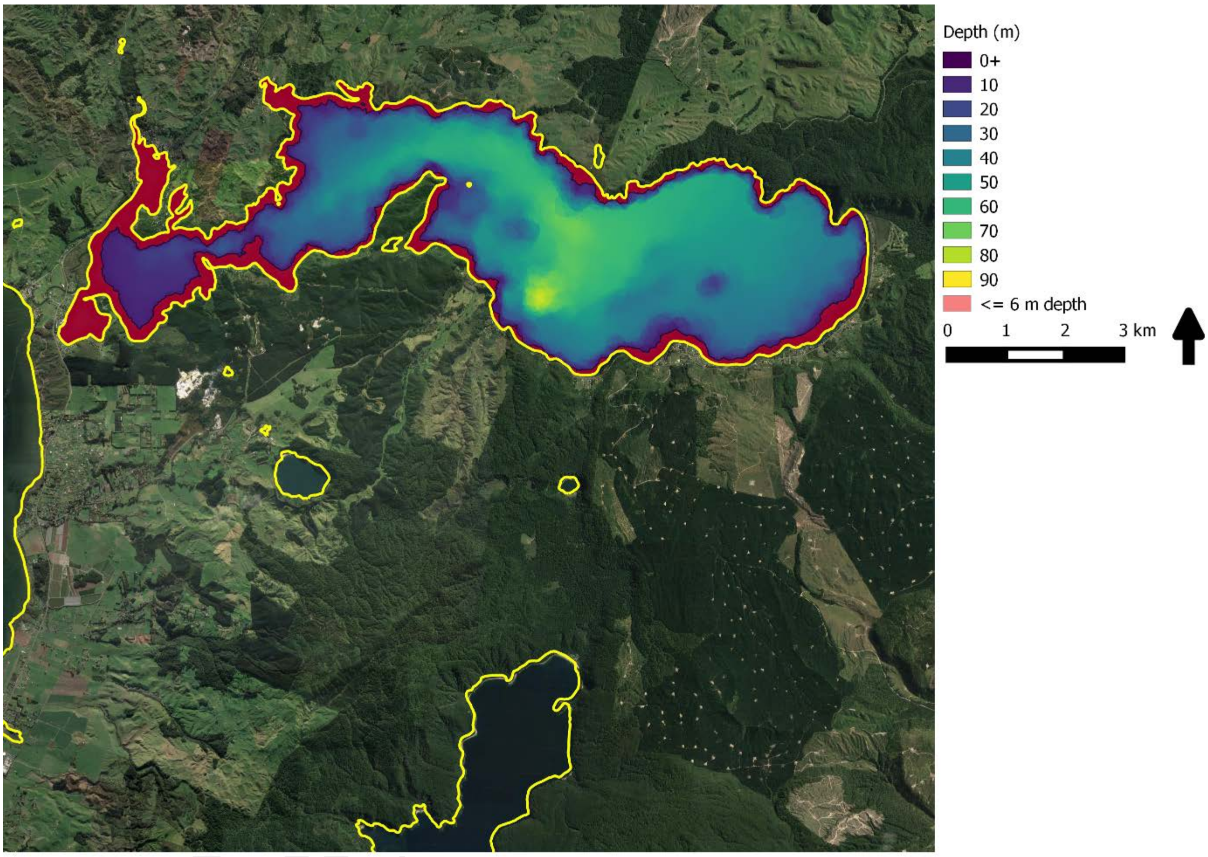

Figure 5. Potential catfish habitat (red polygon) in Lake Rotoiti. Source: Hamilton et al. (2005).

Figure 6. The location of individual bays in Lake Rotoiti. Source: NZMS 260 Map Series, Land Information New Zealand.

4.3 External and internal nutrient loads

Prior to installation of the Ohau Channel diversion wall, total external loads to Lake Rotoiti were estimated to be 364 t N yr^{-1} and 29 t P yr^{-1}, including loads from the Ohau Channel. Since installation of the diversion wall in July 2008, the external load is likely to have been about 214 t N yr^{-1} and 9 t P yr^{-1} (BOPRC 2009).

We have assumed that internal and external loads to Lake Rotorua (Table 4) have been unchanged since the installation of the Ohau Channel diversion wall. Depending on their biomasses and mean individual weights, catfish could add 4-100 t N yr^{-1} and 0.4-8 t P yr^{-1} to Lake Rotorua and 1-29 t N yr^{-1} and 0.1-2.3 t P yr^{-1} to Lake Rotoiti.

Table 4. Predicted nutrient loads attributable to brown bullhead catfish excretion compared to external, internal and total loads of total nitrogen (TN) and total phosphorus (TP) in lakes Rotorua and Rotoiti. Assumed scenarios include mean individual catfish weights of 53 and 231 g and biomasses of 12, 53, and 169 kg ha^{-1} within the ≤6 m littoral zone of the lakes. Internal and external loads from BOPRC (2009) are after installation of the diversion wall in 2008.

A. Total nutrients.

Load source	Nutrient loads (t yr^{-1})	Projected additional nutrient internal nutrient load from catfish excretion (t yr^{-1})					
		53 g mean catfish weight			231 g mean catfish weight		
		12 kg ha^{-1}	*53.2 kg ha^{-1}*	*169 kg ha^{-1}*	*12 kg ha^{-1}*	*53.2 kg ha^{-1}*	*169 kg ha^{-1}*
Rotorua							
External TN	556						
External TP	39.1						
Internal TN	360	7.09	31.42	99.82	4.04	17.93	56.97
Internal TP	36	0.57	2.52	8.02	0.39	1.74	5.52
Total TN	916						
Total TP	75.1						
Rotoiti							
External TN	214						
External TP	9						
Internal TN	50	2.02	8.96	29.46	1.15	5.11	16.24
Internal TP	19.5	0.16	0.72	2.29	0.11	0.50	1.58
Total TN	264						
Total TP	28.5						

B. Proportion of load source.

Load source	Nutrient loads (t yr^{-1})	Proportion of load (%)					
		53 g mean catfish weight			231 g mean catfish weight		
		12 kg ha^{-1}	*53.2 kg ha^{-1}*	*169 kg ha^{-1}*	*12 kg ha^{-1}*	*53.2 kg ha^{-1}*	*169 kg ha^{-1}*
Rotorua							
External TN	556	1.3	5.7	18.0	0.7	3.2	10.2
External TP	39.1	1.5	6.4	20.5	1.0	4.5	14.1
Internal TN	360	2.0	8.7	27.7	1.1	5.0	15.8
Internal TP	36	1.6	7.0	22.3	1.1	4.8	15.3
Total TN	916	0.8	3.4	10.9	0.4	2.0	6.2
Total TP	75.1	0.8	3.4	10.7	0.5	2.3	7.4
Rotoiti							
External TN	214	0.9	4.2	13.8	0.5	2.4	7.6
External TP	9	1.8	8.0	25.4	1.2	5.6	17.6
Internal TN	50	4.0	17.9	58.9	2.3	10.2	32.5
Internal TP	19.5	0.8	3.7	11.7	0.6	2.6	8.1
Total TN	264	0.8	3.4	11.2	0.4	1.9	6.2
Total TP	28.5	0.6	2.5	8.0	0.4	1.8	5.5

5 Discussion

We have assumed that brown bullhead catfish will primarily occupy depths of ≤6m in summer, when water temperatures are highest. This assumption is based on acoustic tracking of catfish in Lake Taupo (Dedual 2002). Lake Rotorua has about 23.5 km^2 of habitat ≤6m deep (29.1% of its area) that is spread almost completely around the lake, whereas Lake Rotoiti has about 6.7 km^2 of habitat ≤6m deep (19.9% of its area). The shallow areas of Lake Rotoiti are mainly at the western end (Okere Arm, Okawa Bay, and Te Weta Bay) with only a few shallow bays in the eastern basin (Te Karaka Bay, Te Arero Bay, and Wharetata Bay).

Potential annual contributions of nutrients by catfish excretion to lakes Rotorua and Rotoiti are highly dependent on water temperature and the biomass and size of catfish. In July 2018, catfish were at low densities in Lake Rotoiti relative to densities in shallow Waikato lakes and are not known to be present in Lake Rotorua. However, due to the recent prolific successful breeding of catfish in Lake Rotoiti, as shown by the large number of young of the year caught between Nov 2017 and May 2018, we can be certain that the biomass of catfish will increase.

In addition, juvenile catfish have now been found in the Ohau Channel, which increases the chance that catfish will enter Rotorua if they have not already done so. Fyke nets set in Te Weta Bay, Lake Rotoiti, up to July 2017 had a mean catch rate of about 3.5 catfish net^{-1} $night^{-1}$ (0.19 kg net^{-1} $night^{-1}$, Shane Grayling, Bay of Plenty Regional Council, unpublished data). Waikato lakes with a high abundance of catfish, for instance, Lake Milicich, which is a 2-ha peat lake, had mean catch rates of 14.8 catfish net^{-1} $night^{-1}$ (3.23 kg net^{-1} $night^{-1}$) during the marking phase of a mark-recapture population estimation (Hicks et al. 2017). We conclude that catfish in Lake Rotoiti are likely to expand in size, range, and density and are likely to reach Lake Rotorua. While it is uncertain what biomass will eventually establish in the lakes, we can predict that for Lake Rotorua, catfish could contribute 0.4 to 10.9% of the total annual load of N and 0.5 to 10.7% of the total annual load of P. For Lake Rotoiti, catfish could contribute 0.4 to 11.2% of the total annual N load and 0.4 to 8.0% of the total annual P load.

Given that the presence of catfish will not change the external nutrient loads, we can look instead at the potential contribution of catfish nutrient excretion to the internal nutrient loads, and here the potential impact is more concerning. For Rotorua, catfish could contribute 1.1 to 27.7% of the internal N load and 1.1 to 22.3% of the internal P load. For Rotoiti, catfish could contribute 2.3 to 58.9% of the internal N load and 0.6 to 11.7% of the internal P load (Table 4B). Uncertainties around these predictions include whether catfish would add to existing nutrient recycling or would to some extent replace an existing source, such as excretion from goldfish (*Carassius auratus* or morihana), which also thrive in the littoral zones of the Rotorua lakes. In our opinion, nutrient recycling by catfish would be in addition to other internal sources because goldfish and catfish frequently coexist in Waikato lakes at high biomasses (Hicks et al. 2015) and have dietary differences that reduce competition (Kane 1995). Of the range of scenarios that we evaluated, based on the current size and abundance of catfish in Te Weta Bay where fish had a mean weight of 53 g in 2016 before extensive removal, we suggest that the most likely scenario should catfish establish widely is that they could add 7.09-31.42 t N and 0.57-2.52 of t P to Lake Rotorua and 2.02-8.96 t N and 0.16-0.72 of t P to Lake Rotoiti (Table 4A). Note that this is in effect not a new source of nutrients, but is an enhancement of nutrient recycling from the benthos, which is ultimately is derived from external loading.

One constraint on catfish expansion in the Rotorua lakes, which has probably restricted the expansion of catfish in Lake Rotoiti up to this point, is the higher elevation (about 300 m) and thus slightly cooler temperatures (annual mean air temperature 12.5°C, Rotorua Airport 1981-2011) than for lakes in the Waikato region (40-60 m elevation; annual mean air temperature 13.6°C, Hamilton Airport 2000-2016), where catfish thrive. Te Weta Bay, where the majority of catfish have been found, is a sheltered, shallow bay with abundant macrophytes and rocky habitats in the deeper areas. The prolific breeding that was seen as a pulse of juveniles in Lake Rotoiti in January-May 2018 was almost certainly a result of a 2-5°C temperature anomaly of warmer-than-average surface water in Lake Rotoiti in December 2017 (Figure 7) that is likely to have stimulated catfish breeding. Future temperature increases may bring more of these warm anomalies that could promote catfish breeding.

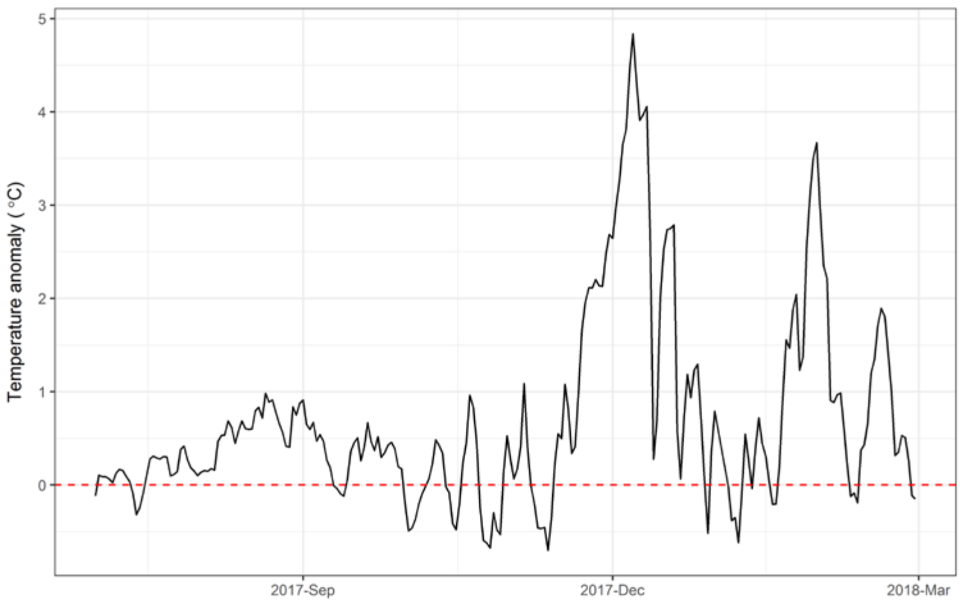

Figure 7. Temperature anomaly of surface water in Lake Rotoiti from July 2017 to March 2018 compared to the daily means of data from the Lake Rotoiti Narrows lake buoy for 2008-2017. Source: unpublished data, Chris McBride, University of Waikato.

Another source of uncertainty is the suitability of different habitats within the littoral zones of both lakes. Rocky habitats were the most suitable for catfish in Lake Taupo, weedy habitats were next most suitable, and sandy habitats were least suitable (Barnes 1996; Barnes and Hicks 2003). Thus the distribution of rocky and weedy habitats within the littoral zones of lakes Rotoiti and Rotorua may further constrain catfish abundance. While precise lake-wide predictions of nutrient additions from catfish to lakes Rotoiti and Rotorua are problematic because of lack of knowledge of detailed habitat, but this research represents an initial step in understanding the implications of the catfish incursion in the Rotorua lakes. We can conclude with some certainty that catfish abundance is likely to increase in shallow, sheltered bays with macrophytes and is likely to increase internal nutrient recycling there.

6 Acknowledgements

This study was funded by the Bay of Plenty Regional Council. We thank Chris McBride, University of Waikato, for provision of data and technical assistance. We acknowledge the bathymetry data for lakes Rotorua and Rotoiti from the Coastal Marine Group at the University of Waikato.

7 References

Barnes GE. 1996. The biology and general ecology of the brown bullhead catfish (*Ameiurus nebulosus*) in Lake Taupo. Master's thesis, University of Waikato, Hamilton. 114 p.

Barnes GE, Hicks BJ. 2003. Brown bullhead catfish (*Ameiurus nebulosus*) in Lake Taupo. Pages 27-35 in Munro, R. (ed). *Managing invasive freshwater fish in New Zealand*. Proceedings of a workshop hosted by Department of Conservation, 10-12 May 2001, Hamilton. New Zealand Department of Conservation, Wellington.

BOPRC 2009. Lakes Rotorua and Rotoiti Action Plan. Environmental Publication 2009/03, Environment Bay of Plenty, Rotorua District Council, Te Arawa Lakes Trust, Rotorua.

Beyá J, Hamilton D, Burger D. 2005. Analysis of catchment hydrology and nutrient loads for Lakes Rotorua and Rotoiti. *CBER Contract Report No. 74*. Centre for Biodiversity and Ecology Research, Department of Biological Sciences, School of Science and Engineering, The University of Waikato, Hamilton.

Blair JM, Hicks BJ. 2009. An investigation to determine origin: age and otolith chemistry of a brown bullhead catfish (*Ameiurus nebulosus*) found at Okawa Bay, Lake Rotoiti. *CBER Contract Report No. 98.* Prepared for Department of Conservation. Centre for Biodiversity and Ecology Research, Department of Biological Sciences, School of Science and Engineering, The University of Waikato, Hamilton.

Collier K, Leathwick J, Ling N. 2015. Determining invasion risk of non-indigenous fish. Section 7.1 in Collier KJ & Grainger NPJ eds. New Zealand Invasive Fish Management Handbook. Lake Ecosystem Restoration New Zealand (LERNZ; The University of Waikato) and Department of Conservation, Hamilton, New Zealand. Pp 138-148.

Dedual, M. 2002. Vertical distribution and movements of brown bullhead (*Ameiurus nebulosus* Lesueur 1819) in Motuoapa Bay, southern Lake Taupo, New Zealand. Hydrobiologia 483: 129–135.

Dugdale TM, Hicks BJ, de Winton M, Taumoepeau A. 2006. Fish exclosures versus intensive fishing to restore charophytes in a shallow New Zealand lake. *Aquatic Conservation: Marine and Freshwater Ecosystems 16*: 193-202.

Hamilton D, Alexander W, Burger D. 2004. Nutrient budget for Lakes Rotoiti and Rotorua. Part I: Internal nutrient loads. *CBER Contract Report No. 76.* A report for the Lakes Water Quality Society, Centre for Biodiversity and Ecology Research, Department of Biological Sciences, School of Science and Engineering, The University of Waikato, Hamilton.

Hamilton D., Chris McBride C., Uraoka T. 2005. Lake Rotoiti fieldwork and modelling to support considerations of Ohau Channel Diversion from Lake Rotoiti. Unpublished report.

Hicks BJ, Brijs J, Daniel AJ, Morgan D, Ling N. 2015. Biomass estimation of invasive fish. Section 6.2 in Collier KJ & Grainger NPJ eds. New Zealand Invasive Fish Management Handbook. Lake Ecosystem Restoration New Zealand (LERNZ; The University of Waikato) and Department of Conservation, Hamilton, New Zealand. Pp 116-122.

Hicks BJ, Tempero GW, Powrie WS. 2017. Fish population and biomass estimates from mark-recapture for Lake Milicich, a shallow Waikato peat lake. *ERI Report No. 88*. Client report prepared for NIWA. Environmental Research Institute, Faculty of Science and Engineering, The University of Waikato, Hamilton, New Zealand. 19 pp.

Holmlund CM, Hammer M. 1999. Ecosystem services generated by fish populations. *Ecological Economics*, *29*: 253–268. http://doi.org/10.1016/S0921-8009(99)00015-4

Imerito A. 2007. Dynamic Reservoir Simulation Model DYRESM v4.0 Science Manual. Centre for Water Research, University of Western Australia. Exchange Organizational Behavior Teaching Journal. Centre for Water Research, University of Western Australia.

Kane, D. S. 1995. The status of fish in Hamilton Lake (Lake Rotoroa). Master's thesis, University of Waikato, Hamilton. 121p.

Morgan, DKJ, Hicks BJ. 2013. A metabolic theory of ecology applied to temperature and mass dependence of N and P excretion by common carp. *Hydrobiologia*, 705: 135–145.

McDowall RM. 1990. New Zealand freshwater fish: a guide and natural history. Auckland: Heinemann Reed.

Schaus MH, Vanni MJ, Wissing TE, Bremigan MT, Garvey JE, Stein RA. 1997. Nitrogen and phosphorus excretion by detritivorous gizzard shad in a reservoir ecosystem. *Limnology and Oceanography 42*: 1386–1397.

Tempero GW, Hicks BJ. 2017. Responses of the fish community and biomass in Lake Ohinewai to fish removal and the koi carp exclusion barrier. *Waikato Regional Council Technical Report 2017/10*, Waikato Regional Council, Hamilton.

Vanni, M. J. (2002). Nutrient cycling by animals in freshwater ecosystems. *Annual Review of Ecology and Systematics 33*: 341–370. http://doi.org/10.1146/annurev.ecolsys.33.010802.150519

Villéger S, Grenouillet G, Suc V, Brosse S. 2012. Intra- and interspecific differences in nutrient recycling by European freshwater fish. *Freshwater Biology 57*: 2330–2341. http://doi.org/10.1111/fwb.12009