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

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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

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Cover picture: Parental care in brown bullhead catfish, showing and adult guarding a school of juveniles. Photo credit: Jim Bannon.

*Reviewed by*:

Kevin Collier

Environmental Research Institute

University of Waikato

Hamilton, New Zealand

*Approved for release by*:

Karin Bryan

Director, Environmental Research Institute

University of Waikato

Hamilton, New Zealand

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# 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).

Catfish have most likely been in Lake Rotoiti for more than 20 years but since 2016 they have been found more widely in the western end of Lake Rotoiti, including Okere Arm and Okawa Bay, in the Ohau Channel and in December 2018 catfish were first found in Lake Rotorua around Mokoia Island. In 2016, catfish densities were relatively low in Lake Rotoiti, but increased in 2018 to a mean catch rate 63.7 catfish $net^{-1}$ $night^{-1}$ in Te Weta Bay. Other Lake Rotoiti sites with catfish had mean catch rates between 0.13 and 3.1 catfish $net^{-1}$ $night^{-1}$.

Potential annual contributions of nutrients by catfish excretion to lakes Rotorua and Rotoiti are highly dependent on water temperature and the areal biomass and mean size of catfish. In 2018 catfish in Lake Rotoiti were very abundant in some locations due to the recent prolific successful breeding of catfish in Lake Rotoiti. Catfish have clearly spread between 2016 and 2018 and we can be certain that the areal biomass of catfish will increase further as these juveniles grow.

Fyke nets set in Te Weta Bay 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 $net^{-1}$ $night^{-1}$). While it is uncertain what biomass will eventually establish in the lakes, we can predict that for Lake Rotorua, scenarios of 12-169 kg $ha^{-1}$ of catfish could contribute 0.4 to 10.9% of the total annual load of TN and 0.5 to 10.7% of the total annual load of TP. For Lake Rotoiti, the same catfish areal biomass could contribute 0.4 to 11.2% of the total annual load of TN and 0.4 to 5.5% of the total annual load of TP, based on estimates of catfish biomass in Waikato shallow lakes. These estimates do not consider warm-water discharges from thermal spring around lakes Rotorua and Rotoiti.

Uncertainties around our 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). We regard nutrient inputs by catfish excretion as enhanced nutrient recycling from the benthos due to feeding activities, which is ultimately is derived from external loads to the lakes.

# 1 Introduction

Invasive fish can contribute significantly to ecosystem processes that release nutrients (Holmlund and Hammer 1999), which can increase 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 invertebrates to the water column, further stimulating new primary production and zooplankton (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 per unit area (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 (kōura, *Paranephrops planifrons*) 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 is 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 the western end of Lake Rotoiti, including Okere Arm and Okawa Bay, and recently in the Ohau Channel (Francis 2019). Catfish densities were relatively low in Lake Rotoiti, but increased in 2018 to a mean catch rate 63.7 catfish net$^{-1}$ night$^{-1}$ in Te Weta Bay. Other sites with catfish had mean catch rates between 0.13 and 3.1 catfish net$^{-1}$ night$^{-1}$. This compares to a mean catch rate of 14.8 catfish net$^{-1}$ night$^{-1}$ in Lake Milicich in the Waikato Region (Hicks et al. 2017); catfish were found in Lake Rotorua around Mokoia Island in December 2018 (Ba, unpublished data).

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 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, Tempero et al. 2019).

# 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 area of depth greater than 26 m comprises only 0.14 km$^2$ or 0.2 % of the total lake area. 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 and Mokoia Island (Figure 1).

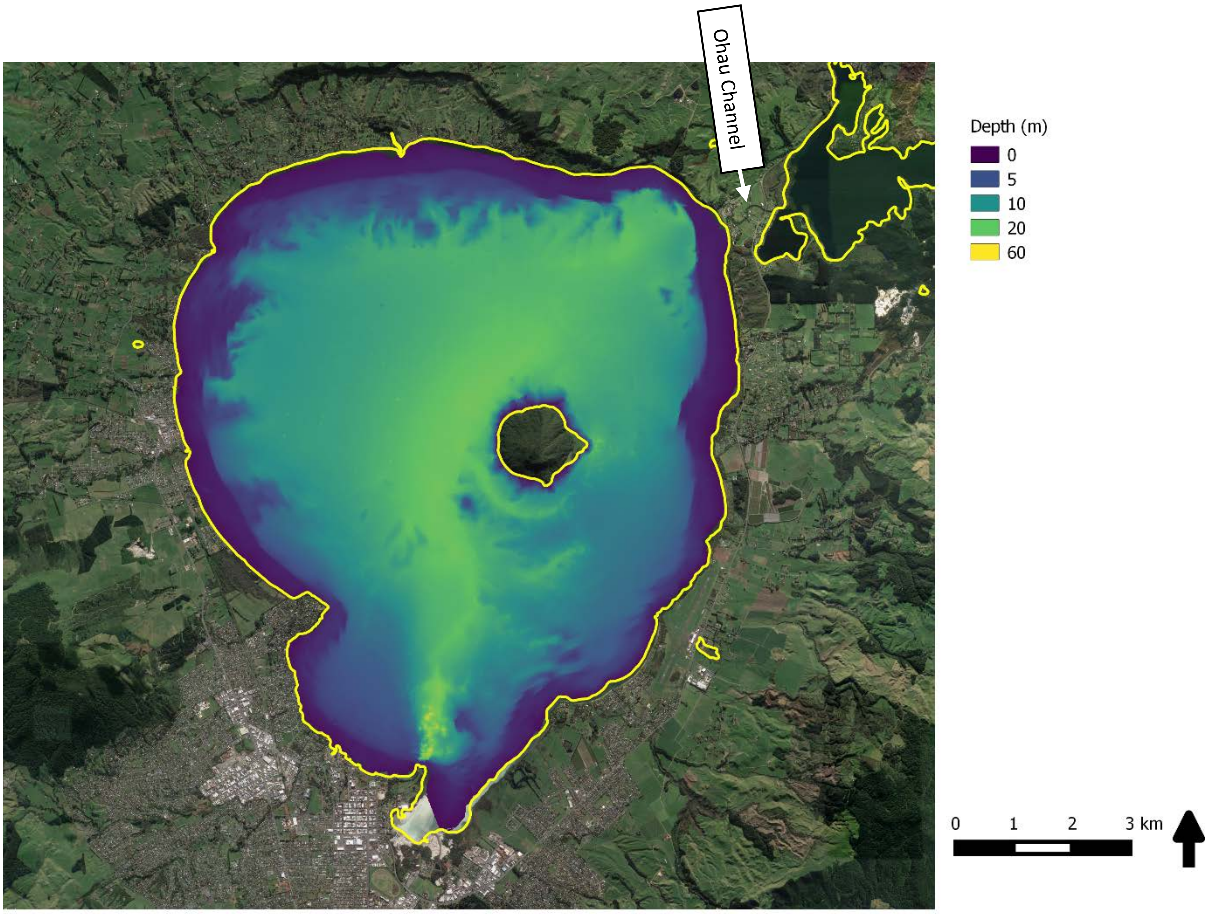


Figure 1: Bathymetry of Lake Rotorua. Source: Coastal Marine Group side-scan sonar survey, The University of Waikato.

## *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, The 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).

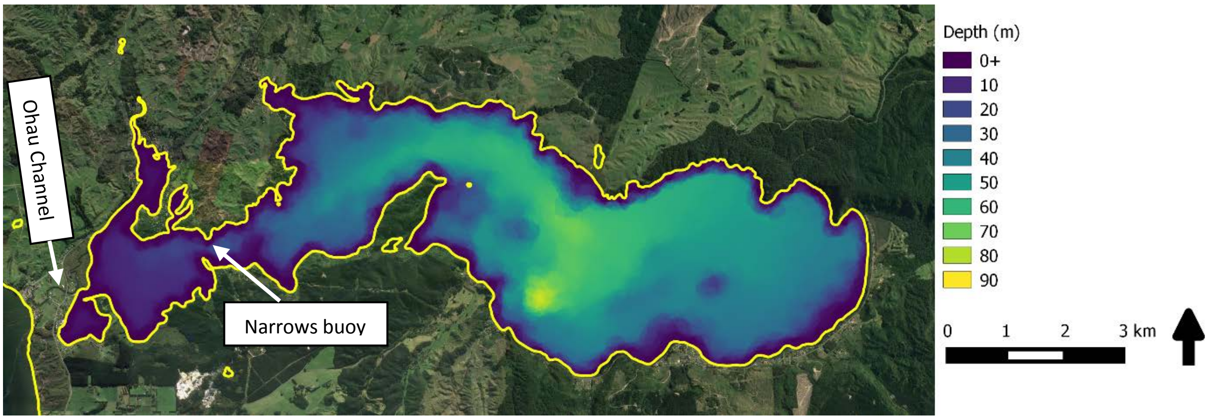


Figure 2. Bathymetry of Lake Rotoiti. Source: Coastal Marine Group side-scan sonar survey, The University of Waikato; Hamilton et al. (2005).

# 3 Methods

## *3.1 Daily water temperature modelling*

Because temperature controls metabolic rate in ectothermic (cold-blooded) organisms such as fish, information on water temperature is essential for estimating rates of nutrient excretion (Morgan and Hicks 2013). For Lake Rotorua, 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.

For Lake Rotoiti we used resampled daily surface water temperatures (Table 1) derived from the autonomous monitoring buoy located near the Narrows water quality monitoring site (Figure 2), which is close to Te Weta Bay.

Table 1. Annual daily water temperatures of the littoral zones used in the nutrient excretion modelling.

| Statistic | Water temperature | | | |
|---|---|---|---|---|
| | Rotorua | | Rotoiti | |
| | $^{o}C$ | $^{o}K$ | $^{o}C$ | $^{o}K$ |
| Annual daily mean | 16.1 | 289.3 | 16.2 | 289.4 |
| Annual daily median | 16.7 | 289.8 | 15.8 | 289.0 |
| Annual daily minimum | 2.0 | 275.1 | 10.3 | 283.4 |
| Annual daily maximum | 28.0 | 301.1 | 25.5 | 298.7 |

## *3.2 Estimation of excretion*

Excretion was estimated from allometric scaling models (Morgan and Hicks 2013, Hicks unpublished data; Table 2) 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 3). 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 each lake by multiplying by the projected areal biomasses of catfish.

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 with 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 depths down to 14 m in winter, but cooler temperatures will restrict excretion rates then. We projected nutrient excretion for six scenarios, but we did not consider the influence of thermal discharges on water temperatures. These six scenarios were chosen to reflect two fish sizes (53 g, the mean weight of catfish in Te Weta Bay, Rotoiti, from March 2016 to July 2017 and 231 g, the mean weight for catfish in Lake Milicich in the Waikato Region; Table 3) and three catfish biomasses (12, 53, and 169 kg ha$^{-1}$; which are the minimum, maximum, and mean for the biomasses of catfish in the Waikato Region in Table 3).

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) |

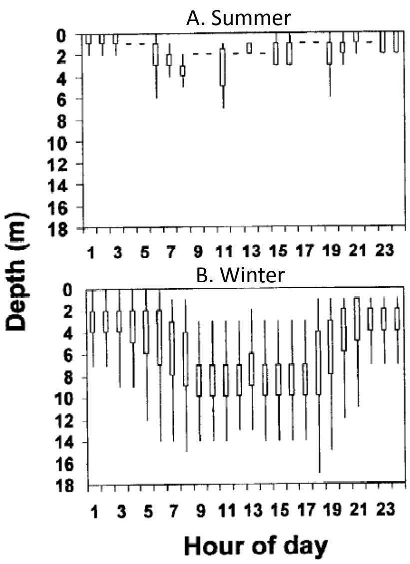


Figure 3. Depths occupied by brown bullhead catfish in Lake Taupo in A. summer and B. winter as recorded by acoustic tracking. The boxes give the upper and lower 25 percentiles of the values around the medians. Whiskers indicate the 10 and 90 percentiles of the observations). Modified from Dedual (2002).

# 4 Results

## *4.1 Potential catfish habitat in Lake Rotorua*

Based on the assumption derived from acoustic tracking in Lake Taupo that catfish are primarily limited to littoral habitat ≤6m deep, Lake Rotorua has about 23.5 $km^2$ (29.1%) of potential habitat out of a total lake area of 80.8 $km^2$ (Figure 4). This littoral zone ranges from about 500 m to >1 km wide around most of the lake margin and Mokoia Island.

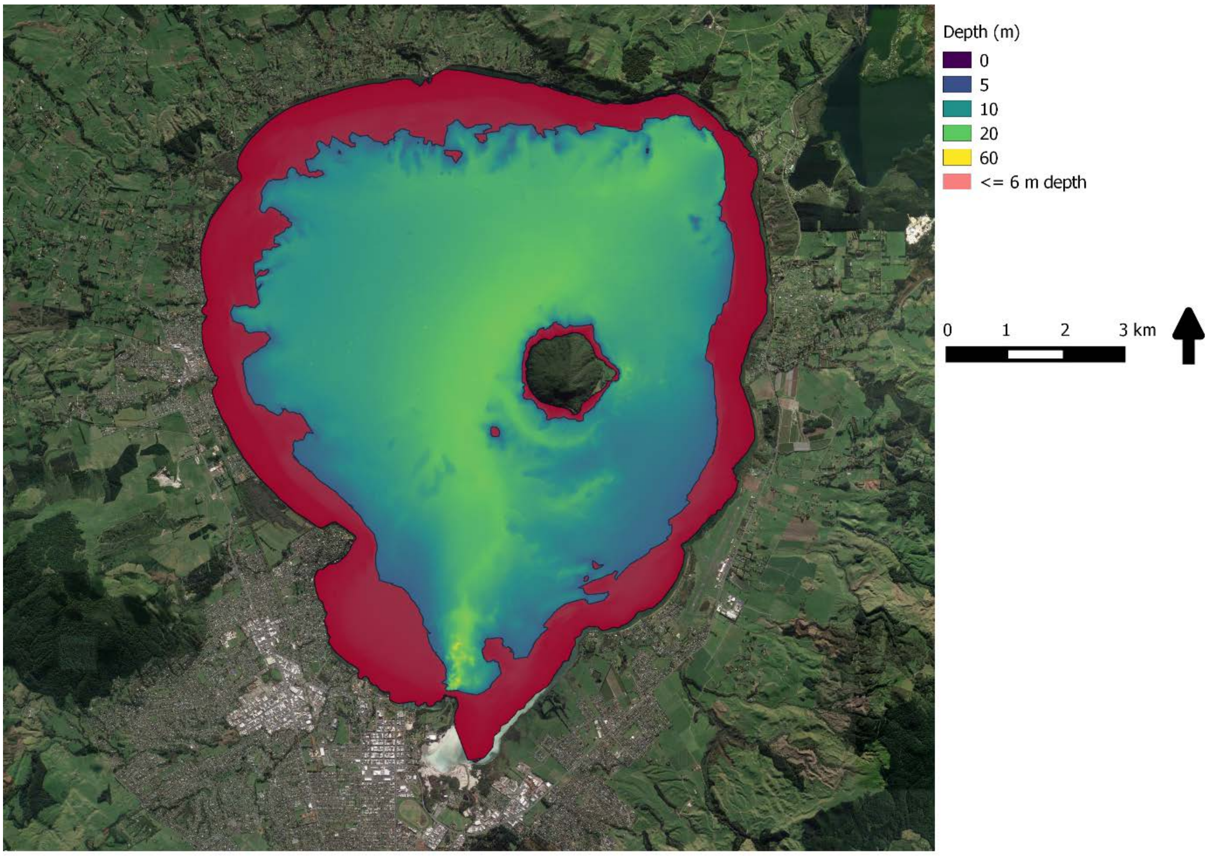


Figure 4. Potential catfish habitat (red shading) in Lake Rotorua. Source: Coastal Marine Group side-scan sonar survey, The University of Waikato.

## 4.2 Potential catfish habitat in Lake Rotoiti

We estimate 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.

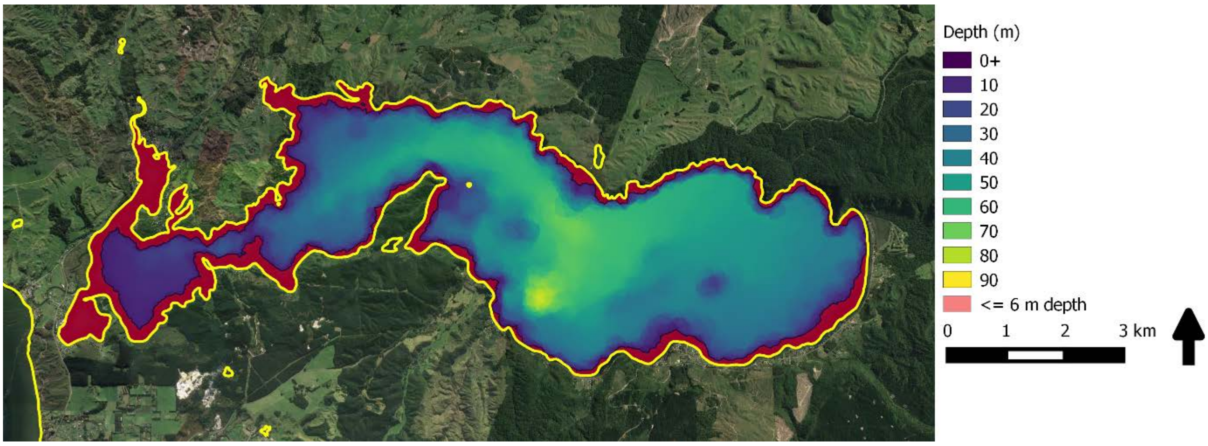


Figure 5. Potential catfish habitat (red shading) in Lake Rotoiti. Source: Hamilton et al. (2005).

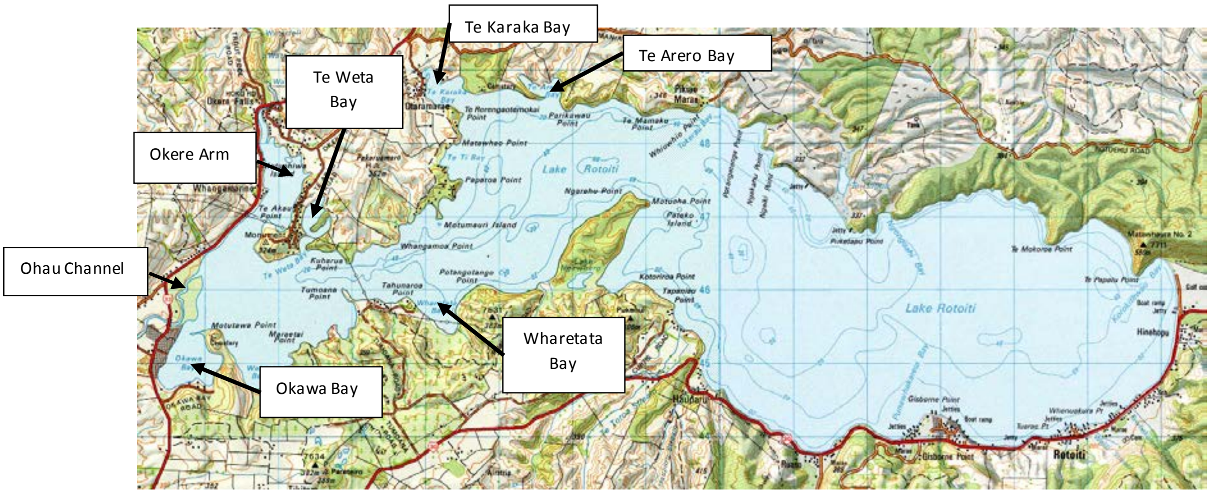


Figure 6. The location of individual bays in Lake Rotoiti showing the Ohau Channel, which connects to Lake Rotorua. Source: NZMS 260 Map Series, Land Information New Zealand.

## 4.3 External and internal nutrient loads

Prior to installation of the Ohau Channel diversion wall (BOPRC 2009), 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 TN $yr^{-1}$ and 9 t TP $yr^{-1}$ (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.

Table 4. Projected 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. −, addition of catfish does not affect these projections.

*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 kg $ha^{-1}$* | *169 kg $ha^{-1}$* | *12 kg $ha^{-1}$* | *53 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 | 7.09 | 31.42 | 99.82 | 4.04 | 17.93 | 56.97 |
| Total TP | 75.1 | 0.57 | 2.52 | 8.02 | 0.39 | 1.74 | 5.52 |
| **Rotoiti** | | | | | | | |
| External TN | 214 | – | – | – | – | – | – |
| External TP | 9 | – | – | – | – | – | – |
| Internal TN | 50 | 1.89 | 8.38 | 26.61 | 1.08 | 4.78 | 15.18 |
| Internal TP | 19.5 | 0.15 | 0.67 | 2.14 | 0.10 | 0.46 | 1.47 |
| Total TN | 264 | 1.89 | 8.38 | 26.61 | 1.08 | 4.78 | 15.18 |
| Total TP | 28.5 | 0.15 | 0.67 | 2.14 | 0.10 | 0.46 | 1.47 |

*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 kg $ha^{-1}$* | *169 kg $ha^{-1}$* | *12 kg $ha^{-1}$* | *53 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 | 3.9 | 12.4 | 0.5 | 2.2 | 7.1 |
| External TP | 9 | 1.7 | 7.4 | 23.8 | 1.1 | 5.1 | 16.3 |
| Internal TN | 50 | 3.8 | 16.8 | 53.2 | 2.2 | 9.6 | 30.4 |
| Internal TP | 19.5 | 0.8 | 3.4 | 11.0 | 0.5 | 2.4 | 7.5 |
| Total TN | 264 | 0.7 | 3.2 | 10.1 | 0.4 | 1.8 | 5.8 |
| Total TP | 28.5 | 0.5 | 2.4 | 7.5 | 0.4 | 1.6 | 5.2 |

# 5 Discussion

Potential annual contributions of nutrients by catfish excretion to lakes Rotorua and Rotoiti are highly dependent on water temperature and the areal biomass and mean size of catfish. In 2018 catfish in Lake Rotoiti were very abundant in some locations (mean catch rate 63.7 catfish net$^{-1}$ night$^{-1}$ in Te Weta Bay; Francis 2019) due to the recent prolific breeding of catfish in Lake Rotoiti. Catfish have clearly spread between 2016 and 2018 (Francis 2019) and we can be certain that the areal biomass of catfish will increase further as these juveniles grow.

Fyke nets set in Te Weta Bay 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). While it is uncertain what biomass will eventually establish in the lakes, we can predict that for Lake Rotorua, scenarios of 12-169 kg ha$^{-1}$ of catfish could contribute 0.4 to 10.9% of the total annual load of TN and 0.5 to 10.7% of the total annual load of TP. For Lake Rotoiti, the same catfish areal biomass could contribute 0.4 to 11.2% of the total annual load of TN and 0.4 to 5.5% of the total annual load of TP, based on estimates of catfish biomass in Waikato shallow lakes. These estimates do not consider warm-water discharges from thermal spring around lakes Rotorua and Rotoiti.

Uncertainties around our predictions (Table 4) 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). We regard nutrient inputs by catfish excretion as enhanced nutrient recycling from the benthos due to feeding activities, which is ultimately is derived from external loads to the lakes.

Water temperature is one constraint on catfish expansion in the Rotorua lakes that probably restricted the expansion of catfish in Lake Rotoiti before 2016. The higher elevation of lakes Rotorua and Rotoiti (about 300 m) results in 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 in Lake Rotoiti, 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 summer in January-May 2018 was almost certainly a result of a 4-5$^{o}$C anomaly of warmer water temperatures in Lake Rotoiti in November and December 2017 (Figure 7, from unpublished data, Chris McBride, The University of Waikato) that is likely to have stimulated breeding. Future temperature increases may bring more of these warm anomalies that promote catfish breeding.

Another 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), which was also the case for catfish in Lake Rotoiti (Francis 2019). 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, 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 to increase internal nutrient recycling there. Modelling work is currently underway in the MBIE-funded Lakes Resilience Programme that will augment this study.

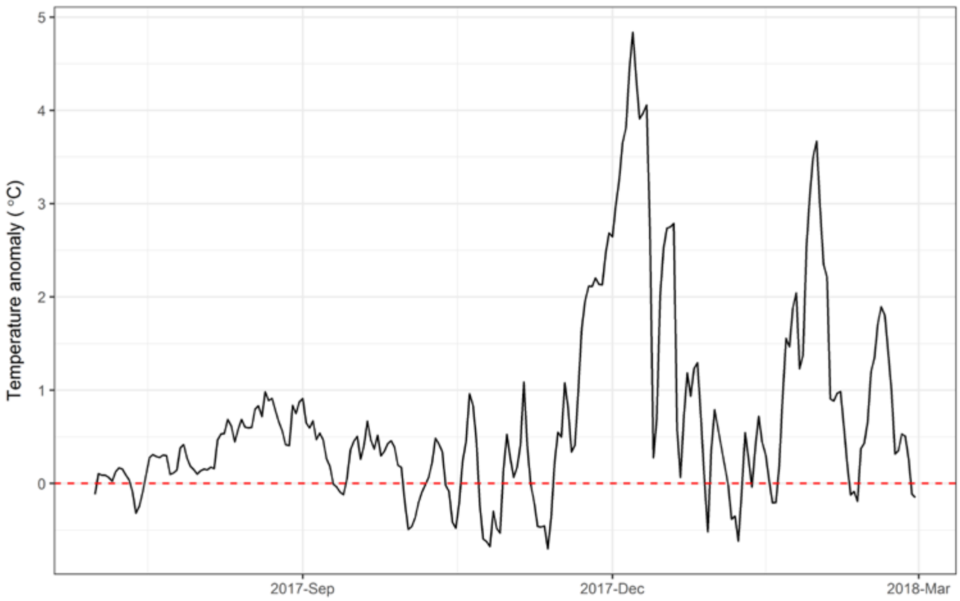


Figure 7. Temperature anomaly in Lake Rotoiti surface waters from July 2017 to January 2018 compared to the mean of data from 2005-2017. Source: unpublished lake buoy data, Chris McBride, The University of Waikato.

## 6 Acknowledgements

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

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