Identifying the factors limiting mahinga kai recruitment

Prepared for Whakaora Te Waihora Partners

July 2015

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NIWA CLIENT REPORT No: CHC2015-078
Report date: July 2015
NIWA Project: ENC13509

Quality Assurance Statement		
	Reviewed by:	Dr Don Jellyman
	Formatting checked by:	Tracy Webster
	Approved for release by:	Charles Pearson

Rough southerly swells overtopping the gravel bar when the lake is closed may be an important recruitment mechanism for a range of fish species during years with limited lake openings. [Shannan Crow, NIWA]

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Executive summary

The freshwater fisheries in Te Waihora (Lake Ellesmere) are of exceptional significance to Ngāi Tahu and are considered to be nationally significant. The highly valued fishery is sustained by recruitment of freshwater fishes from the ocean, but this is restricted by the natural closure of the gravel bar at the outlet of the lake. The outlet is manually opened to allow fish recruitment to occur and minimise flood risk, but managers require a more detailed understanding of the recruitment timing for key fish species such as tuna (eels) and pātiki (flatfish). This knowledge will help managers sustain the fish populations in Te Waihora by ensuring ongoing recruitment into the lake. The present report addresses the first objective of the Investigation brief D5 of the Whakaora Te Waihora programme, which aims to identify the factors limiting mahinga kai recruitment in Te Waihora.

Seine-nets (c. 6 mm mesh) and fine meshed fyke nets (“super fyke”) (c. 2 mm mesh) were used to sample recruiting fish on 18 occasions at each of three sites around the outlet of Te Waihora between July 2013 and February 2015. Over the course of the study the lake was manually opened to the sea on nine occasions and sampling was focussed around these periods to maximise catches of recruiting fish. Catch data were then used to examine the relative abundance of freshly recruited freshwater fishes over the two years of sampling.

A total of 45,501 fishes and 15 species were captured during the course of the study. Common smelt were the most abundant species (n=27,513), followed by common bullies (n=14,616), yellowbelly flounder (n=1,117), inanga (n=1,116), yelloweye mullet (n=433), shortfin eel (n=355), torrentfish (n=336), sand flounder (n=137), and New Zealand sprat (n=87), while six additional species made up less than 0.2% of the total catch (n=71). Recruitment was approximately 67% higher in 2013 than in 2014, which was likely to be due to the lake being open for 107 days in 2013 compared to 49 days in 2014. The importance of lake openings to fish recruitment was supported by an exponential increase between relative abundance of recruiting fish and increased lake opening duration. Freshly recruited fish were observed to have entered the lake while the outlet was closed. These fish presumably entered the lake by travelling over the gravel bar on surging waves during a large southerly swell. These “overtopping” events transported freshly recruited fish on multiple occasions and may have contributed between 5-12% of the fish recruitment during the study.

Combined results from the present study and previous research suggests that shortfin glass eel recruitment is likely to occur between September-November, but early October may be the peak period. Longfin glass eels were caught for the first time in Te Waihora and recruitment is likely to occur from September-October. Recruitment of eels will be highest during new moon phases because glass eels prefer the low light conditions associated with this moon phase and the large tides help passively transport fish into the lake. For flatfish species, black flounder may recruit into Te Waihora between October-December, but the peak month appears to be October. Recruitment of sand flounder appears to be quite variable and fish may enter Te Waihora between May-December. Yellowbelly flounder recruitment in the present study occurred from September-December, but peak recruitment occurred from mid-November to mid-December. Large numbers of torrentfish recruits were caught for the first time and they recruited between mid-May and December, well outside the previously suggested period of spring and summer. Recruitment periods for common bully and common smelt were difficult to identify because these fishes can form self-sustaining freshwater resident populations (non-diadromous). Any diadromous common bully and common smelt recruitment was likely to have occurred from April-August and August-November, respectively.

The presence of fish recruitment during periods of lake-outlet closure confirms the observations of Ngāi Tahu fishers about mahinga kai species entering the lake by moving over the gravel bar during southerly/south-westerly storms. Given the current uncertainty around the amount of recruitment that is likely to occur during overtopping events, it is not recommended that these events be considered during the decision-making process to open the lake for fish recruitment.

It is likely that the optimal lake opening scenario for fish recruitment would be to have a high lake level followed by an extended opening that encompasses the new moon. This would result in a larger volume of fresh water being released into the ocean, creating larger plumes to attract recruiting fish into the lake. The new moon phase would also ensure large tidal exchange occurs in Te Waihora, which will provide a mechanism for transport recruiting fish.

When the lake is open to the sea, the primary factor that will influence whether recruits can enter the lake will be water velocity. Juvenile fish are relatively weak swimmers and fish such as shortfin glass eels (one of the stronger swimmers of the potential recruits) have a maximum sustained swimming speed of only 0.3 m/s. When the engineered cut is completed the lake outflow velocity exceeds 2 m/s, which will prevent fish from entering the lake until freshwater outflows reduce and seawater inflows increase in volume. Some fish may be able to enter the lake by moving along any sheltered areas of the outlet once the cut is fully formed, but these may be limited numbers.

Tidal transport of fish will be the dominant mechanism for fish entering Te Waihora, and it appears that once the lake drops below 0.8 m there will be significant tidal exchange at the outlet. Therefore, we expect that increasing the number of days the lake is open below a level of 0.8 m should increase the numbers of recruits. It takes around 7 days for the lake to reach this height after it is opened, therefore it is recommended that a lake opening should be maintained for a period of at least 7 days until the lake reaches 0.8 m.

To ensure sufficient freshwater fish recruitment and allow outgoing migrations of adult spawning fish, we recommend that the lake openings should be considered during the following three opening periods: (1) lake opening of ≥9 days between 15 April to 31 May, which will allow outgoing spawning eels in particular to exit Te Waihora, (2) a lake opening >20 days between 1 July to 31 August, which will allow common bully, common smelt and torrentfish to enter Te Waihora, and (3) a lake opening >25 days between 15 September and 15 November, which encompasses the timing of longfin glass eel recruitment, all of the shortfin glass eel recruitment and the majority of the recruitment period for black, yellowbelly and sand flounder. Consideration of the wind, tide and outlet morphology during lake opening decisions would allow managers to further enhance recruitment into Te Waihora. We acknowledge that these three opening periods only consider fish recruitment, and that other values would also need to be considered during lake opening decisions.

1 Introduction

Te Waihora (Lake Ellesmere) is of exceptional significance to Ngāi Tahu as a tribal taonga, providing a major source of mahinga kai and mana (Te Runanga o Ngāi Tahu and Department of Conservation 2005). The lake is considered nationally significant for both customary and commercial fisheries, contributing about a quarter of New Zealand's commercial eel catch and supporting a significant flatfish fishery. The highly valued fishery is sustained by recruitment of freshwater fishes from the ocean, but this is restricted by the natural closure of the gravel bar at the outlet of the lake. The outlet is manually opened to prevent undue land inundation which allows fishes to recruit into and out of the lake. However, managers now require a more detailed understanding of the recruitment timing for key mahinga kai species because the lake can now be opened at certain times specifically for fish recruitment (and fish escapement).

Management of mahinga kai fisheries within the lake is hindered by a lack of information on the recruitment patterns of key species (eels and flounder), the current status of fisheries within the lake, and the influences of ecosystem processes (such as prey availability) on mahinga kai abundance. The collection of baseline fisheries data has been considered the most robust approach for addressing these knowledge gaps as it will provide an index of the current status of mahinga kai species for use as a reference against which subsequent changes can be evaluated. Baseline fisheries knowledge also allows more effective management strategies to be developed for the enhancement of these resources (i.e.,, establishment of Kōhanga areas, re-establishment of macrophytes and modified lake opening regimes to benefit mahinga kai and prey fish recruitment).

In the Whakaora Te Waihora (WTW) programme, Investigation brief D5 is responsible for 'Fish restocking/recruitment including a review of fisheries management'. This brief has four primary research-based objectives, these are:

1. Identify the factors limiting mahinga kai recruitment. Specifically, the recruitment of yellowbelly flounder, shortfin eels and longfin eels will be monitored around lake openings using seine and fyke nets. Data will be used to generate relationships between mahinga kai recruitment and season, lake opening regime and species abundance. Identification of recruitment periods for these species will assist in the development of lake opening regimes.

2. Monitor the growth, sizes and relative abundance of key mahinga kai species. Specifically catch rates, condition, growth rates and length and weight distributions of shortfin eels will be monitored throughout the lake by fyke netting. The results will be used to compare the productivity of the shortfin eel fishery in different areas of the lake, evaluate the effectiveness of the establishment of the Horomaka Kōhanga area and identify factors that may influence survival, growth and maturation of mahinga kai species.

3. Identify and evaluate the effectiveness of in-lake and wider catchment interventions aimed at providing protected or enhanced environments for mahinga kai species and their prey. Specifically, the effectiveness of enhancing in-lake spawning habitat for non-diadromous populations of prey species (bullies and inanga) will be determined through assessing inanga spawning habitat availability and quantifying the extent of non-diadromous populations of these species. In addition, the effects of macrophyte re-establishment on mahinga kai habitat and prey availability will be assessed by

monitoring colonisation of re-established macrophyte beds by mahinga kai species and fish and invertebrate prey. Enclosure experiments will also be used to determine the effects of macrophyte re-establishment on fish biomass, size and survival.

4. Determine the effectiveness of the establishment and enhancement of Kōhanga areas in protecting mahinga kai species. Specifically population estimates of shortfin eels in the Horomaka Kōhanga reserve will be developed through mark-recapture and used as a baseline to monitor future changes in abundance resulting from the establishment of the reserve. Additionally, the movements of individual eels in and out of the reserve will be monitored through radio-telemetry. Telemetry data and population estimates will be used to calculate the number of eels within the Kōhanga reserve whose daily movements out of the protected area put them at risk of capture by commercial fishery operations.

This is the research report for the first objective focussed on identifying the factors limiting mahinga kai recruitment. The recruitment of tuna (eels) and pātiki (flounder) in Te Waihora is of primary interest to Ngāi Tahu, but there are also other taonga fish species in the lake that are considered mahinga kai under the Crown's Settlement Offer to Ngāi Tahu. These include piripiripohatu (torrentfish) and paraki (common smelt). Inaka (inanga/whitebait) are also of interest as they are a traditional food source.

1.1 Background fisheries recruitment information for Te Waihora

A comprehensive review of fish recruitment knowledge for Te Waihora was conducted by Jellyman (2012) and this was advanced (and all available data compiled) by Crow and Bonnett (2013). These reports should be consulted for an extensive background on fisheries information, however, it is also relevant to include some background information on the fish fauna of Te Waihora for this report to provide some context for a study on fish recruitment.

Te Waihora catchment contains a diverse range of fishes with a total of 46 species recorded from the lake and its major tributary the Selwyn River (Jellyman 2012, Crow and Bonnett 2013). Of the 46 species recorded from Te Waihora, 26 are freshwater/estuarine fishes while the remaining are marine species. Of the freshwater species not resident in Te Waihora, many are in transit from the sea to riverine habitats. Hence the lake provides an important migration corridor for many species. Most long-term resident fish species in the lake are tolerant of varying levels of salinity (euryhaline) (i.e., eels, flatfish, common smelt, inanga, common bullies). While most flounder species and mullet are abundant, the remaining marine species are only occasionally present during periods of extended lake opening.

Species abundance in the lake is dominated by six or seven species although their numbers can vary markedly depending on the time of the year. Many of the 46 fish species present in the catchment are recorded only as "present" or "often found", but six species were recorded as abundant by Jellyman (2012). These abundant species were shortfin eels, yellowbelly flounder, black flounder, sand flounder, yelloweye mullet and common bullies. Glova and Sagar (2000) also reported these six fishes as well as common smelt as being the most abundant of the 13 species caught from around Te Waihora with fine-mesh fyke nets in 1995. Catches reported from Jellyman (2012) collected in 2008 with seine nets and otter trawls found that common bullies were the numerically dominant species in the lake, comprising >90 % of total fish abundance. Also despite their small size compared to species like eels, common bullies made up about 44% of the fish biomass (total weight) in the lake (Jellyman 2012).

The focus of this project was on factors limiting mahinga kai recruitment and more specifically the recruitment of yellowbelly flounder, shortfin eel and longfin eel. However, other noted mahinga kai species as well as other taonga fish species in the lake that are considered mahinga kai were also a focus of this project. Below we briefly outline the major fish species of interest in the recruitment research.

1.1.1 Eels (tuna)

Two species of freshwater eel are found in Te Waihora and its tributaries; the shortfin eel (shortfins) and the longfin eel (longfins). Both species are diadromous, with adults moving out of fresh water near the end of their lives to spawn at sea. Juveniles arrive in New Zealand inshore waters after a larval life of 6-7 months for shortfins and 8 months for longfins (summarised in Jellyman and Bowen 2009). These fish enter fresh water as glass eels from about July to December (Jellyman 1977a). Although the overall recruitment season is extensive (6 months), the main months for glass eel migration into Canterbury fresh waters is considered to be September-October for shortfins and August-September for longfins (Jellyman 1977a; 1979; Jellyman et al. 1999) (Table 1-1). However, this recruitment timing is based on data from other parts of Canterbury, not from sampling in Te Waihora.

Table 1-1: Proportions of both species of glass eel caught at the mouth of the Ashley River, 1996-2006.

	Shortfin (%)	Longfin (%)
July	2	5
August	3	49
September	51	34
October	35	6
November	9	6
Total caught (species proportion)	4739 (91%)	481 (9%)

In Te Waihora, shortfin eels have always dominated eel stocks in the lake, but the proportion of longfins has declined with time from 4.3% in 1974-82 to 0.5% in 1997-98 (Jellyman and Smith 2009). More recent fisheries surveys have highlighted the significance of longfin eel populations in lake tributaries, with the eel population in numerous tributaries comprised of more than 70% longfins (Jellyman and Graynoth 2010). It seems likely that most longfin glass eels that enter the lake will eventually utilise riverine habitat rather than the lake, although whether juvenile longfins (i.e., elvers) spend a significant amount of time growing in the lake or whether they simply head straight into lake tributaries is largely unknown.

1.1.2 Flatfish (pātiki)

The flatfish population in Te Waihora is dominated by three main species: black flounder (*Rhombosolea retiaria*), yellowbelly flounder (*R. leporina*) and sand flounder (*R. plebia*) (also called dabs, three corners, and whites). Occasionally small quantities of greenback flounder are recorded;

juvenile common sole frequently enter the lake, but do not survive to enter the fishery. The abundance and catch of flatfish varies greatly from year to year, as does the proportion of the three main species in the catch.

The main species of flatfish in Te Waihora do not spawn in the lake, and populations in the lake depend on recruitment of juveniles from the sea when the lake is open. Some adult fish may also move into the lake when it is open, but probably not in great numbers. Maturing adult flounders migrate out of the lake during lake openings in winter and spawn at sea (Jellyman 2012). Crow and Bonnett (2013) reviewed available data from Te Waihora on flatfish recruitment and concluded:

- Juvenile yellowbelly flounders are the earliest species to arrive in the lake with some arriving in July, but peaking in August and September. Recruitment may continue until November or December.
- Juvenile sand flounders were next to arrive, and appeared to have the shortest recruitment period from the study by Taylor and Graynoth (1996), with most arriving in the lake during August. Other studies suggest that recruitment may occur over a much longer period.
- Juvenile black flounders arrived later, mostly during October and November.

However, Crow and Bonnett (2013) cautioned that the timing of flatfish recruitment into the lake was not completely understood because it was based mainly on sampling in one year (1994) when the lake was open for extended periods, and not open after October.

1.1.3 Common smelt (paraki)

Common smelt (*Retropinna retropinna*) is the only smelt species recorded from Te Waihora; Stokell's smelt (*Stokellia anisodon*) is present in a number of large rivers nearby, but has never been recorded from the Te Waihora catchment (Crow and Bonnett 2013). Common smelt are frequently encountered in Te Waihora and it is likely that both diadromous (i.e., spend parts of their lifecycle at sea and in fresh water) and non-diadromous (i.e., spend their lifecycle in fresh water) types co-exist. Spawning of smelt occurs in fresh water, but this has not been observed in Te Waihora. Spawning is likely to take place on shallow, sandy beaches or in slack water around river and stream mouths (McDowall 1990), at depths of 0.5 – 2.5 m (Rowe et al. 2002). Spawning can occur over a prolonged period in summer and autumn (McDowall 1990).

Common smelt predominantly occur along western shorelines and are sparse offshore so abundance estimates for these fish vary considerably depending on sampling location and whether shoreline or offshore sampling methods were used. In previous studies, common smelt have comprised 3% of the total catch (Glova and Sagar 2000), 3.5% of the trawl caught fish (Graynoth and Jellyman 2002) and 21.6% of shore-based seine fishing (NIWA unpubl. data, Crow and Bonnett 2013). Most smelt caught in Te Waihora are between about 60 and 85 mm. At entry into fresh water from the sea, juvenile smelt of diadromous origin can be as small as 45 – 60 mm, but are usually 70 – 90 mm (McDowall 1990). Any common smelt in Te Waihora that are smaller than 45 mm are likely to have hatched within the lake and be non-diadromous (i.e., landlocked), or have not made it out to sea after hatching because of mouth closure.

1.1.4 Torrentfish (piripiripohatu)

Torrentfish, as the name suggests, prefer fast water. Unlike a number of other diadromous fish species in the lake, torrentfish cannot form landlocked populations so maintaining these fish in the

Te Waihora catchment requires recruits to enter the lake from the sea. Torrentfish larvae are unlikely to spend a significant amount of time in the lake and Jellyman (2012) stated that “they simply use Te Waihora as a conduit to and from the sea”.

Almost nothing is known about the timing of torrentfish recruitment into Te Waihora because so few of the larvae have ever been caught. In a fyke netting survey in 1995 (summer), Glova and Sagar (2000) captured over 170,000 fishes but only a single torrentfish (45 mm) was caught. A NIWA study that conducted seine netting at Fishermans Point and otter trawls at Timberyard Point from 2005-2008 caught almost 60,000 fishes, but only 3 were torrentfish (NIWA unpubl. data, Jellyman 2012). Although catches of this fish has historically been low, it was hoped that intensive sampling around lake opening times would result in better catch data to provide information about recruitment timing for this taonga species.

1.1.5 Inanga (inaka)

Inanga are the most common of New Zealand‘s five whitebait species, and are commonly encountered in Te Waihora (Glova and Sagar 2000). Inanga are typically diadromous but like common smelt, it is thought that both diadromous and non-diadromous forms of inanga coexist in Te Waihora (Jellyman 2012). Whether or not inanga are diadromous will affect whether juvenile fish re-enter the lake or whether they rear in the lake and/or tributaries. Spawning of these fish is thought to be from mid-February to mid-April (Jellyman 2012) with diadromous recruits (i.e., whitebait) re-entering the lake during the whitebait season (August to November) where good catches can be made at Taumutu (Taylor and Graynoth 1996).

1.1.6 Common bully

Common bullies dominate the fish community of the lake, comprising 92% of the abundance and 44% of the biomass (Glova and Sagar 2000; Jellyman 2012). Similarly, common bullies accounted for 93.4% of the fish abundance in trawl catches reported by Graynoth and Jellyman (2002). There is some suggestion that numbers of bullies in Te Waihora have increased over time (Jellyman and Todd 1998), possibly associated with a loss of macrophytes. However, commercial eel fishers have speculated that common bully numbers may have declined in recent years, which if correct, would have important implications for the eel fishery because bullies are an important component in the diet of eels, particularly at sizes greater than 400 mm (Kelly and Jellyman 2007).

Common bullies can form both diadromous and non-diadromous populations which can coexist. Bullies spawn in spring and summer (McDowall 1990), and in diadromous populations, the newly hatched larvae are swept out to sea and return to fresh water as juveniles 15-20 mm long in autumn. In non-diadromous populations, the entire life-cycle occurs within fresh water and larvae do not go to sea. Larval bullies are pelagic (i.e., they occur in the water column), and those originating from non-diadromous stock will live in the water column of the lake until they reach 15-20 mm in length, at which stage they will move to the shallow littoral areas and commence benthic (bottom) living. Thus, shore-based fishing methods are unlikely to capture non-diadromous bully larvae. The migratory status of common bullies in Te Waihora has not been determined, but it is presumed that the majority of fish are non-diadromous (Jellyman 2012). The rationale for this conclusion was: (1) voluntary landlocking of common bullies is common and can occur in large lakes with small (or infrequently opened) outlets like Te Waihora, (2) there is a strong representation of a range of size classes in the lake, even when the lake has been closed during the recruitment period (3) larval bullies have been caught in the centre of the lake (Taylor and Graynoth 1996). Upcoming work in this project (Investigation brief D5) aims to determine what proportion of the population is of diadromous and non-diadromous origin for different parts of the lake.

2 Methods

2.1 Study sites

Recruitment of mahinga kai species was monitored at three sites close to the outlet of Te Waihora over two years. The first site (Te Kōrua) was located in Te Kōrua inlet approximately 800 m from the lake outflow. The second site (Boat shed) was located approximately 450 m from the lake outflow. The third site (Water tower) was located close to Fishermans Point approximately 950 m from the lake outflow (Figure 2-1).

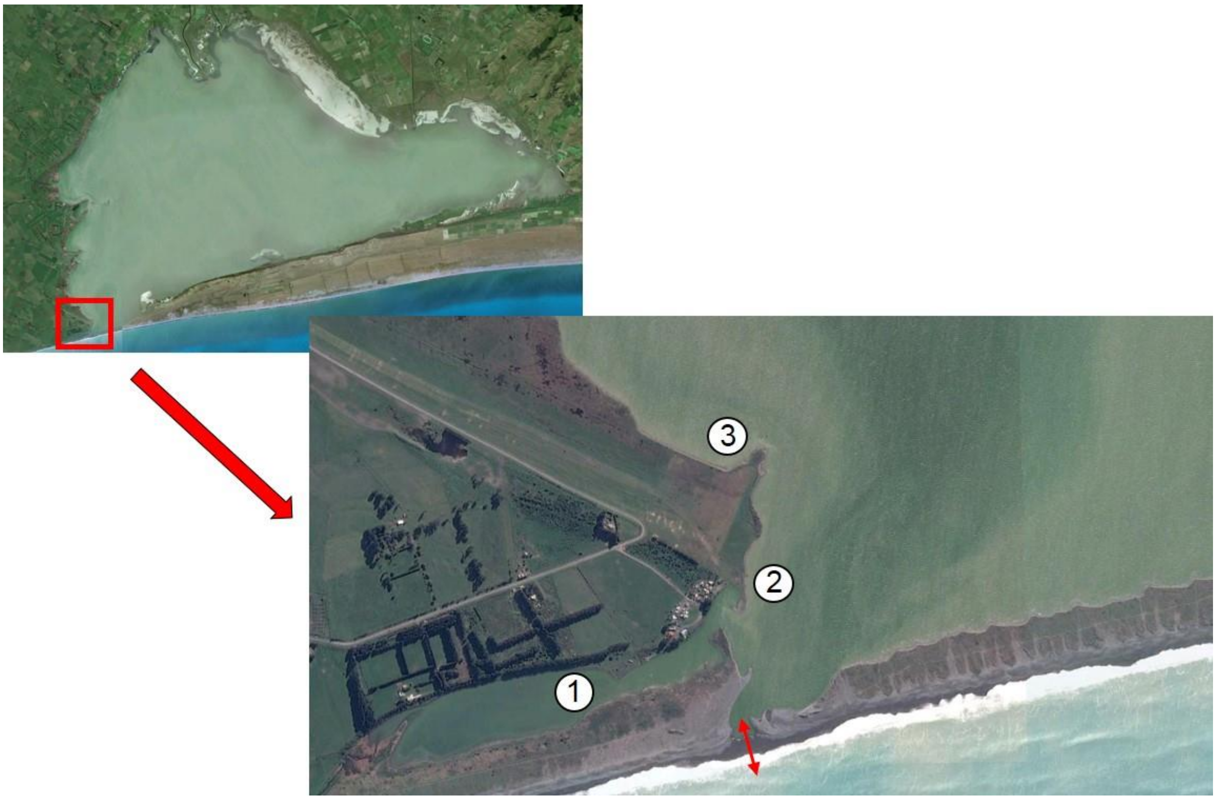

Figure 2-1: Location of recruitment monitoring sites in Te Waihora. Site 1 = Te Kōrua, Site 2 = Boat shed, Site 3 = Water tower. The double-headed red arrow shows the location of the lake opening site.

2.1.1 Lake openings

Over the course of the study the lake was manually opened to the sea on nine occasions. After three of the openings large sea swells closed the lake outlet after only three days, prompting another reopening effort. These three re-openings mean that there were really six major lake opening events during the study for fish to utilise for recruitment (Figure 2-2). There were only two lake openings in 2013 but both openings lasted for over 45 days (Appendix A). In 2014, there were more lake opening events, but the maximum number of successive days that the lake was open was only 16 (Appendix A). Prior to the first lake opening in 2013, the lake level reached 1.81 m.a.s.l submerging thousands of hectares of surrounding farmland. This was the highest lake level recorded in 73 years; it reached 1.85 m in June 1945 (Melissa Shearer, Environment Canterbury, pers. comm.)[1].

[1] The minimum opening levels for Te Waihora were formally set in 1947.

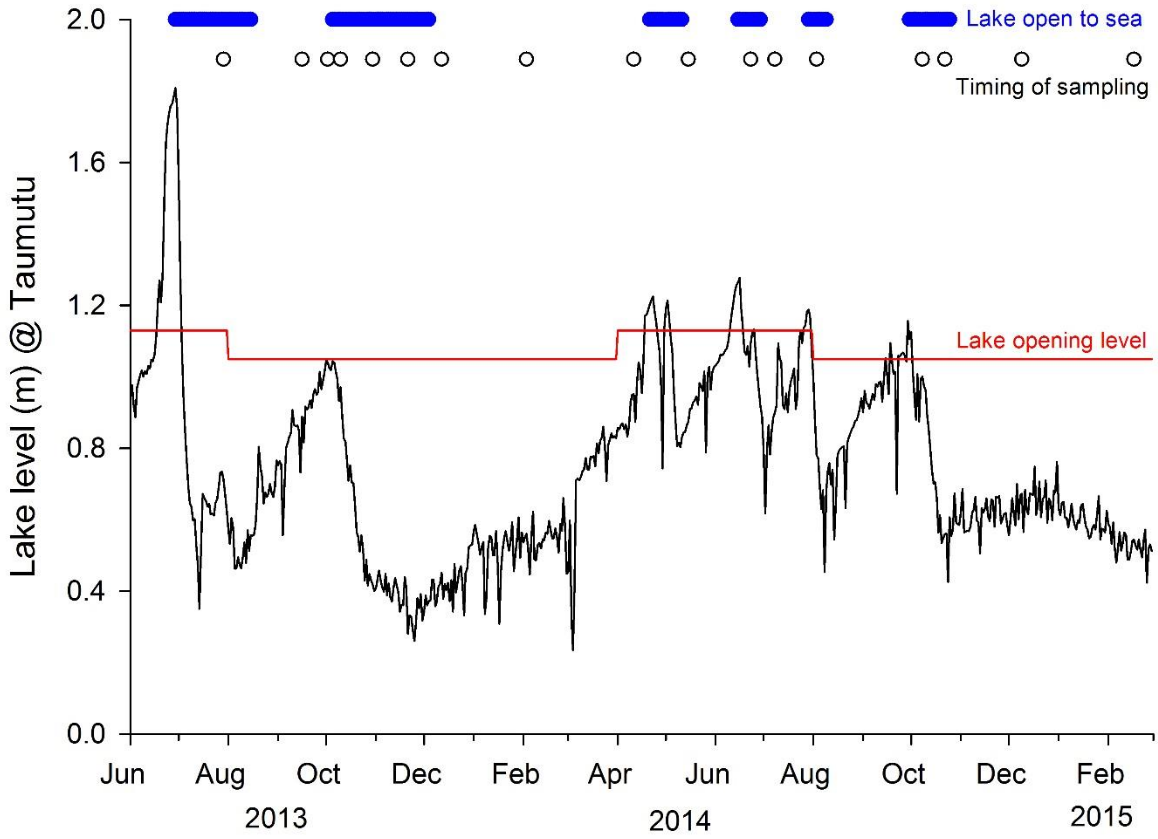

Figure 2-2: Variation in the lake level (m) of Te Waihora as recorded at the Taumutu recording site. The consented lake opening regime is displayed in red. The blue bars indicate the periods when the lake was open to the sea; short-term lake closures (i.e., 3 days) during these periods are not visible (see Appendix A for further detail). The open circles indicate sampling times. Lake level data were supplied by Environment Canterbury.

The lake closes when large waves, typically associated with southerly (and south-westerly) winds, transport gravel that covers the outlet. Depending on the extent of gravel transportation, the section of gravel separating the lake from the sea can be highly variable in terms of beach width and height. Sea water can 'overtop' this beach barrier and enter the lake during high seas. Lake salinity from the Environment Canterbury (ECan) logger was used to identify overtopping events. Likely overtopping events, based on salinity data, were cross-checked with wind direction data from a logger in Lincoln (Broadfield Ews) to confirm that overtopping events were associated with southerly/south-westerly winds.

2.2 Survey design and methodology

Sampling was conducted at various times between July 2013 and February 2015 with a strong focus of monitoring recruitment around the timing of lake openings. Manual lake openings of Te Waihora are undertaken based on pre-defined 'trigger levels' which vary seasonally: the lake is opened in Winter (1 April – 31 July) when levels reach 1.13 m.a.s.l and is opened in Summer (1 August – 31 March) when the lake level exceeds 1.05 m.a.s.l. As the number and timing of lake openings varies markedly between years (see Appendix A), recruitment monitoring was opportunistic. During periods when the lake was regularly open, sampling was carried out approximately every four to five weeks (although additional sampling was also done shortly after a new lake opening). In total, the recruitment monitoring occurred on 18 occasions (Figure 2-2).

The sampling method involved two approaches: (1) sampling large areas of the lake, both lake bed and water column, during the day using fine-meshed seine nets. This method was expected to capture larval, juvenile and adult fish and particularly freshly recruited flatfish, and (2) sampling with fine-meshed “super fyke” nets to intercept/capture fish species moving around the lake at night; this method was expected to capture fewer fish than seine netting but was targeting freshly recruited fish that might be moving at night such as glass eels. The fine mesh on the super fyke nets (c. 1-2 mm mesh) also allowed them to capture smaller fish than the seine net. On each sampling occasion, two seine hauls were conducted at each site (with the exception of 30/08/13 and on 22/11/2013 at the Te Kōrua site when only one haul was conducted because of extreme fish numbers) for a total of 101 seine hauls during the study. The seine net was 25 metres (m) long and had a stretched mesh size of 5 millimetres (mm). Haul area varied between site visits (up to 750 m^2) and depended on water depth (i.e., when lake levels were low, researchers walked in a line perpendicular to the shore to a minimum water depth of 30 cm before commencing seining), substrate composition and the presence of ‘snags’ (i.e., debris that may catch the nets). The seine net was dragged by two researchers on either end of the net towards the shore and once the net was dragged out of the water the seine net was opened and all fish were separated (often from thousands of mysid shrimps) and placed in buckets for processing.

A single super-fyke net was set at each sampling site and left to fish overnight on the sampling dates listed in Table 2-1. Since the lake is prone to strong ‘wind fetch’ effects (see Figure 2-3 and Appendix B), care was taken to ensure the cod end of the net was in the deepest water possible to avoid/minimise any captured fish being stranded by changes in lake level. In calm conditions/sheltered sites (e.g., Te Kōrua), a super-fyke net was set with the leader (length 12 m, mesh size 1 mm) perpendicular to the shoreline. During strong winds and currents, fyke nets were orientated parallel to the wind or current to minimise the likelihood that the net would break because of debris build-up or roll over causing the mouth of the net to close over/collapse. This occurred on some of the dates when ‘wind’ or ‘broke’ are noted in Table 2-1. When winds were too strong at all sites and clearly going to damage the super-fyke nets they were not set; see grey boxes and some occasions when ‘wind’ is noted in Table 2-1. When the lake was open, a super-fyke net was generally orientated towards the lake mouth with the leader positioned at an angle that should maximise the chance of catching recruits. In the final chamber of each super-fyke net, a section of standard 12 mm fyke net mesh was sown across the opening so that small fish could be separated from any large eels captured that might eat them in the net.

Table 2-1: The timing of fish recruitment sampling at the three study sites. For seine netting and super fyke sampling, 'X' denotes when a sampling event occurred.

Sampling date	Lake status	Days since opening	Days since closed	Level opened	Level closed	Seine netting			Super fyke		
				(m)	(m)	Te Kōrua	Boat shed	Water tower	Te Kōrua	Boat shed	Water tower
29/07/2013	Open	31	0	1.81	NA	X	X	X			
30/08/2013	Closed	63	15	1.81	0.52				X	X	X
16/09/2013	Closed	80	32	1.81	0.52	X	X	X	X	X	X
3/10/2013	Closed	97	49	1.81	0.52	X	X	X	X	X	X
10/10/2013	Open	6	0	1.07	NA	X	X	X	X	wind	X
30/10/2013	Open	26	0	1.07	NA	X	X	X			
21/11/2013	Open	48	0	1.07	NA	X	X	X	X	X	wind
12/12/2013	Closed	69	8	1.07	0.52	X	X	X	X	low	low
3/02/2014	Closed	122	61	1.07	0.52	X	X	X	X	wind	wind
11/04/2014	Closed	189	128	1.07	0.52	X	X	X			
15/05/2014	Closed	14	4	1.25	1.03	X	X	X	X	X	X
23/06/2014	Closed	9	2	1.24	1.12	X	X	X	X	wind	X
8/07/2014	Closed	15	9	1.18	0.85	X	X	X	wind	wind	X
3/08/2014	Open	6	0	1.19	NA	X	X	X	X	wind	X
8/10/2014	Closed	9	2	1.15	0.99	X	X	X	X	X	X
22/10/2014	Open	14	0	1	NA	X	X	X	X	X	broke
9/12/2014	Closed	62	45	1	0.58	X	X	X	X	wind	wind
17/02/2015	Closed	132	115	1	0.58	X	X	X	X	X	X

Note for super fyke sampling, grey cells indicate that sampling was not attempted on this date.

Figure 2-3: The effect of wind direction on habitat availability for fish in Te Waihora. These photos show the extent of change in wetted area that can occur on successive days around the recruitment sampling sites, due to differences in the prevailing wind direction.

2.3 Catch processing

Fish caught by seining and fyke netting were anaesthetised with a clove oil based fish anaesthetic. Fish were identified to species level and the lengths of up to 50 individuals were measured for each species at each site to the nearest mm; length measure (fork length or total length) varied depending on species (see Jellyman et al. 2013). The weight of these 50 random individuals was then measured. For fish species where more than 50 fish were caught at a site, the remaining fish (for a seine or superfyke net) were bulk weighed. The total catch weight was then divided by the average weight of the 50 measured individuals to give an estimate of the total number of fish caught. Where less than 50 individuals of a given species were caught at a site, all individuals in each seine or fyke net were counted and measured to the nearest mm.

It was not possible to accurately identify glass eels, whitebait or any of the small flounder species in the field so these fish were collected and brought back to the laboratory for identification under a microscope.

2.4 Data analysis

To examine changes in fish length through time and identify when recruits were entering Te Waihora, box plots were made for the nine species of primary interest: shortfin eel, longfin eel, yellowbelly flounder, sand flounder, black flounder, common smelt, torrentfish, inanga and common bully. Fish length data from both seine and super-fyke sampling methods were used in the box plot time series.

Seine netting data were used to examine changes in length-frequency distributions over time for these nine fish species. Data were not pooled for these graphs because the different sampling methods vary in their effectiveness at catching certain species and size ranges. As almost 10 times as many fish were caught seine netting, only these data were used to examine variation in length-frequency data through time. The only exception was shortfin eel, where a graph panel of super-fyke data only is also presented because the majority of shortfin eels were caught using this sampling method.

To further examine the timing of recruitment for the nine species, histograms of the number of recruits through time were made for each species. In these figures, the extent of lake opening periods and the lunar cycle stage were displayed as they were important predictors of recruitment timing; lunar cycle has been shown to be an important factor for glass eel recruitment in particular (Jellyman and Lambert 2003). To ascertain the timing of recruitment, one of key decisions is determining at which size a fish is considered a 'fresh recruit' compared to a juvenile fish. The following upper size limits for key species (and the rationale) were as follows:

- Shortfin eel and longfin eel were considered to be fresh recruits if they were less than 70 mm. Shortfin glass eels tend to be a few millimetres shorter than longfin glass eels when they enter fresh water (see Jellyman and Lambert 2003), but because it is easy to distinguish glass eels from elvers, the same size limit was used for both species because it did not influence results. Shortfin eels were either caught as glass eels or were not recorded less than 75 mm long.

- Yellowbelly flounder, sand flounder and black flounder had a recruit size limit of 35 mm. This size limit was based on previous work by Taylor and Graynoth (1996) who defined this size as freshly recruited flounder.

- Common smelt were difficult to determine a size limit for recruits because the lake probably has fish of sea-run and landlocked origin. Size limits were based on McDowall (1990): juvenile smelt of diadromous origin can be as small as 45 – 60 mm, but are usually 70 – 90 mm. Therefore, recruits were considered to be <70 mm but a separate analysis of common smelt <45 mm was also conducted since fish below this size limit were likely to be recruits that have hatched in fresh water and not gone out to sea.

- Torrentfish recruits were considered to be less than 50 mm. As only four torrentfish had been caught during previous surveys of Te Waihora (see Section 1.1.4) it was decided that no torrentfish would be excluded based on length since so little is known about the recruitment of these fish. As torrentfish were not expected to be spending a significant amount a time in the lake, it was not known whether variation in size might be caused by delays in entering the lake or if certain lake conditions might slow movement through the lake.

- Inanga recruits were considered less than 60 mm. This size cut-off was based on the size range of migrating *G. maculatus* from previous studies of their size variability in whitebait catches (McDowall and Eldon 1980).

- Common bully recruits were consider as fish smaller than 35 mm. Larval bullies are pelagic and will be in the water column (if non-diadromous) or won't re-enter the lake until they are 20 mm.

To examine whether the number of recruits (based on the fish sizes outlined above) being caught was related to lake opening conditions, three factors were examined: (1) lake status – open or closed, (2) days since the lake opened, and (3) days since the lake closed. Regression analysis was conducted on the number of recruits for each of the nine species and a range of potential curves fitted to data. Regression analyses were performed in Sigmaplot Version 12. Only significant regression relationships ($P < 0.05$) are shown in the results.

To investigate whether the different sampling methods (i.e., seine netting versus super-fyke nets) had a bias favouring particular fish species or certain fish sizes, catch data were analysed. Each species where 10 or more fish had been caught using both methods had their length-frequency distributions compared using kernel density estimation (KDE); KDE is a non-parametric technique for visualising the distribution of a variable such as fish length. For example, kernel density functions that strongly overlap indicate that both methods are providing similar estimates of fish length for the population, whereas divergent curves indicate that the methods are sampling certain sized fish more than other sizes. Kernel density estimations were carried out using the SM package in R (R Development Core Team, 2015).

The relationship between lake opening duration (i.e., the total number of days the lake was open to the sea during an opening period) and recruit catch-per-unit-effort (CPUE) was analysed to determine whether the number of recruits entering the lake increased or decreased with extended openings. Recruit CPUE was calculated based on the number of recruits caught across all sampling trips during a particular lake opening period, this value was then multiplied by the number of days the lake stayed open after accounting for the number of sampling occasions that had occurred. Data for common smelt recruits were excluded when calculating CPUE because we could not be certain about whether these fish had recruited from the sea or whether they were of lake-reared; their inclusion could have greatly influenced results. This was considered an exploratory analysis since there are a number of factors that affect the number of recruits entering the lake (e.g., timing of lake opening, the length of time before tidal exchange occurs) and because only limited data were available.

An additional analysis was also conducted to compare CPUE for recruits (again common smelt were excluded as outlined above) that had entered the lake when it was open compared to when the lake was closed (see Section 4.1 on fish recruitment during gravel overtopping events). Any recruits caught when the lake was open to the sea and within 15 days of the lake having closed were assumed to have recruited during lake openings (note, this 15-day cut-off was arbitrary but it is assumed that this should have been sufficient time for most fresh recruits to have exited the area around the lake outlet). Recruits caught more than 30 days after the lake had closed were assumed to have entered the lake via an overtopping event. As previously mentioned, we considered an overtopping event to have occurred only if there was a spike in salinity data (well above the average concentration during the study of 10.8 ppt) that corresponded with southerly/south-westerly winds[2]. Recruit CPUE associated with overtopping events were then compared to recruit CPUE from lake openings to estimate the percentage of recruits that come from overtopping events. As CPUE data were not available for all overtopping events, a minimum and maximum CPUE value for missing dates was estimated based on other samples from similar date. This allowed an estimated percentage range to be calculated for recruits from overtopping events.

[2] Salinity data from mid-January to the beginning of April were unavailable but this is not a period of major fish recruitment, nor is it a time when large south-westerly storms are common to cause overtopping.

3 Results

Across the study, 10 freshwater/estuarine species and 5 marine species were recorded (Table 3-1). Seine netting surveys caught 13 species but did not catch either longfin eel or lamprey, these species were only caught in super-fyke nets.

Common smelt were the most abundant species caught from seine netting (see Appendix C) and they comprised 63.5% of the total catch (Table 3-1). Over 12,000 common bully were caught seine netting which accounted for approximately 30% of the total catch. The third most abundant species was yellowbelly flounder with 1,107 fish caught. Inanga, yelloweye mullet, torrentfish and sand flounder were the only other species to have more than 100 fish caught during seine netting surveys.

Common smelt and common bully were again the most abundant fish caught in the super-fyke net surveys, however in contrast to seine netting surveys, approximately twice as many common bully were caught compared to common smelt (Table 3-1). These two species accounted for over 80% of the total catch for super-fykes. Inanga (10.2%) and shortfin eel (6.4%) were the only other two species to contribute to more than 1% of the total catch across all super-fyke surveys.

Table 3-1: The number and % (of total catch) of each fish species caught from seine and superfyke netting during the study.

Common name	Scientific name	Seine netting		Super-fyke net	
Freshwater/estuarine species		Number caught	% of catch	Number caught	% of catch
Yelloweye mullet	*Aldrichetta forsteri*	403	0.97	30	0.68
Shortfin eel	*Anguilla australis*	73	0.18	282	6.43
Longfin eel	*Anguilla dieffenbachii*	0	0	5	0.11
Torrentfish	*Cheimarrichthys fosteri*	317	0.77	19	0.43
Inanga	*Galaxias maculatus*	669	1.62	447	10.19
Lamprey	*Geotria australis*	0	0	1	0.02
Common bully	*Gobiomorphus cotidianus*	12,263	29.62	2,353	53.65
Common smelt	*Retropinna retropinna*	26,302	63.53	1,211	27.61
Black flounder	*Rhombosolea retiaria*	41	0.10	2	0.05
Brown trout	*Salmo trutta*	6	0.01	12	0.27
Marine species					
Kahawai	*Arripis trutta*	2	0.005	0	0
Estuarine stargazer	*Leptoscopus macropygus*	2	0.005	0	0
Yellowbelly flounder	*Rhombosolea leporina*	1,107	2.67	10	0.23
Sand flounder	*Rhombosolea plebeia*	133	0.32	4	0.09
New Zealand sprat	*Sprattus muelleri*	80	0.19	7	0.16
		41,415		**4,386**	

3.1 Eels (tuna)

3.1.1 Shortfin eel

There were 355 shortfin eels caught during the study and approximately 80% of these fish were caught using super-fyke nets (Table 3-1). Shortfin eels were present on 13 of the 18 sampling occasions and were caught in super-fyke nets on all but one of these occasions. They ranged in size from 54 to 1070 mm, with the largest fish being caught seine netting (Figure 3-1, Figure 3-2). Approximately one-third of shortfin recruits were caught seine netting but the majority (two-thirds) were caught in super-fyke nets (Figure 3-2, Figure 3-3). Super-fyke nets were more effective at catching small recruits compared to seine nets which were primarily catching only the larger recruits (Figure 3-4). The largest number of shortfin recruits (i.e., glass eels) was recorded on 3/10/13, during a new moon phase, when the lake had been closed for 49 days (Figure 3-5). When the lake was next opened on 5/10/13, two recruits were recorded six days after opening but five recruits were caught 48 days after the lake had been opened (Figure 3-5). Unfortunately lake conditions meant super-fyke nets could not be set on the previous sampling trip (30/10/13) but no shortfin recruits were caught when seine netting on this trip.

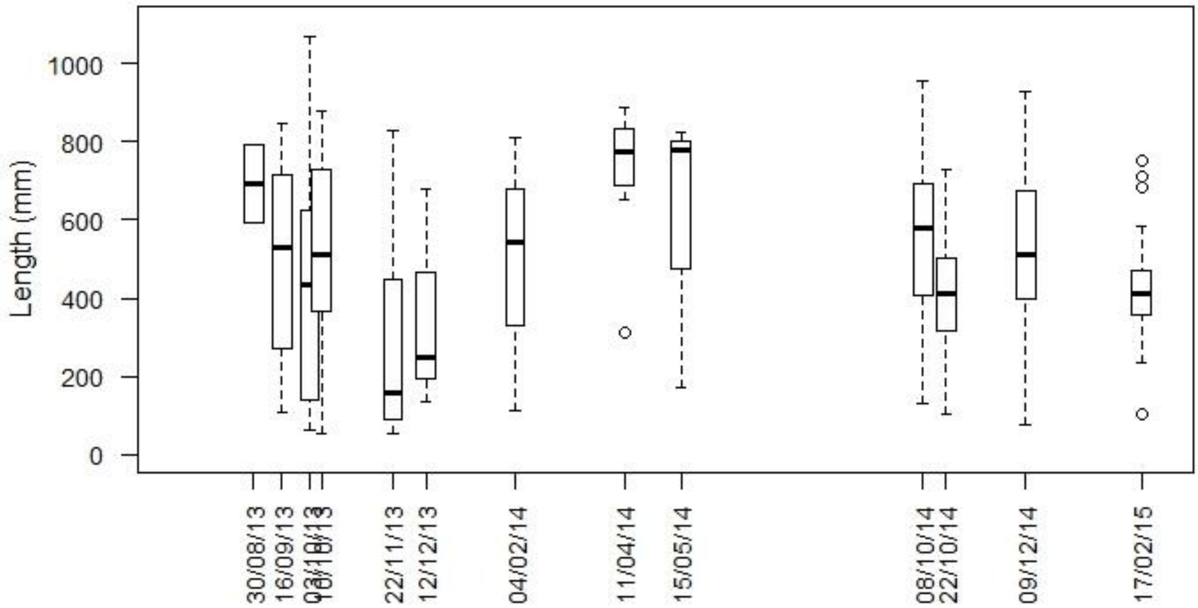

Figure 3-1: Box plots of variation in shortfin eel length on each sampling occasion over the duration of the study. Box plots are only shown for dates when fish were caught.

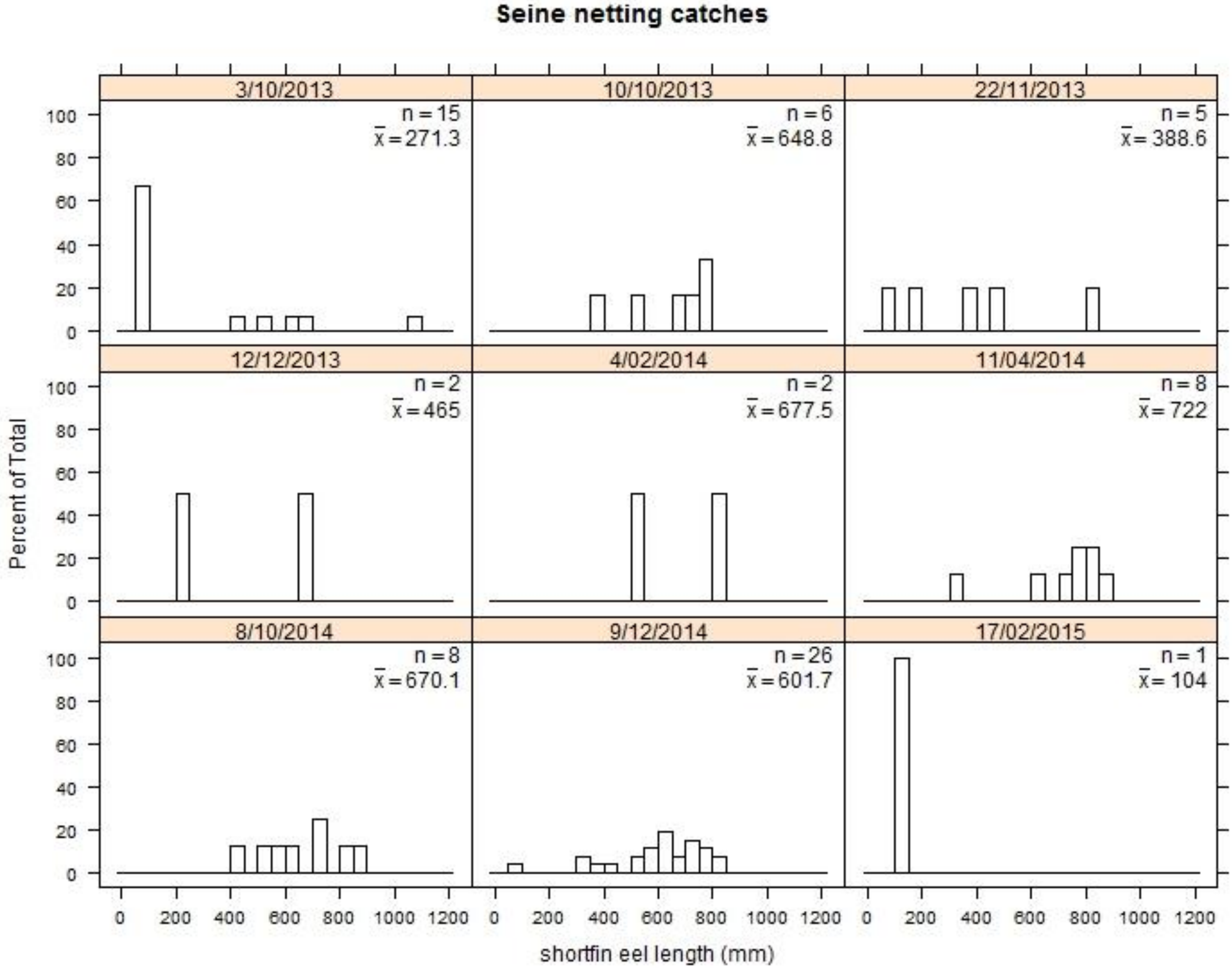

Figure 3-2: Length-frequency histograms of shortfin eel caught on each sampling occasion. Results are for seine netting catches only and data are pooled across the three sampling sites. Each graph panel displays the number of fish measured (n) and mean fish size ($\overline{x}$) for each sampling occasion. Size class bins were 50 mm.

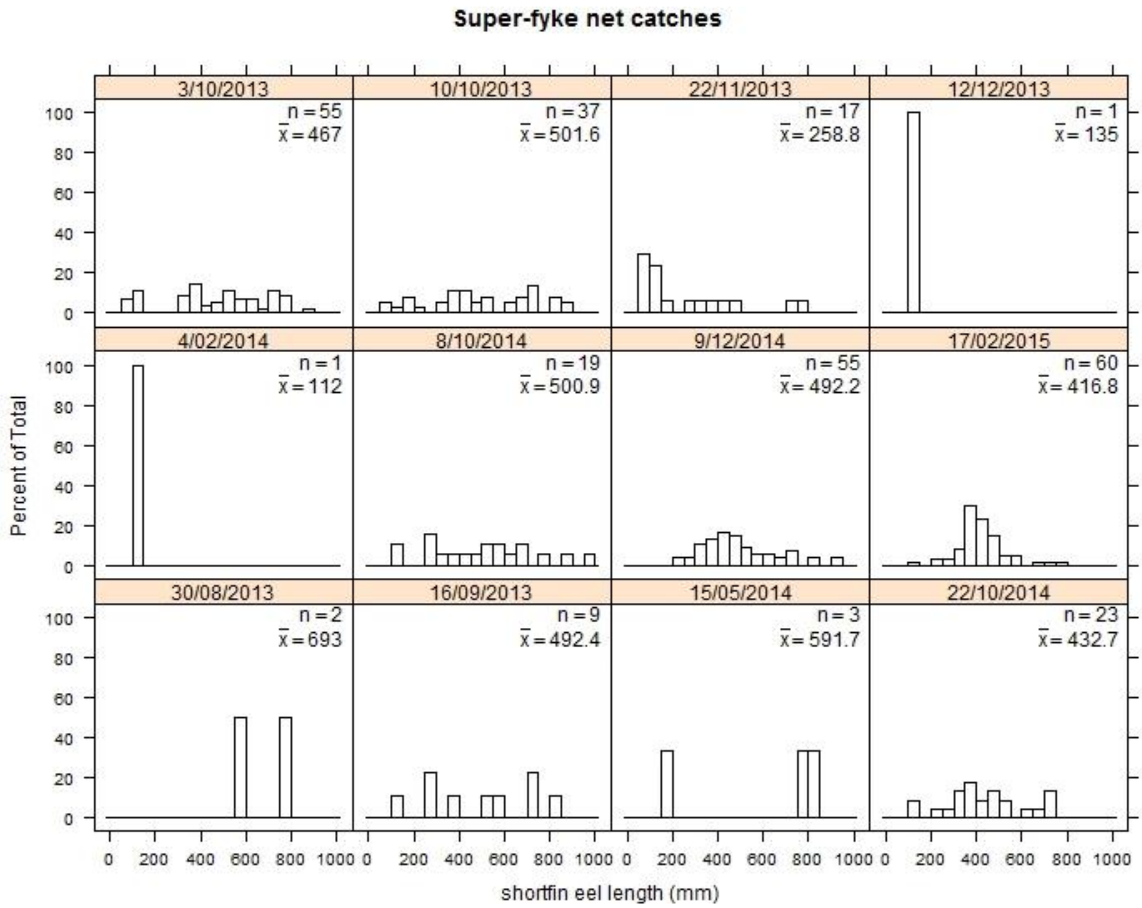

Figure 3-3: Length-frequency histograms of shortfin eel caught on each sampling occasion caught using super-fyke nets. Data are pooled across the three sampling sites. Each graph panel displays the number of fish measured (n) and mean fish size ($\overline{x}$) for each sampling occasion. Size class bins were 50 mm.

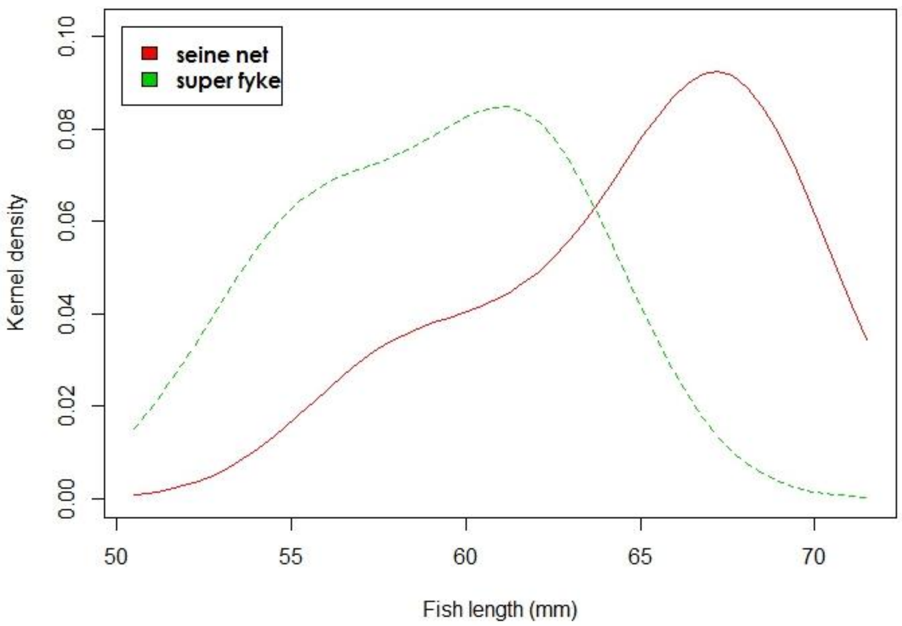

Figure 3-4: Comparison of sampling methods for shortfin eel recruits (<70 mm). n=5 (seine), n=9 (super fyke).

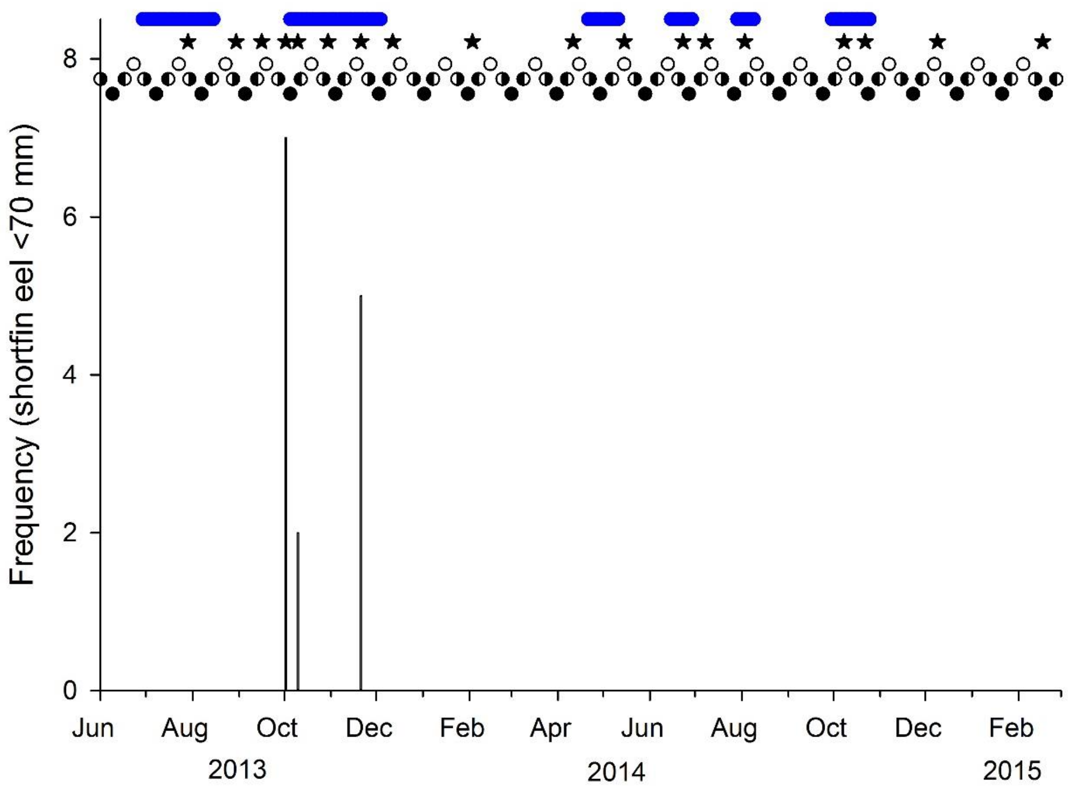

Figure 3-5: The timing of shortfin eel recruitment. Shortfin eels were caught using seine and super-fyke nets. The blue bars indicate the periods when the lake was open to the sea. The star symbols indicate sampling times. Lunar phase is also shown with filled circles indicating new moon and open circles indicating full moon phases.

3.1.2 Longfin eel

Only five longfin eels were caught during the study and all were caught using super-fyke nets (Table 3-1). Crucially, four of the five fish were glass eels; longfin glass eels have not previously been recorded from around the outlet of Te Waihora (or anywhere in the lake) to definitively determine recruitment timing. The longfin glass eels were all caught across a six week period during 2013 (Figure 3-6, Appendix D). On the first occasion a glass eel was caught when the lake had been closed for 15 days and on the second occasion the lake had not been open to the sea for 49 days (Figure 3-7). The only date when a longfin glass eel was caught during a lake opening was on 10/10/13 when the lake had been open for six days (Figure 3-7); super-fyke nets were not able to be set on the next sampling occasion on 30/10/13 and none were recorded during the following trip (21/11/13) when shortfin glass eels were recorded (Appendix D).

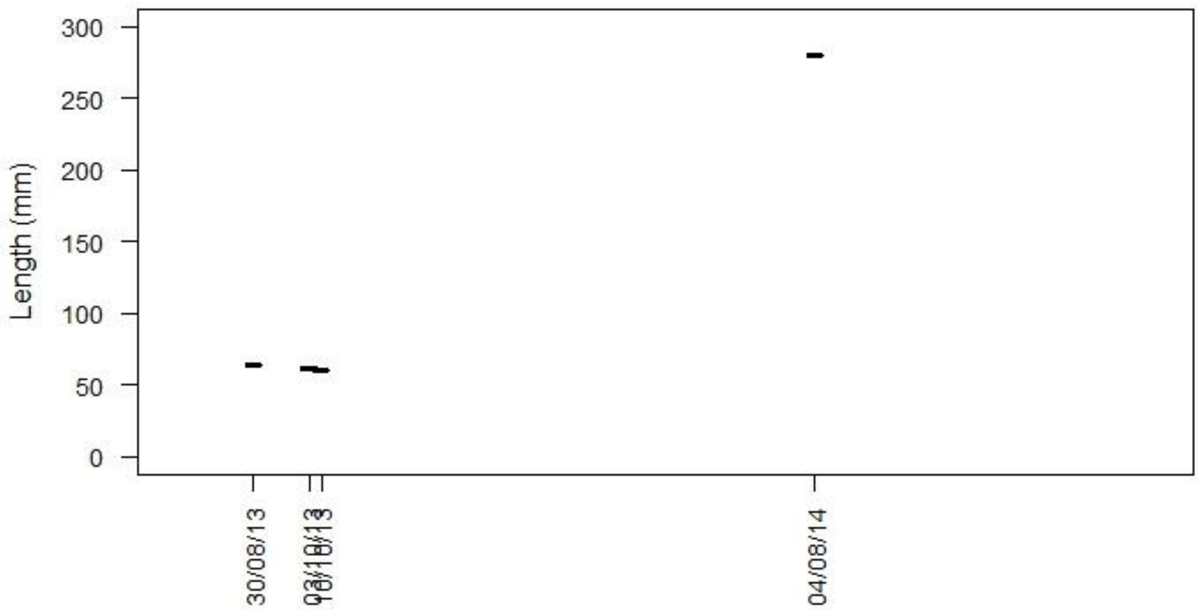

Figure 3-6: Box plots of variation in longfin eel length on each sampling occasion over the duration of the study. Box plots are only shown for dates when fish were caught.

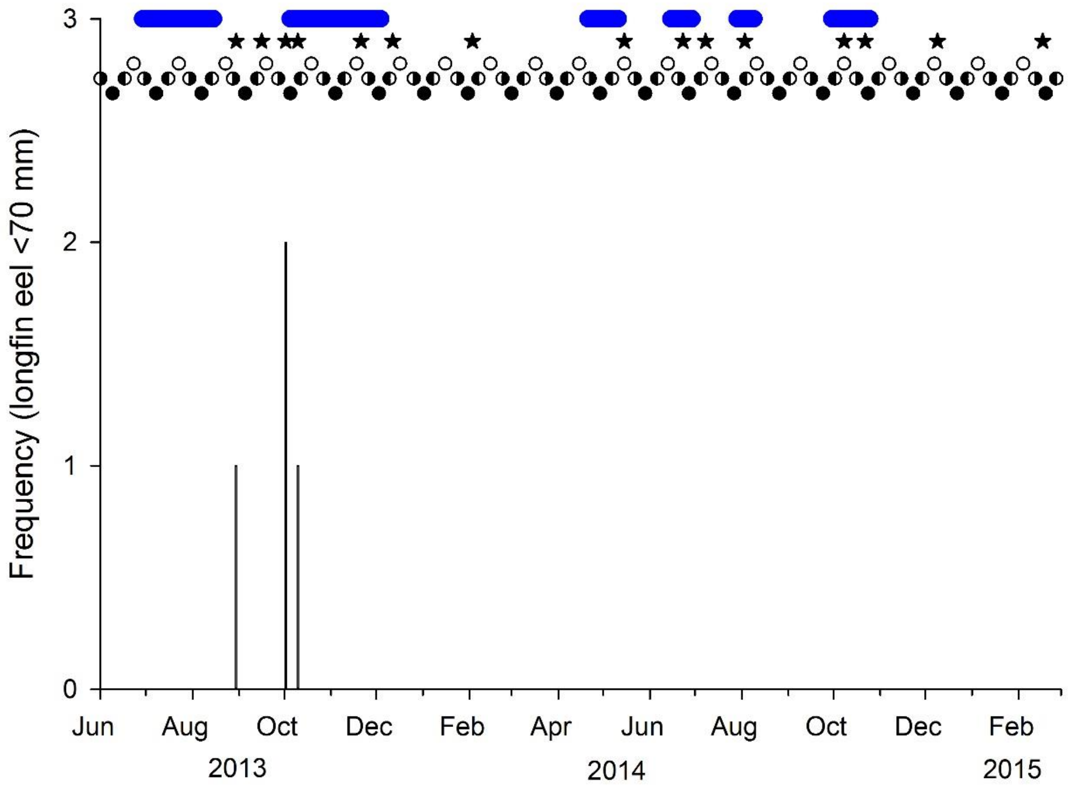

Figure 3-7: The timing of longfin eel recruitment. Longfin glass eels were only caught in super-fyke nets. The blue bars indicate the periods when the lake was open to the sea. The star symbols indicate sampling times. Lunar phase is also shown with filled circles indicating new moon and open circles indicating full moon phases.

3.2 Flatfish (pātiki)

3.2.1 Yellowbelly flounder

Yellowbelly flounder were recorded on almost every sampling trip (17 out of 18) and of the 1,117 fish caught during the study, 99% were caught seine netting (Table 3-1). Yellowbelly flounder ranged in size from 14 to 340 mm although fish larger than 200 mm were not caught during sampling in 2013 (Figure 3-8). Fish larger than 200 mm were regularly caught on sampling trips in 2014 and 2015 so the mean fish size on each sampling occasion tended to be considerably higher when compared to 2013 data (Figure 3-9). Across the size range of fish caught, seine nets tended to be capturing a high proportion of juveniles and only a small proportion of adults whereas super-fyke nets where catching a few juveniles but a far greater proportion of large yellowbelly flounder (Figure 3-10a). When only yellowbelly recruits were examined, it was evident that seine nets were catching a wider size range of recruits compared to super-fyke nets (Figure 3-10b). Yellowbelly flounder recruited into Te Waihora between mid-September and late-December although the recruitment peak was between mid-November and mid-December in both 2013 and 2014 (Figure 3-11). Over 65% (275) of all recruits caught during the study were captured on 21/11/13 after the lake had been open for 48 days. Small numbers of recruits (i.e., <5) were recorded on two occasions between September and October 2013 when the lake had been closed for 32 and 48 days, respectively (Figure 3-11, Appendix D). In 2014, the largest influx of yellowbelly flounder recruits occurred on 9/12/14 when 48 recruits were caught (compared to a peak of 275 recruits on 21/11/13); at this time the lake had been closed to the sea for 45 days (Figure 3-11, Appendix D).

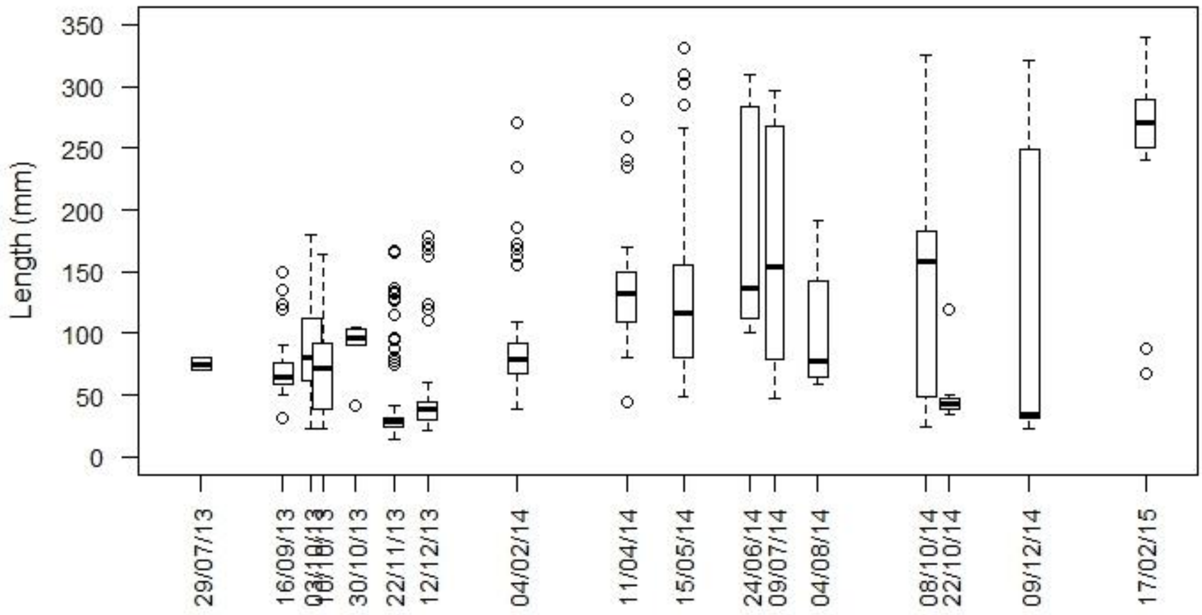

Figure 3-8: Box plots of variation in yellowbelly flounder length on each sampling occasion over the duration of the study. Box plots are only shown for dates when fish were caught.

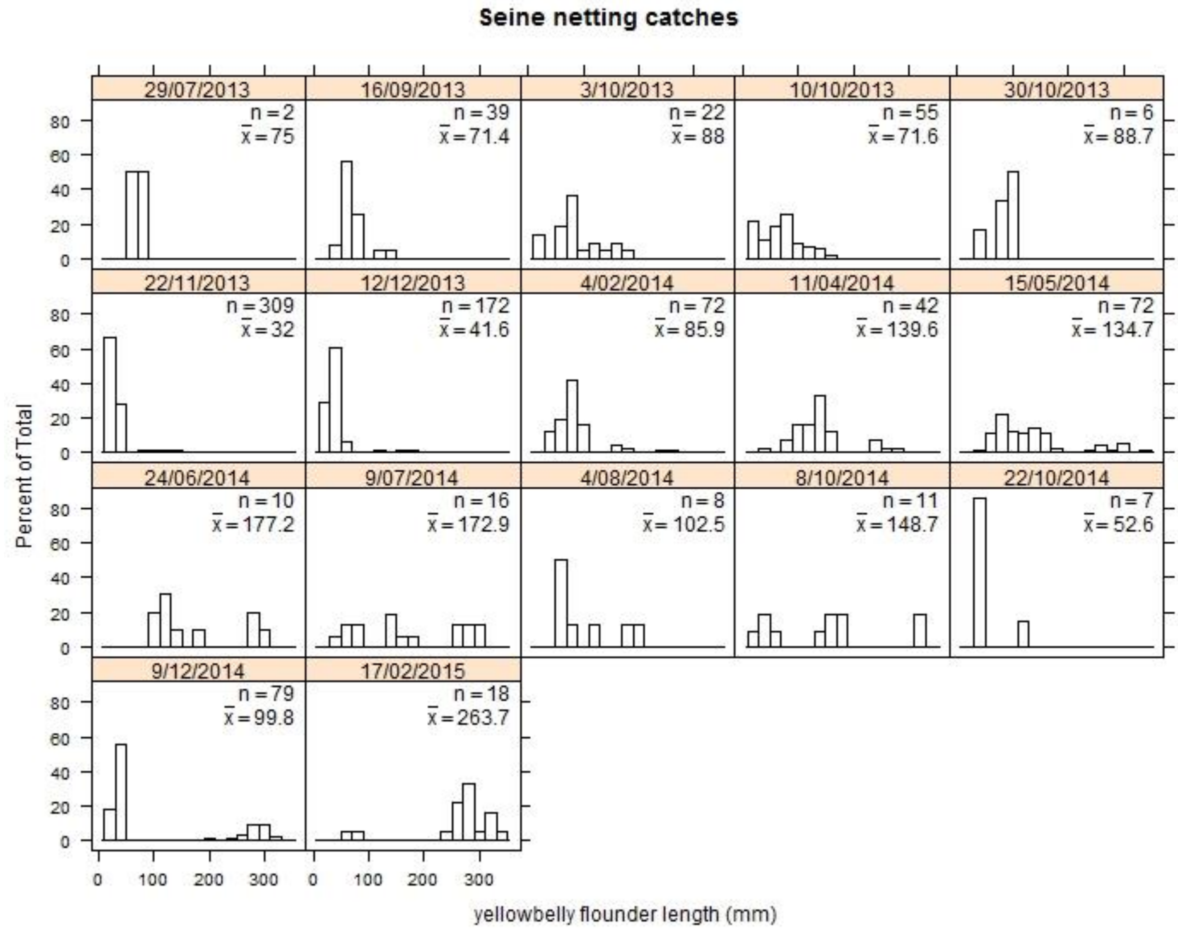

Figure 3-9: Length-frequency histograms of yellowbelly flounder caught on each sampling occasion. Results are for seine netting catches only and data are pooled across the three sampling sites. Each graph panel displays the number of fish measured (n) and mean fish size ($\overline{x}$) for each sampling occasion. Size class bins were 20 mm.

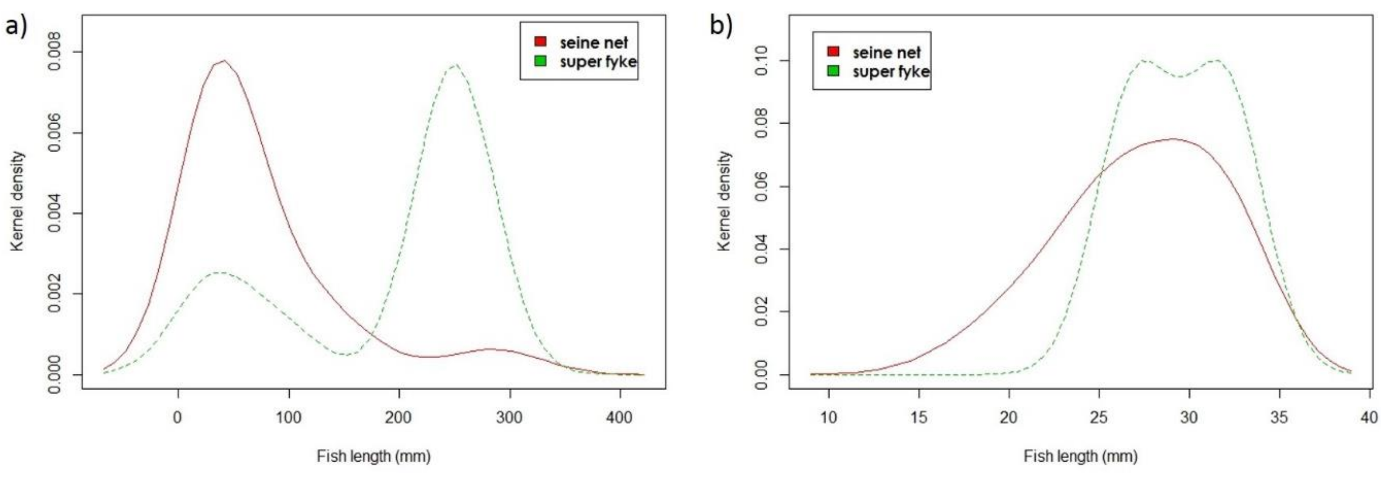

Figure 3-10: Comparison of sampling methods for yellowbelly flounder. Data for all sizes of yellowbelly flounder (a) and yellowbelly flounder recruits only (<35 mm) (b) are shown. For (a), n=940 (seine), n=10 (super fyke). For (b), n=396 (seine), n=2 (super fyke).

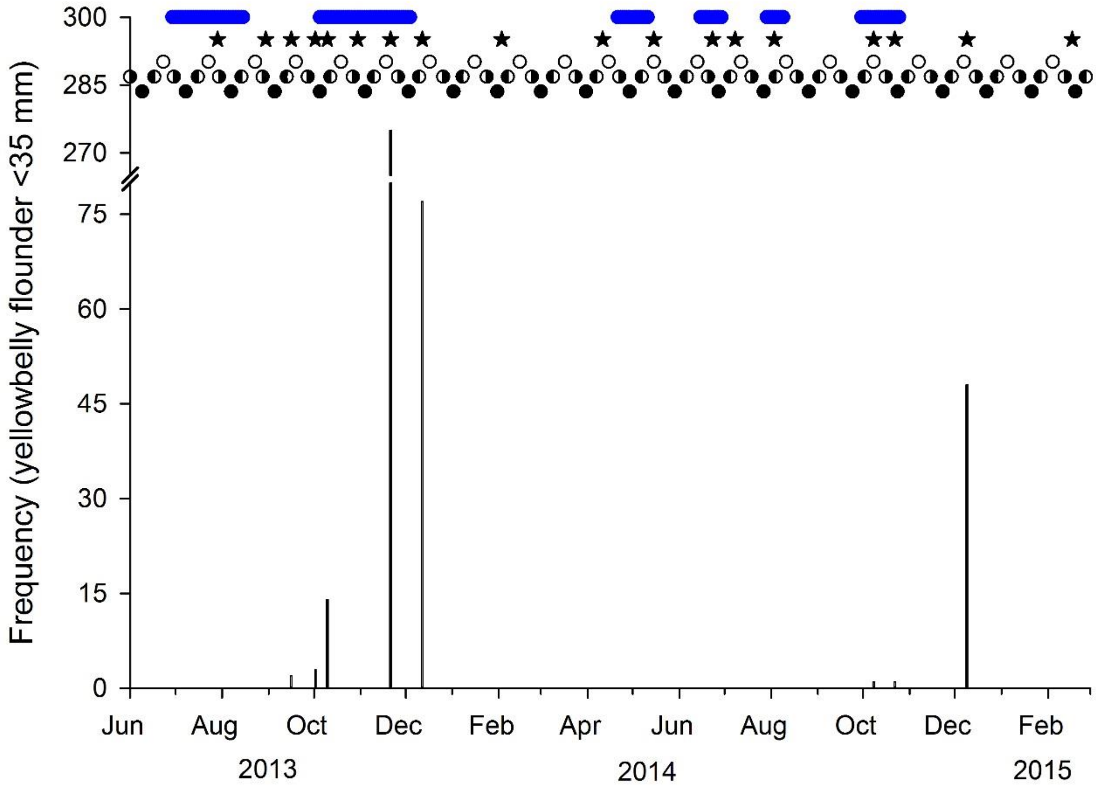

Figure 3-11: The timing of yellowbelly flounder recruitment. Yellowbelly flounder were caught using seine and super-fyke nets. The blue bars indicate the periods when the lake was open to the sea. The star symbols indicate sampling times. Lunar phase is also shown with filled circles indicating new moon and open circles indicating full moon phases.

3.2.2 Sand flounder

The occurrence of sand flounder in catches was sporadic. Similar to yellowbelly flounder the vast majority of fish (>97%) were caught seine netting (Table 3-1). Sand flounder were caught on 9 out of 18 sampling trips but on six sampling occasions only a single fish was recorded (Figure 3-12). Sand flounder ranged in size from 23 to 296 mm (Figure 3-13). A number of fish sized 40 – 45 mm were caught between December 2013 and February 2014 but fresh recruits (<35 mm) were only caught on 9/12/14 (Figure 3-13). The large influx of sand flounder recruits (56 fish) on 9/12/14 coincided with the recruitment influx of yellowbelly flounder when the lake had been closed to the sea for 45 days (Figure 3-14, Appendix D).

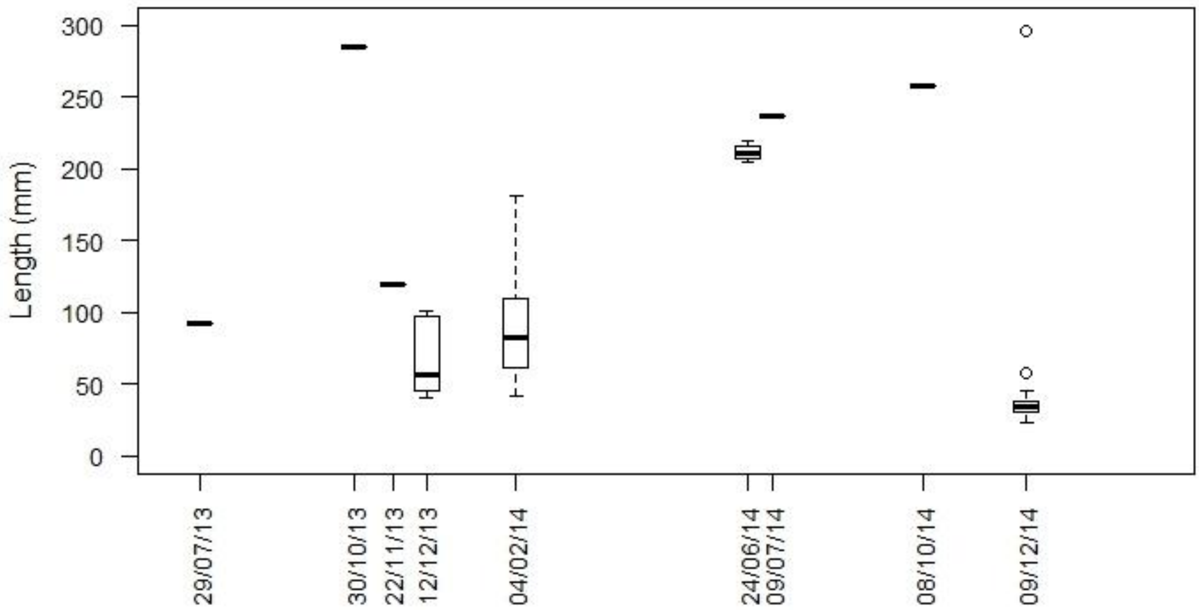

Figure 3-12: Box plots of variation in sand flounder length on each sampling occasion over the duration of the study. Box plots are only shown for dates when fish were caught.

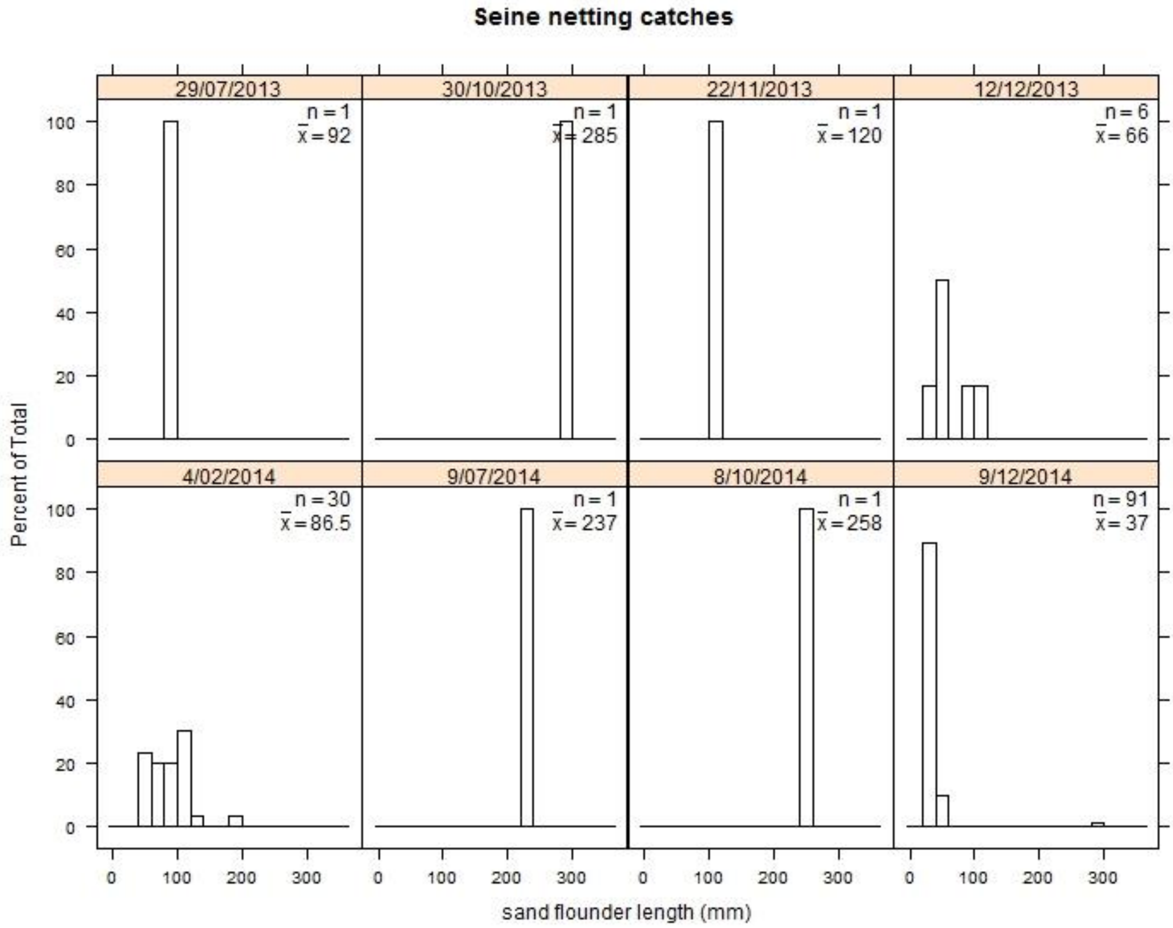

Figure 3-13: Length-frequency histograms of sand flounder caught on each sampling occasion. Results are for seine netting catches only and data are pooled across the three sampling sites. Each graph panel displays the number of fish measured (n) and mean fish size ($\bar{x}$) for each sampling occasion. Size class bins were 20 mm.

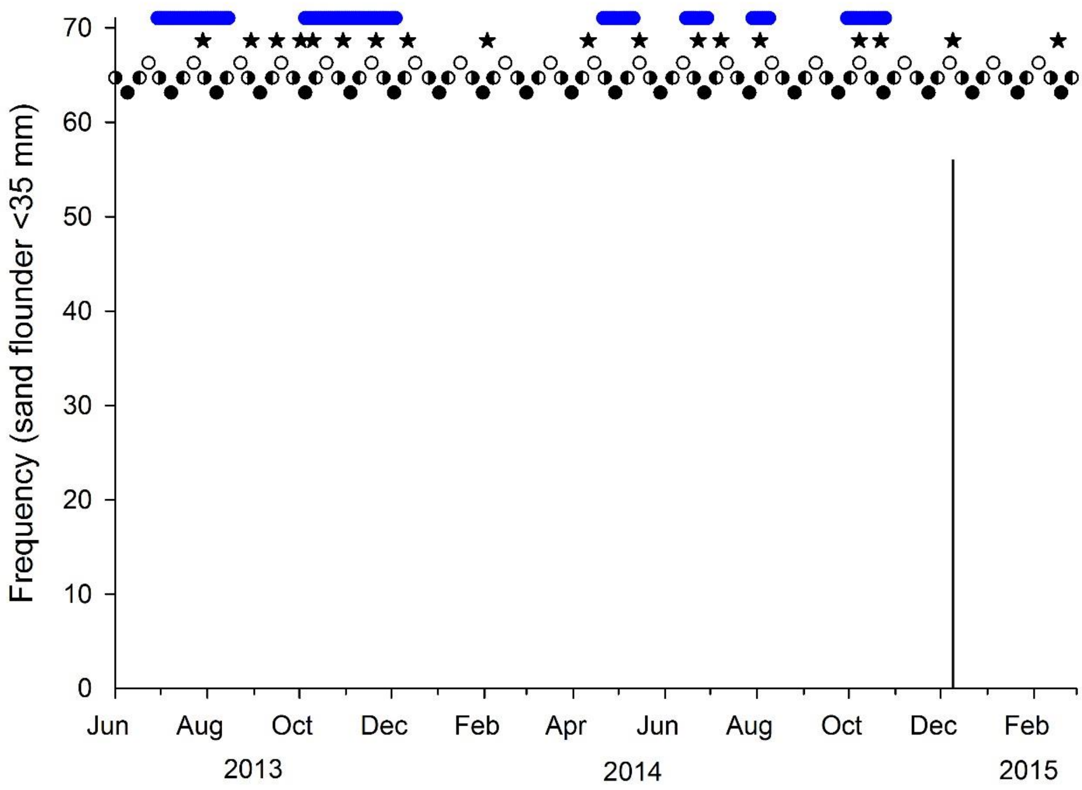

Figure 3-14: The timing of sand flounder recruitment. Sand flounder were caught using seine and super-fyke nets. The blue bars indicate the periods when the lake was open to the sea. The star symbols indicate sampling times. Lunar phase is also shown with filled circles indicating new moon and open circles indicating full moon phases.

3.2.3 Black flounder

Black flounder were similar to sand flounder in that they were only caught sporadically on 9 out of 18 sampling trips (Figure 3-15). Like the other flounder species, the majority of the 41 fish caught were done so using seine nets (Table 3-1). Black flounder ranged in size from 19 to 404 mm but fresh recruits, all sized between 19 – 22 mm, were caught on only one occasion (Figure 3-16, Figure 3-17). These recruits were caught on 30/10/13 during a lake opening that had lasted for 26 days (Figure 3-17, Appendix D).

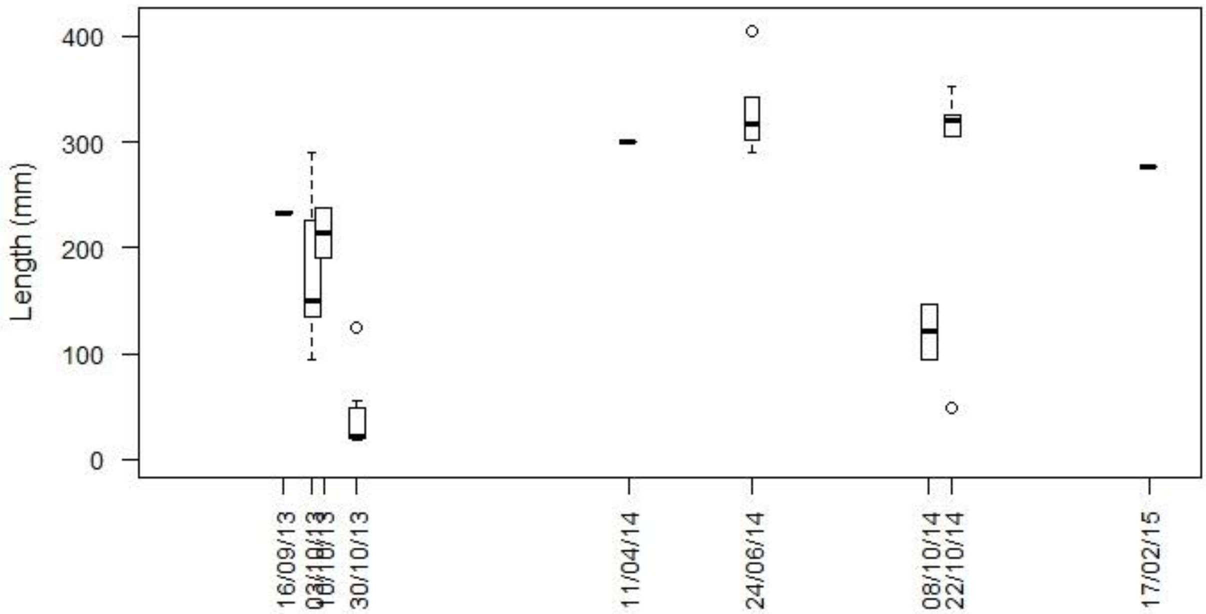

Figure 3-15: Box plots of variation in black flounder length on each sampling occasion over the duration of the study. Box plots are only shown for dates when fish were caught.

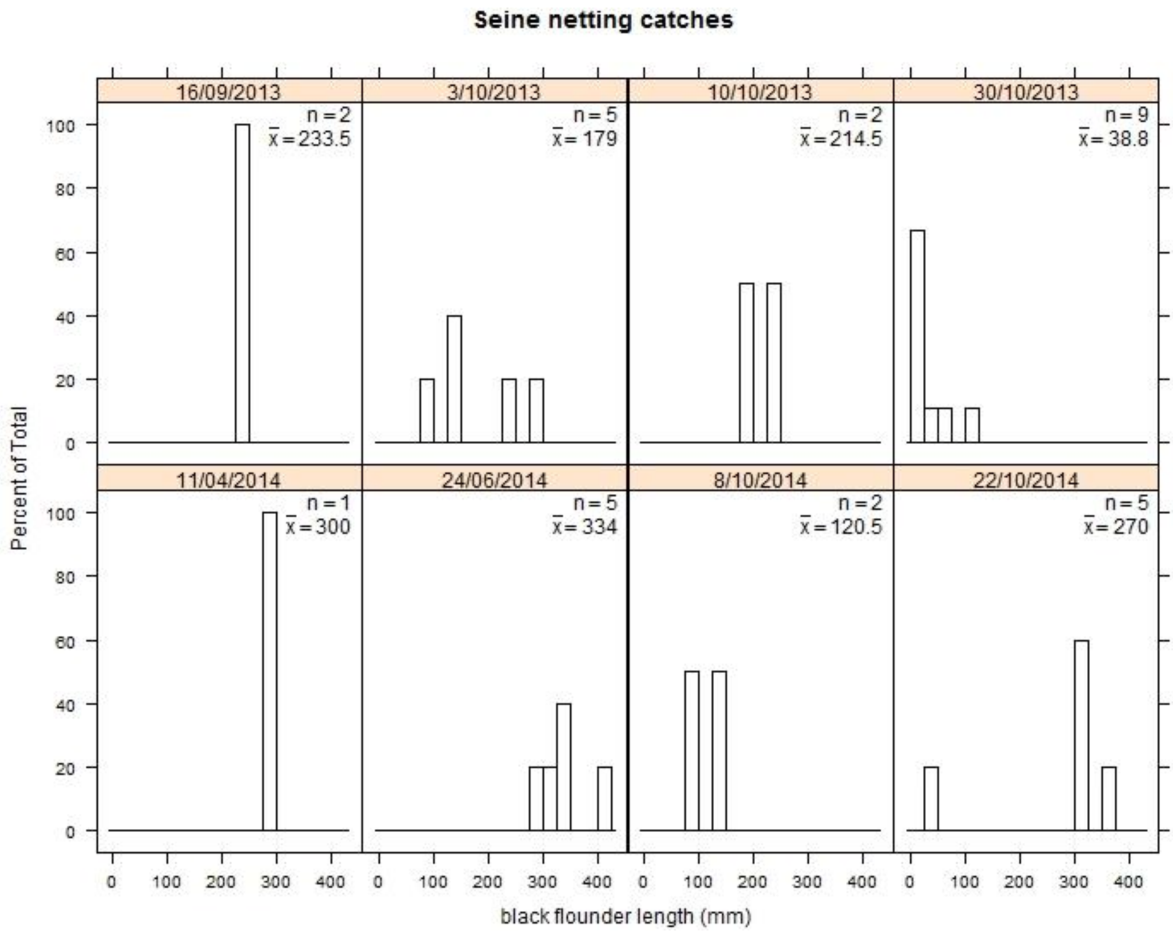

Figure 3-16: Length-frequency histograms of black flounder caught on each sampling occasion. Results are for seine netting catches only and data are pooled across the three sampling sites. Each graph panel displays the number of fish measured (n) and mean fish size ($\overline{x}$) for each sampling occasion. Size class bins were 25 mm.

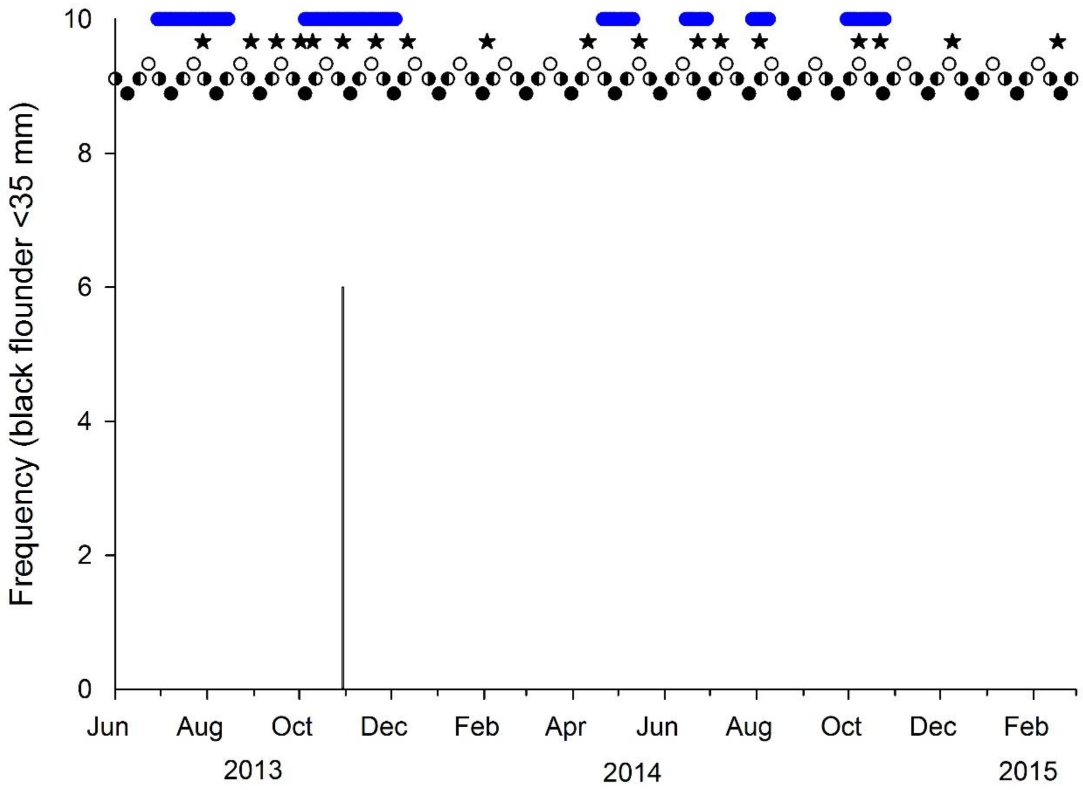

Figure 3-17: The timing of black flounder recruitment. Black flounder were caught using seine and super-fyke nets. The blue bars indicate the periods when the lake was open to the sea. The star symbols indicate sampling times. Lunar phase is also shown with filled circles indicating new moon and open circles indicating full moon phases.

3.3 Common smelt (paraki)

More than 27,500 common smelt were caught across all sampling occasions and more than 95% of these fish were caught seine netting (Table 3-1). Common smelt were caught on 17 of the 18 sampling trips since none were caught when only super-fyke nets were set on 30/08/13. Since high numbers of smelt were usually caught when sampling, numerous fish were measured for length-frequency data. Common smelt ranged in size from 17 to 135 mm, but there were only minimal changes in median and mean smelt size during the survey work; mean size varied from 63.4 – 76.1 mm (Figure 3-18, Figure 3-19). The size distribution of common smelt being caught by seine netting and super-fykes was almost identical when all fish and recruits only were examined (Figure 3-20a,b). As previously mentioned, it is likely that both diadromous and non-diadromous common smelt co-exist in the lake making it more difficult to determine the timing of recruitment. Common smelt (<70 mm) were present in the lake all year round but increases in the abundance of fish below this size limit were evident from August through to mid-December (Figure 3-21). Although the highest number of smelt recruits (<70 mm) in 2013 occurred when the lake was closed, consistently high numbers of recruits were caught when the lake was open to sea (Figure 3-21). Much higher numbers of smelt recruits (<70 mm) were recorded in 2013 compared to 2014 (Figure 3-21).

Common smelt less than 45 mm should have spent their entire lifecycle in fresh water and may peak in abundance at different times of the year to sea-run smelt. These freshwater recruits (<45 mm) were much less abundant than recruits (<70 mm) and instead of peaking between August through to mid-December, they were most common between mid-November and mid-February (Figure 3-22).

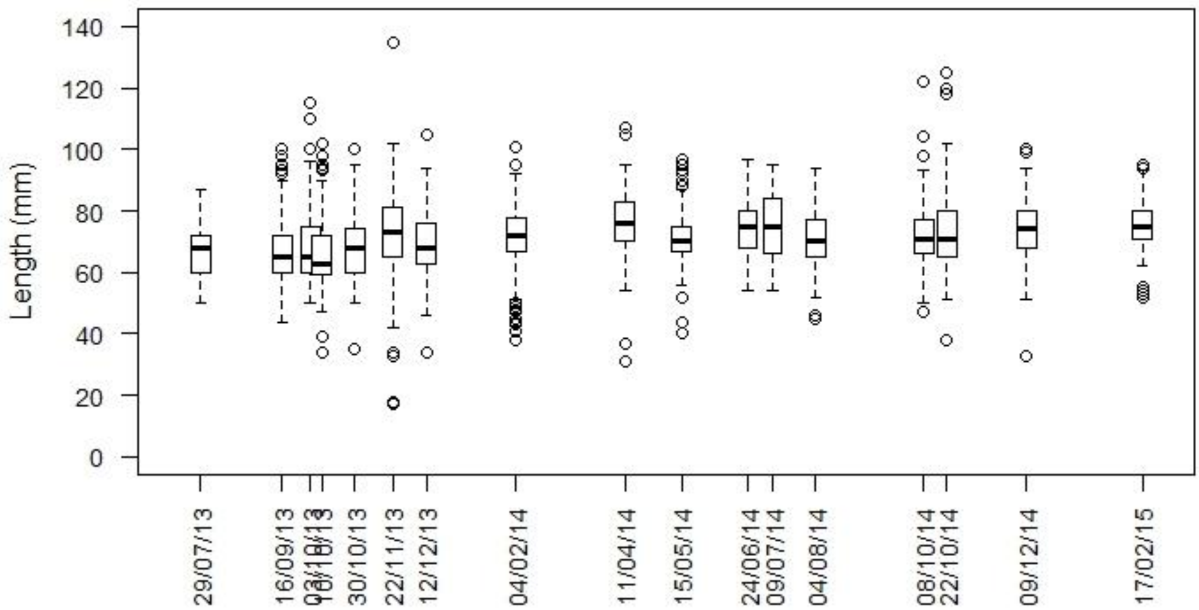

Figure 3-18: Box plots of variation in common smelt length on each sampling occasion over the duration of the study. Box plots are only shown for dates when fish were caught.

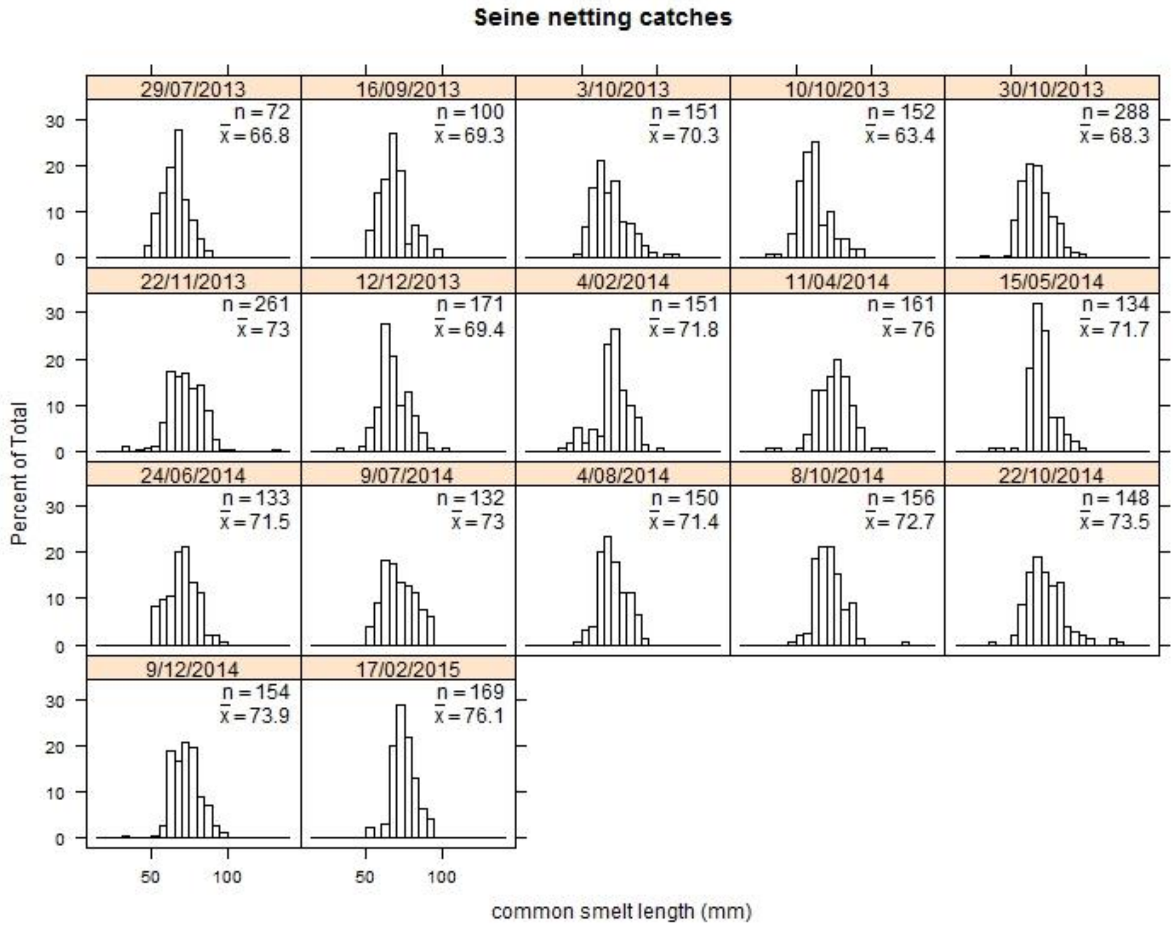

Figure 3-19: Length-frequency histograms of common smelt caught on each sampling occasion. Results are for seine netting catches only and data are pooled across the three sampling sites. Only a subset of fish were measured on each sampling trip. Each graph panel displays the number of fish measured (n) and mean fish size ($\bar{x}$) for each sampling occasion. Size class bins were 5 mm.

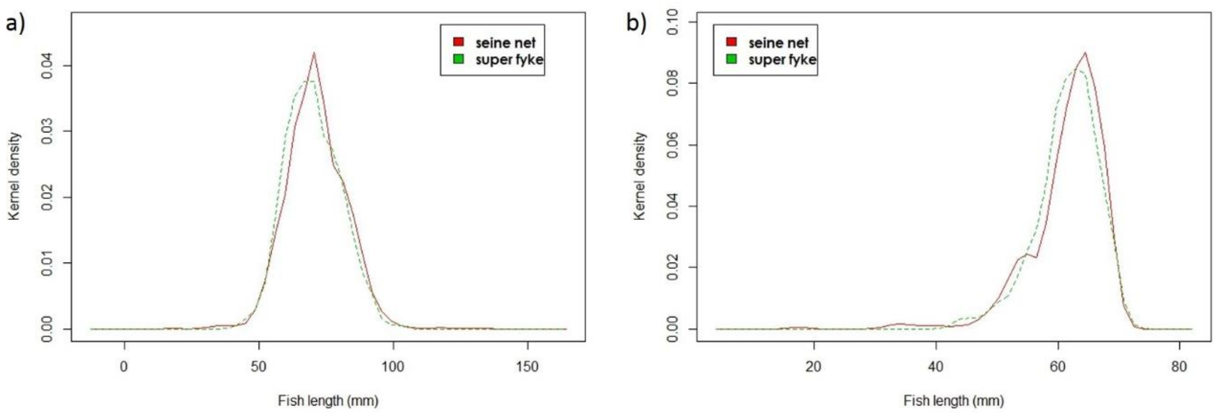

Figure 3-20: Comparison of sampling methods for common smelt. Data for all sizes of common smelt (a) and common smelt recruits only (<70 mm) (b) are shown. For (a), n=2685 (seine), n=992 (super fyke). For (b), n=1124 (seine), n=450 (super fyke).

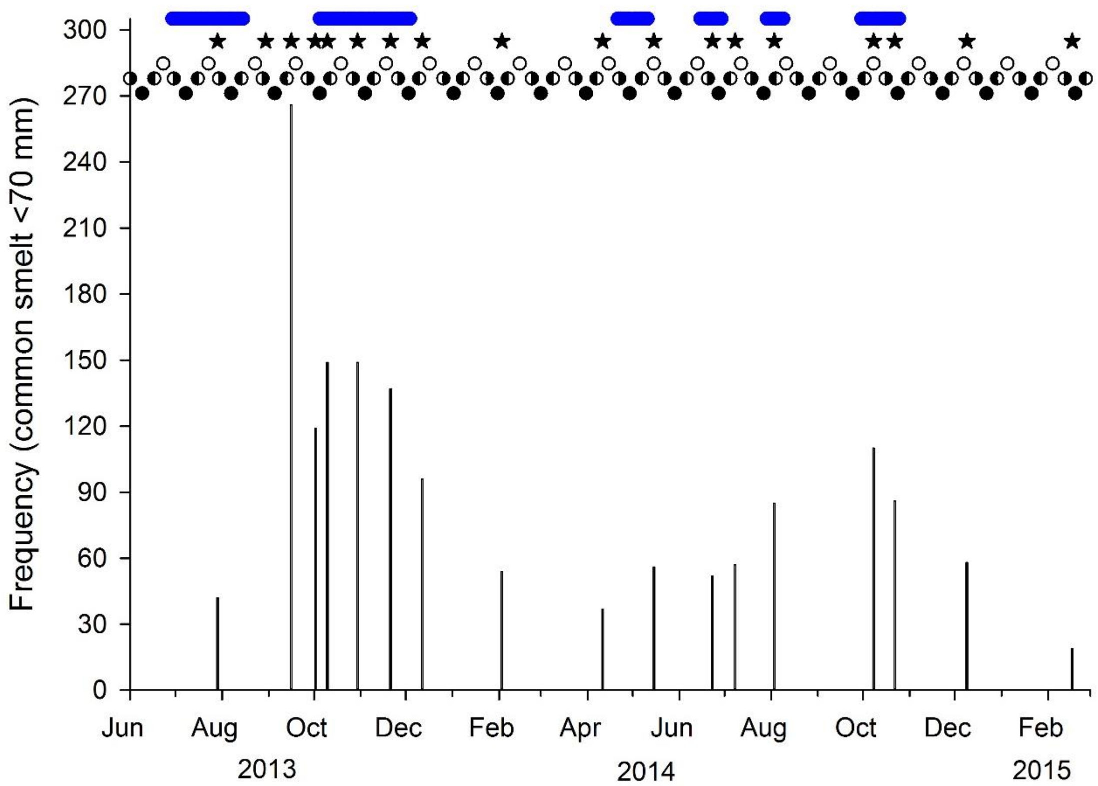

Figure 3-21: The timing of common smelt (<70 mm) recruitment. Common smelt were caught using seine and super-fyke nets. The blue bars indicate the periods when the lake was open to the sea. The star symbols indicate sampling times. Lunar phase is also shown with filled circles indicating new moon and open circles indicating full moon phases.

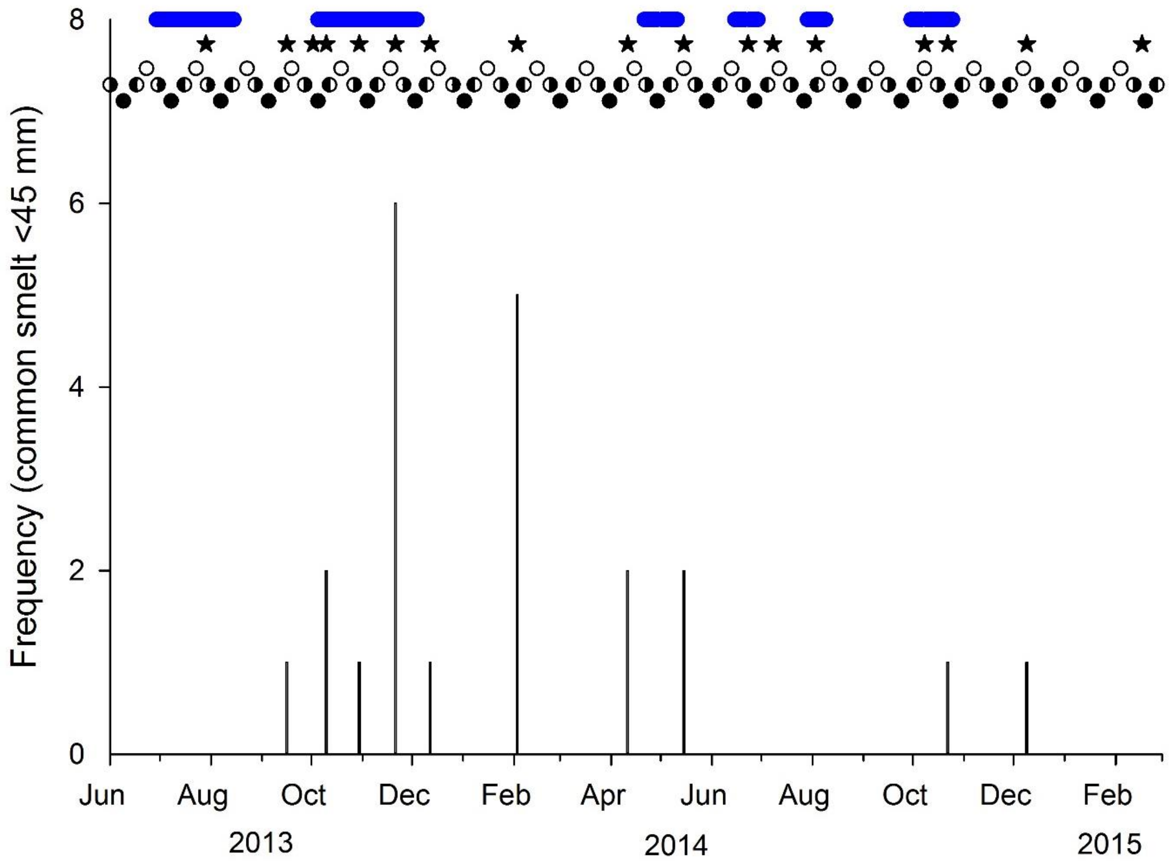

Figure 3-22: The timing of common smelt (<45 mm) recruitment. Common smelt were caught using seine and super-fyke nets. The blue bars indicate the periods when the lake was open to the sea. The star symbols indicate sampling times. Lunar phase is also shown with filled circles indicating new moon and open circles indicating full moon phases.

3.4 Torrentfish (piripiripohatu)

There were 336 torrentfish caught during the study and 94% of these fish were caught using seine nets (Table 3-1). Torrentfish larvae were recorded on 12 of the 18 sampling trips (Figure 3-24). Torrentfish were recorded on 11 occasions at the Boat shed and Water tower sites – on 10 of these occasions they were recorded at both sites – but they were only recorded once at the Te Kōrua site. Only torrentfish larvae were caught, since juvenile and adult fish live in rivers, and they varied in length from 16 – 50 mm (Figure 3-24). Approximately 80% of the torrentfish caught were ≤35 mm (Figure 3-24). The mean length of torrentfish increased through the year (Figure 3-25) and the size distribution of fish caught using seine and super-fyke netting methods was nearly identical (Figure 3-26).

In 2013, torrentfish recruits were recorded from mid-September through to mid-December and in 2014 from mid-May to mid-December; peak recruitment was between mid-July and mid-October (Figure 3-24, Figure 3-27). The largest influx of torrentfish recruits was on 3/8/14 when 101 fish were caught; at this time the lake had been open to the sea for 6 days. There was a significant relationship between the number of recruits caught and days since the lake was opened; the number of recruits declined exponentially with increasing days since the opening (Figure 3-28). However, there were multiple instances of recruitment when the lake was closed to sea. For example, 63% of recruits caught in 2013 were after the lake had been closed for over 30 days (Figure 3-27, Figure 3-28, Appendix D). Whilst 55% of recruits in 2014 were caught when the lake was closed, the majority were caught within 10 days of the lake having closed. There was a notable exception in 2014 when 15 recruits were caught after the lake been closed for 45 days (Figure 3-27, Figure 3-28, Appendix D).

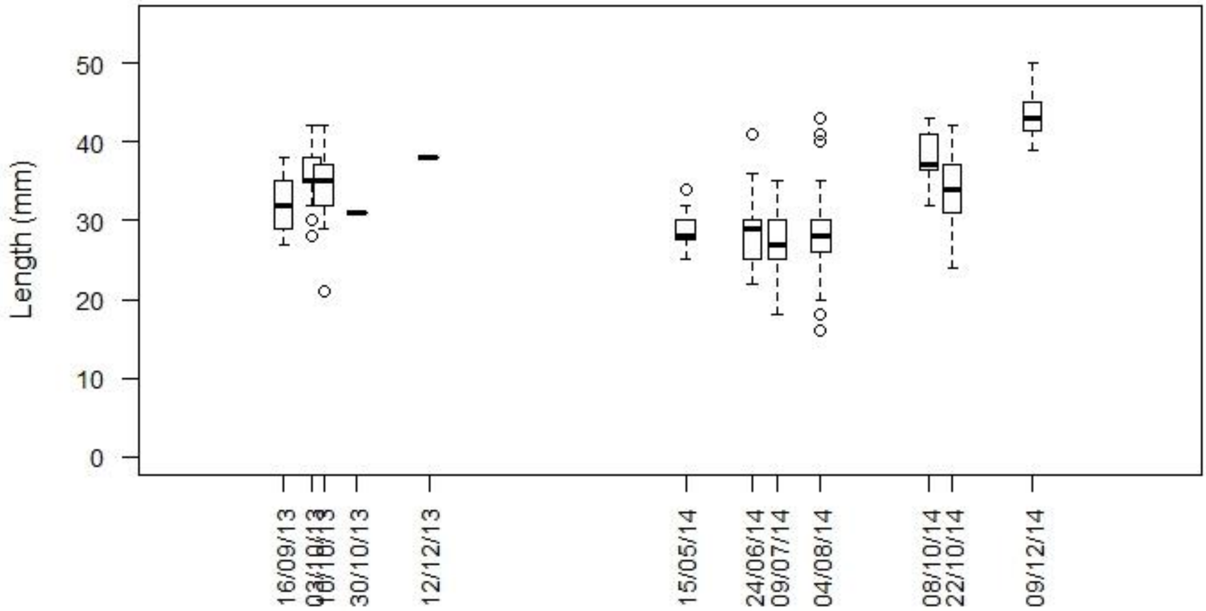

Figure 3-23: Box plots of variation in torrentfish length on each sampling occasion over the duration of the study. Box plots are only shown for dates when fish were caught.

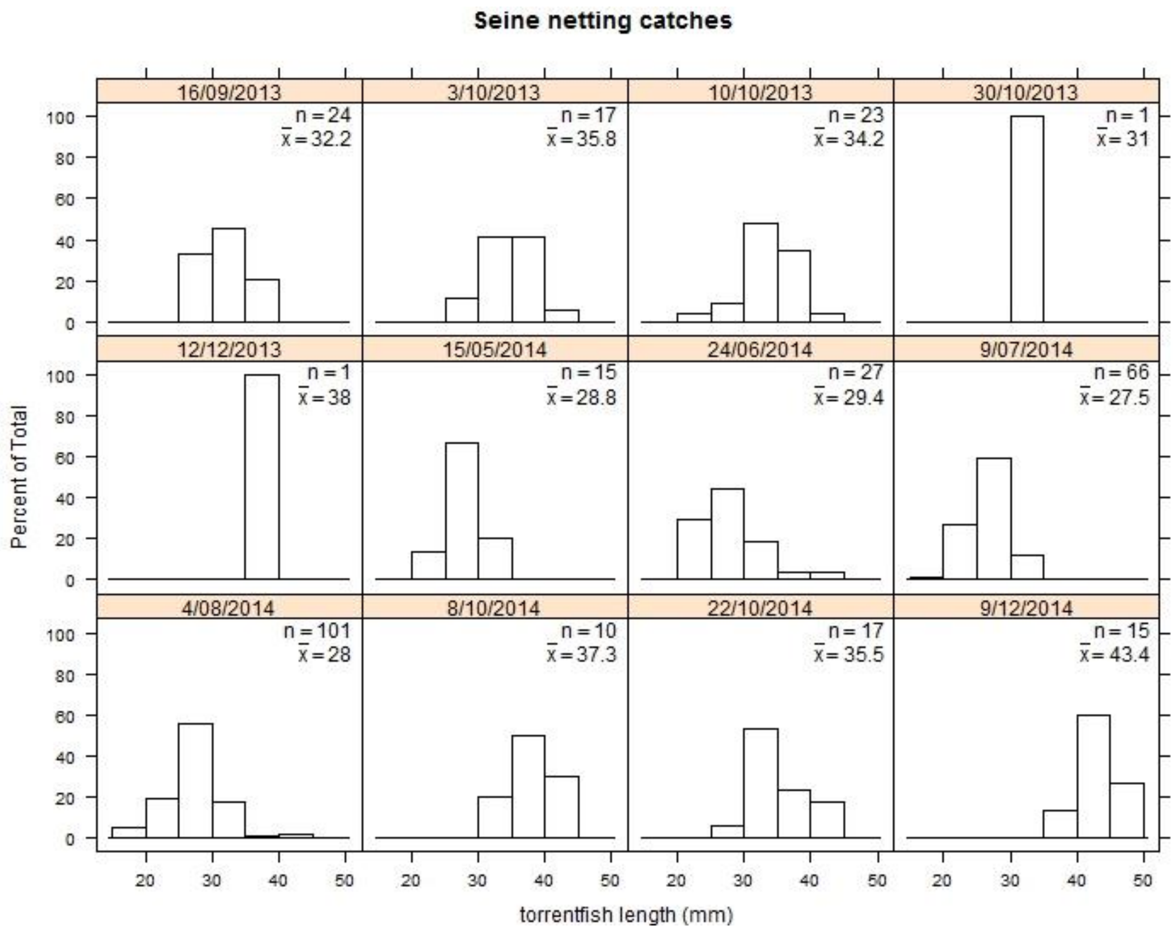

Figure 3-24: Length-frequency histograms of torrentfish caught on each sampling occasion. Results are for seine netting catches only and data are pooled across the three sampling sites. Each graph panel displays the number of fish measured (n) and mean fish size ($\bar{x}$) for each sampling occasion. Size class bins were 5 mm.

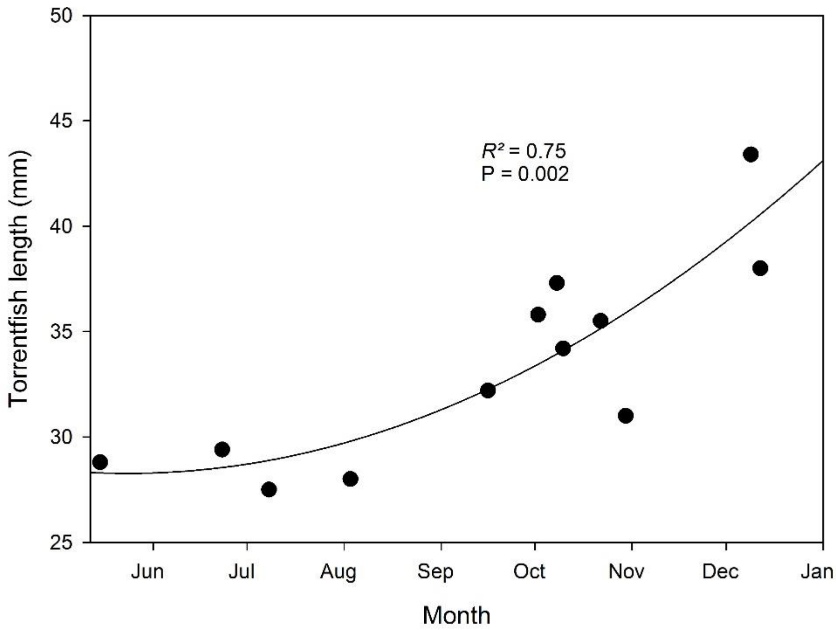

Figure 3-25: The change in mean torrentfish length over time.

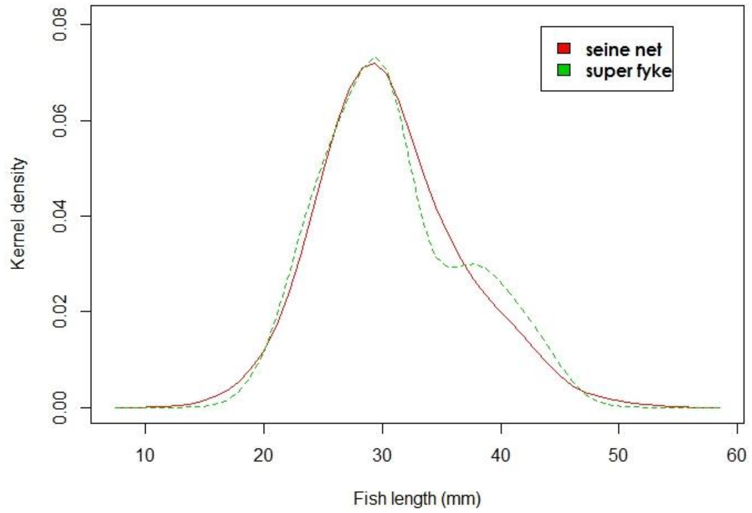

Figure 3-26: Comparison of sampling methods for torrentfish. No torrentfish outside of this size range were caught. n=317 (seine), n=19 (super fyke).

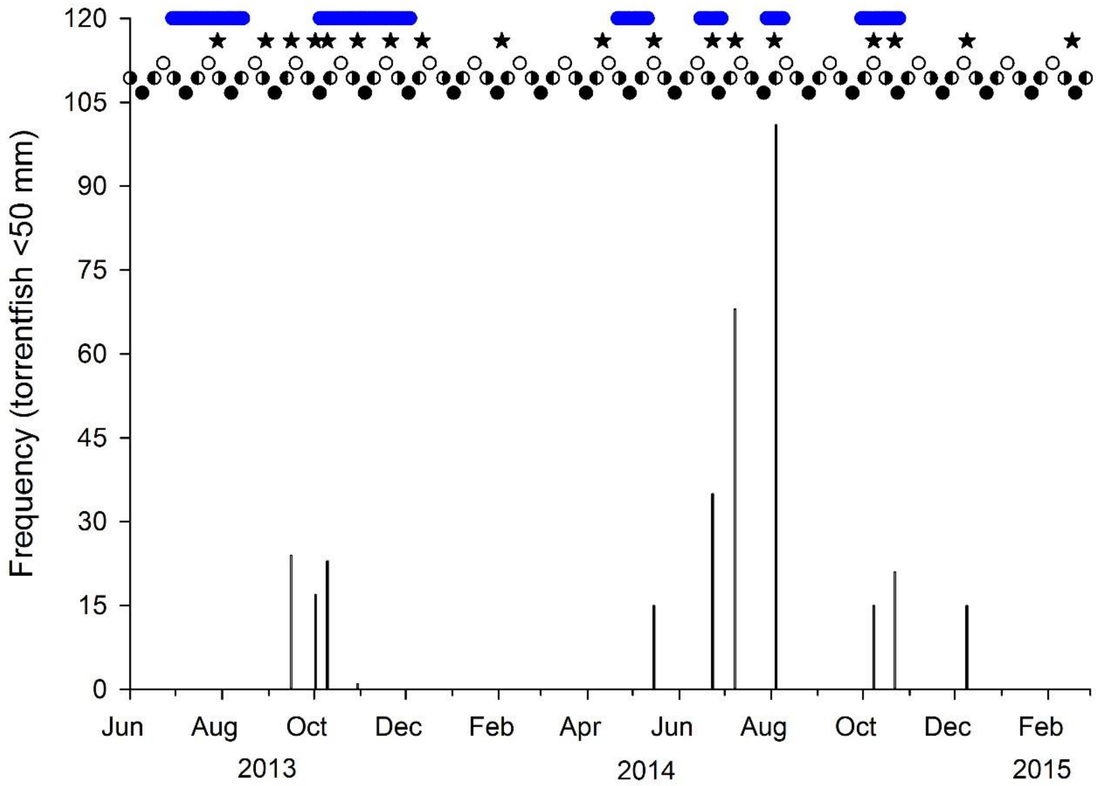

Figure 3-27: The timing of torrentfish recruitment. Torrentfish were caught using seine and super-fyke nets. The blue bars indicate the periods when the lake was open to the sea. The star symbols indicate sampling times. Lunar phase is also shown with filled circles indicating new moon and open circles indicating full moon phases.

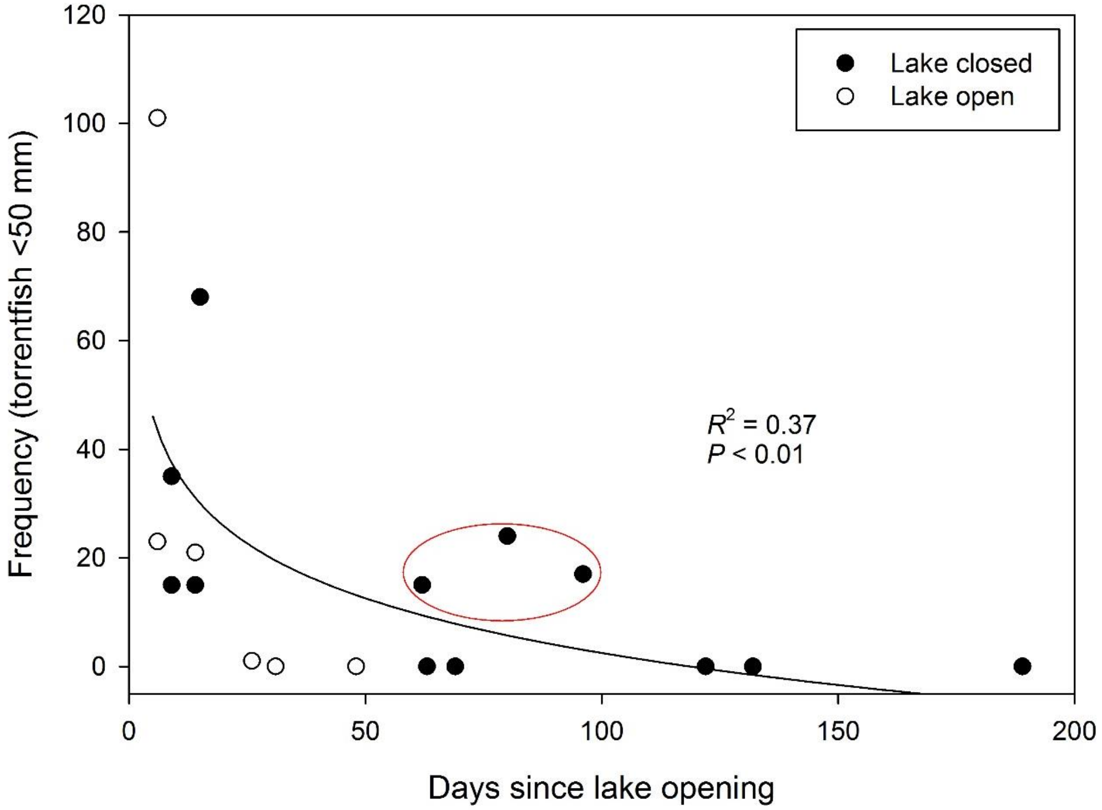

Figure 3-28: The relationship between the number of days since Te Waihora was opened to the sea and the number of torrentfish recruits captured. The red circle indicates the three sampling dates when fresh torrentfish recruits were caught after the lake had been closed for at least 30 to 50 days.

3.5 Inanga (inaka)

A total of 1,100 Inaka were caught during the surveys (Table 3-1). Whilst more fish were caught seine netting rather than in super-fyke nets, these fish comprised only 1.6% of the total seine catch compared to 10.2% of the total super-fyke catch (Table 3-1). Inanga were regularly caught during sampling as they were recorded from 16 of the 18 sampling occasions (Figure 3-29). They were most commonly caught at Te Kōrua (13 occasions) compared to 9 occasions at the other two sampling sites. Inanga ranged in size from 17 to 125 mm; the 17 mm fish was actually a larval fish caught on 4/8/14 presumed to be heading out to sea when the lake was open. Mean fish size was variable between sampling occasions although this was in large part due to variable abundance more than shifting size distributions (Figure 3-30). There were consistent differences in the size distribution of inanga being caught by seine and super-fyke nets (Figure 3-31). The super-fyke nets captured smaller sizes than seine nets for all sizes of inanga and when only recruits were examined (Figure 3-31). The number of recruits entering the lake was highest for both years when the lake had an extended open period between August and late November (Figure 3-32). However, as for torrentfish, significant numbers of inanga recruits were caught in 2013 and 2014 after the lake had been closed for periods longer than 30 days (Figure 3-32).

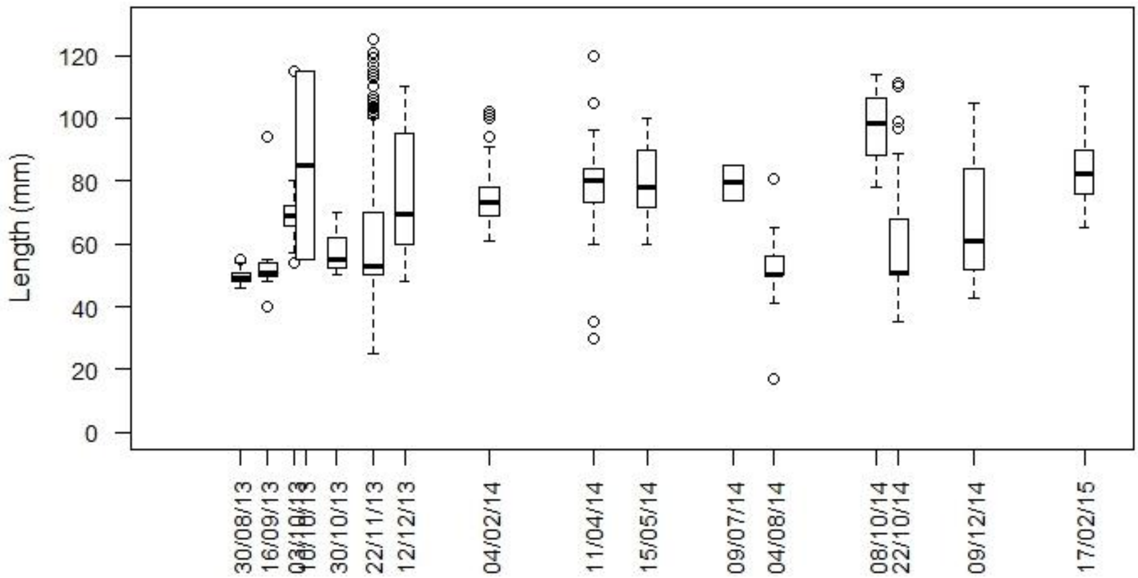

Figure 3-29: Box plots of variation in inanga length on each sampling occasion over the duration of the study. Box plots are only shown for dates when fish were caught.

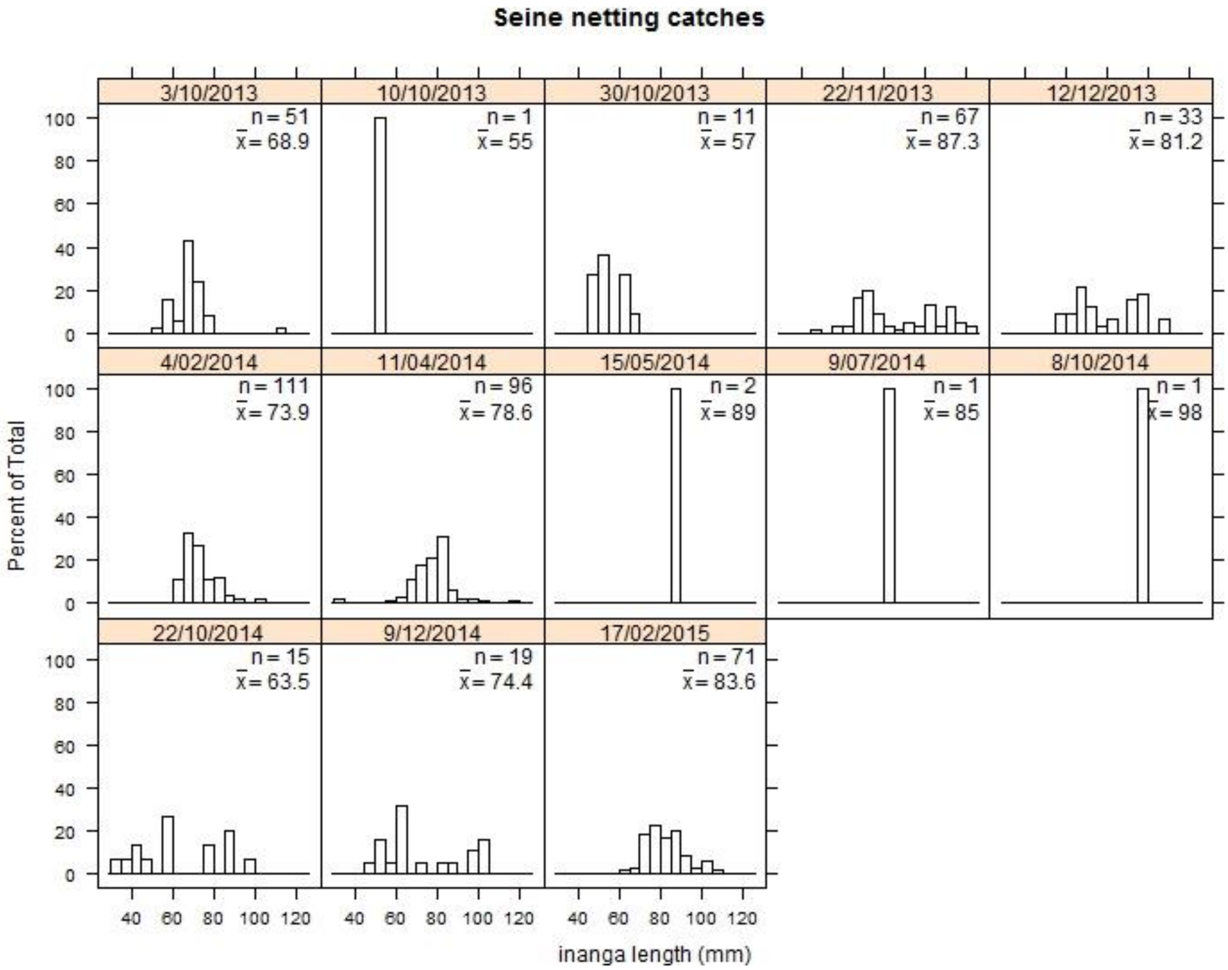

Figure 3-30: Length-frequency histograms of inanga caught on each sampling occasion. Results are for seine netting catches only and data are pooled across the three sampling sites. Only a subset of fish were measured on each sampling trip. Each graph panel displays the number of fish measured (n) and mean fish size ($\overline{x}$) for each sampling occasion. Size class bins were 5 mm.

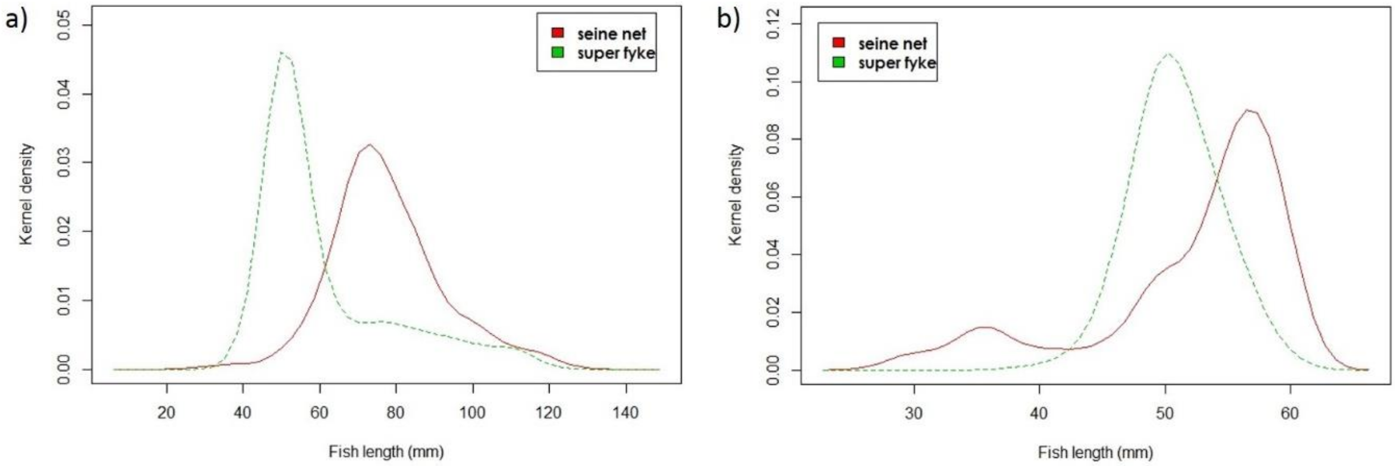

Figure 3-31: Comparison of sampling methods for inanga. Data for all sizes of inanga (a) and inanga recruits only (<60 mm) (b) are shown. For (a), n=479 (seine), n=372 (super fyke). For (b), n=35 (seine), n=255 (super fyke).

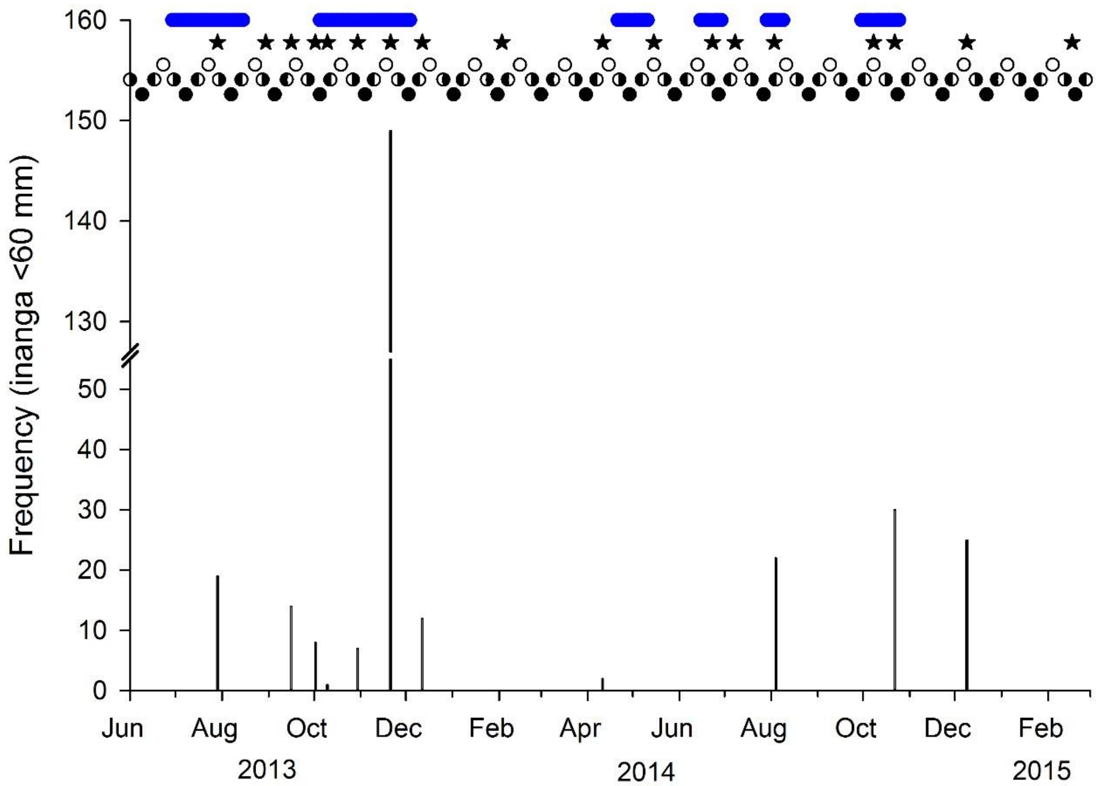

Figure 3-32: The timing of inanga recruitment. Inanga were caught using seine and super-fyke nets. The blue bars indicate the periods when the lake was open to the sea. The star symbols indicate sampling times. Lunar phase is also shown with filled circles indicating new moon and open circles indicating full moon phases.

3.6 Common bully

Common bully were the only species to be caught at all sites on all sampling occasions (Figure 3-33). In total, there were 14,616 common bully caught during the study and 84% of these fish were caught using seine nets (Table 3-1). They were the most abundant species in super-fyke catches (Table 3-1). Common bully ranged in size from 19 to 130 mm but during most of the survey their mean size was between approximately 50 to 65 mm (Figure 3-34). The notable exception to this was during autumn and winter 2014 when mean and median lengths were closer to 40 mm (Figure 3-33, Figure 3-34). The comparison of sampling methods showed that seine nets tended to sample a smaller size distribution of common bully whereas the super-fyke net data seemed to be showing two year-class size peaks (Figure 3-35a). When only the length data for common bully recruits was examined, it was apparent that super-fyke nets were catching the very small recruits (<30 mm) more effectively than seine nets (Figure 3-35b). As for common smelt, the recruitment timing of common bully is complex because both diadromous and non-diadromous populations occur in the lake. The majority of common bully recruits in 2013 were recorded from mid-October to December but only one sampling event occurred during mid-April and early August (Figure 3-36). In 2014, higher numbers of common bully recruits were recorded between mid-April and early August. A similar sized recruitment peak was observed in between mid-October to December 2014, compared to the same period in 2013, but the numbers of recruits was far more variable during these months in 2014 (Figure 3-36).

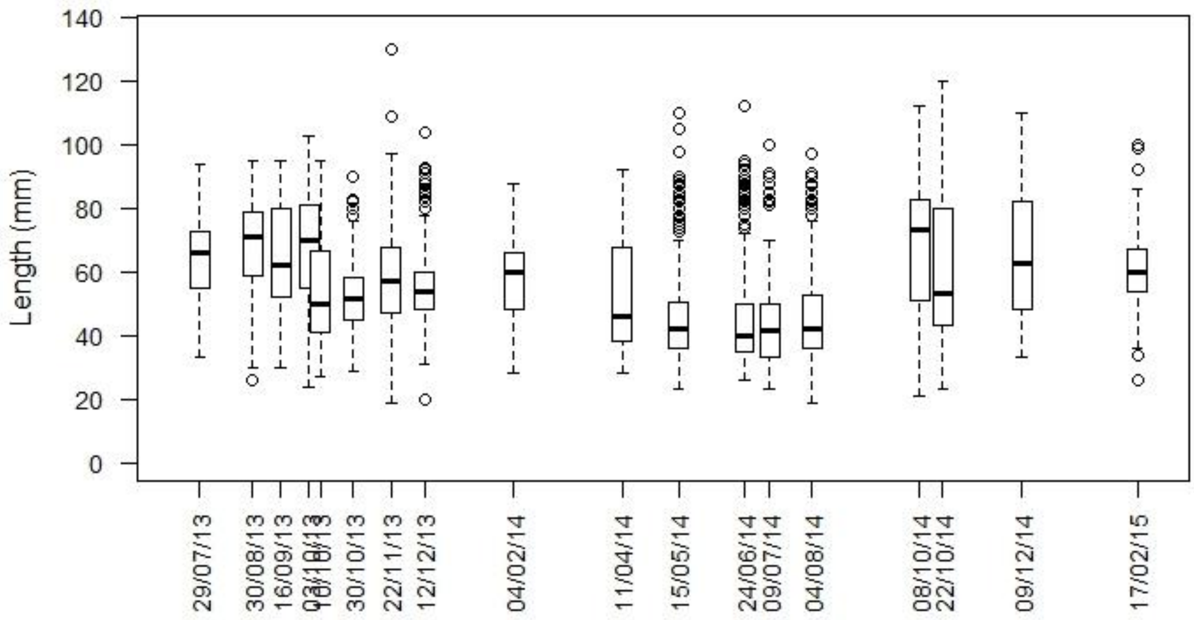

Figure 3-33: Box plots of variation in common bully length on each sampling occasion over the duration of the study. Box plots are only shown for dates when fish were caught.

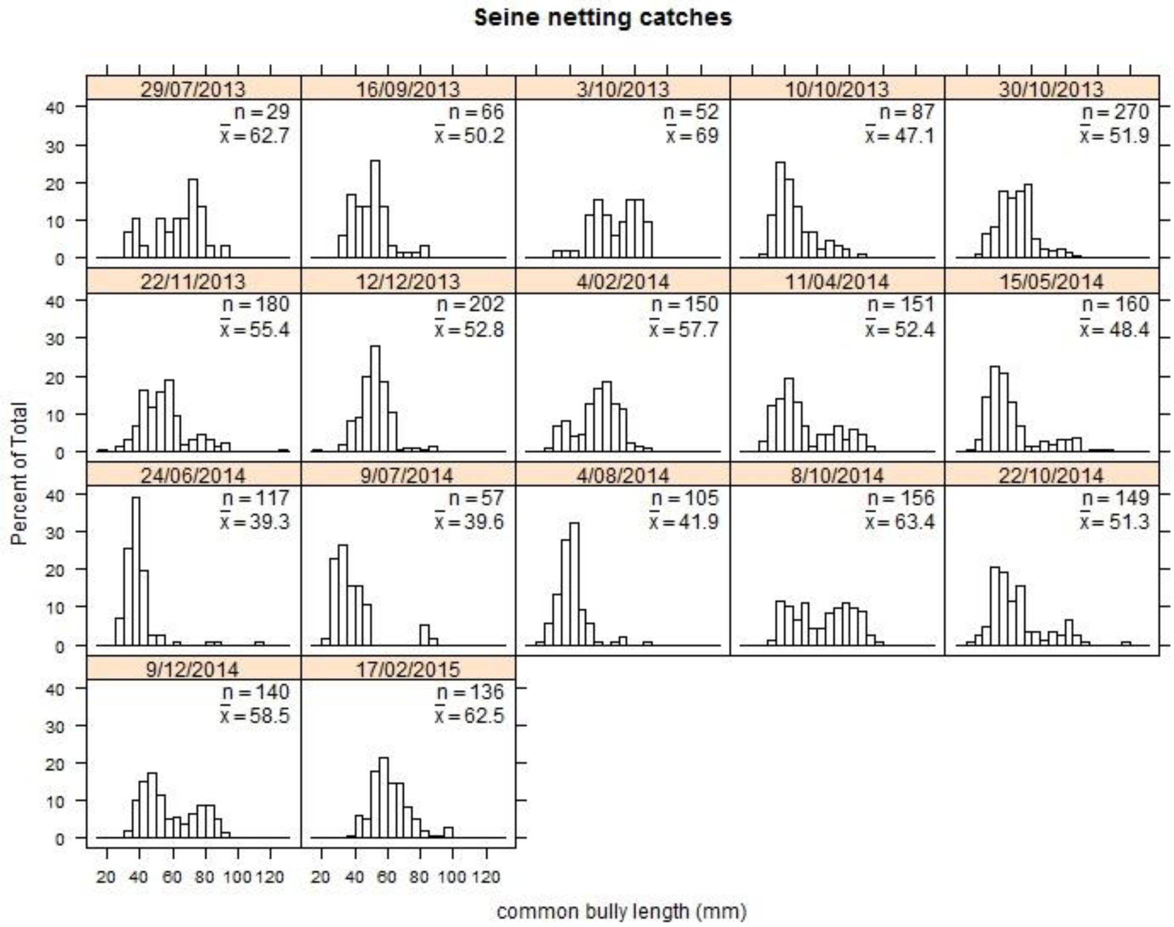

Figure 3-34: Length-frequency histograms of common bully caught on each sampling occasion. Results are for seine netting catches only and data are pooled across the three sampling sites. Only a subset of fish were measured on each sampling trip. Each graph panel displays the number of fish measured (n) and mean fish size ($\overline{x}$) for each sampling occasion. Size class bins were 5 mm.

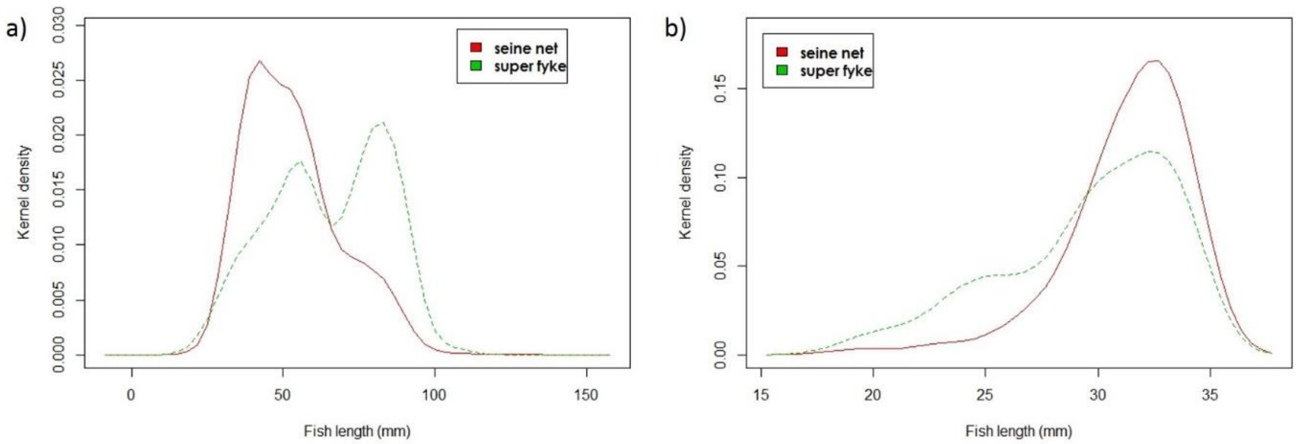

Figure 3-35: Comparison of sampling methods for common bully. Data for all sizes of common bully (a) and common bully recruits only (<35 mm) (b) are shown. For (a), n=2207 (seine), n=1249 (super fyke). For (b), n=171 (seine), n=81 (super fyke).

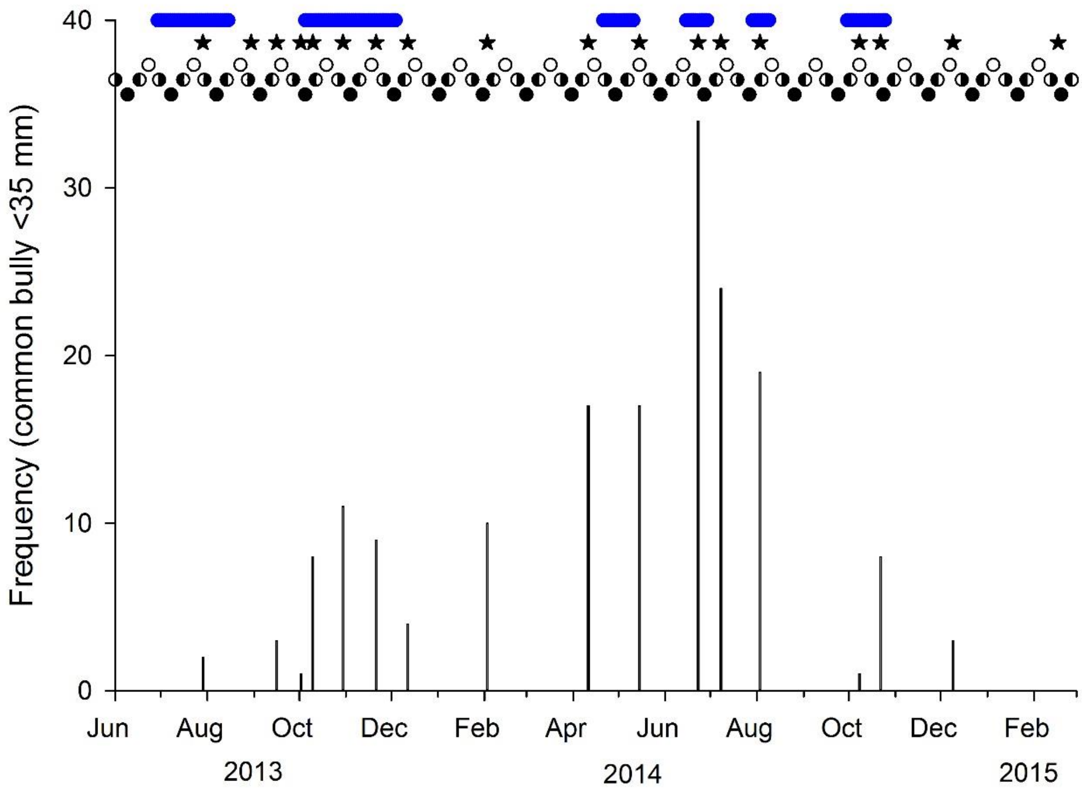

Figure 3-36: The timing of common bully recruitment. Common bully were caught using seine and super-fyke nets. The blue bars indicate the periods when the lake was open to the sea. The star symbols indicate sampling times. Lunar phase is also shown with filled circles indicating new moon and open circles indicating full moon phases.

3.7 Factors influencing fish recruitment

A comparison of total recruit CPUE between years (from June to December) showed that after variation in sampling effort had been accounted for, recruitment was approximately 67% higher in 2013 than in 2014. However, the lake was open for 107 days in 2013 compared to 49 days in 2014 for the June to December period (Appendix A).

Recruit CPUE increased exponentially (as shown by the exponent value on Figure 3-37) as lake opening duration increased. For example, if a lake opening lasted 60 days, CPUE should be greater than 9000 (Figure 3-37). It should be noted that only limited data are available to construct this relationship.

Salinity data were used to construct a time series that display how lake salinity changes in response to lake openings in relation to the timing of the recruitment sampling (Figure 3-38). On Figure 3-38, numbers 1 and 3 indicate overtopping events associated with an influx of fish recruits of various species (Appendix D). The overtopping event in January 2014 (see number 2) did not correspond to a time period when as many diadromous species were trying to enter the lake (Appendix D). The comparison of recruit CPUE in relation to the number of sampling trips completed during lake openings and lake closures (i.e., when lake overtopping events could have occurred), suggested that the potential contribution to fish recruitment from overtopping events during our study period was between 4.8 – 11.7 %.

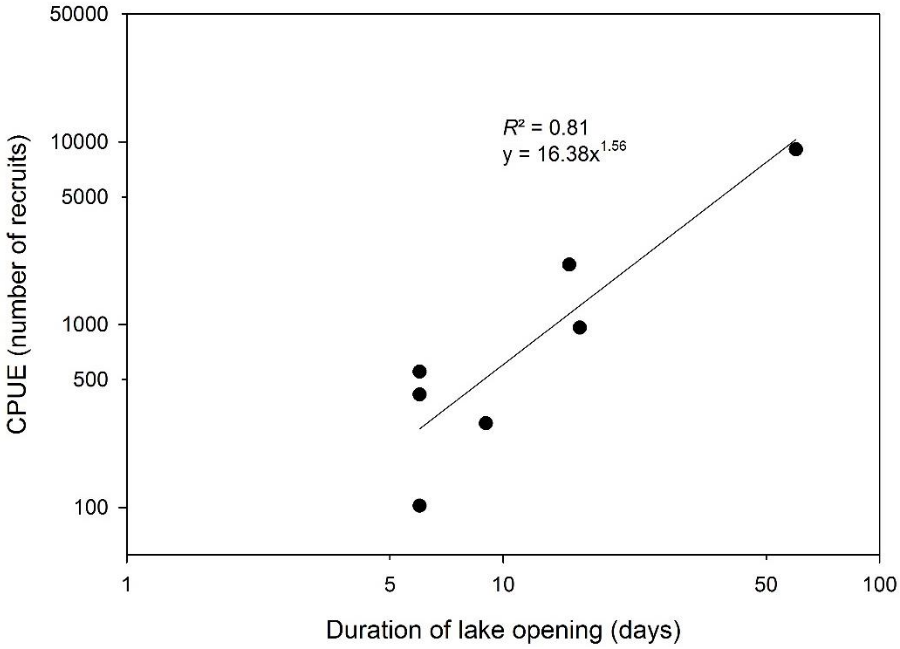

Figure 3-37: Relationship between the number of recruits and the number of days the lake was open to the sea. Both axes are on a logarithmic scale. It should be noted that CPUE is only a measure of relative abundance and not total fish recruitment. CPUE data have been used to make a relative comparison using pooled data from our sampling sites.

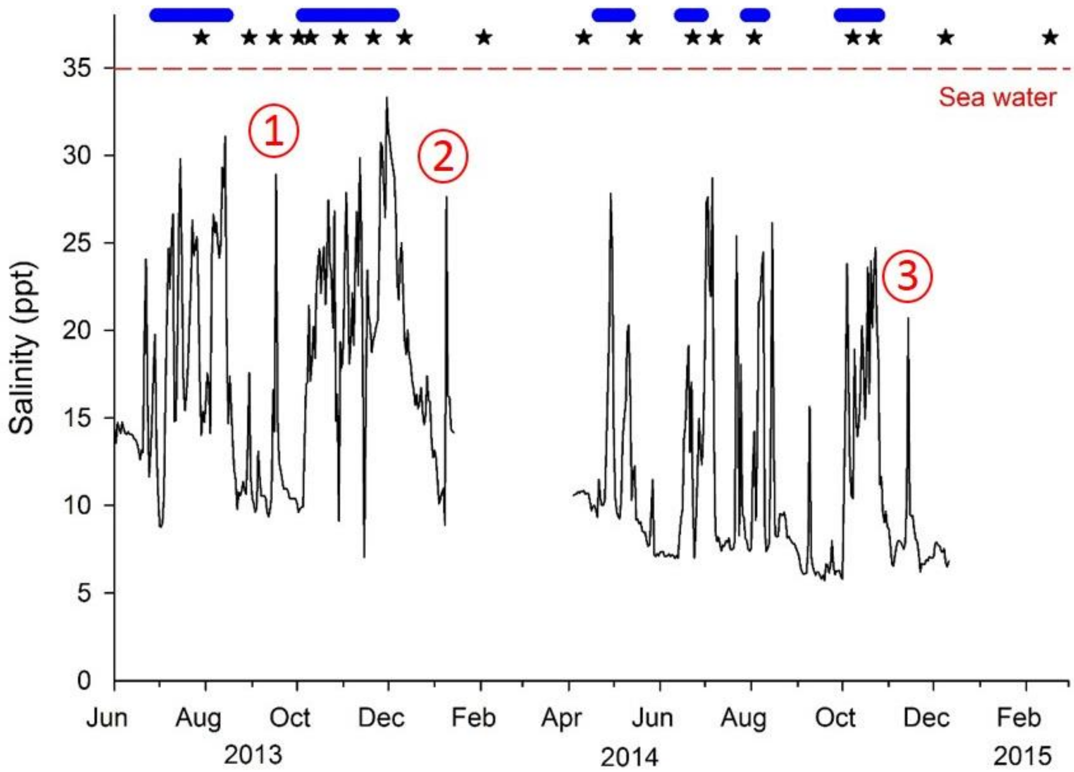

Figure 3-38: Variation in mean daily lake salinity concentration over the duration of the study. The numbers on the plot indicate overtopping events that occurred when the lake was closed to the sea that are particularly relevant to the study (note, not all overtopping events are numbered). The blue bars indicate the periods when the lake was open to the sea, star symbols indicate sampling times and the dashed red line indicates the concentration of sea water. Salinity data were not available from mid-January to April 2014.

An analysis was undertaken to examine how many days it takes until seawater inflows enter Te Waihora under differing lake levels. Salinity data were available for the nine lake openings although as one of the lake openings occurred during a full moon phase, it was excluded because larger tide heights meant it was not comparable with other lake openings (Figure 3-39a). Higher lake levels prior to the lake being opened meant that it took longer (i.e., more days) for the first seawater inflows to be recorded (Figure 3-39a). Even at high lake levels, seawater inflows were recorded within five days of the lake opening (Appendix E). There was no relationship present between the lake level prior to opening and the lake level of the first freshwater inflow (Figure 3-39b). Seawater inflows first occurred at a lake level ranging from 0.91 to 1.25 m, although on average, seawater inflows were detected at 1.07 m. The lack of a relationship in Figure 3-39b is because high lake levels (e.g., 1.8 m) drain faster than lower lake levels (1.0 m) and after five to six days the lake is at a similar height regardless of the initial lake opening height (see Appendix F).

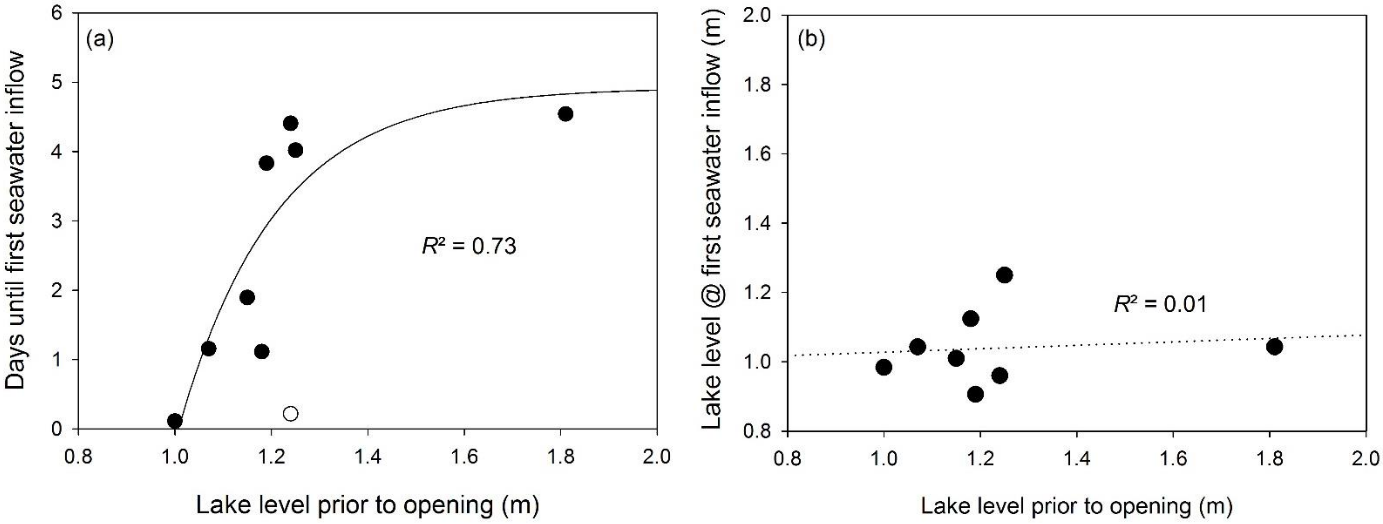

Figure 3-39: Relationship between the level of Te Waihora prior to an opening event and the number of days it takes until seawater inflows occur. Only filled black circles are used to fit regression lines in (a) and (b). The open symbol was excluded from (a) because it occurred during a full moon phase when tide heights were much larger. The time until a seawater inflow occurs is calculated based on salinity data recorded every 15 minutes by an ECan data logger buoy and lake level data are from the corresponding 15 min time interval from the ECan water level recorder at Taumutu. Significant regression lines are indicated by solid lines whereas dotted lines indicate non-significant regression lines.

4 Discussion

The primary mahinga kai species in Te Waihora are tuna (longfin and shortfin eels) and patiki (sand, black and yellowbelly flounder) which require access to and from the sea to complete their lifecycle. Whilst these are the main food-gathering species of interest to Ngāi Tahu there are also a number of other taonga fish species in the lake that are considered mahinga kai and this project has been able to advance our current understanding of recruitment of all these species. Below we discuss the refinement of knowledge on all the species that were investigated and discuss how the timing of the lake opening regime may influence the recruitment of different species. In conjunction with the lake opening timing it should be noted that one of the major findings of this report is that lake openings are not the only recruitment method for some fish species. Large southerly storms, particularly south-westerly storms, are capable of overtopping the gravel bar around the lake outlet and allowing fish to recruit over the bar during wave surges from the ocean (see Section 4.1 for more detail). It is difficult to quantify how much of a contribution this method could make to the recruitment of some species and as seawater inflows over the bar will be directly related to the height of the lake outlet, tides (and lunar phase), sea surge and south-westerly fronts, it is not known whether this method will be available to fish in all years.

Jellyman (2012) provided a comprehensive review of the state of knowledge on incoming fish recruitment and outgoing fish movements for Te Waihora. For particular fish species, the review used data from other parts of Canterbury (e.g., Ashley River) to suggest likely recruitment timings because data were not available for Te Waihora. The current project was able to catch recruits for all mahinga kai species for the first time in a single study, including data on new species (torrentfish). Data on the recruitment timings found in the present study and data summarised by Jellyman (2012) are outlined in Figure 4-1. Refinements to the recruitment timing of each mahinga kai species is further discussed in Section 4.2 below.

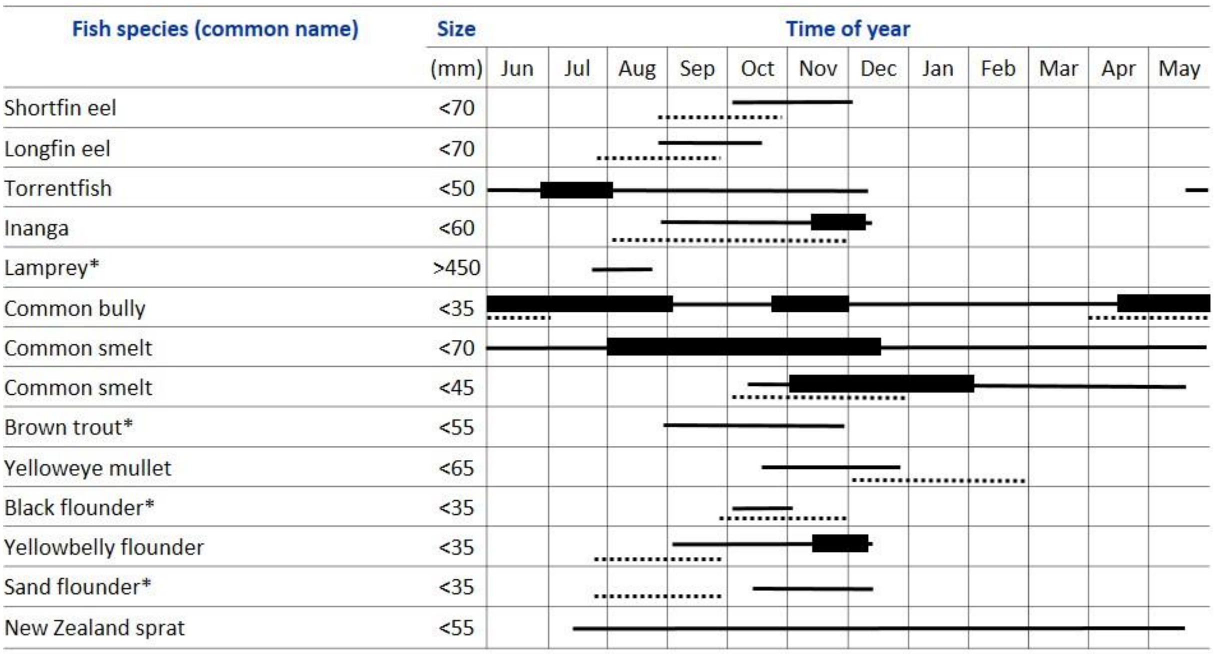

Figure 4-1: Calendar of fish recruitment in Te Waihora. Solid lines indicate the timing of recruitment identified from the current study and dotted lines indicate the timing period identified in Jellyman (2012). The main recruitment periods are depicted with a black rectangle for the species were sufficient data were

available. * denotes species where only limited data were available to determine recruitment timing. Lamprey recruits were not found but as an adult was captured re-entering fresh water it was included for completeness.

4.1 Strong seas that ‘overtop’ the bar

The presence of fish recruitment during periods of lake-outlet closure, confirms the observations of Ngāi Tahu fishers about mahinga kai species entering the lake by moving over the gravel bar during southerly/south-westerly storms. The average length of the cut in the Te Waihora gravel bar has been 250 m since 2003, which provides some indication of the distance that glass eels would need to travel to enter the lake. Overtopping events would require far less energy to get into the lake since they are transported passively by wave energy. Our results suggest that this method is highly likely to be facilitating the recruitment of longfin eel, shortfin eel, torrentfish, yellowbelly flounder and sand flounder. Common smelt and common bullies may also enter the lake during overtopping events, but this cannot be confirmed in the present study because fish that were caught may not have been diadromous recruits.

A salinity balance model for Te Waihora suggested that lake-overtopping events contribute a similar amount to the salinity balance as ocean ingress during lake openings (Spigel 2009). This suggests that lake overtopping events are one of the largest contributors to the saline balance of the lake and that overtopping events can provide a significant amount of the total water volume of the lake. Similarly, a report by Horrell (2008) estimated that up to 80 m^3/s of sea water can be entering the lake, two weeks after lake-outlet closure, at the peak of overtopping events during rough seas. The large amounts of water continuously surging over the outlet can also be seen in Figure 4-2. The extensive contribution made to the saline balance and the large amount of ocean flows observed during overtopping events, suggests that fish recruitment during these events may be significant. The overall recruitment during these overtopping events, however, is likely to be much less than what occurs during lake openings. Lake openings will result in larger recruitment than overtopping events because fish have almost continuous access to the lake once the flow at the outlet becomes tidal. This is generally supported by our estimate that 5-12 % of the total recruitment into the lake occurs during overtopping events. Given the current uncertainty around the amount of recruitment that is likely to occur during overtopping events, it is not recommended that these events be considered during the decision making process to open the lake for fish recruitment. In addition, fish entering the lake during overtopping events may suffer injuries/abrasion.

It should be noted that the contribution of overtopping events to recruitment will largely be dependent on barrier height. South-westerly storms that occur within a couple of weeks of lake closure while the outlet is low, should result in much larger seawater inflows (and thus fish recruitment) into the lake, compared to when the beach barrier has built to a sufficient height to keep most south-west storm waves out. Horrell (2008) recorded seawater inflows a month after lake-outlet closure of almost 60 m^3/s during a south-west storm event so it is thought that extreme storms could still overtop a fully-formed beach barrier at any time of the year.

Figure 4-2: Significant amounts of sea water overtop the gravel bar at the closed outlet of Te Waihora on 16 September 2013. This picture was taken during a sampling trip and shows sea water overtopping the gravel bar and entering Te Waihora (the sampling date corresponds to the number 1 on Figure 3-38).

The present research has found that recruitment can occur by over-topping events, but it has previously been suggested that eels can enter the lake by making their way through the substrate. We agree with Jellyman (2012) that this would be unlikely. Subterranean recruitment of juvenile eels has been observed in catchments on the West Coast of the South Island that are have been buried by mine tailings (Robert McDowall pers. comm.). This subterranean recruitment has also been suggested to occur at Te Waihora and Wairewa (Lake Forsyth), but Jellyman (2012) considered this unlikely because of the finely compacted substrate. A survey of Wairewa (Jellyman and Cranwell 2005) found evidence of poor recruitment over recent years, something that would not be expected if glass eels were able to penetrate the gravel bar in any significant quantity. In the present study, glass eels were captured during lake closures, but these catches were associated with lake overtopping events. If recruitment was occurring through the gravel bar, it would have been expected that glass eels would be present in catches throughout the lake closure events and not just around lake overtopping events. A recent substrate sample from the outlet found that the substrate had a median size of 5 mm (Figure 4-3), suggesting the substrate would be too compacted for glass eels to move through. Subterranean recruitment may have occurred historically if gravel substrates were larger, but present substrate conditions appear to be too fine to permit glass eel recruitment. Environment Canterbury and local residents at Taumutu have also reported that they “perceive that there is less coarse material on the barrier at the opening location now than there used to be.”

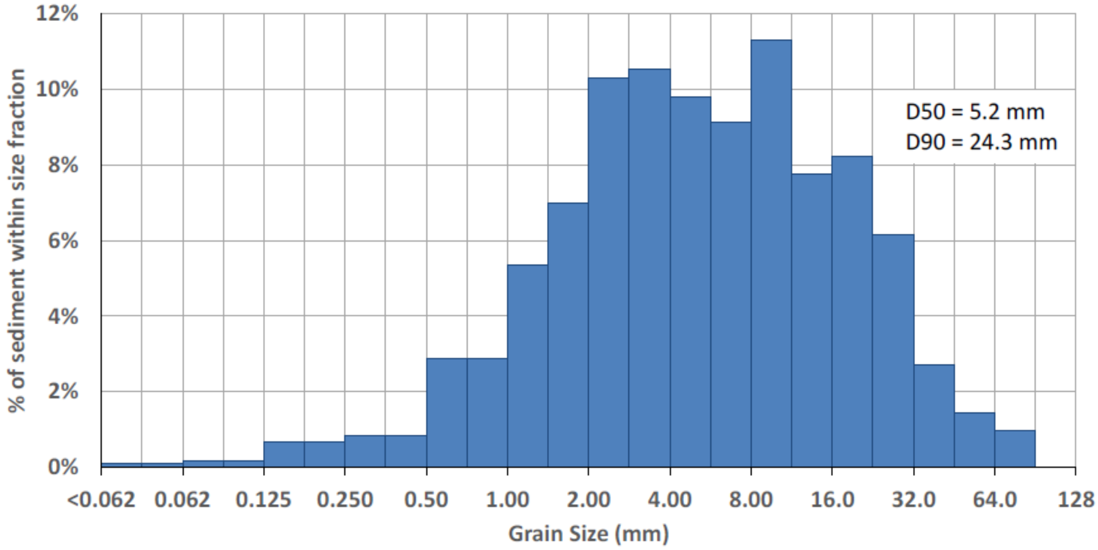

Figure 4-3: A sample of the grain size distribution taken from the cut made through the gravel bar at the lake opening site. The sample is from material excavated during an opening event in July 2013. This figure is taken from the report by Measures et al. (2014).

4.2 Changes to our understanding of fish species recruitment in Te Waihora

4.2.1 Eels (tuna)

Shortfin eels

Combined results from the present study and previous research suggests that shortfin recruitment is likely to occur between September-November, but early October may be the peak period. The present study captured a limited number of freshly recruited shortfins (<70 mm) between October-November, which are the first documented captures of shortfin glass eels at the Te Waihora outlet. Specifically, in 2013 the recruitment period of juvenile shortfin eels appears to have lasted from at least 3/10/13 to 22/11/13, and had ceased by 12/12/13. The existing literature suggests that the primary recruitment time for juvenile shortfin is on spring tides in September and October (Jellyman 2012). This timing is supported by the present study, with the majority of recruitment occurring between the 10/10/13 and the 22/11/13.

Shortfin recruitment information for Te Waihora has previously been inferred from glass eels catches from the Ashley River, where September-October were the dominant months of recruitment. While the Ashley River peak recruitment period started a month earlier than Te Waihora, it is consistent with the peak observations for October in the present study. The absence of recruitment during September in the present study is perhaps unsurprising given that the lake was closed during this month during each year. The largest single catch of shortfins in the present study, however, was observed on 3/10/13 when the lake had been closed for 49 days, suggesting that the glass eels may have recruited during a lake overtopping event. Assuming that the largest salinity change during September 2013 was responsible for transporting these glass eels, then it is likely that these fish entered the lake mid-September (Figure 3-38).

Differences in recruitment between the Ashley River and Te Waihora could be explained by later arrivals of shortfins. Martin et al. (2009) found that elver catches occur earlier in the summer for the

North Island compared to South Island, suggesting that recruitment periods occur later in the summer, the further south a catchment occurs. Although, Te Waihora is only 70 km south of the Ashley River (in a straight line) this corresponds to c. 170 km of coastline with the presence of Banks Peninsula separating the two catchments, so it is possible there are small differences in recruitment timing between the Ashley River and Te Waihora. Alternatively, it is possible that shortfin elvers were present, but not captured during September in the present study.

Longfin eels

Combined results from the present study and previous research suggests that longfin recruitment into Te Waihora is likely to occur from September-October. The longfin glass eels observed in the present study were all captured across a six week period between the 30/8/13 to the 10/10/13. Unfortunately, only 4 glass eels were captured but these are the first documented captures of longfin glass eels at the Te Waihora outlet. Jellyman et al. (1999) recorded peak months of longfin recruitment in Canterbury as August – September, which is broadly consistent with the findings in the present study. The largest single catch of longfin glass eels in the present study was in October, but this was only based on 2 fish. Nevertheless, if the lake was open during September-mid October it would encompass the peak recruitment times suggested in Jellyman et al. (1999) and the present study.

The capture of longfin glass eels during lake closures reemphasises the presence of fish recruitment from lake overtopping events. One of the glass eels was caught after the lake had been closed for 15 days and another was caught after the lake had been closed for 49 days. The only date when a longfin glass eel was captured while the lake was open, was on 10/10/13 when the lake had been open for six days.

Further considerations for eel recruitment decisions

The present study supports the conclusions of Jellyman (2012) that eel recruitment in Te Waihora is complex and intermittent, making it challenging to identify specific key recruitment times. In previous years when trawling has been carried out, glass eels appeared to have been absent for 3 out of 8 seasons (Jellyman 2012), indicating that recruitment is inconsistent between years. Identifying peak recruitment times that are consistent across years based on catches is complicated by recruitment occurring during sporadic lake-overtopping events and differences in lake opening times between years. The present study was the first to record glass eels of both species at the Te Waihora outlet, but only a few glass eels were caught and there were slight differences between years (particularly for longfins). Glass eel recruitment of both species in the present study was consistent with previous studies that suggest the preferred invasion period for glass eels entering Te Waihora will be the spring period, but particularly during September and October. The only way to conclusively identify when glass eels are arriving would be to detect their arrival at the coastline outside of Te Waihora, but this would require ocean trawls that will probably be cost-prohibitive.

Opening the lake when new moon phases are approaching may maximise recruitment of glass eels into Te Waihora because glass eels are sensitive to light. Jellyman and Lambert (2003) suggested new-moon spring tides were likely to be the dominant recruitment period because it is associated with little or no moonlight. The importance of the new moon phase to recruitment, may be supported by the present study because glass eels were absent in the catches during 2014 where no lake openings coincided with new moon phases. Because of their sensitivity to light, glass eels are most likely to migrate during darkness (Jellyman 1977b; Jellyman and Lambert 2003; Jellyman 2012).

Typically, any recruitment in Te Waihora will commence around sunset and peak catches occur within 1-2 h after sunset (Jellyman 2012).

The large tides associated with the new-moon will also help transport glass eels because they are not strong swimmers and few will enter the lake immediately after the lake opens to the sea. The maximum sustained swimming speed of shortfin glass eels is 29 cm/sec, with burst speeds of 79 cm/sec (Langdon and Collins 2000). Thus they will be unable to swim against the outflow of water that accompanies the initial breaching of the bar at Te Waihora\ Lake Ellesmere where velocities frequently exceed 2.0 m/s (Taylor 1996). As the lake level drops, the outgoing flows will ease and the migrating glass eels will take advantage of any incoming tide to passively transport them into the lake by a process known as selective tidal transport. This selective tidal transport mechanism is typical of other *Anguilla* species (Creutzberg, 1961; McCleave and Kleckner 1982; Jellyman and Lambert 2003). When flows reverse during the outgoing tide phase, glass eels are thought to burrow into the substrates and await the next incoming tide to transport them further upstream. Glass eels will also become more concentrated along adjacent banks of the outlet during the ebb tide, but more dispersed during flood tides (Jellyman, 1979). Once glass eels are beyond the tidal influence, further upstream migration is delayed as glass eels undergo some physiological adaptations (Jellyman 1979; Ciccotti et al. 1995). After these physiological adjustments are complete, the upstream migration recommences and glass eels are less inhibited by daylight (Jellyman, 1979; Sorensen and Bianchini, 1986) and actively swim further into the lake (Jellyman 1979; Gascuel 1986). Most of the shortfin glass eels will utilise any small interstitial spaces in the fine substrates as cover (Jellyman et al. 2003), and will be closer to inshore areas than offshore areas (Jellyman and Chisnall 1999).

4.2.2 Flatfish (pātiki)

A review of other studies of flatfish recruitment (Table 4-1) supports the observed timings of juvenile black flounders into Te Waihora. Although black flounder recruits were only caught on 30/10/13 in limited numbers, October was also the peak month of recruitment recorded by Taylor and Graynoth (1996). Jellyman (2011) reported peak recruitment one month earlier in November, but recruitment in October was the second largest reported catch (31.4 flounders/seine vs. 53.3 flounders/seine for October and November respectively). Combined findings indicate that black flounder may recruit into Te Waihora between October-December, but the peak month appears to be October.

Recruitment of sand flounder appears to be quite variable between studies, with fish entering Te Waihora between May-December (Table 4-1). Jellyman (2011) reported sand flounders were recruiting into the lake between August-October, but August was the peak recruitment period. Taylor and Graynoth (1996) reported sand flounder recruitment earlier in the year, with juveniles being captured between May-July. The present study only observed juvenile sand flounder in December, much later that either of the previous studies. These combined findings suggest that sand flounder recruitment may occur intermittently over a period of up to six months. This is consistent with observations of sand flounder recruitment in Otago, where sand flounder recruited between June-January (Roper and Jillett 1981).

The observed recruitment peak for yellowbelly flounder in the present study was slightly later than previous research, with the observed peak recruitment occurring from mid-November to mid-December (Table 4-1). The observed recruitment period in the present study was between September-December, which is similar to the observed period in Jellyman (2011) of July-Dec. Graynoth and Taylor (1996) reported yellowbelly recruits earlier in the year between March-October, but the lake did close in October and prevent any further recruitment (sampling was also stopped after this). Peak recruitment times in both Jellyman (2011) and Taylor and Graynoth (1996) was August, but the present study found the highest numbers of yellowbelly recruits were present from mid-November to mid-December in both 2013 and 2014. In 2013, the catches of yellow-belly flounder in the present study were the highest recorded from a single sampling event. The present study recorded 45 juvenile yellowbelly flounder/seine haul, with the previous highest catches being 29/seine haul (Jellyman 2011). These large catches of yellowbelly flounder were likely to be associated with the extended 48 day opening period that occurred during this sampling period. The differences in peak recruitment times recorded by the various studies make it difficult to identify the key months of recruitment. Given the present study recorded the highest catches of yellowbelly flounder, and that there was an extended lake opening allowing the most unrestricted recruitment period of all the studies, we suggest that mid-November to mid-December will be the key recruitment time for yellowbelly flounder.

Table 4-1: Recruitment timings of the three flounder species into Te Waihora from previous studies. Note that Te Waihora was not open from October onwards during data collection from the Taylor and Graynoth (1996) report.

Species	Location	Recruitment period	Single largest recruitment month	Author
Black flounder	Te Waihora	Oct - Dec	Nov	Jellyman (2011)
	Te Waihora	Sept-Nov	Oct	Taylor and Graynoth 1996
	Te Waihora	Oct	Oct	Present study
Sand flounder	Te Waihora	Aug - Oct	Aug	Jellyman (2011)
	Te Waihora	May-July	June	Taylor and Graynoth 1996
	Te Waihora	Dec	Dec	Present study
Yellowbelly flounder	Te Waihora	July-Dec	Aug	Jellyman (2011)
	Te Waihora	Mar-Oct	Aug	Taylor and Graynoth 1996
	Te Waihora	Sept-Dec	mid Nov-mid Dec	Present study

4.2.3 Common smelt (paraki)

Defining the recruitment timing of common smelt was complicated despite it being the most abundant fish. Separating recruits of landlocked origin (<45 mm) suggested that these recruits tended to peak slightly later in the year than the larger sea-run recruits (Figure 4-1). Based on McDowall (1990), we defined sea-run recruits as being less than 70 mm, but our data suggest that sea-run recruits entering Te Waihora vary more widely in size. The variability in size of recruits make it difficult to determine a size cut-off for this shoaling species that can have a wide range of size ranges present in catches; typically length varied between 50 – 100 mm in catches. A range of size cut-offs from 60 to 75 mm were actually examined for common smelt, but recruitment timing was no better defined using a different size threshold. One clear pattern was apparent for sea-run smelt, regardless of the size threshold used to define them as sea-run recruits, which was that much higher numbers of sea-run recruits were recorded in 2013 than in 2014. It is likely that the long lake-opening durations during 2013 resulted in significant tidal exchange between the lake and the sea, allowing for lengthy periods of access to the lake for recruiting fish. The extended access in 2013 means that conditions were far more favourable for sea-run common smelt recruitment than in 2014.

4.2.4 Torrentfish (piripiripohatu)

The recruitment of torrentfish in Te Waihora has received very little attention from fisheries scientists to date. This is perhaps unsurprising given the numbers caught are usually very low. As previously mentioned, two NIWA studies that caught approximately 230,000 fishes only recorded four torrentfish, making it difficult to draw conclusions about recruitment timing. In contrast, the present study caught 336 torrentfish from two-thirds of the sampling occasions, which enabled us to determine recruitment timing. The timing of juveniles returning back into fresh water from the sea is considered to be between spring and summer (McDowall 2000). However, since spawning periods appear to differ greatly between rivers that are geographically close (e.g.,, Ashley River – December to March, Rakaia River – April to May; Glova et al. 1987), making general predictions about torrentfish recruitment can be difficult. In this study, torrentfish recruitment occurred between mid-May and December, which was consistent with the April-September recruitment period observed in the Rakaia (Scrimgeour and Eldon 1989). The largest number of recruits caught on a sampling trip in the present study was in late winter.

Whether or not torrentfish spend a significant amount of time in the lake has largely been unknown but it has been previously suggested that torrentfish use Te Waihora as a conduit to and from the sea (Jellyman 2012). There are now dual lines of evidence to suggest that torrentfish do not stay in the lake to grow but instead quickly seek fresh water: (1) very few torrentfish have historically been caught at the same locations we sampled, in studies that did not focus sampling around lake opening events, and (2) torrentfish were recorded only once in Te Kōrua inlet compared to 11 times at the other two sampling sites suggesting they are moving around the lake edge heading towards more significant freshwater signals rather than staying near the mouth of the lake for growth. Given that the mean length of torrentfish recruits that were captured increased between mid-May and December, this would tend to suggest that juvenile torrentfish are capable of growing in the marine environment whilst waiting for access into the lake. This may mean that torrentfish have more flexibility as to the timing of lake openings than other fish species; whether being larger at the time of recruitment is an advantage (i.e.,, stronger swimmer) or a disadvantage (i.e.,, larger prey item for predators) is unknown, notwithstanding the potential for high rates of mortality at sea for larger juveniles.

It is clear from analyses that lake openings are not the only recruitment method into the lake available to torrentfish. After the lake closed on 15/8/13, no torrentfish recruits were found when sampling was conducted 15 days later. However, fresh torrentfish recruits were caught 32 and 49 days after the lake had been closed. Given the volume of sea water overtopping the gravel beach when sampling in September 2013 (see Figure 4-2), finding that overtopping events resulted in fresh torrentfish recruits entering the lake fitted with previous statements from members of Ngāi Tahu who had made general observations of fish recruitment (although not specifically torrentfish) during these conditions.

4.2.5 Inanga (inaka)

It has previously been suggested that both diadromous and non-diadromous forms of inanga coexist in Te Waihora (Jellyman 2012). Whether or not both types occur was not investigated in this study but if correct, no marked differences were apparent in the timing of recruitment of this species (Figure 4-1). Two larval inanga (<25 mm) were caught in superfyke nets on 22/11/13 and 4/8/14 but the larvae of diadromous inanga should have all gone to sea before June. Therefore, these may have been the larvae of non-diadromous forms of inanga, but this cannot be confirmed. The timing of inanga migrations into Te Waihora largely overlapped with that of Jellyman (2012) although the present study did not find recruits at the beginning of August but did find them up until mid-December. Given the importance of the whitebait fishery the timing of recruitment is reasonably well defined.

As juvenile inanga are a shoaling species, tidal exchange is the primary mechanism for inanga recruitment into the lake. It is unlikely to be a coincidence that the largest number of inanga recruits caught during the survey was during the new moon phase of the longest lake opening period in the study. The new moon phase would have resulted in the largest movement of sea water into the lake (excluding any storm events) and is most likely why inanga recruitment at this particular time was approximately five times higher than at any other time of the study.

4.2.6 Common bully

Te Waihora contains both diadromous and non-diadromous bullies. In other lakes in New Zealand there can be three distinct spawning periods during the year for common bully and females can contain two different sizes of eggs at a time (McDowall 1990), so it is perhaps unsurprising that common bully recruits were recorded all year round during the present study (Figure 4-1). Whilst recruits were present throughout the year, there was a noticeable peak between mid-April and early August; this overlaps (and extends) the main period of recruitment that Jellyman (2012) considered to be April to early July (Figure 4-1). Unlike other species where it was clear that lake openings and overtopping events were contributing recruits, the year-round presence of recruits meant that bully recruitment could not be linked to barrier overtopping. High numbers of recruits were clearly associated with lake opening events in mid-autumn through to winter and major numbers of recruits were not recorded outside of lake openings.

4.3 Optimal lake opening conditions for fish recruitment

Sustaining the multitude of values within Te Waihora effectively requires a comprehensive understanding of how varying lake levels influence habitat, aquatic biota (e.g., fish and birds), surrounding land owners and infrastructure. The information and ideas below are concerned only with maximising fish recruitment into the lake and have not taken into account many of the additional components that need to considered as part of the wider management of the lake. Initially we examine the conditions for optimal fish recruitment and then conclude by determining how the lake could practically be managed, based on current management practices, to maximise fish recruitment into Te Waihora.

4.3.1 Lake level and freshwater plume size

The lake level prior to opening will influence the size of the freshwater plume in the ocean, which is likely to attract recruiting freshwater fishes. Opening the lake at a higher lake level should, on average, result in a larger volume of water being released into the ocean. We hypothesised that when the lake was opened at higher levels there would be a larger freshwater plume detectable at sea (although the extent of freshwater plumes in the marine environment can be affected by a number of factors) because a larger volume of fresh water should have been released. An example of this scenario is shown in Figure 4-4 where the lake has been opened on two different dates in spring, but the size of the freshwater plume is much larger after 7 days when the lake was opened at 1.41 m (September 2004) compared to a lake opening event that occurred at 1.25 m (November 2003). It is possible to quantify the area of these freshwater plumes using satellite imagery (see Schwarz et al.

2010) and we have examined how these plume sizes vary with lake level change. Lake level change is considered to be the difference between the lake level prior to opening and the level after it was closed. The analysis showed that the minimum area of a freshwater plume increased with greater changes in lake level (Figure 4-5). We would expect that larger freshwater plumes should attract more diadromous fish recruits to the lake, given that some recruiting flounder species have been shown to seek out areas of low salinity (Bos and Thiel 2006).

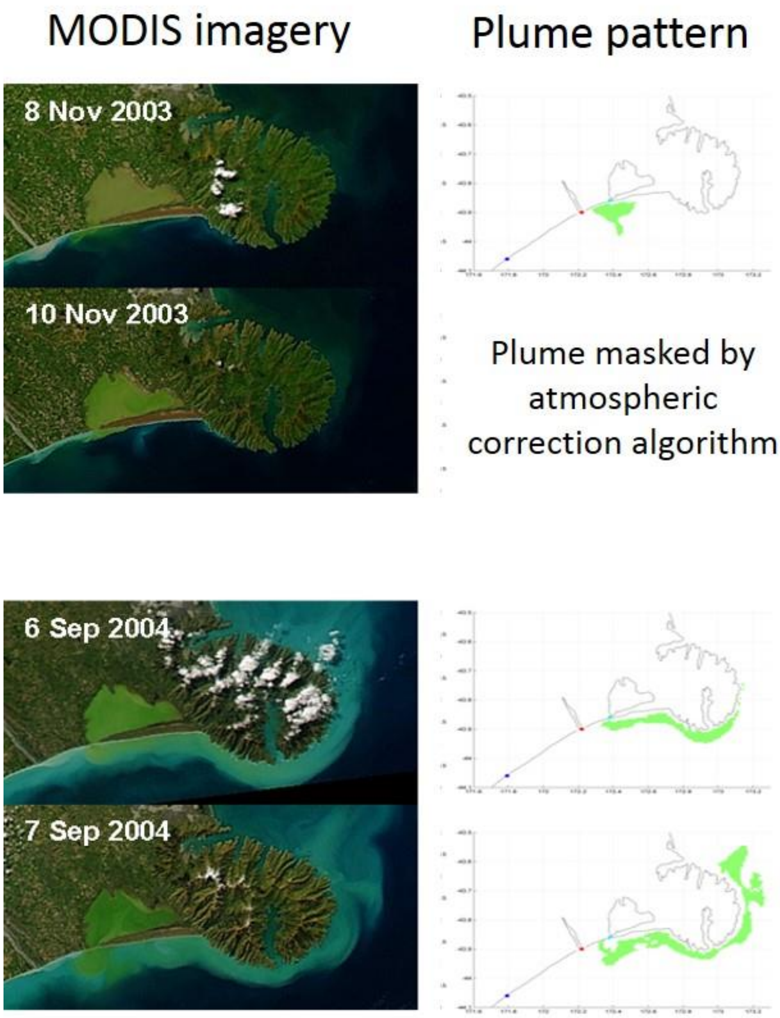

Figure 4-4: MODIS imagery of Te Waihora openings from November 2003 and September 2004 showing the extent of freshwater plume. MODIS: Moderate-resolution Imaging Spectrometer. The lake was opened at 1.25 m.a.s.l in Nov 2003 and at 1.41 m.a.s.l in Sep 2004. Images from 8 Nov 2003 and 6 Sep 2004 show plume patterns 7 days after opening. Figure modified from Schwarz et al. (2010).

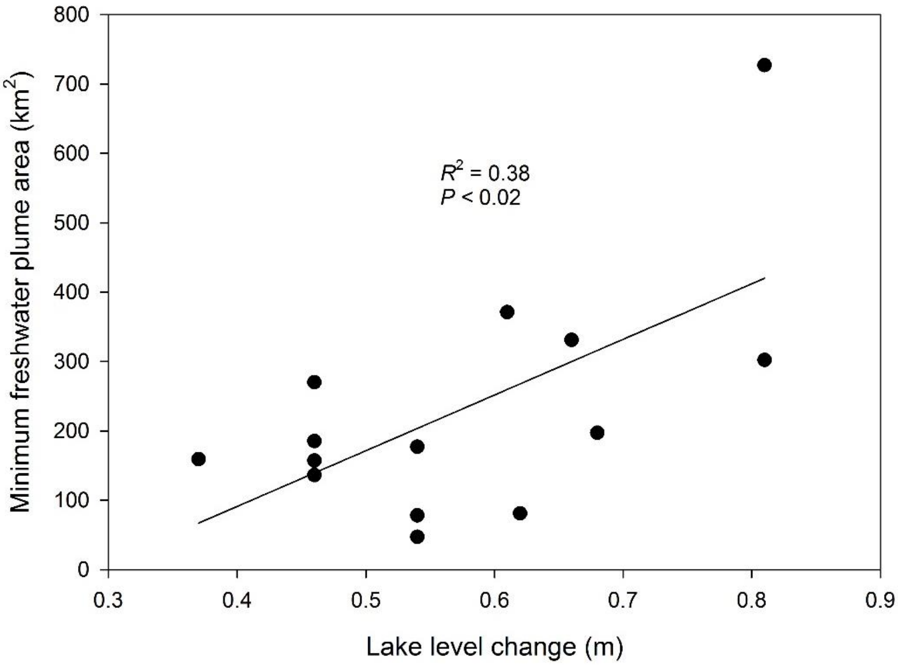

Figure 4-5: Relationship between lake level change and the minimum area of the resultant freshwater plume. Freshwater plume area was calculated from MODIS imagery (Schwarz et al. 2010) and we have only used data for the minimum plume area. Lake level change is considered to be the difference between the lake level prior to opening and the level after it was closed. Multiple data points may be present if plume area was calculated for different dates.

Larger freshwater plumes created by the discharge from Te Waihora would be expected to attract more recruits than smaller plumes, but it is also important to recognise that freshwater plumes will be present throughout the year as freshwater outflows from southern rivers move northwards past the lake opening site for Te Waihora (see Figure 4-6). For many of the diadromous species that enter Te Waihora shortly after a lake opening, it may be that the juvenile fishes had already cued into freshwater plumes originating from riverine discharges and that recruitment into Te Waihora is simply opportunistic. However, we would speculate that the recruitment of some species will be targeted because some species such as shortfin glass eels have been shown to respond to olfactory cues in fresh water (McCleave and Jellyman 2002). Similarly, Rakaia based white-baiters have previously mentioned that when Te Waihora is open to the sea they get reduced catches, because all the whitebait are cueing into Te Waihora (D. J. Jellyman, pers. comm.). In comparison to Te Waihora, the Rakaia River would have a much more consistent year-round freshwater attractant flow although peak outlet flows from Te Waihora can exceed 400 m^3/s (Measures et al. 2014) which is *c*. twice the mean discharge of the Rakaia River (211 m^3/s at Fighting Hill)]. Despite the Rakaia having more consistent freshwater plumes, the abundance of shortfins in Te Waihora is much higher considering that the commercial fishery in the lake is managed separately from the rest of Northern Canterbury (Ministry for Primary Industries 2012). Thus, discharge from Te Waihora would be expected to contain a higher concentration of shortfin odour to act as an attractant for shortfin glass eels.

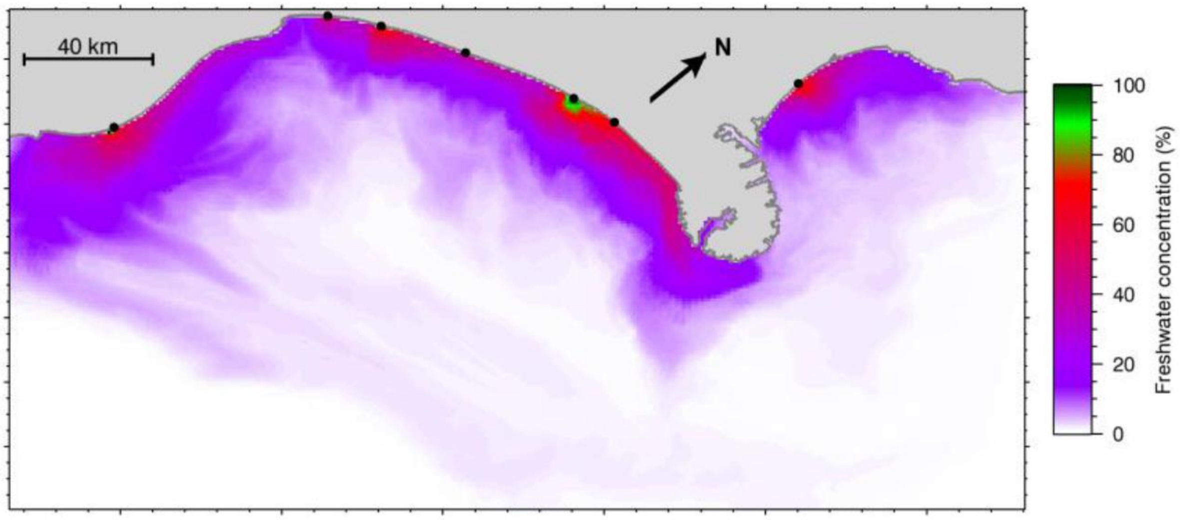

Figure 4-6: Maximum surface freshwater concentration as calculated over a one-year period (Apr 09-Apr 10). Statistics are calculated for the sum of the eight freshwater tracers; these tracers are the Clutha River (not shown), Waitaki (far left), Opihi, Rangitata, Ashburton, Rakaia, Te Waihora and Waimakariri (far right). Figure is taken from Hadfield and Zeldis (2012).

It is likely that the optimal lake opening scenario for fish recruitment would be to have a high lake level followed by an extended opening that encompasses the new moon. This would result in a large plume of fresh water from Te Waihora being discharged to sea, and then under the prevailing sea conditions, working its way from the Canterbury Bight around Banks Peninsula and towards Pegasus Bay; presumably past nursery habitats for a number of fish species found in the lake. If an extended lake opening followed major lake releases, then the eventual flow reversals (i.e., freshwater outflows on the low tide and seawater inflows on the high tide) should move large numbers of recruits, which have been attracted to the source of the outflow, into the lake. Even though there was only two openings during 2013, their extended duration meant they permitted higher fish recruitment into the lake compared to 2014. Moreover, recruit CPUE increased with lake opening duration so the most recruits entered Te Waihora during the longest lake opening. We were not able to quantify whether freshwater plume size had any influence on fish recruitment. If a new-moon phase occurred during the lake opening this would also encompass the optimal conditions for eels to recruit using selective tidal transport under the low light conditions (Jellyman and Lambert 2003).

4.3.2 Lake outflows and inflows

The volume of fresh water being discharged from Te Waihora peaks after the lake has been open for four days at an average discharge of 160 m^3/s (Figure 4-7; Measures et al. 2014). This is because it takes several days for the engineered cut through the gravel bar to sufficiently widen/scour for peak discharge to occur. The largest discharge from a lake opening during 2001 – 2011 was predicted to be approximately 475 m^3/s following a lake opening height of 1.53 m (Figure 4-7); the peak discharge following the lake opening at a height of 1.81 m should have far exceeded 500 m^3/s. Since such a large volume of fresh water is still being discharged after four to five days, recording the first seawater inflows within five days of the lake opening (regardless of its original lake opening height) was unexpected. It takes on average 24 days for the outlet flow to reach 0 m^3/s (Figure 4-7), if the lake stays open for this length of time, but an ever-increasing amount of sea water will have been entering the lake after four to five days (although daily seawater inflows can vary depending on tide height).

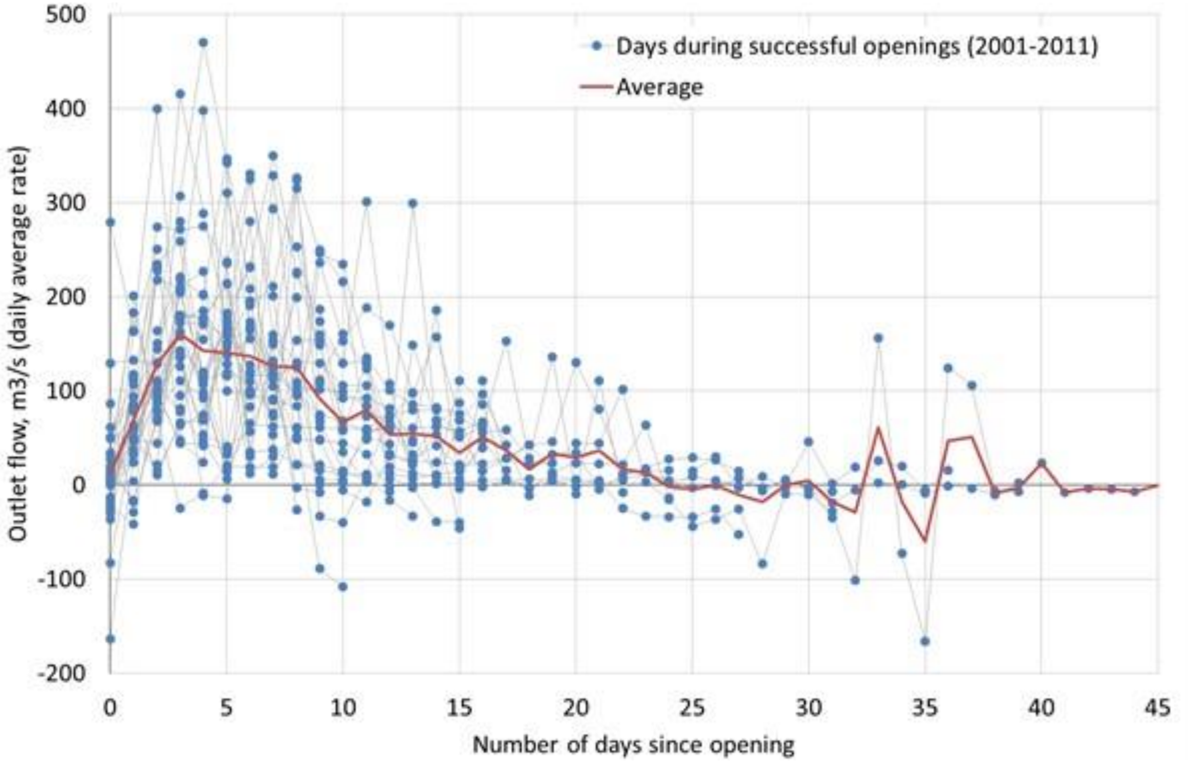

Figure 4-7: Daily average flow rate at the outlet of Te Waihora following successful lake openings. Data are from successful openings from 2001 – 2011. Daily average outlet flow rate is hindcast using water balance modelling. This figure is reproduced from Measures et al. (2014).

When Te Waihora is open to the sea, the average outlet flows across a 10-year period are relatively comparable as the lake decreases from a level of 1.35 m to a level of 0.8 m (Figure 4-8). Once the lake level drops below 0.8 m there is a major decrease in outlet flow and it is assumed that the sudden drop-off in freshwater outflows is linked to an increase in seawater inflows below a lake level of 0.8 m (Figure 4-8). The time taken to reach a lake level of 0.8 m for lake openings that occurred during the study was six to seven days (Appendix F). At lake levels below 0.8 m there should be significant seawater inflows occurring during parts of the tidal cycle, which is one of the reasons mean daily freshwater outflows sharply decrease below a lake level of 0.8 m. As tidal transport during seawater inflows is a primary mechanism for fish recruitment, we expect that increasing the number of days the lake is open below a level of 0.8 m should result in increased numbers of recruits.

It is worth noting how different lake opening levels altered the rate of lake level change. After eight days, the average lake level was actually lower for the opening events at 1.81 and 1.19 m than for the opening events that occurred at 1.07 and 1.00 m, presumably because they had scoured a wider lake outlet allowing a greater volume of water to be drained at a faster rate (Appendix F). Therefore, somewhat counterintuitively, shallow lake openings (< 1.10 m) may actually take longer to drop below a level of 0.8 m than deeper lake openings (> ~1.2 m). Note, we have only examined this relationship for the four lake openings during our study that lasted longer than 14 days so we recommend this relationship is examined over a longer data set.

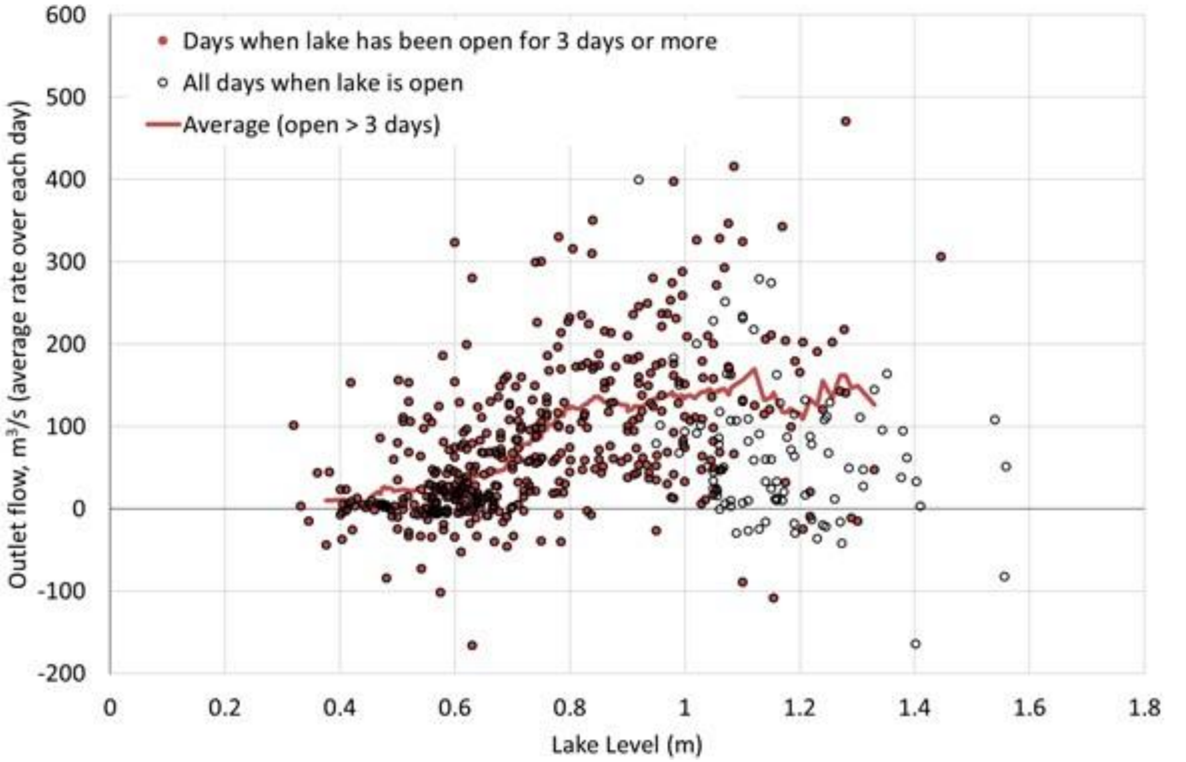

Figure 4-8: Daily average flow rate at the outlet of Te Waihora at differing lake levels from 2001 – 2011. Data used to produce the red line excludes data points from the first three days of lake openings when the cut is still growing rapidly. Daily average outlet flow rate is hindcast using water balance modelling. This figure is reproduced from Measures et al. (2014).

When the lake is open to the sea, the primary factor that will influence whether recruits can enter the lake will be water velocity. Juvenile fish are relatively weak swimmers and fish such as shortfin glass eels (one of the stronger swimmers of the potential recruits), as previously mentioned, have a maximum sustained swimming speed of only 0.3 m/s (Langdon and Collins 2000). When the engineered cut is completed lake water starts rushing out to sea and in doing so starts to scour a wider, deeper cut. The high water velocities across the cut for a fully developed opening vary between 1 and 3 m/s (Figure 4-9) and cross-sectional data on water velocities towards the edges and on the bottom of the cut indicates that velocities vary between approximately 0.5 – 1 m/s (Figure 4-10). In addition to water velocity, substrate movement on the edge and bottom of the cut as it is developing will mean that no juvenile fish recruitment will occur prior to or around peak discharge. Jellyman (2012) stated that for the purposes of juvenile fish recruitment, "the duration of any opening needs to be long enough for the loss of hydraulic head to allow some flood-tide movement into the lake". Whilst we have shown that the first seawater inflows occur within five days on a lake opening (Figure 3-39), the loss of enough hydraulic head for any meaningful fish recruitment is unlikely to occur until the lake level drops below 0.8 m; which on average takes over eight days if the lake opening day is considered day 0 (Figure 4-11). However, the majority of fish recruitment into the lake is likely to occur when the lake starts to have flow reversals which has been shown to occur at a lake level of 0.66 m (G. Horrell, pers. comm.). Analysis of lake level openings for the past 20 years suggests that, on average, it takes just over 12 days to reach a lake level of 0.66 m if the lake opening day is considered day 0 (Figure 4-11).

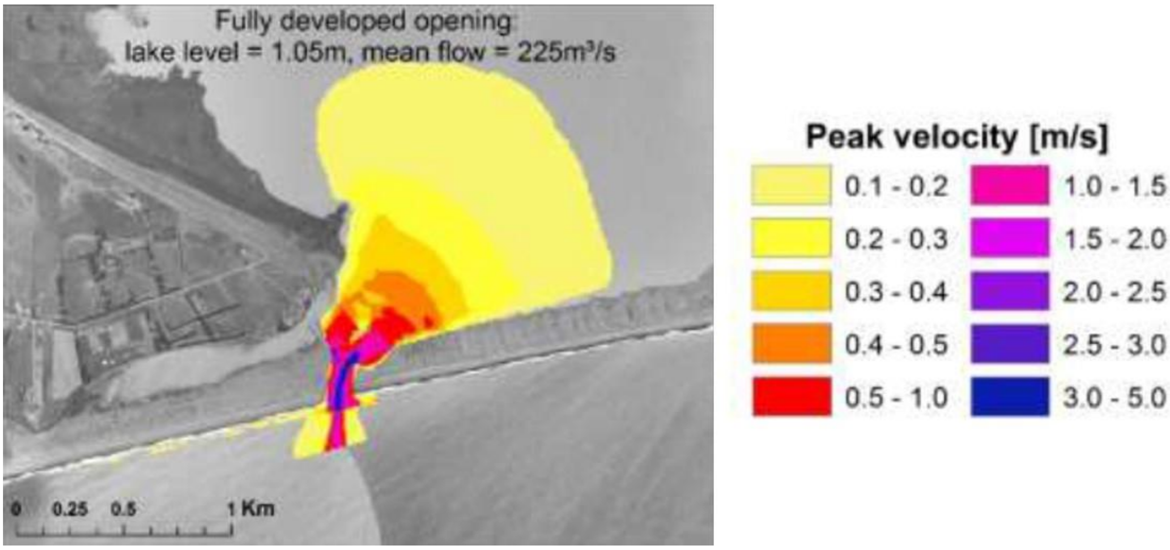

Figure 4-9: Peak depth averaged velocity for a typical lake opening event. For this model, the lake level at the time of opening was 1.05 m. Figure modified from Measures et al. (2014).

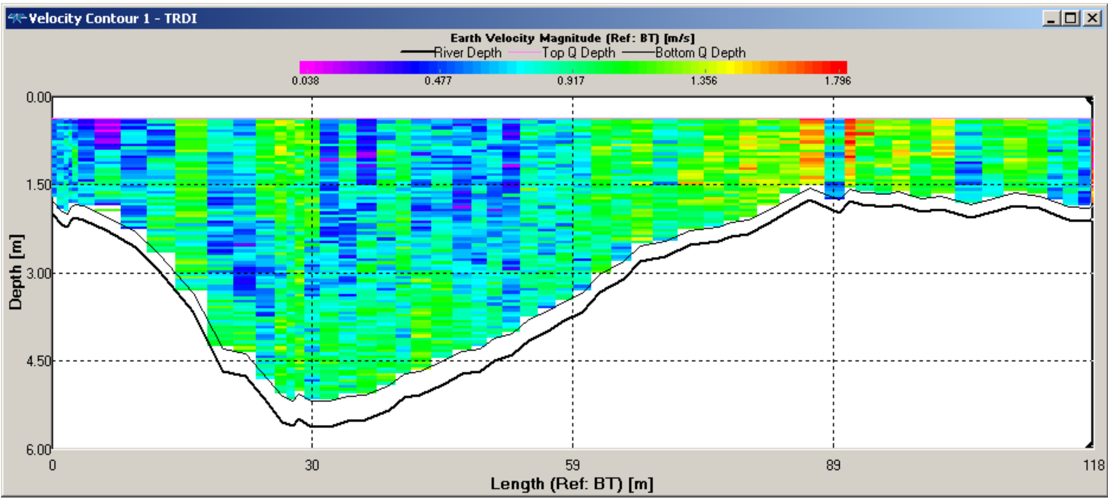

Figure 4-10: Cross-section of water velocity variation at the outlet of Te Waihora. This velocity cross-section was measured at peak discharge during a lake opening in June 2008; outflow 223 m^3s^{-1}. Figure reproduced from Horrell (2008).

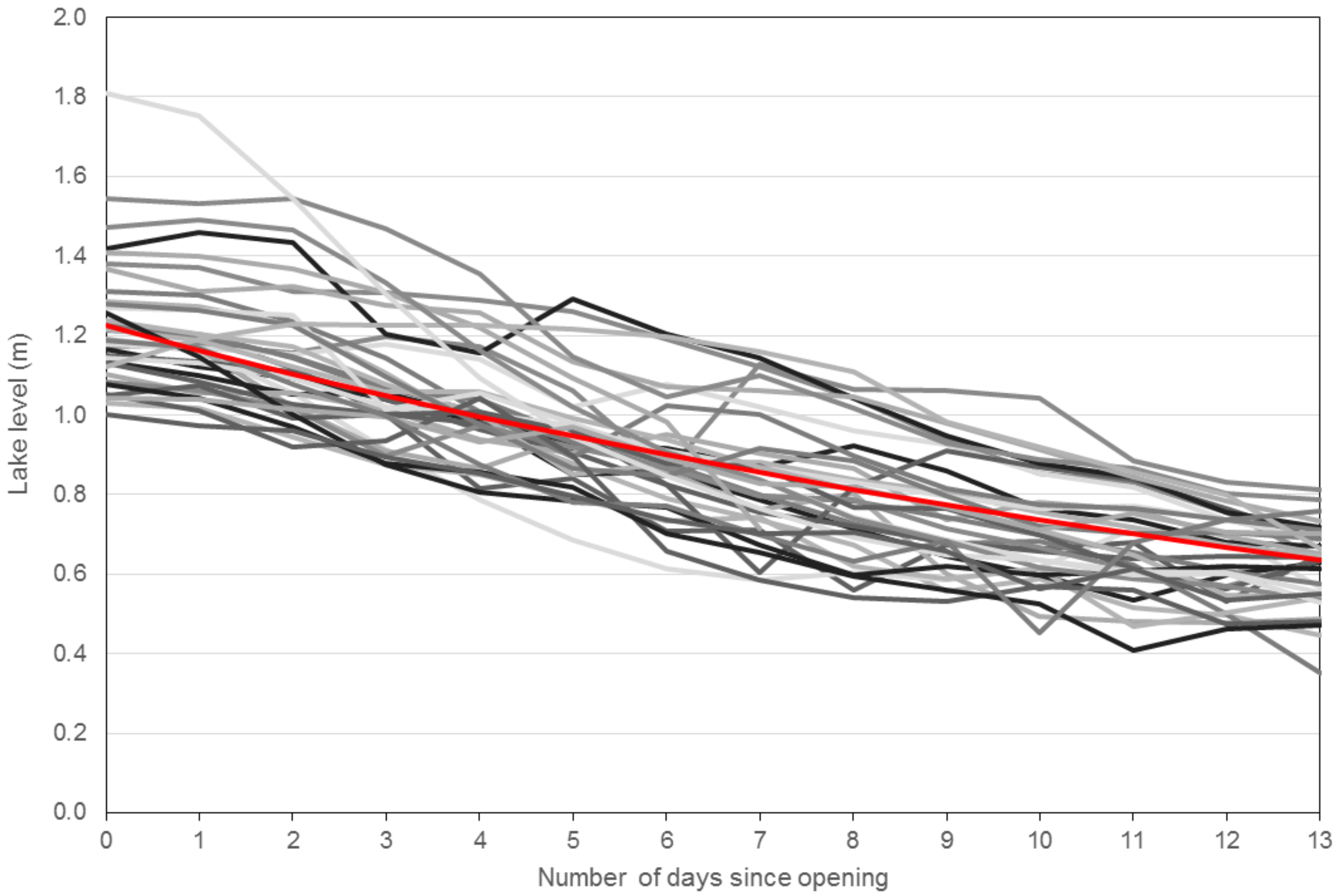

Figure 4-11: The rate of change in lake level plotted against the number of days for all lake opening events (>14 days) from 1995 to 2014. The red line is the average of all exponential decay trendlines that were fitted to time-series data. There were 36 lake openings of more than 14 days for which lake data were available during the last 20 years.

4.3.3 A practical lake opening regime to maximise fish recruitment

This study has confirmed that longer lake openings result in higher fish recruitment into Te Waihora, so to maximise fish recruitment into the lake, the longer the lake is open from June to December the more recruitment will occur. However, Ngāi Tahu (and commercial fishers) are primarily interested in maximising the recruitment of tuna and pātiki and with potentially limited lake openings available, getting the timing of lake opening events to coincide with the main recruitment timings for these species is essential.

The current protocol for opening the lake is that when trigger levels are reached (or close to being reached) there is a lake opening panel[3] that is consulted prior to any engineering works being undertaken. The current trigger levels for opening the lake are:

- 1 April to 31 July = 1.13 m
- 1 August to 31 March = 1.05 m

[3] The panel comprises ECan, Ngāi Tahu and other interested parties such as commercial fishers, lake settlers, etc.

There are also provisions so that openings can be made for fish migrations in and out of the lake. The timing of these provisions are:

- 1 April to 15 June = any level (autumn fish passage opening, primarily fish escapement)
- 15 September to 15 October = any level (spring fish opening, primarily fish recruitment)

In practice, 'any level' actually requires the lake to be at a level of 0.9 m because below this level it is very difficult to create a successful lake opening (Measures et al. 2014). Although a provision has been made for fish passage requirements, an opening event that is unrelated to trigger levels will only occur during these periods if prompted by someone on the lake opening panel (T. Davie, pers. comm.).

In an attempt to design a lake opening regime that will both maximise the recruitment of key mahinga kai fish species (i.e., tuna and pātiki) and be practical for lake management, historical lake opening data from 1947 – 2007 were examined to determine when the lake is most frequently opened (Figure 4-12). A thorough analysis on lake opening data for the last 20 years (1995 to 2014[4]) were also conducted to determine general patterns in lake management. Based on lake opening data we placed the following practical constraints on managing the lake for fish recruitment:

- Most lake openings should occur from July through to October
- Lake openings per year: 3 (20 year average = 3.40 ± 0.35)
- Number of days open per year: 65 (20 year average = 64.6 ± 6.9)
- Timing of lake openings: minimal between 10 December and 20 April (only 3 openings during this period for the last 20 years)

[4] As of 10 July 2015 the lake had not yet been opened this year, although a lake opening is imminent.

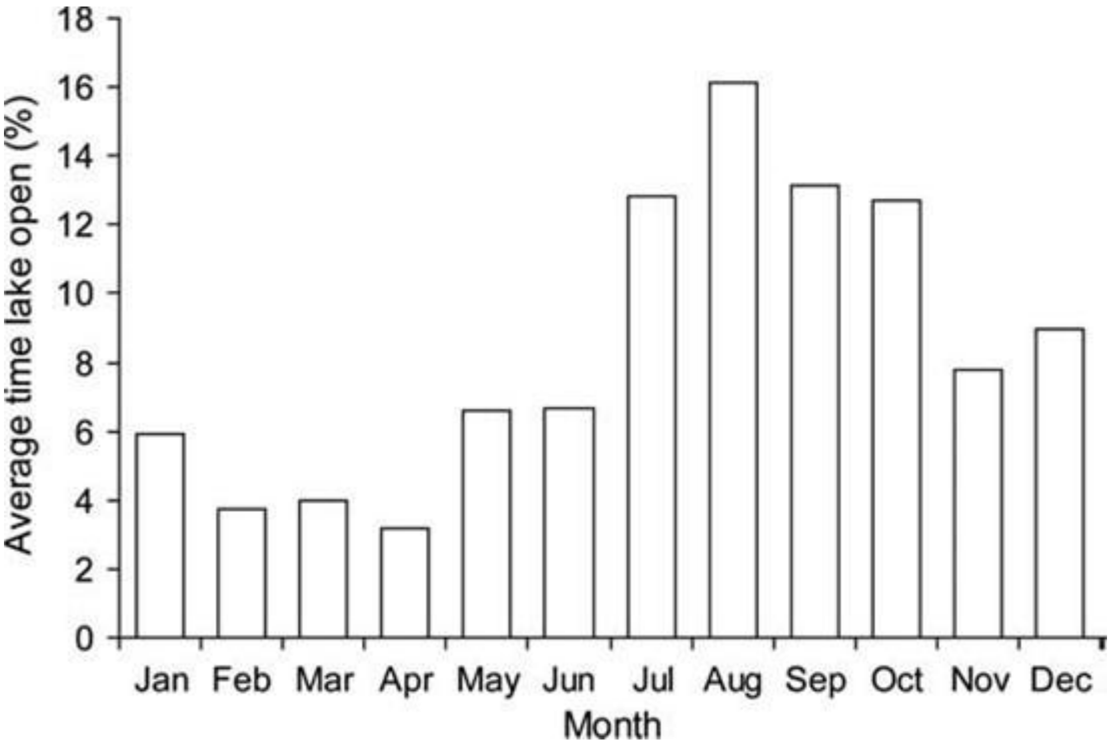

Figure 4-12: The percentage of time per month that Te Waihora was open to the sea. Data are from 1947 – 2007. Reproduced from Jellyman (2011).

A practical constraint around whether or not the lake should be reopened was not included. From examination of recent lake opening data it is unclear if there is a standard protocol around whether the lake is reopened if it naturally closes just below the trigger level. For example, when the lake closed on 16/6/09 at a lake level of 1.10 m (trigger level: 1.13 m) it was not reopened for another five weeks when the lake level has risen to 1.27 m[5]. However, on 21/6/14 the lake closed at a level of 1.12 m (trigger level: 1.13 m) and the lake was reopened three days later.

Based on the present study as well as new hydrology and salinity analyses we recommend the following opening regime to maximise recruitment and outgoing migrations of mahinga kai species whilst allowing for the practical operating constraints outlined above:

- Opening 1: Lake opening of ≥9 days between 15 April to 31 May
- Opening 2: Lake opening >20 days between 1 July to 31 August
- Opening 3: Lake opening >25 days between 15 September to 15 November

Opening 1: This opening is primarily to let adult eels and flounder out to sea. An opening of at least 9 days should ensure the lake level has dropped below 0.8 m and there has been some seawater inflows into the lake. Whilst some eels may be hanging around the outlet, the presence of seawater inflows may provide an additional cue to direct outgoing migrant fish towards the lake outlet so they can head out to sea. If this opening does not occur, it will generally be non-fatal for silver (migrating) eels, as after repeated failures, many eels will eventually revert back into the feeding stage (Jellyman

[5] It is not known whether or not there was a failed attempt to reopen the lake in June 2009 as this data is not recorded in the lake opening times data file supplied by ECan.

2012). However, reverting back to a 'feeder' is likely to cause a loss of condition meaning an eel is unlikely to be able to migrate the following season; instead such eels will probably skip a year and attempt to migrate the following year provided they have regained adequate condition.

Opening 2: This opening is for the recruitment of common bully, common smelt and torrentfish. As common bully are the main prey fish species for the growth of the key mahinga kai species, it is important that they can gain access into the lake (although the relative contribution of diadromous compared to non-diadromous bullies is still currently being resolved). Common bully recruits entering the lake will be small and be relatively weak swimmers so having a one-week period of tidal exchange is considered important for substantial numbers of these recruits to enter the lake. This is also the main recruitment period for the taonga fish species such as torrentfish. Torrentfish recruits will be better swimmers than common bullies and would be expected to be entering the lake within a week of the lake opening although significant tidal exchange should further assist recruitment.

Opening 3: This opening partially encompasses the timing of longfin eel recruitment, all of the shortfin eel recruitment and the majority of the recruitment period for black, yellowbelly and sand flounder. Some glass eels in the vicinity of the lake outlet may recruit into the lake within a week of the lake opening (although moon phase may play an important role), whereas it is likely that the majority of flounder recruits will enter the lake on seawater inflows. Given that it takes over 12 days on average before the lake drains to a level where flow reversals are occurring, we consider it necessary that a similar length of time elapses for the majority of flounder recruits to be able to enter the lake. Detailed daily data of flounder recruitment variability is not available, but an extended opening period once flow reversals are occurring should result in high recruitment. Another important feature of an extended opening is the size of the resulting freshwater plume that enters the ocean, as this provides the odour cue for recruiting juvenile fish. A more prolonged opening will produce a larger plume, and since the majority of fish species have a recruitment window that overlaps Opening 3, having the longest opening duration at this time should also result in a number of species recruiting into the lake. If the lake level can be held slightly higher prior to Opening 3, this could increase the size of the freshwater plume (if oceanic conditions are favourable) and thus potential recruitment. For the purposes of sustaining mahinga kai species in Te Waihora, Opening 3 is the most crucial of all the suggested openings.

We consider that having three openings in a calendar year should be practical during many years. Note, the last calendar year in which all three of these opening timings and durations were met was 1981. For Opening 2 and Opening 3, if the lake closes within a few days of opening, attempts should be made to reopen the lake until the lake level drops below 0.8 m and significant tidal exchange occurs. Lake level openings that do not drop below 0.8 m may significantly restrict fish recruitment into the lake given the poor swimming speeds of the larval fish and the high flows at the outlet.

It is also recommended that the lake is not opened after 30 November if possible because this can cause extended low-lake periods which can be detrimental to fish populations. Summer opening events between December and February are relatively rare but tend to occur at least once every 10 years; note that lake openings in November will mean that the lake is often still open in December. It is important to recognise that the southerly conditions that close the lake outlet are also rare during summer so lake openings that occur in December tend to result in the lake being open for more than two months (e.g., the lake was opened on 15/12/12 at 1.08 m and resulted in the lake being open for 68 days). Evaporation outflows tend to be approximately proportional to (or slightly exceed) inflows from tributary inflows and rainfall inflows and as there is minimal rough sea inflows at this time (Horrell 2010) which means the likelihood of major increases in lake height over the summer period is relatively low. The effects of extended low summer lake levels are generally negative and include: (1) the loss of lake margins, restricting feeding areas for fish, (2) water temperatures are higher which can result in decreased water quality and increased likelihood of algal blooms, which can potentially be toxic, (3) access to potential spawning habitat around lake margins is reduced, and (4) the lake is shallower which reduces the water depth for pelagic feeding fishes. Jellyman (2012) noted that "one issue that has not been researched is the assertion by commercial fishers that a low lake is preferred in summer to a partially-low lake – the reason being that a partially low lake can be high enough to just cover Greenpark Sands, and this acts as a "heat trap" during warm summer days, and elevates water temperature appreciably"; the approximate lake levels considered to be low versus partially-low were not stated. Given the majority of fish species have already recruited prior to December (although November lake openings will still often see the lake open for some December recruitment), on balance it seems that there may be more detrimental effects of a December (or other summer months) lake opening than benefits for fish communities.

Additional considerations for lake openings

- Wind conditions are an important consideration for lake openings for fish because the wind fetch effect on the lake can be significant. Horrell (2008) noted that the wind fetch effect was so extreme during very strong south-westerly conditions that it dropped the lake level by over 0.7 m in 30 minutes. From the perspective of fish recruitment, opening the lake during any southerly wind would be a poor decision because these storms drive the lake water to the northern side of the lake leaving minimal habitat available around the outlet for recruits to move into (and potentially confining predatory fish into a small area). However, lake openings during southerly conditions are generally unlikely because attempts to open the lake can often be unsuccessful because wave-driven gravel movement means that the lake outlet is constantly being blocked by new gravel.

- Lunar phase is something that should be considered for lake openings because of its effect on tide heights and this is the most likely tidal phase for glass eel recruitment. Opening the lake during half-moon phases and allowing the level to reduce to 0.8 m (tidal exchange point) prior to the new moon, would allow the maximum amount of tidal transport to occur during these large tides.

- The height of the gravel bar is not actively managed after the lake outlet has naturally closed over, although some management of the sea wall may occur. Because we have shown that overtopping events can make an important contribution to fish recruitment, it would be expected that a lower gravel bar would permit more overtopping events and therefore more fish recruitment to occur. If the opening regime outlined above can be followed then this may not be necessary, but in years when lake openings may not be able to be timed appropriately, then managing the height of the gravel bar may be another aspect that could be managed to maintain fisheries values.

4.4 Conclusions

This report is focussed on fish recruitment and although our recommendations have been placed within the context of historical lake opening data, they do not attempt to integrate the needs of all stakeholders. It is acknowledged that lake openings take time to prepare and there are financial considerations; although by placing our recommendations within the context of previous lake openings, our suggested three opening times should be financially viable (there could be additional re-opening costs associated with our recommendations). There will of course be some years in which there is an urgent need to open the lake (e.g., heavy rainfall in the catchment and rapidly rising lake levels) and such events may not coincide with key fish recruitment times. It is important that when this occurs the lake opening panel acknowledges the potential effect on fish recruitment so that a lake opening for fish recruitment can be prioritised for the following year so that fish recruitment is not impacted across multiple years; if it does, a lower abundance of flatfish in the lake is likely to result.

At present, it is not possible to close the lake once it has been opened and prevent undue low levels occurring. The impact of a low summer lake levels on the lake fishery has never been quantified, but impacts are likely to be primarily negative. As stated previously, there are likely to be issues for marginal vegetation, fish feeding and spawning, but whether high summer lake temperatures increase mortality rates of fishes is unknown. Land inundation modelling indicates that at a level of 1.05 m, the lake area has already been reduced by 492 ha which is a 2.3% decrease when compared to the winter maximum level of 1.13 m (see Appendix H). There is a linear decline in lake surface area as lake level decreases and at a lake level of 0.9 m, lake area is reduced by over 1400 ha compared to the winter level of 1.13 m; this major change to lake area means that less habitat is available for feeding and refuge space is available for fresh recruits in the lake.

The recommendations in this report are focussed on ensuring adequate fish recruitment, but providing fish escapement is also essential for long-term management of mahinga kai species. Our recommendations should improve the effectiveness of lake openings for fish recruitment, but it will be up to those responsible for managing the timing of lake openings to ensure they are appropriate for fish and that lake trigger levels do not solely define lake opening management.

5 Acknowledgements

We acknowledge the efforts of all the people who assisted with data collection for this report, in particular Greg Kelly (NIWA), Julian Sykes (NIWA), Don Jellyman (NIWA) and Michael Greer (ECan) assisted with much of the field work. Don Jellyman is also thanked for his identification of small flounder in the laboratory. We thank Tiriana Smith, Mandy Home and Don Brown for assistance with site access and site selection. Sophie Allen, Kelly Smith and Hannah Mitchell provided valuable field assistance and discussions on site selection. Local landowners are thanked for providing access to sampling sites. Lake level data were supplied by Melissa Shearer (ECan) and lake salinity data were provided by Alex Ring (ECan). Funding for this project was provided by the Whakaora Te Waihora Partners.

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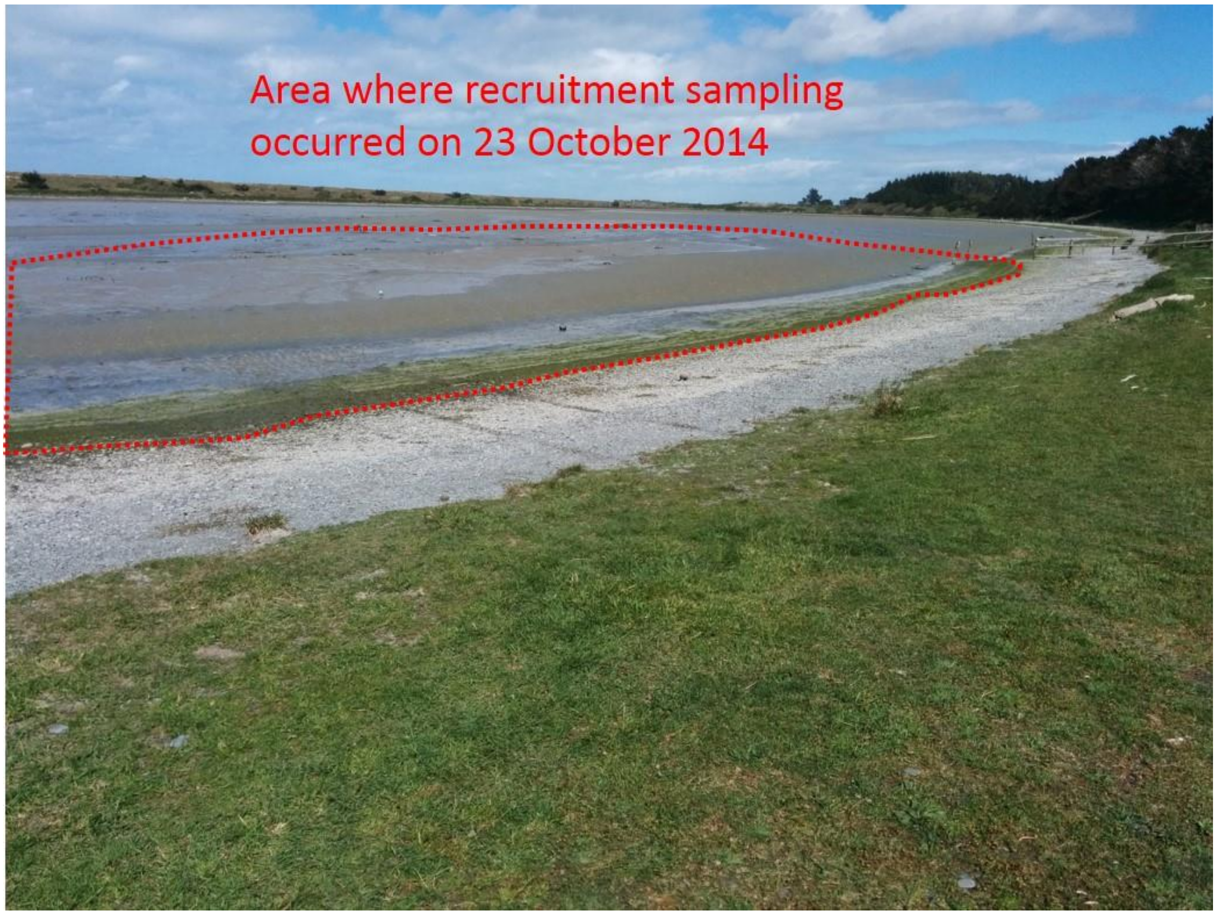
Appendix A Timing of lake openings/closures for the last decade

Date open	Openings per year	Date Closed	Days open	Level Opened	Level Closed
30-Aug-04	1	19-Sep-04	19	1.41	0.6
9-Jan-05		9-Feb-05	31	1.08	0.4
11-Aug-05	2	27-Aug-05	16	1.16	0.7
16-Jun-06		4-Jul-06	18	1.36	0.7
17-Aug-06		31-Aug-06	14	1.29	0.67
6-Nov-06	3	21-Nov-06	15	1.07	0.66
21-May-07		29-May-07	8	1.18	0.93
9-Jul-07		25-Jul-07	16	1.21	0.62
20-Oct-07	3	23-Oct-07	3	1.09	0.96
12-Jun-08		25-Jun-08	13	1.21	0.72
3-Aug-08		18-Aug-08	15	1.52	0.79
1-Sep-08		2-Oct-08	31	1.28	0.6
15-Oct-08	4	15-Oct-08	0.33	0.63	0.63
9-Jun-09		16-Jun-09	7	1.53	1.1
21-Jul-09	2	3-Sep-09	44	1.27	0.59
31-May-10		6-Jul-10	36	1.41	0.65
13-Aug-10	2	21-Sep-10	39	1.29	0.7
30-Mar-11		7-Apr-11	8	1.12	0.95
22-May-11		1-Jun-11	10	1.17	0.7
4-Aug-11		9-Aug-11	5	1.17	1.02
26-Aug-11		4-Sep-11	9	1.35	0.86
6-Oct-11	5	10-Nov-11	35	1.08	0.59
15-Jun-12		29-Jun-12	14	1.26	0.84
16-Aug-12		21-Sep-12	36	1.49	0.57
15-Dec-12	3	21-Feb-13	68	1.08	0.51
29-Jun-13		15-Aug-13	47	1.81	0.52
5-Oct-13	2	4-Dec-13	60	1.07	0.51
21-Apr-14		29-Apr-14	8	1.25	1.03
2-May-14		11-May-14	9	1.24	0.84
15-Jun-14		21-Jun-14	6	1.24	1.12
24-Jun-14		29-Jun-14	6	1.18	0.85
29-Jul-14		9-Aug-14	15	1.19	0.73
30-Sep-14		6-Oct-14	6	1.15	0.99
9-Oct-14	7	25-Oct-14	16	1	0.58

Note: NIWA research commenced during the first lake opening event in 2013. The lake did not open between October 2014 and June 2015.

Appendix B Wind fetch impact on sampling area



This photograph was taken on 24 October 2014, the day after the super fyke net had been processed at the Te Kōrua site (and two days after seine netting was conducted).

Appendix C Typical catch from seine netting

This photograph shows a typical species catch from a single seine net haul. With high numbers of common bully (upper left) and common smelt (upper right; not completely sort when photo taken) and then a mixture of other species (bottom left) such as adult inanga, sprat and various flounder species. The photo on the bottom right shows the separated flounder catch which contains both new recruits as well as small and moderate-sized sand and yellowbelly flounder; none shown are of commercial size.

Appendix D Variation in the number of recruits through time

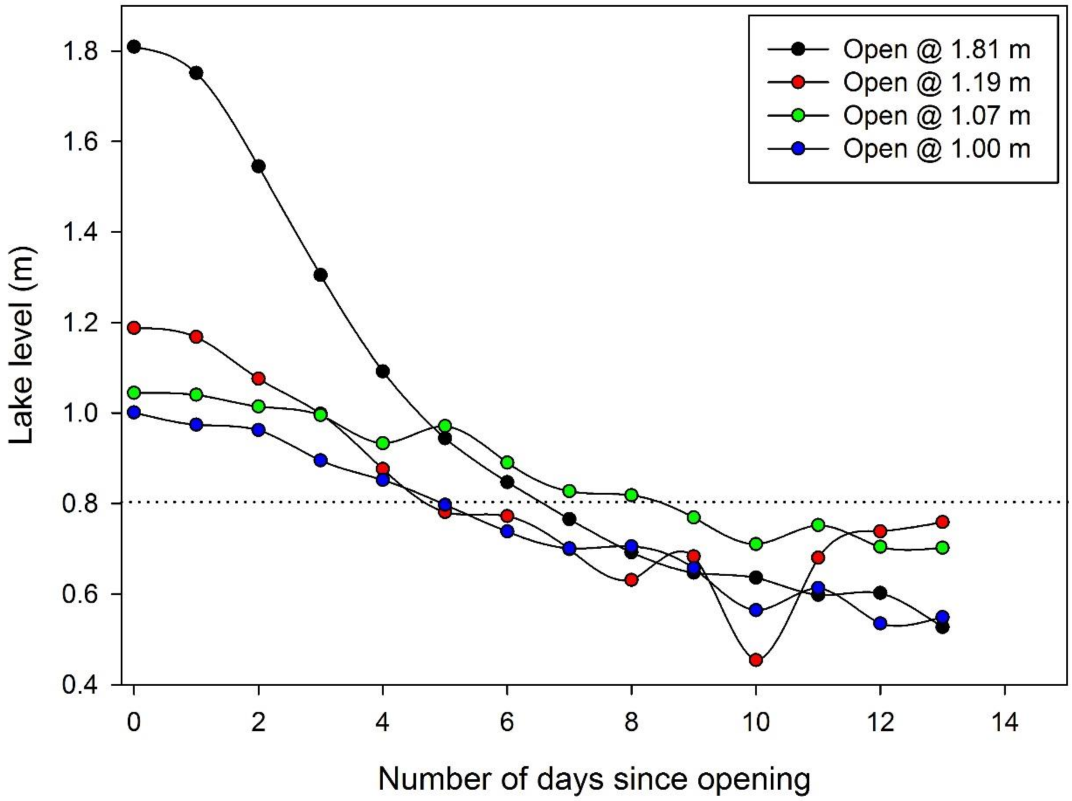
Date	Lake status	Days since opened	Days since closed	SE <70	LE <70	TF <50	IN <60	CS <70	CB <35	YF <35	SF <35	BF <35
29/07/2013	Open	31	0	0	0	0	19	42	2	0	0	0
30/08/2013	Closed	63	15	0	1	0	0	0	0	0	0	0
16/09/2013	Closed	80	32	0	0	24	14	266	3	2	0	0
3/10/2013	Closed	97	49	7	2	17	8	119	1	3	0	0
10/10/2013	Open	6	0	2	1	23	1	149	8	14	0	0
30/10/2013	Open	26	0	0	0	1	7	149	11	0	0	6
21/11/2013	Open	48	0	5	0	0	149	137	9	275	0	0
12/12/2013	Closed	69	8	0	0	0	12	96	4	77	0	0
3/02/2014	Closed	122	61	0	0	0	0	54	10	0	0	0
11/04/2014	Closed	189	128	0	0	0	2	37	17	0	0	0
15/05/2014	Closed	14	4	0	0	15	0	56	17	0	0	0
23/06/2014	Closed	9	2	0	0	35	0	52	34	0	0	0
8/07/2014	Closed	15	9	0	0	68	0	57	24	0	0	0
3/08/2014	Open	6	0	0	0	101	22	85	19	0	0	0
8/10/2014	Closed	9	2	0	0	15	0	110	1	1	0	0
22/10/2014	Open	14	0	0	0	21	30	86	8	1	0	0
9/12/2014	Closed	62	45	0	0	15	25	58	3	48	56	0
17/02/2015	Closed	132	115	0	0	0	0	19	0	0	0	0

Note: SE=shortfin eel, LE=longfin eel, TF=torrentfish, IN=inanga, CS=common smelt, CB=common bully, YF=yellowbelly flounder, SF=sand flounder, BF=black flounder. The numbers indicate the size limit for recruits in mm.

Appendix E Timing of seawater inflows after lake openings

Date Opened	First record of seawater inflow			Salinity concentration (ppt)	
	Date	Time	Salinity (ppt)	15 mins pre-inflow	15 mins post-inflow
29/06/2013	4/07/2013	0:45	23.3	8.9	16.2
5/10/2013	6/10/2013	15:30	19.6	10.6	26.1
21/04/2014	25/04/2014	12:15	20.1	10.1	10.3
2/05/2014	6/05/2014	21:30	16.5	9.2	31.0
15/06/2014	15/06/2014	17:00	24.0	7.2	26.3
24/06/2014	25/06/2014	14:30	25.2	8.1	28.0
29/07/2014	2/08/2014	7:45	28.7	7.2	31.7
30/09/2014	2/10/2014	9:15	10.2	6.3	28.7
9/10/2014	9/10/2014	14:30	11.2	10.0	25.7

Appendix F Rate of lake level change for different opening



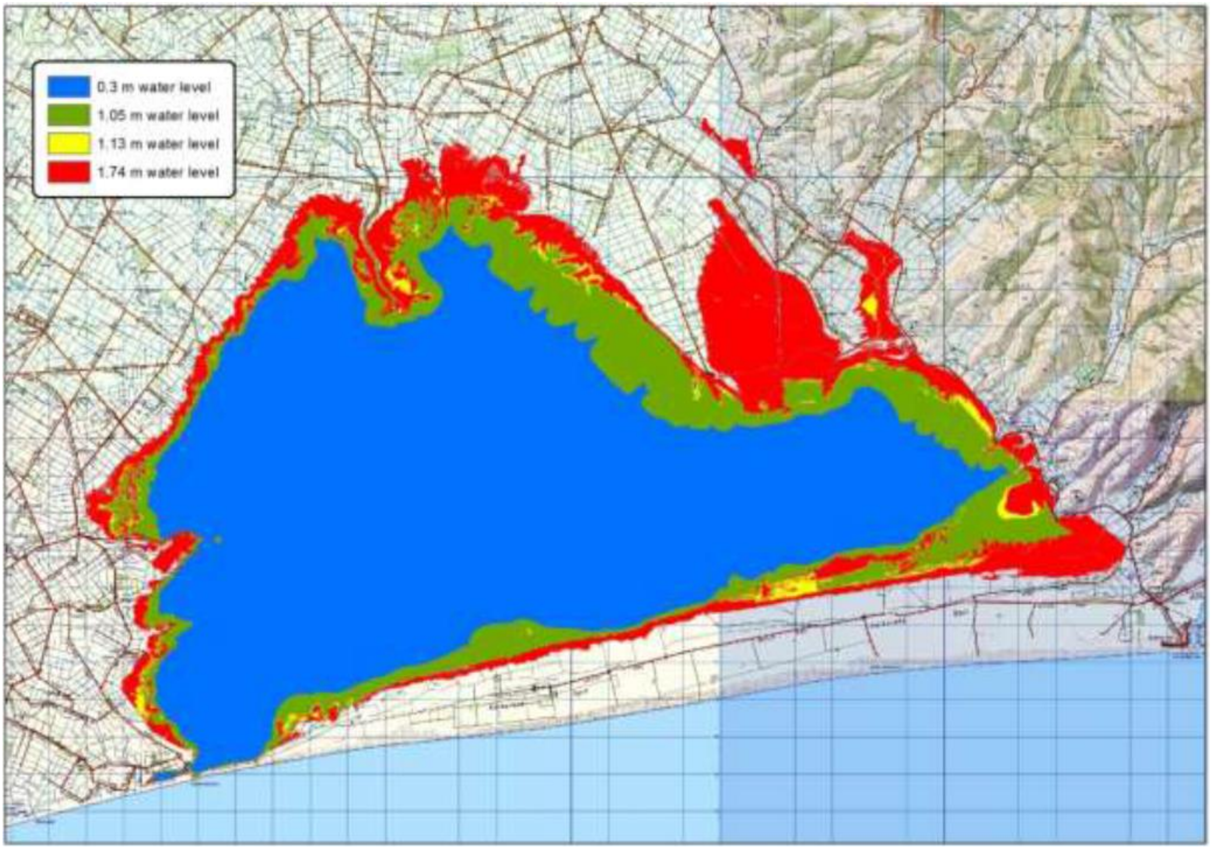
The rate of change in lake level plotted against the number of days since a lake opening events. Data are shown for all lake openings during the present study that lasted for a minimum of 14 days.

Appendix G Sea water inflows over gravel barrier

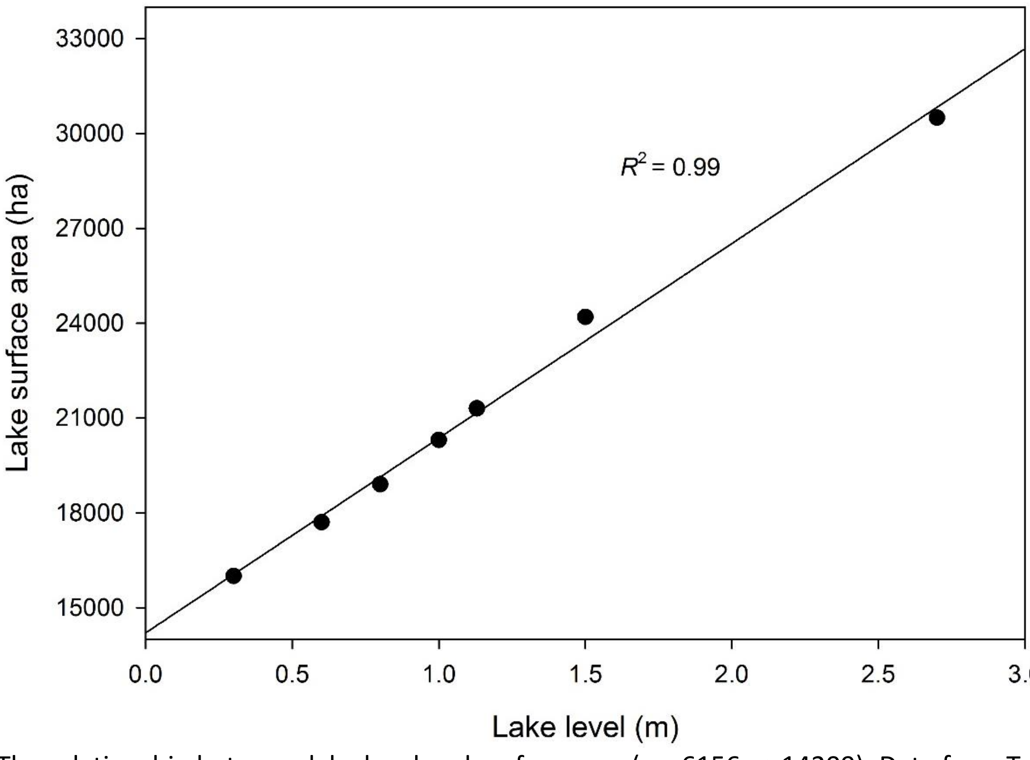
Sea water inflow estimated at 20 $m^3 s^{-1}$ at 1630 hours on 6 July 2008 with a beach barrier. Photo: G. Horrell, NIWA.

Leatherjackets on the lake shore near the outlet, victims of a south-westerly storm on the 5 July 2008.

Appendix H Land inundation at different water levels



The spatial extent of different water levels in Te Waihora (from Measures et al. 2014), including the recent high flood level of 1.74 m.



The relationship between lake level and surface area (y = 6156x + 14209). Data from Taylor (1996).