Waterways
Centre for Freshwater Management

Spatial effects of the Canterbury earthquakes on inanga spawning habitat and implications for waterways management

WCFM & MERG Research Report 2016-002

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REPORT:	WCFM & MERG Research Report 2016-002
TITLE:	Spatial effects of the Canterbury earthquakes on inanga spawning habitat and implications for waterways management
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DATE:	4 February, 2016

Executive Summary

The Canterbury earthquakes resulted in numerous changes to the waterways of Ōtautahi Christchurch. These included bank destabilisation, liquefaction effects, changes in bed levels, and associated effects on flow regimes and inundation levels. This study set out to determine if these effects had altered the location and pattern of sites utilised by inanga (*Galaxias maculatus*) for spawning, which are typically restricted to very specific locations in upper estuarine areas.

Extensive surveys were carried out in the Heathcote/Ōpāwaho and Avon/Ōtākaro catchments over the four peak months of the 2015 spawning season. New spawning sites were found in both rivers and analysis against pre-earthquake records identified that other significant changes have occurred.

Major changes include the finding of many new spawning sites in the Heathcote/Ōpāwaho catchment. Sites now occur up to 1.5km further downstream than the previously reported limit and include the first records of spawning below the Woolston Cut. Spawning sites in the Avon/Ōtākaro catchment also occur in new locations. In the mainstem, sites now occur both upstream and downstream of all previously reported locations. A concentrated area of spawning was identified in Lake Kate Sheppard at a distinctly different location versus pre-quake records, and no spawning was found on the western shores. Spawning was also recorded for the first time in Anzac Creek, a nearby waterway connected to Lake Kate Sheppard via a series of culverts.

Overall the results indicate that spawning is taking place in different locations from the pre-quake pattern. Although egg survival was not measured in this study, sites in new locations may be vulnerable to current or future land-use activities that are incompatible with spawning success. Consequently, there are considerable management implications associated with this spatial shift, primarily relating to riparian management. In particular, there is a need to control threats to spawning sites and achieve protection for the areas involved. This is required under the New Zealand Coastal Policy Statement 2010 and is a prominent objective in a range of other polices and plans.

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Section 1 Introduction

1.1 Overview

The Waterways Centre for Freshwater Management (WCFM) and Marine Ecology Research Group (MERG) at the University of Canterbury are currently collaborating on the 'Resilient Shorelines' research programme centred around a PhD project and associated projects with external organisations and community groups. The research is developing methods for assessing the vulnerability of rivermouth and estuarine ecosystems exposed to sea level rise and applications to planning for climate change. The Avon-Heathcote Estuary/Ihutai and associated waterways is the primary case study site (Figure 1).

This report has been prepared by WFCM and MERG for the Ngāi Tahu Research Centre, IPENZ Rivers Group[1] and other organisations interested in waterways management. It provides information on initial findings in relation to the effects of the Canterbury earthquakes on inanga spawning sites in the study area. In the context of the wider research these are sites of high ecological and cultural importance located on the shoreline of the upper estuarine ecosystem.

Figure 1. Overview of Christchurch city, Avon-Heathcote Estuary/Ihutai, Avon/Ōtākaro and Heathcote/Ōpāwaho catchments, and sub-catchments mentioned in this report. [Basemap: Environment Canterbury].

[1] The Rivers Group is a joint technical group of the Institution of Professional Engineers NZ (IPENZ) and Water New Zealand.

1.2 Background

Our study focuses on the management of riparian margins at estuaries and rivermouths. These are unique places where fresh and saltwater meet on the coastal margin. Estuaries have been evaluated as being some of the most valuable ecosystems for humanity in terms of productivity and ecosystem services (Barbier et al., 2011; Jarvis, 1992). They are hugely important for a wide range of recreational, cultural and commercial uses (UNEP/GPA, 2006) as well as providing habitat for iconic and threatened species, many of which depend on these systems for some or all of their life cycle (DOC & MfE, 2000).

The wider context for the work reported here is to develop methodologies for modelling the impacts of sea level rise on estuaries and coastal rivermouths using the Avon-Heathcote Estuary/Ihutai as a case study system. The study is using effects of the Canterbury earthquakes relating to ground level changes as a means to simulate and understand the changes that may occur under sea level rise. In relation to the ecosystems of interest, an initial objective was to establish the magnitude of earthquake-induced changes. Subsequent steps include establishing the relationships between observed changes and physical drivers of interest to the understanding of sea level rise, particularly water levels and salinity.

After the 2010-2011 Canterbury earthquake sequence, topographic and bathymetry measurements confirmed that significant changes had occurred in ground levels in and around the Avon-Heathcote Estuary/Ihutai (Beaven et al., 2012). Modelling of the estuary in pre- and post-quake configurations also indicated considerable changes to the hydrodynamic regime including an estimated 15% reduction in the tidal prism (Measures et al., 2011). In recognition that the magnitude of observed earthquake effects was likely to be sufficient to drive long-term ecological changes in the distribution of estuarine species and habitats, a number of research efforts to measure change were initiated (e.g., Cochrane et al., 2014; Zeldis et al., 2012).

The Avon-Heathcote Estuary/Ihutai can be characterised as a barrier-enclosed lagoon system (Hume & Herdendorf, 1988; Hume et al., 2007). As is common worldwide, the estuary and associated waterways are attractive for human settlement and associated uses. The Avon-Heathcote Estuary/Ihutai supports a wide range of values (Boyd, 2011; Jupp et al., 2007; Owen, 1992) and is of high significance for tangata whenua (Jolly et al., 2013; Lang et al, 2012; Pauling et al., 2007).

The protection of estuarine species and ecosystems is recognised as being of high importance nationally (DOC & MfE, 2000), regionally (ECan, 2005, 2013) and locally (CCC, 2015; Jolly et al., 2013). Current national policy under the New Zealand Coastal Policy Statement 2010 includes requirements, *inter alia*, to 'preserve the natural character of the coastal environment and to protect it from inappropriate subdivision, use, and development', and requirements to 'protect indigenous biological diversity in the coastal environment' in various ways (DOC, 2010a). This reflects that several matters of national importance identified under s6 of the Resource Management Act 1991 are relevant to the management of the coastal environment.

These include:

> *s6(a) the preservation of the natural character of the coastal environment (including the coastal marine area), wetlands, and lakes and rivers and their margins, and the protection of them from inappropriate subdivision, use, and development;*

s6(b) the protection of outstanding natural features and landscapes from inappropriate subdivision, use, and development;

s6(c) the protection of areas of significant indigenous vegetation and significant habitats of indigenous fauna;

s6(d) the maintenance and enhancement of public access to and along the coastal marine area, lakes, and rivers; and

s6(e) the relationship of Māori and their culture and traditions with their ancestral lands, water, sites, waahi tapu, and other taonga.

1.3 Upper estuarine margins and inanga spawning habitat

We define the 'upper estuarine' margin as the riparian environment that occurs between the inland/upstream extent of saltmarsh vegetation and the maximum upstream intrusion of saltwater. Because the latter occurs only during high tides, the upper estuarine margin is characterised by considerable variation because of the strong influence of riverine flow on the position of the freshwater-saltwater interface. Upper estuarine margins provide spawning habitat for inanga, *Galaxias maculatus*, a diadromous fish species currently listed as 'at risk' in New Zealand (Goodman et al., 2014).

Inanga are highly valued by many sectors of the community. Juvenile inanga comprise the bulk of the 'whitebait' catch (McDowall & Eldon, 1980), a fishery of immense cultural and recreational importance to New Zealanders (Booth et al., 2013; DOC 2010b; Kelly, 1988; McDowall, 1965). Protection of inanga is confirmed in a range of statutory documents at national and regional levels. Inanga are an important species for mahinga kai and the protection and enhancement of inanga populations is a cultural priority (Lang et al 2012; Jolly et al., 2013). Inanga are also identified as a taonga species in the Ngāi Tahu Claims Settlement Act 1998 (NZ Government, 1998)

Inanga are known to spawn near the interface between saline and freshwaters (Taylor, 2002). Aside from some exceptions where populations have become land-locked, suitable habitat for spawning in these locations is a necessity for the persistence of inanga (Hickford & Schiel, 2011a). Inanga have a specialised reproductive strategy that is synchronised with the spring tide cycle. Spawning may occur at any time of the year though there is a defined peak of activity in late summer and autumn (Taylor, 2002). Current evidence suggests that all adult inanga eventually migrate to the upper estuarine environment to spawn (Burnet 1965), and pre-spawning aggregations of ripe adults are often observed in those locations (Benzie, 1968). At other times, the same adult populations are typically found higher in the catchment (Hill, 2013). Spawning usually occurs on, or close to, the days of spring high tides though it has been reported in association with flood events at other times (Taylor, 2002).

Eggs are laid in riparian vegetation just below the spring tide high-water level and are therefore effectively in a terrestrial environment for most of their development period (Benzie, 1968a; Richardson & Taylor, 2002; Hickford & Schiel, 2011a). The eggs hatch in response to inundation (e.g., on subsequent spring tides) after a 2-4 week development period (Taylor, 2002). Over this time the eggs are vulnerable to a variety of threats primarily involving terrestrial aspects of the riparian margin. Many of these relate to land use and/or are amenable to management.

Previous research indicates that strong behavioural adaptations underpin this spawning strategy, and that inanga spawning will occur on upper estuarine margins even when the habitat conditions are not favourable for egg survival (Hickford & Schiel, 2011a; Hickford & Schiel 2014). When the spawning habitat is not suitable, egg mortality may be extremely high. For example, Hickford & Schiel (2014) recorded eggs mortalities of up to 85% where spawning had occurred in short mown grass and up to 100% in grasses grazed by livestock. Desiccation of the developing eggs was the primary factor thought to be responsible for this high mortality. Despite such findings, adult inanga appear to devote considerable effort to investigating the riverbank environment prior to spawning. There are many observations of spawning aggregations moving from site to site prior to selecting one for spawning (e.g., Mitchell & Eldon 1991). Where ideal riparian habitat is not found, spawning may occur anyway. Thus there is potential for a large ‘population sink’ problem where rivers provide suitable habitat for adult inanga, but the condition of spawning habitat at the upper estuarine margin is unsuitable leading to limited spawning and high egg mortality. Precisely this situation has been detected in several rivers on West Coast that support large populations of adult inanga yet are effectively population sinks due to the absence of suitable spawning habitat (Hickford & Schiel, 2011a).

In the more general case, the above situation provides a possible explanation for the decline of inanga from their previous abundance, and degradation of spawning habitat is thought to be the major underlying factor (Hickford et al., 2010; Mitchell, 1991, 1994). Despite that limits on the catch of juvenile inanga (whitebait) may also be needed. This suggests that the protection of existing spawning habitat is highly important for inanga conservation. Specific information on where spawning occurs is essential for considering the effects of land use and riparian management options, and to understand the potential impacts of environmental changes such as sea level rise.

Information on the exact location of spawning sites indicates that they occur close to the ‘saltwater wedge’ referring to the upstream extent of saltwater intrusion (Taylor, 2002), although studies have also shown that sizeable areas in this vicinity may be utilised (e.g., Hicks et al., 2010; Barbee et al., 2011). This well-documented association suggested that a measurable shift in spawning site locations would occur in response to earthquake-induced ground level changes in the Avon-Heathcote Estuary/Ihutai catchment if these were of sufficient magnitude to alter the position of the saltwater wedge. Investigating this hypothesis was the focus of the present study. This report provides details of our initial findings to assist parties interested in inanga spawning habitat and its management. We provide information on the post-quake location of spawning and results from spawning area and productivity measurements taken over the 2015 season. We describe the observed changes versus previously known locations and discuss the significance of these in relation to earthquake effects and long-term management. Key management issues to address the post-quake context are identified and recommendations provided for protecting spawning sites in the 2016 season.

Section 2 Methodology

2.1 Study area

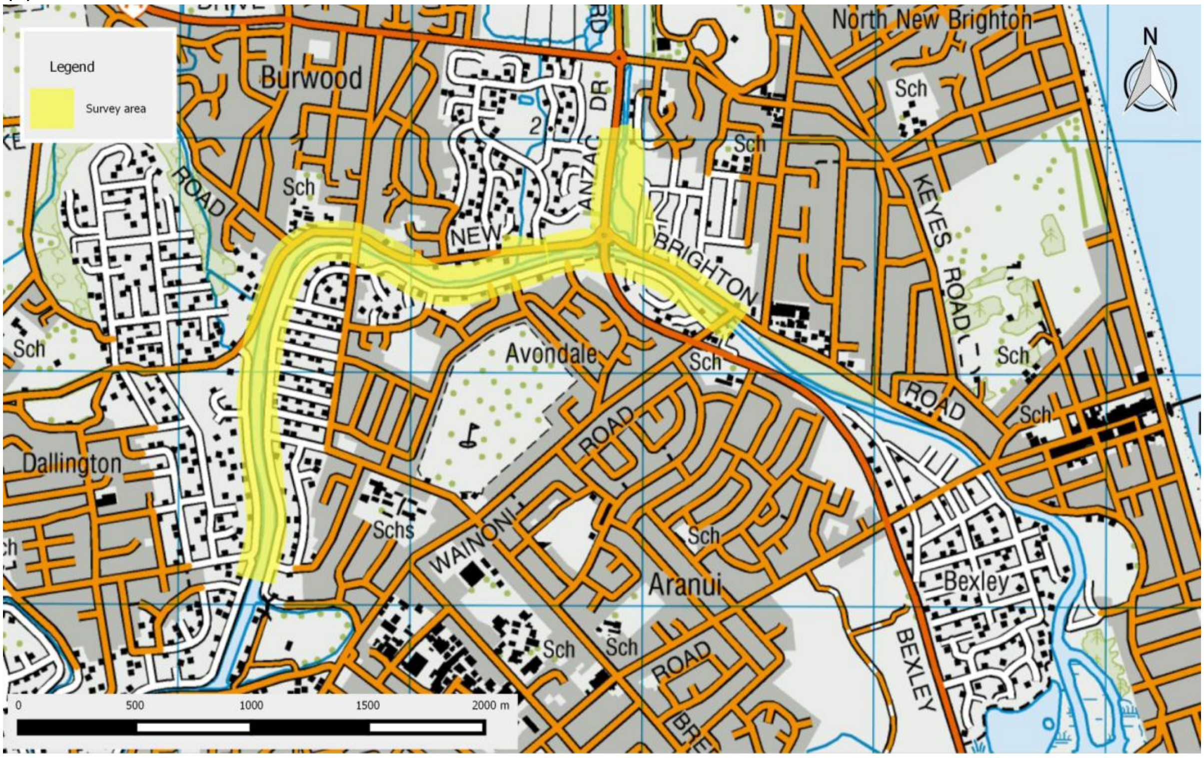
Key objectives for the study were to produce a 'census' style survey of all spawning in the Ōtautahi / Christchurch waterways over the 2015 spawning season, and to detect potential shifts relate to new salinity or inundation conditions. The study area was chosen to meet this objective whilst remaining manageable. To develop the survey design, initial estimates of earthquake induced changes in spring tide saltwater wedge positions were obtained using hand held meters. Previous reports indicate that spawning may occur both upstream and downstream of the saltwater wedge location (Taylor, 2002) and reaches for inanga spawning site surveys were identified accordingly. The initial results were used to assist the identification of reaches of potential interest. Although not definitive in terms of possible conditions during future events, these data indicated that the saltwater wedge position had shifted upstream in the Avon/Ōtākaro and Heathcote/Ōpāwaho.

Beginning December 2014 more detailed salinity measurements were take using Odyssey conductivity/temperature logger arrays deployed over approximately two week intervals across spring tide periods. Additional measurements of bottom and surface salinities were taken on spring tides using a YSI 30 handheld conductivity/salinity/temperature meter with the probe positioned 10 cm from the bottom and top of the water column. In these surveys the progression of the flood tide was followed upstream to establish the maximum upstream extent of saltwater intrusion following the methods of Richardson & Taylor (2002). In our case, the salinity meter was deployed from bridges or by using kayaks. For comparative purposes pre-quake information on the salinity regime was compiled using literature review and personal communications with known researchers with a particular focus on establishing the previous position(s) of the saltwater wedge.

The combined results from salinity testing to end-January were used to establish extents for the area to be surveyed beginning February. The survey area extents were set at the southern end of Aynsley Terrace (Heathcote/Ōpāwaho) and Pembroke Street (Avon/Ōtākaro) (Figure 2). This extent included all reaches within the limit of saltwater intrusion which were thought to contain suitable vegetation.

In the Heathcote/Ōpāwaho the reach further upstream in the vicinity of Wilsons Road has been recorded as a spawning site during a period in which the Woolston Cut was open allowing saltwater penetration further upstream (Eldon et al. 1989). It was not included in the current survey area and no spawning was found upstream of Opawa Road to indicate the need to extent the survey reach further. The small spawning site previously recorded at Steamwharf Stream in the lower Heathcote/Ōpāwaho was surveyed in this study. However, no eggs were found and it was excluded from the maps presented for clarity. Earthquake related changes at this site were reported by Taylor & Blair (2011) and our observations confirmed that riparian conditions at the site remained unsuitable for spawning with liquefaction sediments only partially colonised with new vegetation. In the Avon/Ōtākaro the survey area included Lake Kate Sheppard, a sub-catchment connecting with Travis Wetland to the north, and Anzac Creek, a small waterway near Anzac Drive that is connected to Lake Kate Sheppard via culverts.

(a)



(b)

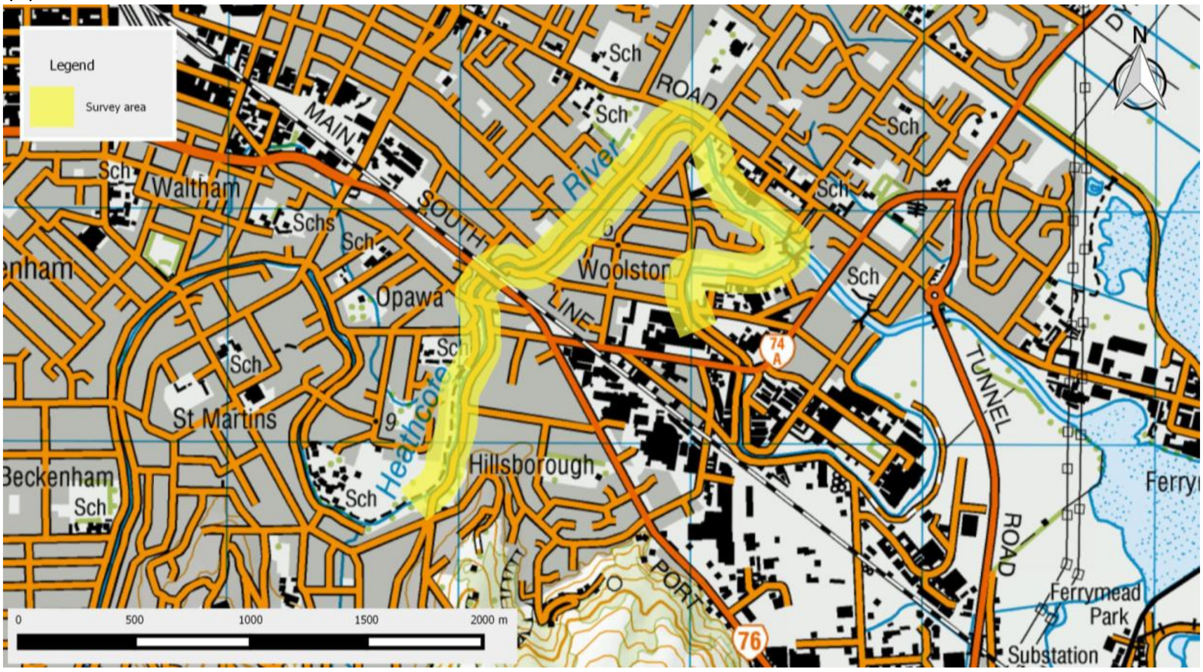


Figure 2. Survey locations: (a) Avon/Ōtākaro catchment. (b) Heathcote/Ōpāwaho catchment. [Basemap: LINZ].

The downstream limits of the survey extent were guided by the transition to dominant saltmarsh vegetation which is considered to be unsuitable for spawning (Mitchell & Eldon 1991). The survey reaches extended from the limit of saltmarsh vegetation to beyond the upstream extent of saltwater intrusion and therefore included all of the upper estuarine margin, as defined above. The exception was within the Lake Kate Sheppard area (a sub-catchment of the Avon / Ōtākaro) where, due to the logistical limitations, only a partial survey of all waterways meeting this definition was achieved.

2.2 Spawning site surveys

2.2.1 Survey schedule

Mortality of eggs between the time of spawning and the survey is a potentially confounding factor. To minimise this effect, a standardised survey schedule was applied to the overall survey design to improve the comparability of results between months within each catchment (Table 1). Each month, surveys were started in the Heathcote/Ōpāwaho on the 6th day after the peak tide sequence. Four to five days of survey effort were typically required in each catchment with each month having some variation in the amount of data to be collected. Surveys then commenced in the Avon/Ōtākaro followed by Lake Kate Sheppard.

Table 1. Tidal cycle data and survey periods in the different catchments. Lake Kate Sheppard and associated waterways are a sub-catchment of the Avon/Ōtākaro.

Month of spawning	Peak tidal cycle start	Peak tidal cycle end	Lunar phase	Peak tidal height* (m)	Survey periods and catchments		
					Heathcote	Avon	Lake Kate Sheppard
February	22/2/2015	25/2/2015	new moon	2.6	March 3-6	March 7 -12	March 13-15
March	20/3/2015	23/3/2015	new moon	2.6	March 29 - April 3	April 4-8	April 9-11
April	18/4/2015	20/4/2015	new moon	2.6	April 26-30	May 1-5	May 6-8
May	17/5/2015	19/5/2015	new moon	2.6	May 26-30	June 1-4	June 5-6

* Based on predicted tide levels at Port of Lyttelton (Lat. 43° 36' S Long. 172° 43' E) in metres above Chart Datum (Source: LINZ).

2.2.2 Subjective survey method

Spawning sites were identified by surveying riparian vegetation for inanga eggs. To achieve coverage of the survey reaches within the time available the procedures outlined in Hicks et al. (2010) were used. In an initial step, all areas of likely habitat were identified in a 'subjective' survey. These areas were then surveyed using a systematic method to detect egg occurrence (see below). For every location where eggs were found with the systematic method, the survey was extended at least 50m either side of the last occurrence to confirm the full extent of the spawning site irrespective of whether adjacent areas had been earlier deemed unsuitable in the subjective survey.

The subjective survey was most critical at the beginning of the study since it set a precedent for identifying the areas to be included in systematic surveys. Subjectivity was addressed by applying the systematic method to survey a large proportion of the Avon/Ōtākaro study area in February. This included a total of 1767 independent searches across a wide range of riparian vegetation types. A similar exercise was conducted for the Heathcote/Ōpāwaho study area in March which included 1491 independent searches (Figure 3). This technique proved valuable by identifying spawning at several less obvious sites that included locations where spawning had not been previously recorded. Additionally, this provided a solid grounding for applying the subjective survey method to help achieve the objective of a catchment-wide census.

2.2.3 Systematic survey method

Selected reaches were searched systematically for egg occurrence using a randomised block design to improve uniformity of the search effort. The reach was first broken into 5m bank length blocks using a 50m tape measure from a point of origin for each reach. Three egg searches were conducted at random locations within the block. Egg searching involved locating the position of the high water mark within the riparian vegetation and inspecting the stems and (where present) root mats of the plants in that location. This was assisted by beginning searches lower on the bank than the expected highwater position and working upwards through the vegetation. Typically a 30-60 cm wide swathe was inspected in each search depending on the density of vegetation present. If eggs were found in any of the three searches, egg density and band width measurements were taken for all three search sites within the block, as described below.

2.2.4 Egg counts, area of occupancy, and site productivity

Methods for egg counts and density measurements were similar to those used by Hickford & Schiel (2011a, 2013). Three locations were searched within a 5m bank length block (as described above) and for each the width of the egg band was measured to the nearest 5cm at the centreline of the swathe. Occasional outlying eggs were ignored, especially if they appeared to have been washed down from higher upstream or higher on the river bank. A 10x10cm quadrat was then placed in the centre of the egg band and all eggs within the quadrat were counted. Zero counts were recorded where these occurred, such as when the egg distribution was not a continuous band. For quadrats with very high egg densities (>200/quadrat), egg numbers were estimated by further sub-sampling using five randomly located 2x2 cm quadrats and the average egg density of these sub-units was used to calculate an egg density for the larger 10x10 cm quadrat. The mean egg density for each discrete spawning site (as defined below) was calculated as the average of all 10x10 cm quadrats sampled within the site.

Individual sites were considered to be continuous or semi-continuous patches of spawning. All spawning occurrences were associated with a given location that was identified as a spawning site. The identification of sites followed an iterative process as the study progressed and information became available on the repeat use of certain locations and new spawning occurrences at others. At the end of the study a final list of sites was compiled (n = 85) together with summary statistics for each.

Area of occupancy (AOO) is a measure of the area utilised by a species and is a function of the scale at which it is measured (Master et al., 2007; IUCN, 2014). In this study the AOO metric was designed to capture the total area utilised for spawning. For every egg occurrence the upstream and downstream extents of the patch were established by conducting further searches where required and the length of the site measured. AOO was calculated for every patch and these patches were then associated with the concept of a 'site' as above. In most instances, AOO was calculated by multiplying the mean egg band width by the length of the site. For atypical locations where the AOO was not a lineal band (e.g., in low bank gradient areas where a broad or patchy distribution can occur) a different method was used whereby the AOO within 1 m^2 grid cells was measured to provide a more accurate measure of the area occupied. The site was gridded in the field using tape measures and string lines with the grid axis oriented parallel to the bank. At a random location within each cell the egg band width was measured and the AOO for each cell calculated as width x length of the area of spawning within the cell. For many cells this was the entire area of the cell (1 m^2) except for cells at the boundaries of the patch. AOO for the patch was calculated as the sum of AOO from all cells. For gridded sites an egg count was taken from each cell using a 10x10 cm quadrat as above. This improved the level of survey effort versus subsampling based on bank length alone and helped improve consistency in the proportion of AOO that was subsampled at each site. The total productivity of each patch (number of eggs) was calculated by multiplying the average egg density by the AOO.

2.2.5 Historical spawning records

Reports were identified that contained information on pre-quake spawning activity in the catchment. Additional information was obtained from researchers active in the area (M. Taylor, S. McMurtrie, C. Meurk, pers. comm.) and records extracted from the National Inanga Spawning Database (Table 2). Records of shoaling adult fish were not interpreted as the location of spawning sites. Information collection was restricted to confirmed spawning site locations as indicated by the observation of eggs in riparian vegetation.

All information was processed by identifying coordinates for upstream and downstream extents from maps or photographs provided in the original reports, or using original coordinates where possible. Where this information was not available, locations were estimated using the text descriptions provided. These distinctions in the basis for mapping are noted in Table 2. Due to variability in the search effort and methodologies used in the different original surveys there are also other sources of uncertainty in these estimated positions. Details of the methods by which inanga spawning was detected and measured in the field are available in the respective reports.

Spawning reach lengths were digitised in QGIS v2.8.2 (QGIS Development Team, 2015) based on the approximate shoreline position on the river bank to which each record related. Semi-continuous stretches of spawning were lumped into a single reach in some cases, generally following the description of discrete spawning areas and reaches given in the original records. Pre-quake spawning reaches were then mapped against the 2015 data as described above.

Figure 3. Location of systematic surveys conducted in the Avon/Ōtākaro catchment in February (left) and the Heathcote/Ōpāwaho catchment in March (right). These surveys included large continuous sections of riverbank and covered a wide range of vegetation types. Red dots show locations at which spawning was recorded at least once over the study period. [Imagery: LINZ]

Section 3 Results

3.1 Location of pre- and post-quake spawning

Pre-quake records

A total of 14 documents were identified that contained information on pre-quake spawning sites in the study area (Table 2). Together with additional information obtained from researchers active in the area and records extracted from the National Inanga Spawning Database this built up a clear picture of pre-quake spawning locations.

Several trends of interest can be identified. In the Heathcote/Ōpāwaho there is clear influence of the Woolston Cut and tidal barrage manipulations on the location of spawning sites, as discussed in Taylor (1998). The records also show the successful restoration of the reach below Opawa Road as a spawning site, beginning with a series of surveys that first established a suitable location and plan for restoration, and then monitoring of spawning occurrences as the vegetation matured (Taylor 1994 and subsequent surveys). However in 2007 no spawning was found, and it was noted that reed canary grass (*Phalaris arudinacea*) had invaded the site (Taylor & Chapman (2007). There was also no spawning found there by Taylor & Main (2010) and again following the earthquakes (Taylor & Blair, 2011). The records also show that spawning has seldom been found on the true left bank of the Heathcote/Ōpāwaho and in all cases the area involved was small.

Another important discovery was the spawning site at Steamwharf Stream (Taylor, 1999; Taylor & McMurtrie, 2004). Spawning at this site was associated with restoration of the riparian vegetation after removal of a section of boxed drain in this waterway. However, earthquake damage subsequently led to the site apparently being abandoned for spawning (Taylor & Blair, 2011).

In the Avon/Ōtākaro the records also show the benefits, for spawning, of appropriate riparian management in known spawning areas. As detailed in Taylor (1999) the size of the site at Avondale Road grew steadily over the years since its discovery in 1989, assisted by protection from mowing. The spawning reach was 250m in length in 1999, and in later surveys spawning was recorded even further upstream associated with the presence of appropriate habitat. The maximum extent was recorded in 2007 in the vicinity of Sharlick Street (Taylor & Chapman, 2007).

Elsewhere on the Avon/Ōtākaro mainstem, spawning has been recorded at various locations on both banks but the sites have been typically small. Exceptions include at Amelia Rogers Reserve and at Corsers Stream mouth where sites of considerable size were discovered in 2004. At Amelia Rogers Reserve the site had been re-graded and planted in 1993, and at Corsers Stream well established riparian vegetation was also present (Taylor & McMurtrie, 2004). However no spawning was found at either of these sites in 2007 despite the vegetation appearing to be suitable (Taylor & Chapman, 2007).

Spawning was found by University of Canterbury researchers in Lake Kate Sheppard in 2006. Later surveys indicated that the lake was becoming an important new off-channel site that was not subject to the threats from mowing and other bank maintenance works characteristic of the main river. However the spawning sites at the lake were severely damaged in the earthquakes and no spawning was found in the post-quake survey of Taylor & Blair (2011).

Table 2. Information on pre-quake spawning identified in literature review and communication with inanga researchers. One previous post-quake record (Taylor & Blair, 2011) is also included.

Year of survey	Information sources	Number of sites recorded	Catchment	General locations / notes	Description of extent recorded?	Coordinates for extent recorded?
1989	Taylor et al. (1992)	1	Avon	TRB 40m reach downstream and upstream of Avondale Road bridge	Y	N
	Meurk (1989) Eldon et al. (1989)	1	Heathcote (after 1986 commissioning of Woolston Cut)	TLB 70m reach downstream and 20m reach upstream of Wilsons Road bridge, TRB 20m reach downstream of Wilsons Road bridge	Y	N
1991	Taylor et al. (1992)	1	Heathcote	TRB 100m reach within King George V Reserve	Y	N
1993	Taylor (1996)	1	Avon	TRB 15m reach above Avondale Road bridge	Y	N
1994	Taylor (1994)	1	Heathcote (after tidal barrage installed)	TRB 30m reach below Opawa Road bridge	Y	N
1995	Taylor (1995)	1	Heathcote	TRB 50m reach below Opawa Road bridge	Y	Y
1996	Taylor (1996) [++]	1	Avon	TRB 90m reach above and 25m reach below Avondale Road bridge	Y	Y
		0	Heathcote	Opawa Road site mown just prior to spawning season	n/a	n/a
1997	Taylor (1997)	1	Avon	TRB 90m reach above Avondale Road bridge	N	N
		0	Heathcote	No eggs found – soon after remediation works	n/a	n/a
1998	Taylor (1998)	1	Avon	TRB 70m reach above and 20m reach below Avondale Road bridge	Y	N
		1	Heathcote	TRB 50m reach below Opawa Road bridge	Y	Y
1999	Taylor (1999)	1	Avon	TRB 250m reach above Avondale Road bridge	Y	N
		2	Heathcote	TRB from Opawa Road site to just downstream of the rail bridge, in Steamwharf Stream TRB 30m reach starting 20m upstream of Dyers Rd Culvert, and in Linwood Drain	Y	N

2000	Taylor (2000)	1	Avon	TRB at Avondale Road observed by DOC staff	N	N
		0	Heathcote	None despite extensive searching		
2002	University of Canterbury unpubl. data	1	Heathcote	TRB small patch in King George V Reserve	Y	Y
2004	Taylor & McMurtrie (2004)	Multiple	Avon	TRB from Alloway Street to Orrick Crescent; TLB at Amelia Rogers Reserve, above and below Avondale Bridge, and at Corsers Stream mouth	Y	Y
		Multiple	Heathcote	TRB in King George V Reserve, TLB and TRB below Opawa Road bridge, and on both sides of Steamwharf Stream	Y	Y
2006	University of Canterbury unpubl. data	2	Avon	TLB Amelia Rogers Reserve TLB Lake Kate Sheppard	Y	Y
2007	Taylor & Chapman (2007)	Multiple	Avon	TRB from Avondale Road bridge to Sharlick Street (770m) and in Lake Kate Sheppard	Y	Y
		0	Heathcote	None despite extensive searching		Y
2008	Hickford & Schiel (2014)	1	Avon	TRB above Avondale Bridge	Y	Y
2010	Taylor & Main unpubl. data	Multiple	Avon	TRB above Avondale Road bridge	N	?
		1	Heathcote	TLB 12m reach adjacent to Woolston Park	Y	Y
2011	Taylor & Blair (2011)	1	Avon	TRB small reach above Avondale Road bridge	Y	Y
		0	Heathcote	None despite extensive searching	n/a	n/a

++ The first finding of eggs on the TLB of the Avon/Ōtākaro is recorded in Taylor (1996) as being in 1992.

Post-quake spawning sites

A total of 85 spawning sites were identified in the 2015 spawning season over the four month survey period (Appendix 1). These comprised of 32 sites on the mainstem of the Heathcote/Ōpāwaho, 47 on the mainstem of the Avon/Ōtākaro, and six in the Lake Kate Sheppard area. The only previous record of post-quake spawning we are aware of is the small reach at Avondale Road recorded in the survey of Taylor & Blair (2011).

Mapping of 2015 data against pre-quake information reveals clear differences between the post- and pre-quake spawning patterns (Figure 3). The sites were distributed over considerable distances in the two main rivers; approximately 2.5km in the Heathcote/Ōpāwaho and 2.2km in the Avon/Ōtākaro. For both of the main rivers this represents a larger extent of occurrence than has been recorded in any previous year. With the exception of the early records at Wilson Road, the spawning extent is now greater than that of all prior records combined for the mainstem of both rivers.

Notable findings include:

- many more spawning sites in the Heathcote/Ōpāwaho catchment than previously reported. Spawning now occurs approximately 1.5km further downstream from the previously reported downstream limit recorded in Taylor & Main (2010). These are also the first records of spawning below the Woolston Cut.

- spawning sites in the Avon/Ōtākaro catchment extend both upstream and downstream of all previously reported locations. Sites found in previously unreported locations included on the true left bank near the Dudley Creek outlet upstream of Avondale Bridge and a long reach of spawning in the main-stem below Corsers Stream.

- spawning in Lake Kate Sheppard was concentrated at a distinct location versus pre-quake records and no spawning was found on the western shores.

- spawning was also identified in Anzac Creek, a nearby waterway. This is an off-channel tributary of the mainstem connected to a small lake that receives water through culvert connections from Lake Kate Sheppard.

Further detail on management implications is presented in Section 4.

(a)

(b)

Figure 3. Distribution of spawning sites recorded in 2015 compared to all previous records. All reach lengths were generated from upstream and downstream coordinates of confirmed spawning occurrences. The post-quake record from 2011 in the Avon/Ōtākaro is shown as a point for clarity (see Taylor & Blair (2011) for further information on the 2011 survey). (a) Heathcote/Ōtākaro. (b) Avon/Ōtākaro. [Imagery: LINZ]

Figure 4. Post-quake spawning sites [clockwise from top left]: Several new spawning sites were found in the lower Heathcote/Ōpāwaho near Radley Park; many sites in the mid- Heathcote/Ōpāwaho are on small terraces on the face and sometimes at the top of steep banks close to the line of mowing; several in the upper Avon/Ōtākaro are on small terraces at the foot of stop-banks; post-quake spawning was found on both banks in the lower Avon/Ōtākaro below Avondale Bridge; a small wetland beside Anzac bridge within the Mahinga Kai Exemplar site was the furthest downstream spawning site located in the Avon/Ōtākaro; a view across to the eastern shore of Lake Kate Sheppard where spawning was consistently found in the same areas.

3.2 Area of occupancy

Over the four month spawning season a total of 157 separate areas of egg deposition were detected and measured. Some of these represent repeat spawning at the same 'site' as defined above. Three of the 85 sites were used in all four months, whereas 32 sites were only used once.

Summary results are presented for the area occupied by eggs grouped by three key areas within the wider Ihutai catchment (Heathcote River/Ōpāwaho mainstem, Avon River/Ōtākaro mainstem, and Lake Kate Sheppard). In each of these, the maximum area of occupancy (AOO) was recorded in March resulting in a defined peak in AOO across the study area as a whole (Figure 5).

A comparison between catchments shows that all three were significant contributors to the total area of spawning in the Avon-Heathcote/Ihutai system (Figure 6). The relative contribution of each catchment to the total area of spawning was variable between months. However, the season-wide average contributions were very close to a one-third contribution from each catchment (Figure 7). This analysis illustrates that each catchment was of similar importance as a provider of suitable areas for spawning over the four month study.

Within each catchment some sites provided much greater areas of spawning than others. The distribution of AOO for all measurements over all months demonstrates that small areas of spawning were more common than large ones within the study area (Figure 8). The largest AOO for a single site was 14.5 m^2 in March for a site at Lake Kate Sheppard. However, this site was nearly contiguous with adjacent sites that month, and the total area of spawning in the vicinity was measured at 35.8 m^2. Of the mainstem sites, the largest were 8.45 m^2 in the Avon/Ōtākaro, and 13.3 m^2 in the Heathcote/Ōpāwaho. In both rivers many sites were relatively narrow semi-continuous bands of eggs on suitable banks. Broader sites were found in the Heathcote/Ōpāwaho in particular, but were not common. Several very small areas of spawning were also detected with nine occurrences of 0.1 m^2 or smaller being recorded over the study period.

Within each catchment, the distribution of sites of different sizes showed no apparent pattern. In both of the main rivers relatively large sites were recorded throughout the reach in which spawning occurred (Figure 9). In the Lake Kate Sheppard catchment the spawning reach was relatively small within the two waterways surveyed (Anzac Creek and Lake Kate Sheppard itself) and the spawning sites were in similar locations between months, in some cases utilising the same vegetation that had supported spawning previously.

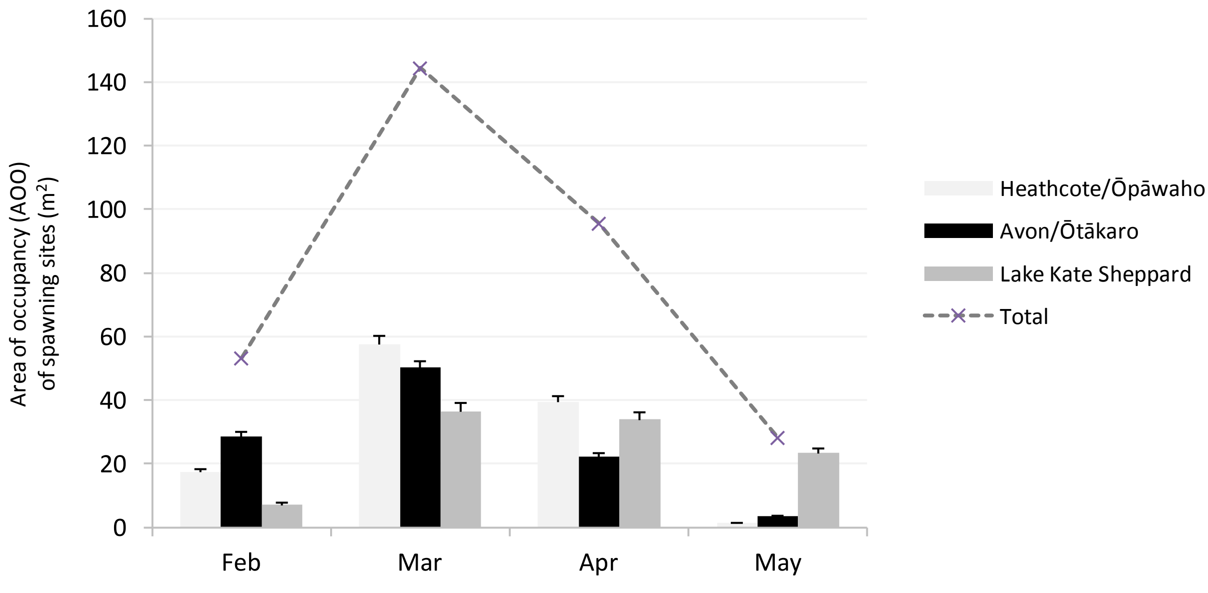


Figure 5. Area of occupancy (AOO) results over four months in the 2015 spawning season. Results are grouped by the three key areas for spawning within the wider Ihutai catchment. See text for further details of the survey extent within each area.

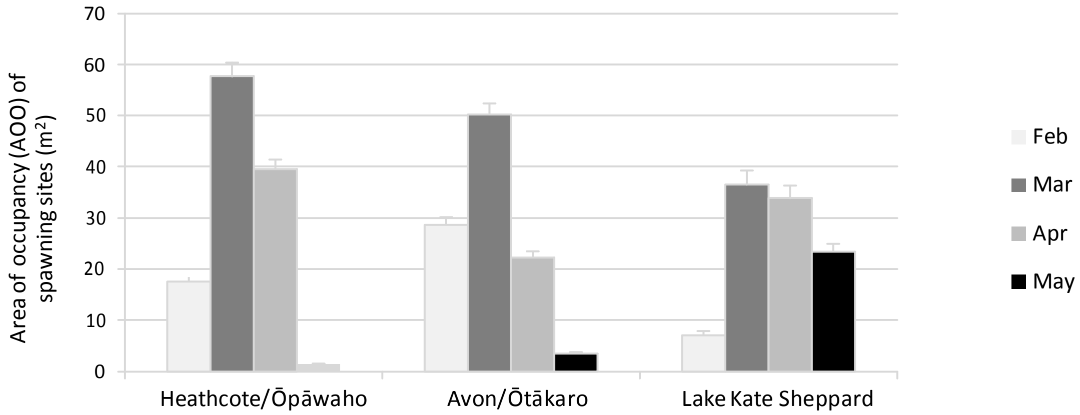


Figure 6. Area of occupancy (AOO) of inanga spawning sites in the three key areas over four months.

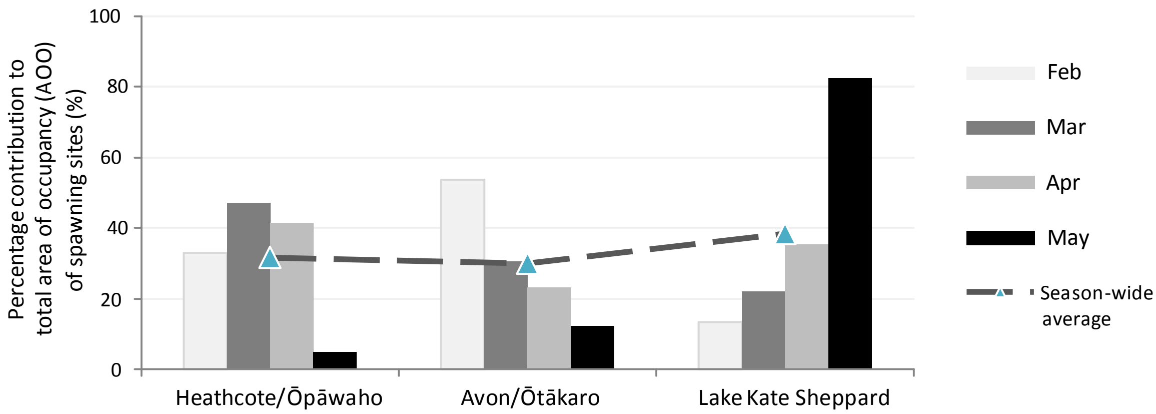


Figure 7. Percentage contribution of the three key areas to the total area of occupancy (AOO) of spawning sites measured each month.

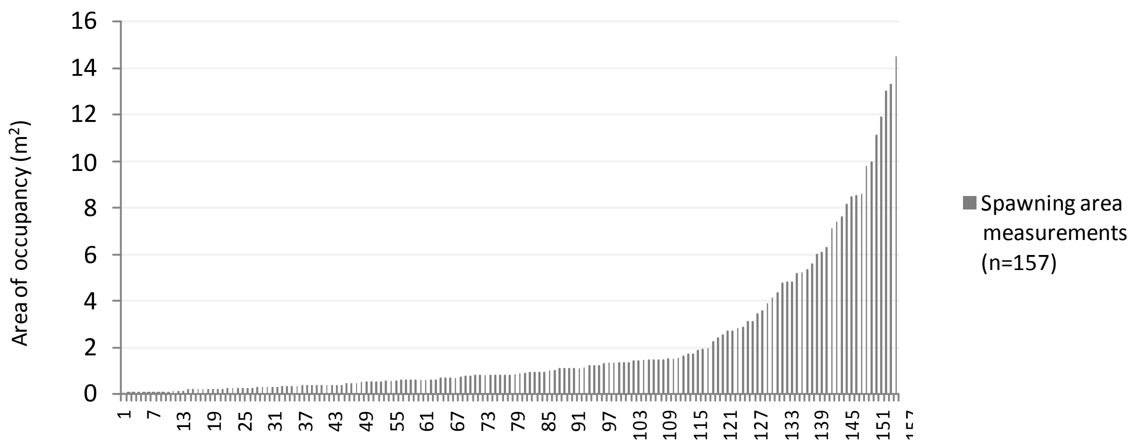


Figure 8. Area of occupancy (AOO) results for 157 individual inanga spawning site measurements taken over four months ranked from smallest (left) to largest (right).

(a)

(b)

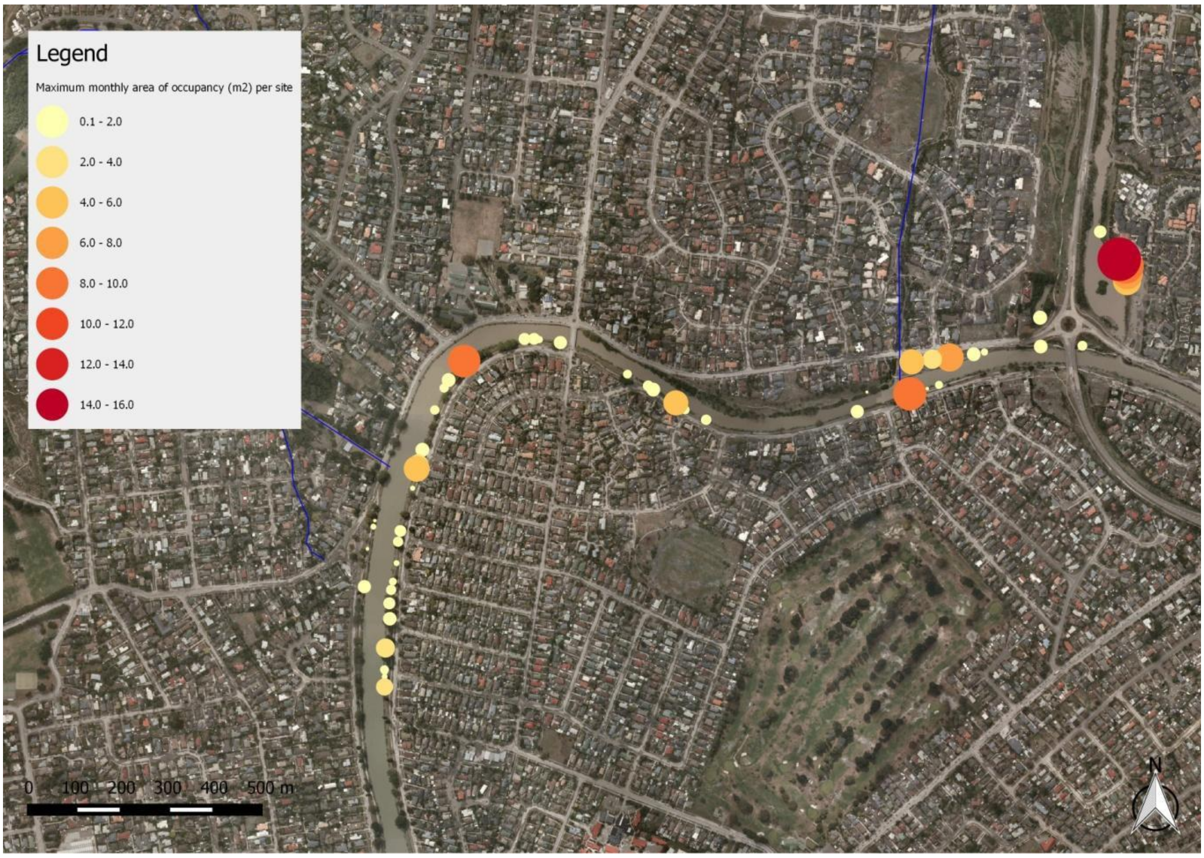


Figure 9. Area of occupancy (AOO) of inanga spawning sites recorded in the 2015 spawning season. Values shown are the maximum monthly AOO measured at each site.
(a) Heathcote/Ōpāwaho mainstem. (b) Avon/Ōtākaro mainstem and Lake Kate Sheppard. [Imagery: LINZ]

3.3 Productivity

The total production recorded over the study period was 11.9 million eggs. March was the most productive month (6.8 million eggs) followed by April (3.1 million eggs). The defined peak in egg production (Figure 10) was commensurate with the peak in AOO (Figure 4). However, different spawning sites varied in their contribution to overall production within the study area in any given month. The catchment contributing most to production in February and March was the Heathcote/Ōpāwaho, whereas in April and May it was Lake Kate Sheppard (Figure 10).

Lake Kate Sheppard was a consistent producer of eggs across all months of the study period whereas production from the mainstem sites was more variable (Figure 11). This is reflected in the percentage contributions of each catchment to productivity each month (Figure 12). For example, in May Lake Kate Sheppard accounted for nearly all of the production in the study area. By contrast, the maximum Avon/Ōtākaro mainstem contribution in any month was 29% of the total production in the wider Avon -Heathcote Estuary/Ihutai system.

The comparison between the percentage contributions to the area of occupancy (Figure 7) and productivity (Figure 12) indicates that egg densities at the Avon/Ōtākaro sites were, on average, lower than sites in the other catchments. Across all 157 measurements the maximum density recorded, in terms of the mean egg density within the area of spawning, was 13.5 eggs/cm^2 at Opawa Road in the Heathcote/Ōpāwaho. This is slightly less than the highest densities recorded in previous studies (e.g., Hickford & Schiel, 2011a).

Densities higher than 10 eggs/cm^2 were also recorded elsewhere in the Heathcote/Ōpāwaho, in Lake Kate Sheppard, and at two small sites in the upper Avon/Ōtākaro (Figure 13). The mean density across all measurements was 0.21.

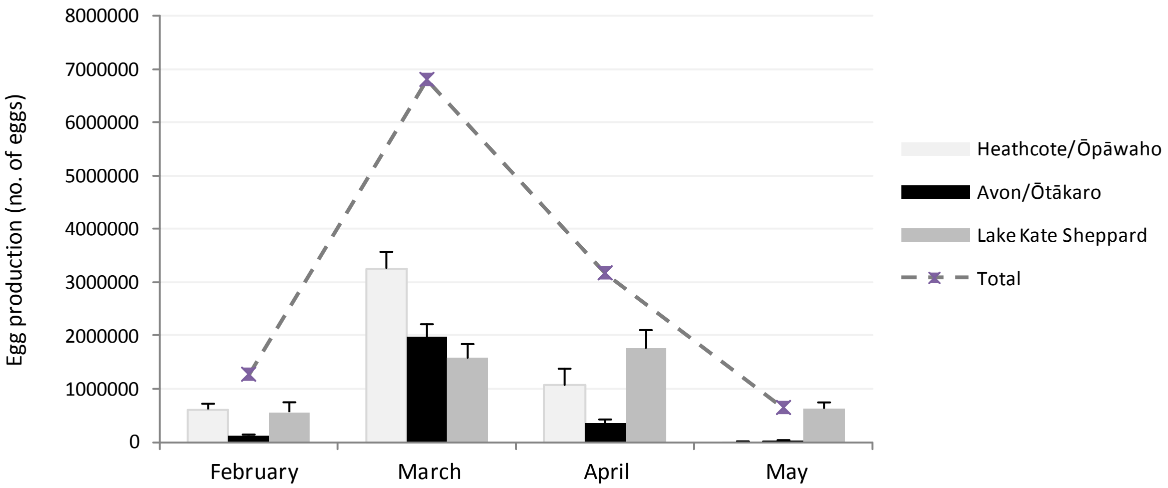


Figure 10. Egg production over four months in the 2015 spawning season.

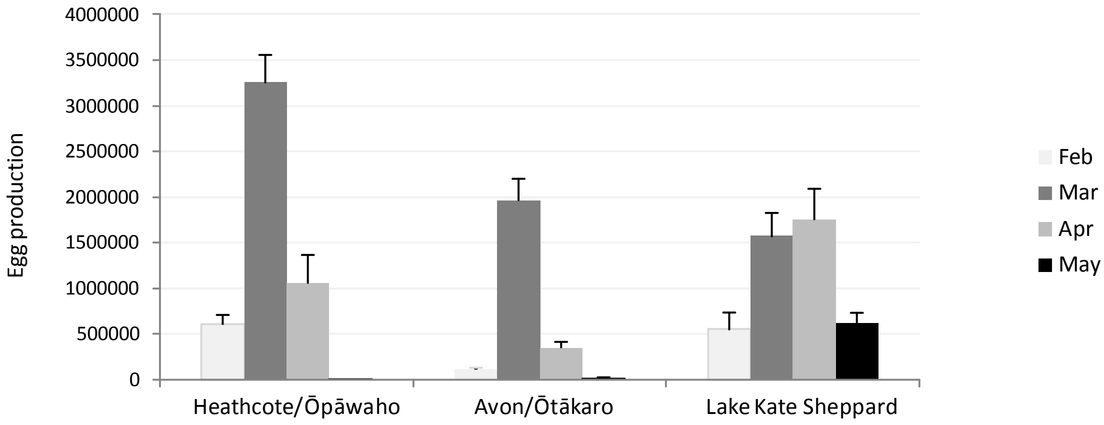


Figure 11. Egg production from the three key areas over four months.

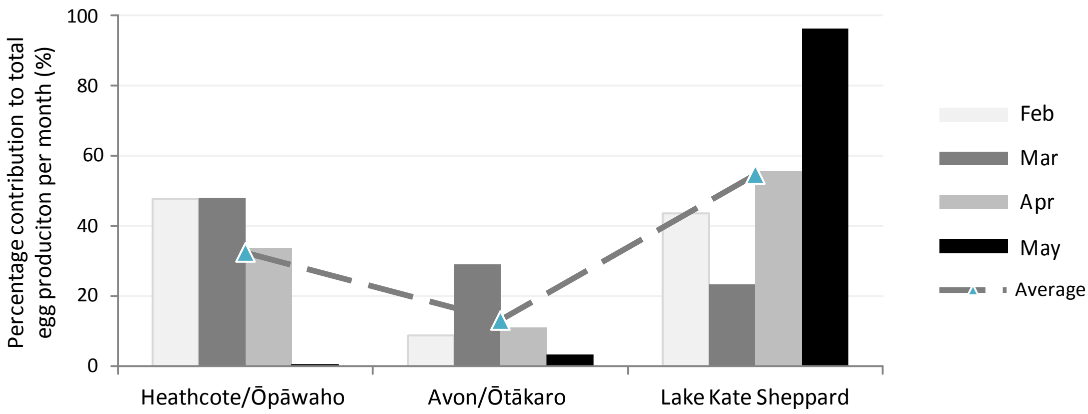


Figure 12. Percentage contribution of the three key areas to the total egg production measured each month.

Figure 13. Example of sites where high egg densities were recorded. [left] A site at Lake Kate Sheppard where high eggs densities were found on all four months of the survey period. [right] High egg densities at a site in the Lower Heathcote/Ōpawāho nearly Radley Park

Section 4 Discussion

4.1 Christchurch City waterways as an inanga source

The number of whitebaiters on the riverbanks in spring provides clear evidence of a substantial whitebait fishery in the Avon/Ōtākaro and Heathcote/Ōpāwaho catchments. However, the whitebait run marks only the half way point of a complex life history. Whitebait that escape capture then mature in lowland waterways before returning to the upper estuarine margin to spawn. If the upper estuarine area of the river they entered six months earlier as a whitebait does not have suitable spawning habitat, then the amount of spawning as well as the survival of any eggs is greatly reduced (Hickford & Schiel 2011a). Rivers with degraded or no suitable spawning habitat become 'sinks', still attracting whitebait and supporting adult populations, but not contributing to further generations. These rivers are entirely dependent on 'source' rivers elsewhere to support their whitebait fisheries and sustain their adult populations.

The level of egg production recorded in this study demonstrates that the Avon-Heathcote catchment is of major importance for inanga spawning. For comparison, an extensive study of known spawning sites on West Coast rivers (Hickford & Schiel, 2011a) recorded a maximum monthly production of 1.7 M eggs in the Orowaiti River. Monthly production in excess of 1 M eggs was recorded in only two of the 14 rivers surveyed. However, since the present study did not measure egg survival, the level of larval production is unknown and would be strongly influenced by the level of disturbance when eggs were present. Consistent with previous reports, some spawning was found at locations with sub-optimal conditions, and at these sites high egg mortality can be expected.

Based on the average weight of 0.52 g for individual whitebait (McDowall & Eldon, 1980), the total egg production measured over the study period represents a potential whitebait stock of around 6170 kg. If spawning sites are favourable a high proportion of the eggs observed may produce larvae. However, larval mortality in the oceanic phase of development is likely to be very high, resulting in only a very small percentage of larvae returning as whitebait (Hickford & Schiel, 2011a). Consequently, the relatively impressive egg production figures recorded in this study account for only a small proportion of the actual whitebait run as judged by catch records and observations. An important conclusion to draw is that much greater levels of inanga spawning are required to increase the whitebait run for cultural and recreational harvest, and to help maintain or improve adult inanga populations.

Losses of spawning areas associated with land-use changes, compounded by a lack of specific information on spawning site locations, is the most likely mechanism behind reported declines in inanga abundance (Goodman et al. 2014). To maintain the whitebait resource and underpin initiatives for enhancement, it is crucial to protect all known spawning habitat. Results from this study provide updated information to assist this objective. They also indicate there is considerable potential for further increasing the level of inanga spawning in the post-quake waterways of Ōtautahi Christchurch (see section 4.4).

4.2 Earthquake-related changes

The post-quake spawning pattern has several important differences to the previously known distribution of spawning sites. In the peak month of the season, being March, the total area of occupancy (AOO) of spawning in the catchment was 164 m^2; much greater than that suggested by previous records. Overall this is good news. The results suggest that the post-quake riparian topography contains more suitable area within the range sought by inanga for spawning, assuming that adult population levels are similar, which may mean that suitable areas pre-quake were simply not available or being used. Irrespective of whether there are more or less adults now, this new configuration of suitable spawning areas requires protection.

The areas involved are mostly on 'new ground' when compared to the pre-quake spawning record. There is anecdotal evidence that some of these surfaces have been created during, or since the earthquakes, such as in the Heathcote/Ōpāwaho where small benches have developed at the foot of steep banks from bank collapses and/or waterborne sediments trapped by riparian vegetation. There appear to be more of these features than existed pre-quake, and they are supporting a considerable amount of spawning.

In other locations, the post-quake areas of spawning clearly relate to changed ground levels leading to a new a shoreline position on an otherwise similar shoreline profile. This situation exists at Lake Kate Sheppard where the previously known spawning surfaces are now lower than they were pre-quake. In these areas, water levels are now higher on the shoreline in relative terms and, in combination with liquefaction effects, the vegetation pattern has changed considerably from the pre-quake conditions. In response, inanga have found suitable conditions at a new site and spawning was consistently found in this area over the 2015 season. The site produced high egg densities in all four months of the study period and was the most productive site in the Avon/Ōtākaro catchment.

In addition to an increase in the area occupied by spawning, the extent of suitable reaches has expanded since the earthquakes. The most marked change is in the Heathcote/Ōpāwaho where spawning now occurs within a 2.4 km stretch of river that extends further downstream than any previous record. Spawning extent in the Avon/Ōtākaro catchment has also expanded and now occurs upstream and downstream of the previously known limits. Overall, this means that a greater length of waterway requires management for the protection of inanga spawning sites. Where threats from competing land uses are present, inanga spawning sites may be vulnerable.

4.3 Management implications

The major implications for management are associated with inanga spawning in new locations. Currently, riparian management in spawning areas consists of a similar range of activities to those used pre-quake. Examples include the use of controls on mowing known spawning sites immediately prior to and during the spawning season, which is important since mowing spawning sites with eggs present or not allowing mowed spawning sites sufficient time to recover before spawning commences leads to greatly increased levels of egg mortality (Hickford & Schiel, 2014). To address the extent of spatial change there is a need to amend management accordingly.

Due to differences in riparian land uses between the main catchments there are a range of implications to consider. Some of key effects and management considerations are summarised in Table 3.

Table 3. Pre- versus post- quake comparison+ of selected attributes for the three major waterways supporting inanga spawning in 2015.

Spawning site attributes	Heathcote/Ōpāwaho mainstem	Avon/Ōtākaro mainstem	Lake Kate Sheppard
Extent of spawning reaches (m)			
pre-quake	2100	1800	180
post-quake	2500	2200	130
Δ Limits of extent (+ is Δ upstream, - is Δ downstream)			
upstream limit	- 1100	+ 230	+ 80
downstream limit	- 1500	- 170	+ 130
Land use activities at spawning sites			
pre-quake	Recreation (including fishing), transport infrastructure, stormwater outlets, retaining walls	Recreation (including fishing), transport infrastructure, stormwater outlets, stop-bank structures	Recreation (including fishing & birdwatching)
post-quake	Recreation (including fishing), transport infrastructure, stormwater outlets, retaining walls	Recreation (including fishing), transport infrastructure, stormwater outlets, stop-bank structures	Recreation (including fishing & birdwatching)
Aquatic activities at spawning sites			
pre-quake	Kayaking, dredge operation	Kayaking, rowing, dredge operation	none reported
post-quake	Kayaking, dredge operation	Kayaking, rowing, dredge operation	none reported
Threats to spawning habitat			
pre-quake	Physical disturbance, vegetation change, mowing/weed-eating in spawning season	Physical disturbance, vegetation change, mowing/weed-eating in spawning season	Physical disturbance, sedimentation
post-quake	Physical disturbance, vegetation change, mowing/weed-eating in spawning season	Physical disturbance, vegetation change, mowing/weed-eating in spawning season	Physical disturbance, sedimentation
Key management activities at spawning sites			
pre-quake	Mowing, weed control, recreation facilities, bank stabilisation	Mowing, weed control, recreation facilities, bank stabilisation, flood management	Weed control, native planting, recreation facilities, water level control
post-quake	Mowing, weed control, recreation facilities, bank stabilisation	Mowing, weed control, recreation facilities, bank stabilisation, flood management	Weed control, native planting, recreation facilities, water level control
Priorities for spawning site protection			
pre-quake	Mowing, weed control, recreation facilities, bank stabilisation	Prevent disturbance of eggs, avoid mowing in spawning season, control invasive weeds, control sediment pollution	Prevent disturbance of eggs, monitor restoration plantings, control invasive weeds, control sediment pollution
post-quake	Mowing, weed control, recreation facilities, bank stabilisation	Protect new spawning locations, change mowing schedule, consider new sites in decisions on stop-banks, maintain controls on invasive weeds & sediment pollution	Protect new spawning locations, consider new sites in decisions on restoration plantings, maintain controls on invasive weeds & sediment pollution

+ pre-quake conditions derived are from historical records, post-quake conditions are as measured in 2015.

New spawning sites in the vicinity of Radley Park in the Heathcote River/Ōpāwaho catchment are relatively well protected at present because they occur in areas where there is a wide strip of undisturbed riparian vegetation. Park maintenance activities in Radley Park (e.g., mowing) are located very close to the area of spawning at some sites but do not pose a direct risk. However, an interesting and potentially challenging result of this study is the finding of considerable spawning in areas of exotic vegetation. This included at Radley Park where spawning was found in patches of reed canary grass (*Phalaris arundinacea*),*)* and in areas dominated by reed sweet-grass (*Glyceria maxima*). Attempts to control these species should therefore be undertaken with caution within inanga spawning reaches. In the case of the Radley Park sites, spawning was also typically found in patches of creeping bent (*Agrostis stolonifera*) which was also present at the sites with patches of *Phalaris* and *Glyceria*. This suggests that gradual removal of the latter might be a safe strategy if grasses such as creeping bent can quickly colonise the site, though timing would be important.

A more unusual situation exists at the well known area of spawning near Opawa Road (Figure 14). In this study four separate patches of eggs were recorded over the study period (recorded as four sites) in this relatively small area. Two of these sites were in patches of reed canary grass with no other species in contact with the eggs, and spawning occurred there over successive months. This further demonstrates the need for a well-informed approach to manipulating vegetation in spawning areas.

Figure 14. Inanga eggs near Opawa Road on reed canary grass (*Phalaris arundinacea*), an exotic species that has invaded many New Zealand waterways. Multiple layers of eggs were typically found at several sites where reed canary grass was dense resulting in relatively high egg densities.

A different situation exists in the remainder of the Heathcote/Ōpāwaho catchment above Radley Street where regular mowing maintains short grass conditions along the riverbank in most places. With the discovery of several spawning sites in this reach this mowing presents a potential threat. The line of mowing was generally observed to be very close to the line of eggs (Figure 15).However, it would only need to be set back around two metres to effectively avoid spawning habitat.

Figure 15. Examples of spawning sites which were mown in late April. In these photos eggs are present in the locations indicated by the flags and were laid earlier in the month when the vegetation was taller. Moving the line of mowing back by 2 metres would afford protection to many such sites on the Heathcote/Ōpāwaho.

Semi-regular clearance of vegetation on the front face of the river banks poses a more serious threat to spawning (Figure 16). Where eggs are present, close to 100% mortality will occur as this band of vegetation coincides with the footprint of spawning sites in the majority of cases. This activity also elevates the risk of bank erosion by exposing the substrate to greater erosive forces in relation to water and wind thereby having a further destabilising effect. For these reasons it is recommended that bank maintenance using weed-eaters is avoided immediately prior to, and during the spawning season.

In the Avon/Ōtākaro catchment, bank stabilisation issues are less of a concern. Instead, much of the spawning reach is characterised by the presence of compacted gravel stop-banks in close proximity to the river bank or otherwise forming it. Many of the spawning sites documented occur in vegetation at the foot of these banks. These new locations are important to consider in connection to the future position of stop-banks and other potential works associated with flood management and decisions on land uses in adjacent Residential Red Zone lands. Some threats from mowing were noted above Alloway Street in areas not previously known for spawning. In the lower catchment, vegetation clearance using weed-eaters on bank faces occurred late in the season (Figure 17). Altering the locations and timing of these maintenance activities offers relatively straightforward management solutions for protecting spawning sites.

Figure 16. An example of vegetation change that is a direct threat to inanga spawning at a site in the mid-Heathcote/Ōpāwaho. [left] conditions at the site in March that supported the production of 118000 eggs. [right] conditions in April following the clearance of vegetation on the banks. Production was reduced to 1875 eggs, as found in remnant patches of vegetation. Close to 100% egg mortality can be expected.

The implications for protecting spawning sites at Lake Kate Sheppard are very different to protecting the spawning sites on the mainstems of the rivers. The area is currently a reserve and there are few activities that pose immediate threats. Ensuring that any future development of the reserve is designed to be compatible with spawning habitat may be important looking ahead, and this includes any plans to extending areas of native plantings. The new spawning sites are in accessible yet easily protected locations and this lends itself to educational visits as well as monitoring. For these reasons, and due to the consistency of use, Lake Kate Sheppard may be a useful location for awareness-raising activities such as the provision of interpretation facilities and as a site for educational programmes. Since the spawning sites are located within the Mahinga Kai Exemplar Project[2] this would fit well with current aspirations for the area.

Figure 17. Two examples of current bank maintenance work using weed-eaters in areas not previously known as spawning sites in the Avon/Ōtākaro catchment. The swathe of vegetation clearance coincides with the location of spawning. [left] The reach below Corsers Stream on the true left bank. In February, spawning was semi-continuous along this reach with production totalling 80000 eggs. [right] A site on true right bank that produced 124000 eggs in March.

4.4 Potential for spawning site restoration

Several new sites in the Heathcote/Ōpāwaho were found a considerable distance downstream of any previous records. This suggests that there is considerable potential to increase the amount of spawning habitat in the Heathcote/Ōpāwaho because there were many areas between the newly-found upstream and downstream limits that did not support spawning, but that may be amenable to restoration. Overall, this provides a beneficial situation for spawning site management. Potential strategies include identifying the 'low hanging fruit' in terms of sites that may be restored with relatively small investments, and/or targeting sites where competing land uses are few.

In general, the size of the potentially suitable reach creates considerable room to move when designing strategies for protection and enhancement alongside other riparian land uses and values. A similar situation exists in the Avon/Ōtākaro, whilst in Lake Kate Sheppard the area suitable for spawning may naturally expand as vegetation recovers from liquefaction effects, particularly on the eastern shoreline.

There are certainly new opportunities for spawning site restoration in the post-quake landscape and investigating these is a practically useful approach for management. To assist this, the Whaka Inaka: Causing Whitebait[3] project is currently underway in the Heathcote/Ōpāwaho and Lake Kate Sheppard catchments. The project brings together many

[2] The Mahinga Kai Exemplar Project is joint project between Avon Ōtākaro Network, Te Rūnanga o Ngāi Tahu and Ngāi Tūāhuriri Rūnanga centred on the Anzac Drive Reserve.
[3] Whaka Inaka: Causing Whitebait is a collaborative project between EOS Ecology, Te Rūnanga o Ngāi Tahu, and the University of Canterbury, and is supported by the Department of Conservation and a range of local groups and organisations.

sectors of the community around the topic of inanga conservation and will provide useful information for waterway managers. Specific objectives include providing information on whether the reach between Radley Street and the Woolston Cut could be remediated to support spawning in the Heathcote/Ōpāwaho catchment. This is a currently a neglected reach where competition for riparian land uses appears to be relatively low and invasive weed species are dominant.

Another important finding of this study relates to the off-channel habitat provided by Lake Kate Sheppard. As was evident before the earthquakes, this engineered system attracted spawning and in 2007 the lake was found to have supported at least as much spawning as the Avondale site where the majority of historical spawning has occurred (Taylor & Chapman, 2007). The extent to which spawning in the lake relates to the resident adult population or includes contributions from inanga resident further upstream, or in Travis Wetland, is currently unknown as is the level of connectivity between these populations in general. However, the post-quake findings are encouraging by demonstrating that the lake has remained a preferred site despite earthquake-related changes. This adds to the evidence that creating additional habitat through the use of channels and other shoreline engineering configurations is an effective strategy where space permits. A particular benefit of this approach is that such areas can be designed to be more easily protected through choosing locations that avoid issues from competing demands. In combination with initiatives to protect known spawning sites these restoration strategies have considerable potential for improving the resilience of inanga spawning to potential perturbations and existing threats.

Lastly, we also draw attention to the need to conserve and enhance adult inanga habitat. If spawning areas become better known and better protected, the size of adult populations may become relatively more important as a limiting factor for larval production. Lack of suitable adult habitat may be especially important in some waterways, and in general this leads to a focus on riparian and in-stream conditions further upstream. In combination with managing upper estuarine margins to support spawning, this suggests that whole-of-catchment waterway corridor initiatives would be beneficial to address the needs of highly mobile species such as inanga.

Section 5 Recommendations

- There are long-established recommendations to not mow riverbank vegetation in known inanga spawning areas during the spawning season since poorly-timed mowing greatly reduces levels of spawning and egg survival. The timing of this restriction is recommended to be December to June to ensure that spawning sites are in suitable condition early in the season and that eggs laid in May are able to survive.
- The areas recommended for restricted mowing in the Avon/Ōtākaro, Heathcote/Ōpāwaho and Lake Kate Sheppard catchments need to be expanded. For the Avon/Ōtākaro this should include both banks between the Anzac Drive bridge and the intersection of Breezes Road and Avonside Drive. For the Heathcote/Ōpāwaho this should include both banks between the intersection of Chichester Street and Cumnor Terrace and the Opawa Road bridge. For Lake Kate Sheppard this should include all of the shoreline.
- Control of invasive weeds such as reed canary grass, reed sweet-grass, and yellow-flag iris must give attention to inanga spawning. The mosaic of riparian vegetation in and around patches of these weeds may contain significant inanga spawning sites.
- Any modifications to the shape of banks or the river bed within the reaches of river important for inanga spawning (see above) must give attention to inanga spawning. There is clear evidence that inanga spawning is responding positively to the post-earthquake reconfiguration of bank shape and steepness.
- The effectiveness of spawning habitat protection and future restoration is also linked to the condition of adult inanga populations. Whole catchment initiatives are needed to address these different life stages and their associated vulnerabilities.

Acknowledgements

We acknowledge the assistance provided by Mark Taylor (Aquatic Ecology Ltd), Shelley McMurtrie (EOS Ecology Ltd) and Colin Meurk (Landcare Research) to identify historical information on inanga spawning sites. We also thank the staff of the Waterways Centre for Freshwater Research and Marine Ecology Research Group and to the many volunteers who have assisted this research. Special thanks to Jesse Burns, Jason Telford, Nicole Wehner, Eimear Egan and Judith Rikmanspoel for assisting with field surveys.

Support for this study was provided by the Ngāi Tahu Research Centre and IPENZ Rivers Group.

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Appendix 1. Inanga spawning sites and locations.

Site ID	NZTM easting	NZTM northing	Catchment / Subcatchment	Maximum area in 2015 (m^2)	Month largest AOO recorded
H1	1574047	5177724	Heathcote/Ōpāwaho	13.30	February
H2	1574076	5177753	Heathcote/Ōpāwaho	1.20	March
H3	1574097	5177720	Heathcote/Ōpāwaho	0.33	March
H4	1574233	5177736	Heathcote/Ōpāwaho	0.13	March
H5	1574292	5177736	Heathcote/Ōpāwaho	4.80	March
H6	1574350	5177759	Heathcote/Ōpāwaho	13.00	March
H7	1574388	5177780	Heathcote/Ōpāwaho	0.13	April
H8	1574403	5177866	Heathcote/Ōpāwaho	1.20	February
H9	1573956	5178375	Heathcote/Ōpāwaho	1.70	April
H10	1573934	5178369	Heathcote/Ōpāwaho	0.30	March
H11	1573920	5178363	Heathcote/Ōpāwaho	3.44	March
H12	1573853	5178297	Heathcote/Ōpāwaho	0.40	April
H13	1573805	5178225	Heathcote/Ōpāwaho	1.70	March
H14	1573798	5178215	Heathcote/Ōpāwaho	3.90	March
H15	1573775	5178228	Heathcote/Ōpāwaho	0.40	April
H16	1573771	5178222	Heathcote/Ōpāwaho	0.40	April
H17	1573712	5178121	Heathcote/Ōpāwaho	1.33	March
H18	1573673	5178078	Heathcote/Ōpāwaho	1.40	April
H19	1573638	5178075	Heathcote/Ōpāwaho	0.47	April
H20	1573642	5178035	Heathcote/Ōpāwaho	0.20	April
H21	1573615	5178046	Heathcote/Ōpāwaho	0.50	April
H22	1573625	5178010	Heathcote/Ōpāwaho	0.30	March
H23	1573615	5178001	Heathcote/Ōpāwaho	0.80	April
H24	1573587	5177971	Heathcote/Ōpāwaho	1.87	March
H25	1573576	5177958	Heathcote/Ōpāwaho	0.27	March
H26	1573547	5177925	Heathcote/Ōpāwaho	9.97	March
H27	1573446	5177867	Heathcote/Ōpāwaho	1.96	March
H28	1573272	5177751	Heathcote/Ōpāwaho	1.13	March
H29	1573092	5177655	Heathcote/Ōpāwaho	0.70	February
H30	1573089	5177653	Heathcote/Ōpāwaho	0.80	February
H31	1573087	5177649	Heathcote/Ōpāwaho	4.33	March
H32	1573084	5177646	Heathcote/Ōpāwaho	2.40	March
A1	1575864	5183543	Avon/Ōtākaro	0.75	February
A2	1575774	5183541	Avon/Ōtākaro	1.44	February
A3	1575652	5183529	Avon/Ōtākaro	0.40	February
A4	1575629	5183524	Avon/Ōtākaro	1.47	February
A5	1575577	5183517	Avon/Ōtākaro	6.09	February
A6	1575554	5183458	Avon/Ōtākaro	0.50	March
A7	1575540	5183513	Avon/Ōtākaro	2.85	February
A8	1575529	5183450	Avon/Ōtākaro	0.10	May
A9	1575495	5183507	Avon/Ōtākaro	4.77	February

A10	1575491	5183438	Avon/Ōtākaro	8.45	March
A11	1575399	5183442	Avon/Ōtākaro	0.07	March
A12	1575378	5183400	Avon/Ōtākaro	1.33	February
A13	1575052	5183381	Avon/Ōtākaro	0.83	February
A14	1575007	5183402	Avon/Ōtākaro	0.60	March
A15	1574987	5183417	Avon/Ōtākaro	4.80	February
A16	1574938	5183445	Avon/Ōtākaro	1.47	March
A17	1574927	5183453	Avon/Ōtākaro	0.88	March
A18	1574882	5183478	Avon/Ōtākaro	0.60	March
A19	1574737	5183545	Avon/Ōtākaro	1.33	April
A20	1574692	5183552	Avon/Ōtākaro	0.40	March
A21	1574680	5183553	Avon/Ōtākaro	1.07	March
A22	1574660	5183553	Avon/Ōtākaro	1.10	May
A23	1574530	5183505	Avon/Ōtākaro	8.13	March
A24	1574496	5183464	Avon/Ōtākaro	1.45	April
A25	1574487	5183447	Avon/Ōtākaro	0.67	March
A26	1574467	5183400	Avon/Ōtākaro	0.67	April
A27	1574440	5183314	Avon/Ōtākaro	1.50	March
A28	1574432	5183285	Avon/Ōtākaro	2.70	March
A29	1574428	5183274	Avon/Ōtākaro	5.17	March
A30	1574419	5183232	Avon/Ōtākaro	0.20	March
A31	1574338	5183162	Avon/Ōtākaro	0.10	March
A32	1574394	5183140	Avon/Ōtākaro	1.07	March
A33	1574335	5183149	Avon/Ōtākaro	0.27	March
A34	1574389	5183117	Avon/Ōtākaro	0.80	March
A35	1574323	5183101	Avon/Ōtākaro	0.10	March
A36	1574385	5183071	Avon/Ōtākaro	0.27	April
A37	1574378	5183031	Avon/Ōtākaro	0.47	April
A38	1574374	5183014	Avon/Ōtākaro	0.80	April
A39	1574316	5183020	Avon/Ōtākaro	1.33	March
A40	1574370	5182985	Avon/Ōtākaro	1.10	April
A41	1574371	5182952	Avon/Ōtākaro	1.40	April
A42	1574362	5182889	Avon/Ōtākaro	2.80	April
A43	1574360	5182842	Avon/Ōtākaro	0.60	April
A44	1574361	5182838	Avon/Ōtākaro	0.33	April
A45	1574361	5182827	Avon/Ōtākaro	0.27	April
A46	1574360	5182822	Avon/Ōtākaro	0.10	April
A47	1574361	5182805	Avon/Ōtākaro	2.25	March
LKS1	1575959	5183682	Lake Kate Sheppard	6.00	April
LKS2	1575960	5183698	Lake Kate Sheppard	7.60	May
LKS3	1575957	5183715	Lake Kate Sheppard	9.80	March
LKS4	1575942	5183729	Lake Kate Sheppard	14.50	March
LKS5	1575901	5183787	Lake Kate Sheppard	1.20	April
LKS6	1575772	5183603	Lake Kate Sheppard	1.53	February

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