River-corridor restoration and whitebait conservation in Steam Wharf Stream, Christchurch

Shane Orchard

Prepared for

Christchurch City Council
July 2020

Cover photograph:
Riparian restoration work at Steamwharf Stream in the lower Heathcote Ōpāwaho catchment.
Photo: S. Orchard

Waterlink Ltd
CONSERVATION PLANNING • RESOURCE MANAGEMENT
439 Marine Parade, Christchurch 8062
Aotearoa / New Zealand
T: +64-3-388 8281 | M: +64-21-318548

This document has been prepared for the sole benefit of the client.
It is the responsibility of the reader to verify the currency of the document version and status.

Document revision and status

Revision	Date	Status	Approved by	Issued by
v1	25/07/2020	Draft for client review	S. Orchard	S. Orchard
Final	30/10/2020	Final	B. Margetts	S. Orchard

River-corridor restoration and whitebait conservation in Steamwharf Stream, Christchurch

Shane Orchard

Prepared for

Christchurch City Council
July 2020

Report WL20072 for Christchurch City Council
© Copyright Waterlink Ltd

This document has been prepared for the sole benefit of the client. Copyright in the form of this report remains with Waterlink Ltd. This report is entitled to full protection given by the Copyright Act 1994 to the holders of the copyright, and reproduction of any substantial passage from the report except for the educational purposes specified therein, is a breach of the copyright of the author and/or publisher. Subject to these conditions, this document may be transmitted, reproduced or disseminated only in its entirety. This copyright extends to all forms of photocopying and any storing of material in any form of information retrieval system.

Disclaimer and usage rights
This document is subject to with the provisions of the agreement between Waterlink Ltd and the client. Findings, recommendations, and professional opinions expressed within this document relate only to the requirements communicated to Waterlink Ltd by the client and may not be applicable to other contexts. Assumptions relied upon in preparing this report include information provided by the client and other third parties, some of which may not have been verified. Waterlink Ltd undertakes no duty, nor accepts any responsibility, to any party who may rely upon or use this document other than the client. This disclaimer shall apply notwithstanding that this report may be made available to other legal entities.

TABLE OF CONTENTS

1. Introduction

1.1 Background

The Canterbury earthquakes caused widespread changes in Christchurch's natural environments, particularly towards the east of the city in the vicinity of the estuary and waterways (Orchard et al. 2020). In addition to widespread hydrological changes, many waterways were affected by small scale bank collapses, lateral spread and liquefaction (Orchard 2017a; Quigley et al. 2016). These effects were pronounced at Steamwharf Stream in the lower Heathcote Ōpāwaho catchment, where stream bank vegetation has been slow to recover. As part of its wider waterway management work, Christchurch City Council (CCC) has initiated a programme of riparian restoration work at the stream with a focus on the local purpose reserve lands near Dyers Road, and attention to maintenance of the stream bed (Fig. 1).

Riparian restoration work has included the stabilisation and revegetation of earthquake- affected areas. Most of these areas are located close to a gravel walking track on the true left bank of the stream that also required upgrading (Fig. 2). These areas were planted in 2018 to re-establish riparian vegetation cover using native species. A particular focus of the project involved the potential to restore spawning habitat for īnanga (*Galaxias maculatus*), a riparian spawning fish that is the main species caught in New Zealand's iconic whitebait fishery (McDowall 1984). As a largely annual species (i.e., one year life cycle), the continued health of īnanga populations is critical to the whitebait fishery, and is highly dependent on the successful completion of each year's life cycle. There is considerable potential to improve whitebait conservation outcomes through habitat protection and restoration work, particularly in areas of known degradation.

This report provides a summary of recent surveys completed to support the above project. It also provides an update to previous surveys completed prior to commencement of the restoration project (Orchard 2018), and includes a comparison with those results to gauge responses to the restoration work.

1.2 Īnanga and whitebait conservation

The conservation status of īnanga is currently 'at risk - declining' in the New Zealand Threat Classification System, in recognition of historical decline (Dunn et al. 2018). The evidence for decline is associated with waterway degradation and habitat loss that has generally been more severe in lowland environments where īnanga are found (Department of Conservation and Ministry for the Environment 2000; McDowall 1990). Assisting the recovery of īnanga populations requires attention to the availability and condition of habitat. Because of the migratory life cycle, different parts of the aquatic landscape are used at different times (McDowall 1992). Critical habitats include migration routes and spawning grounds, in addition to aquatic habitats suitable for the growth and survival of adult fish.

Īnanga spawning grounds are an essential focus because of their critical role in completion of the life cycle, and since they are particularly vulnerable to human impacts. Spawning sites are found in a specific position in the landscape due to a highly specialised spawning behaviour that is synchronised with the lunar tides (Benzie 1968). In tidal waterways, spawning takes place near river mouths with the eggs being laid in riparian vegetation that is inundated on spring high tides (Richardson & Taylor 2002). This results in spawning sites being located high on the river bank where they may be vulnerable to terrestrial activities such as human land uses. Spatial overlap with human activities can pose a hindrance to successful spawning by reducing the availability of suitable habitat or reducing the survival rate of eggs after spawning has occurred (Hickford et al. 2010; Hickford & Schiel 2011a; Orchard et al. 2018a). In urban environments such as Christchurch, engineering, drainage and vegetation management activities have been shown to influence the location and success of spawning events (Orchard 2017b; Orchard & Hickford 2016; Orchard et al. 2018a). Conversely, these activities also present opportunities for ecological engineering and restorative management that can help to improve outcomes for whitebait conservation and the whitebait fishery.

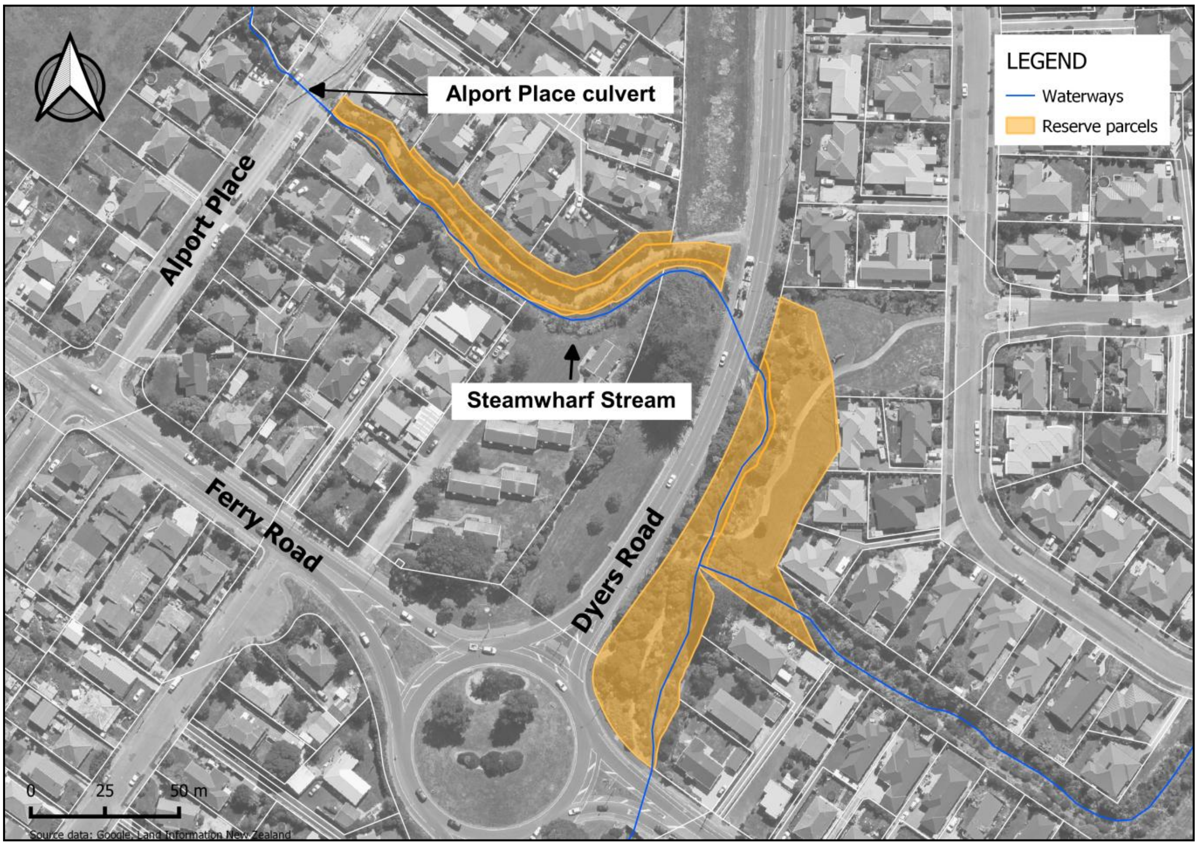

Fig. 1. Overview of the Steamwharf Stream survey area in the lower Heathcote Ōpāwaho catchment.

1.3 Previous work at Steamwharf Stream

Previous studies include the discovery of īnanga spawning sites at Steamwharf Stream by Taylor (2004). These sites were located within a 70 m reach located on the true right bank approximately 100 m upstream of Dyers Road. However, a survey completed after the 2011 earthquakes reported considerable damage to the stream banks in this area, and no spawning sites were found (Taylor & Blair 2011). Another survey completed in 2015 also failed to detect spawning sites and noted a lack of suitable habitat (Orchard & Hickford 2016). In 2016 straw bales were installed as a detection tool (Orchard et al. 2018b) as part of the Whaka Inaka - Causing Whitebait project, and spawning was detected on the bales and also in the riparian vegetation that year (McMurtrie et al. 2016; Orchard et al. 2016). In the following year, another survey also found spawning sites in the riparian vegetation in similar locations to 2016 (Orchard 2017b). Although these results indicated that vegetation recovery was taking place, the naturally occurring spawning sites were confined to small terraces in steep banks near private property boundaries where they were potentially vulnerable to further change. In addition, only a single month was surveyed in 2017, making it difficult to draw conclusions on recovery trends (Orchard 2017b).

In 2018 a four month ‘census’ survey was completed to provide a comparable measurement to the earlier multi-month surveys (Orchard 2018). The results showed that only modest egg numbers (~50, 000 eggs) were produced over the survey period, contrasting markedly with comparable results from 2016 (~300, 000 eggs). Potential explanations included the relatively degraded condition of in-stream habitat for adult fish that year, due in part to vegetation clearance activities in the stream bed (Orchard 2018). Additionally, the culvert at Alport Place was suspected to be a fish barrier. The combination of this potential barrier and a lack of in-stream cover downstream would likely increase fish mortality rates from predation leading to a reduced population size.

In the current study, these aspects have been investigated in two ways. Firstly, a four month census survey was completed to provide a direct comparison to the 2018 survey results. In addition, a fish survey was completed at the beginning of the spawning season (February) to help assess the status of the Alport Place culvert as a potential migration barrier. Working hypotheses included that the Alport Place culvert was a barrier to migration, but that improved riparian and in-stream habitat conditions downstream would have benefitted the fish population relative to 2018. Therefore, we expected to see a) an abundance of adult fish below the Alport Place culvert at the beginning of the spawning season, b) a lack of adult fish above the culvert, and c) improved egg production in comparison to 2018. We were also hoping that some of the restoration sites may be supporting spawning as they were planted with suitable species with this in mind (Fig. 2).

1.4 Scope of this study

The scope of this project included:

a) four spawning surveys over the period Feb - May 2020 with the objective of locating spawning sites following Orchard & Hickford (2018); and
b) a fish survey in February 2020 to assess the Alport Place culvert. Although the scope was limited to single assessment, it included concurrent surveys above and below the culvert.

The remainder of this report is set out as follows: Section 2 describes the survey methodology, Section 3 presents findings from the 2020 field surveys and comparisons with previous surveys, Section 4 discusses management implications, and Section 5 summarises the key results.

Fig. 2. (a) Bank stabilisation restoration work in 2018, which included the installation of straw bales as a mitigation measure to provide temporary spawning habitat. (b) View of the same site in 2020 showing newly established rushes, *Carex* and riparian herbs.

2. Methods

2.1 Study area

Steamwharf stream is a relatively short lowland tributary (ca. 1.5 km in length) of the Ōpāwaho Heathcote River, with most of the baseflow originating from freshwater springs in Thistledown Reserve. The lower reaches are tidal with the upstream limit of salt water intrusion having been recorded in the vicinity of Alport Place on spring high tides (Orchard 2018). Previous studies have recorded īnanga spawning sites in the reach between Alport Place and Dyers Road (Fig. 1), both before and after the Canterbury earthquakes (Orchard 2017b, 2018; Taylor 2004).

For this project, the study area consisted of the reach between Alport Place and Dyers Road for spawning sites surveys based on previous experience (as above). For the fish surveys, the study areas were comparable reaches above and below the Alport Place culvert. This potential fish barrier has recently been investigated by CCC and found to have considerable blockages that likely caused by tree roots (S. Holder, pers. comm.), although flow through the culvert appears relatively unaffected (Fig. 3a). The culvert is a 3 m x 1.5 m concrete box approximately 20 m in length.

2.2 Fish surveys

Fish surveys were completed within 150 m reaches as recommended in Joy et al. (2013). The two survey reaches were located immediately above and below the Alport Place culvert. Each reach was sampled with 12 Gee minnow traps (GMT's) deployed in a staggered fashion throughout the sampling reach as described in Joy et al. (2013). The surveys used G40M traps which are constructed of 6.4 mm square galvanised mesh, with entrance holes of 22 mm diameter, and a maximum trap diameter of 23 cm (Fig. 3b). A visual inspection of each survey reach was completed on 17 February 2020. Traps were deployed later that afternoon for an overnight set, with the two survey reaches sampled concurrently. Other aspects of the sampling procedure are detailed in Joy et al. (2013).

Fig. 3. (a) Alport Place box culvert showing the outlet structure which is fully submerged at typical water levels. (b) Steamwharf Stream in the reach below Alport Place at a GMT (minnow trap) sampling point.

2.3 Spawning site surveys

2.3.1 Survey approach

As with the 2018 survey mentioned above, the spawning surveys followed the census survey approach outlined in Orchard & Hickford (2018), with the objective of locating all spawning sites in the survey reach (Dyers Road to Alport Place). Each survey was completed a few days after the new moon spring high tides, during which spawning typically occurs. Spring high tide periods, tidal heights and survey dates are summarised in Table 1. On each survey, spawning sites were located by direct searches for eggs in riparian vegetation. See Orchard & Hickford (2018) for further details of the search procedure.

2.3.2 Area of occupancy (AOO)

All egg occurrences were associated with a given location that was identified as a spawning site. GPS coordinates were recorded using hand-held units in the field and corrected in QGIS v3.4 (QGIS Development Team 2019), with the assistance of site photographs and landmarks. Individual spawning sites were defined as continuous or semi-continuous patches of eggs with dimensions defined by the pattern of occupancy (Orchard & Hickford 2018). For each site, the upstream and downstream extents of the patch were established, and the length along the riverbank measured. The width of the egg band was measured at the position of each vegetation search transect falling within the spawning site following Orchard & Hickford (2018), and with a minimum of three measurements taken at all sites. Zero counts were recorded when they occurred within a spawning site, as is common where the egg distribution is not a continuous band. Area of occupancy (AOO) was calculated as length x mean width for each site.

2.3.3 Spawning site productivity

Productivity was assessed by direct eggs counts using a sub-sampling method (Orchard & Hickford 2016, 2018). At each transect, as above, a 10 x 10 cm quadrat was placed in the centre of the egg band and all eggs within the quadrat counted. Egg numbers in quadrats with high egg densities (>200 / quadrat), were estimated by further sub-sampling using five randomly located 2 x 2 cm quadrats and the average egg density of these sub-units used to calculate an egg density for the larger 10 x 10 cm quadrat. The mean egg density was calculated from all 10 x 10 cm quadrats sampled within the site, inclusive of zero counts. Productivity was calculated as mean egg density x AOO.

Table 1. Tidal cycle data and survey periods.

Survey Month	Peak tidal cycle start	Peak tidal cycle end	Peak tidal height* (m)	Spawning survey dates
Feb	10/2	13/2	2.6	20/2
Mar	10/	13/3	2.6	16/3
Apr	8/4	11/4	2.6	2/5
May	6/5	10/5	2.6	24/5

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

Table 2. Habitat quality classes.

Class	Quality of habitat for supporting spawning	Expected egg mortality rate	Criteria
1	Poor	High	Vegetation cover <100% or Stem density <0.2cm^{-2}
2	Moderate	Moderate	Vegetation cover 100% Stem density >0.2cm^{-2} Aerial root mat depth <0.5cm
3	High	Low	Vegetation cover 100% Stem density >0.2cm^{-2} Aerial root mat depth >0.5cm

Classification schema
Vegetation cover <100% Class 1
Vegetation cover >100% Class 2 or 3
Stem density <0.2cm^{-2} Class 1
Stem density >0.2cm^{-2} Class 2 or 3
Aerial root mat depth <0.5cm Class 2
Aerial root mat depth >0.5cm Class 3

3. Results

3.1 Fish surveys

In the visual surveys, several shoals of īnanga were observed in the downstream reach (below Alport Place), and none in the upstream reach (Table 3). Most of these fish were in the 6 – 8 cm size range, although some large individuals (up to ca. 12 cm) were also observed. The only fish observed above the culvert was a large longfin eel (estimated at 75 cm in length).

In the GMT surveys, only four īnanga were caught in total, all in the downstream reach. In the upstream reach, two giant bullies were the only fish caught, and they were both relatively large (standard lengths of 90 and 140 mm). However, bullies were relatively abundant in the downstream reach with a total of 24 caught (Table 3).

Table 3. Fish survey results.

(a) Downstream reach (below Alport Place culvert)

	Survey method		Site totals
Fish taxa	**Visual**	**GMT**	
Īnanga	60	4	64
Giant bully	1	19	20
Common bully		5	5
Longfin eel		1	1

(b) upstream reach (above Alport Place culvert)

	Survey method		Site totals
Fish taxa	**Visual**	**GMT**	
Īnanga			0
Giant bully		2	2
Common bully			0
Longfin eel	1		1

3.2 Spawning site surveys

In February, a single spawning site was recorded in the survey reach at the restoration site shown in Fig. 2. It was a relatively large site (5.1 m^2) that occupied a terrace feature on the true left. Most of the eggs were laid in monkey musk (*Erythranthe guttata*) that had spread between planted rushes (*Juncus edgariae* and *J. sarophorus*), with kapungawha / lake club rush (*Schoenoplectus tabernaemontani*) also present nearby (Table 4). Total egg numbers were nearly 200, 000 eggs, making this a relatively productive site in comparison to others recorded in the catchment in recent years.

In March most of the spawning was again located at the above site, with the area of occupancy and egg production being very similar to that recorded the month before (Fig. 4). Additional small sites were found downstream on the true left and a short distance upstream on the true right (sites 1 and 3, respectively, in Table 4).

Spawning activity dropped off considerably in April, with only two small patches of eggs being found, and much reduced egg numbers overall. In May, no spawning sites were found in the reach (Table 4).

Total egg production for the four month period was 380, 000 eggs, and this is considered representative of a seasonal total since there were unlikely to have been many fish ready to spawn on the January spring high tide. Fig. 4 highlights the similar levels of spawning activity in February and March that account for the majority of spawning for the year.

The location of spawning sites and patterns of egg production is shown in Fig. 5.

Table 4. Summary of īnanga spawning activity in Steamwharf Stream in the 2020 spawning season across four months of survey (Feb—May). Site IDs are ordered from downstream to upstream in the reach between Dyers Road and Alport Place.

(a) Area of occupancy (m^2)

					Month		
SiteID	**Bank**	**X**	**Y**	**Feb**	**Mar**	**Apr**	**May**
1	TL	1575115	5177802		0.1	0.2	
2	TL	1575104	5177800	5.1	5.8	0.6	
3	TR	1575100	5177787		0.1		
			Totals	**5.1**	**6.0**	**0.8**	**0**

(b) Egg production

					Month		
SiteID	**Bank**	**X**	**Y**	**Feb**	**Mar**	**Apr**	**May**
1	TL	1575115	5177802		967	1244	
2	TL	1575104	5177800	186150	184494	7104	
3	TR	1575100	5177787		36		
			Totals	**186150**	**185497**	**8349**	**0**

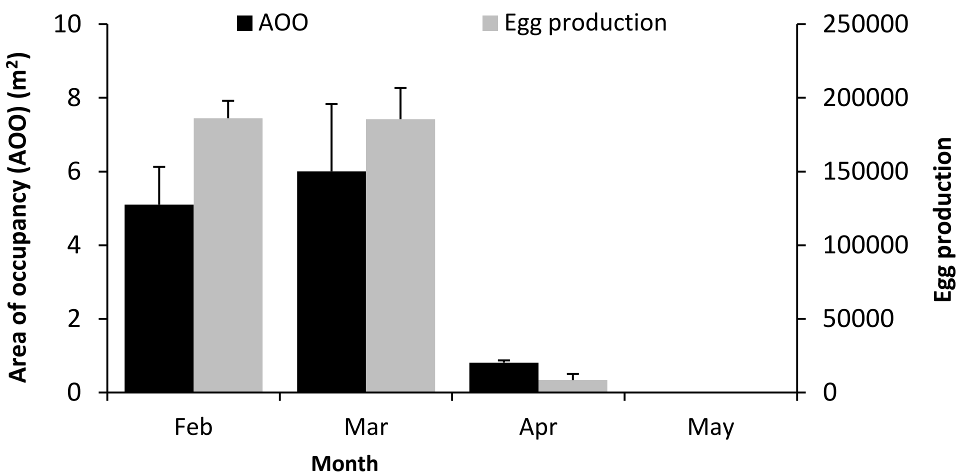

Fig. 4. Total area of occupancy and egg production of īnanga spawning sites in Steamwharf Stream over four months in 2020.

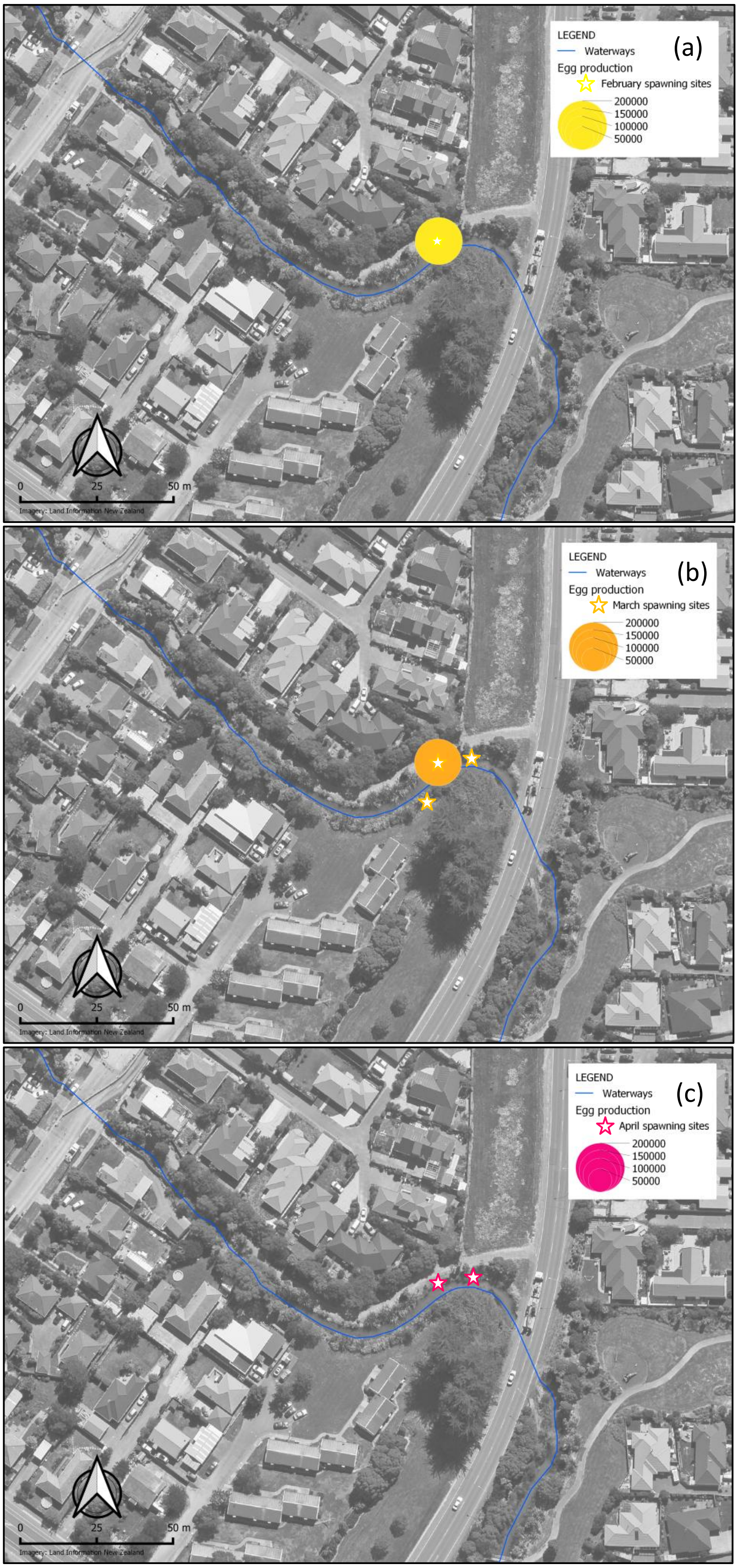

Fig 5. Egg production of īnanga spawning sites over three months in Steamwharf Stream. a) February, (b) March, (c) April 2020. No spawning was record in a further survey in May.

4. Discussion

4.1 Fish distribution and potential migration barrier

Despite the limitations of a single assessment, the combined results of the visual and fish trapping surveys suggest that the Alport Place culvert is presenting a barrier to fish migration. This is consistent with visual observations in 2019 and during other site visits in 2020 in which shoals of īnanga were often seen swimming against the flow at the culvert outlet structure and were not observed upstream (S. Orchard, unpubl. data). Although impacts on the discharge rate are relatively minor at present, the majority of the culvert length appears to be blocked with dense and/or fibrous material. Remediation of the culvert is therefore recommended to allow fish access to the upstream reach of Steamwharf Stream. This has the potential to restore connectivity to around 1 km of adult fish habitat.

In the context of river-corridor management, removal of the migration barrier is likely to assist fish survival rates between the juvenile (whitebait) and adult life stages. A focus on upstream reach also complements the riparian restoration and spawning site enhancement work completed to date since it is expected that the adult fish population will continue to rely on this area for the provision of spawning habitat. The recent restoration work has already delivered gains by increasing the availability of high quality spawning habitat on the stream banks in this area. However, further gains rely on increasing the fish population as a whole through either improving the recruitment of whitebait or reducing the mortality of juvenile and maturing fish. Once reconnected, additional riparian restoration may be warranted in some of the upstream reaches (e.g. below Palinurus Road) to help achieve these objectives. As a relatively short tributary with a regular baseflow, there is great potential to achieve a 'source-to-sea' restoration example in the Steamwharf Stream catchment as a whole.

4.2 Responses to riparian restoration

Results from this assessment indicate that the stream bank restoration activities have had a noticeable effect. A surprising finding was the absence of spawning at locations on the true right bank that had supported the majority of spawning activity in 2016 – 2018. These previously-used sites are located upstream of the sites used in 2020, and the vegetation was in similar condition to the previous years. Despite these sites offering high quality habitat, it appears that the fish have favoured the new site created through restoration activities further downstream, perhaps due to behavioural factors such as the extensive stands of kapungawha / lake club rush adjacent to the spawning site that may promote fish presence and shoaling activity in this area. No spawning had been recorded in this location during any of surveys conducted over the period 2015 – 2018.

4.3 Comparison with previous years

The identification of new spawning sites in restored areas, and high quality spawning habitat elsewhere, suggests that future spawning could occur at several sites in the Alport Place to Dyers Road reach. In addition, riparian conditions have generally improved since 2018. Important locations for future management therefore include all spawning sites recorded since the earthquakes and the three new locations recorded this year.

A comparison with the results of the five previous post-earthquake surveys shows that that this year's spawning activity is the highest recorded since the Canterbury earthquakes (Table 5). The egg numbers were higher than in 2016 when 300, 000 eggs were recorded over a comparable four month period (University of Canterbury & Whaka Inaka Partners, unpubl. data). Importantly, egg numbers were much higher than recorded in the most recent previous survey (2018) and this is likely to be due to the improved vegetation cover and condition of riparian zones.

Table 5. Comparison of post-earthquake īnanga spawning records at Steamwharf Stream. Note that the survey periods differ in some cases. Further details can be found in the original survey reports.

Year	Number of months surveyed	Survey period	Maximum number of spawning sites per month	Maximum AOO (m^2) per month	Total egg production (all surveys) in riparian vegetation	Additional egg production in straw bales (2016)	Total egg production (all sites and surveys)	Data sources and references
2015	3	Feb-May	0	0	0	0	0	Orchard & Hickford (2016)
2016	4	Feb-Apr	2[†]	2.2[‡]	73014	223686	296700	McMurtrie et al. (2016); Orchard et al. (2018a); Orchard et al. (2018b)
2017	1	Apr	2	2.2	18249	0	18249	Orchard (2017b)
2018	4	Feb-May	2	0.7	49829	0	49829	Orchard (2018)
2020	4	Feb-May	3	6.0	379995	0	379995	this report

[†] plus an additional four sites in straw bale installations
[‡] plus additional AOO within the four straw bale installations

4.4 Improvements since 2018

In the 2018 survey, the relatively low number of eggs recorded over a three month period (total of ~ 50, 000 eggs), was interpreted as indicating that relatively low numbers of adult fish were present. At this time, a vegetation clearance campaign had removed large beds of emergent species in the stream channel (Fig. 6). The Alport Place culvert was likely functioning as migration barrier that further limited the availability of instream cover from predators. It is likely that the combination of these effects contributed to higher mortality rates for fish that had entered the catchment that year.

Alleviation of the vegetation clearance effects through cessation of the channel clearance activities and recent riparian restoration provides a plausible explanation for the observed improvement in seasonal egg production. Variability in recruitment is also likely between seasons, as reflected in the number of juveniles (whitebait) in the system after migration and fish population structure thereafter. These aspects could be investigated in future monitoring alongside attention to the overall egg production trend, which is arguably the most telling indicator of outcomes for whitebait conservation.

The total egg production recorded this year provides an important baseline for future assessments, and there is potential of further expansion of the seasonal egg production as discussed in section 4.1.

Fig. 6. Before (left) and after (right) the clearance of in-stream vegetation in March 2018 looking downstream from Dyers Road. Emergent vegetation beds would naturally cover a considerable percentage of the stream bed in this section of the waterway, and further downstream. The vegetation improves habitat values for fish by providing foraging areas and cover from predators.

4.5 Assumptions and limitations

Limitations of this study include mortality between the date of spawning and the date of survey. This can have a bearing on the number of sites detected, the observed AOO, and estimates of egg production (Hickford & Schiel 2011b; Orchard et al. 2018b). This is most likely to have affected results of the April spawning survey which was delayed due to the effects of Covod19. As a consequence, the April spawning results are likely to have underestimated the number of eggs that may have originally been laid. In other respects, the census survey methodology is relatively straightforward to implement in Steamwharf Stream due to the compact study area and narrow riparian margins, and the monthly searches are considered highly likely to have detected all spawning sites. The relatively high egg numbers recorded in February was also an unexpected finding. This early timing is atypical of Christchurch waterways and is worth bearing in mind for future surveys. In comparable studies in both the Ōtākaro Avon and Ōpāwaho Heathcote catchments, peak activity has usually been found in March or April.

5. Conclusions and recommendations

This year's survey results suggest that the CCC restoration initiatives have generated positive outcomes for whitebait conservation in Steamwharf Stream, and provide a useful baseline for future monitoring.

Key recommendations to build on the progress achieved to date include:

- investigate options for remediation of the Alport Place culvert to improve connectivity between the upper and lower catchment.
- monitor the distribution and movement of the adult fish population to identify habitat availability issues and potential improvements generated by attention to the migration barrier.
- consider the merits of further riparian restoration in the reach upstream of Alport Place following connectivity improvements.
- maintain current restoration plantings in the Alport Place to Dyers Road reach and avoid vegetation clearance in the channel where possible.
- monitor future outcomes for whitebait conservation by completing periodic census surveys against the baseline established in this study.

6. Acknowledgements

Thanks to Belinda Margetts, Emily Tredinnick and Katie Noakes at the Christchurch City Council for assistance with different aspects of this project as it has evolved through various stages. Thanks also to partners in the Whaka Īnaka – Causing Whitebait project for earlier work that has improved knowledge of the stream, and to Mike Hickford and others at the University of Canterbury for assistance with some of the spawning surveys mentioned in this report. Thanks to Stephen Holder at CCC for coordination of the current project, and also to Dennis Preston and others in the CCC team who implemented the restoration work.

7. References

Benzie, V. (1968). Some ecological aspects of the spawning behaviour and early development of the common whitebait *Galaxias maculatus attenuatus* (Jenyns). *Proceedings of the New Zealand Ecological Society, 15*, 31-39.

Department of Conservation and Ministry for the Environment. (2000). *The New Zealand Biodiversity Strategy*. Wellington: New Zealand Government. 144pp.

Dunn, N. R., Allibone, R. M., Closs, G. P., Crow, S. K., David, B. O., Goodman, J. M., . . . Rolfe, J. R. (2018). *Conservation status of New Zealand freshwater fishes, 2017*. *Zealand Threat Classification Series 24*. Wellington: Department of Conservation. 11 pp.

Hickford, M. J. H., Cagnon, M., & Schiel, D. R. (2010). Predation, vegetation and habitat-specific survival of terrestrial eggs of a diadromous fish, *Galaxias maculatus* (Jenyns, 1842). *Journal of Experimental Marine Biology and Ecology, 385*(1-2), 66-72. doi:10.1016/j.jembe.2010.01.010

Hickford, M. J. H., & Schiel, D. R. (2011a). Population sinks resulting from degraded habitats of an obligate life-history pathway. *Oecologia, 166*(1), 131-140. doi:10.1007/s00442-010-1834-7

Hickford, M. J. H., & Schiel, D. R. (2011b). Synergistic interactions within disturbed habitats between temperature, relative humidity and UVB radiation on egg survival in a diadromous fish. *PLoS ONE, 6*(9), e24318. doi:doi:10.1371/journal.pone.0024318

Joy, M., David, B., & Lake, M. (2013). *New Zealand freshwater fish sampling protocols. Part 1 Wadeable rivers and streams*. Institute of Natural Resources Te Kura Mataurange o nga Taonga a Papatuanuku, Massey University. 64pp.

McDowall, R. M. (1984). *The New Zealand whitebait book.* Wellington: Reed.

McDowall, R. M. (1990). Conservation of New Zealand's freshwater fishes. *New Zealand Freshwater Fisheries Report, 116*, 1-62.

McDowall, R. M. (1992). Particular problems for the conservation of diadromous fish. *Aquatic Conservation: Marine and Freshwater Ecosystems, 2*(4), 351-355. doi:10.1002/aqc.3270020405

McMurtrie, S., Brennan, K., Hickford, M., Orchard, S., & Lenihan, T. M. (2016). *Whaka Inaka : Causing Whitebait – improving īnanga spawning in Christchurch's waterways*. New Zealand Freshwater Sciences Society Conference. Invercargill, New Zealand, 5-9 December, 2016.

Orchard, S. (2017a). *Floodplain restoration principles for the Avon-Ōtākaro Red Zone. Case studies and recommendations.* Report prepared for Avon Ōtākaro Network, Christchurch, N.Z. 40pp.

Orchard, S. (2017b). *Response of īnanga spawning habitat to riparian vegetation management in the Avon & Heathcote catchments.* Report prepared for Christchurch City Council. 35pp.

Orchard, S. (2018). *Īnanga spawning survey of Linwood Canal and Steamwharf Stream*. Report prepared for Christchurch City Council. 22pp.

Orchard, S., Hickford, M., & Schiel, D. (2016). *Use of artificial habitats to quantify īnanga spawning areas for conservation and management*. New Zealand Freshwater Sciences Society Conference. Invercargill, New Zealand, 5-9 December, 2016.

Orchard, S., & Hickford, M. J. H. (2016). *Spatial effects of the Canterbury earthquakes on īnanga spawning habitat and implications for waterways management*. Report prepared for IPENZ Rivers Group and Ngāi Tahu Research Centre. Waterways Centre for Freshwater Management and Marine Ecology Research Group. Christchurch: University of Canterbury. 37pp.

Orchard, S., & Hickford, M. J. H. (2018). Census survey approach to quantifying īnanga spawning habitat for conservation and management. *New Zealand Journal of Marine and Freshwater Research, 52*(2), 284-294. doi:10.1080/00288330.2017.1392990.

Orchard, S., Hickford, M. J. H., & Schiel, D. R. (2018a). Earthquake-induced habitat migration in a riparian spawning fish has implications for conservation management. *Aquatic Conservation: Marine and Freshwater Ecosystems, 28*(3), 702-712. doi:10.1002/aqc.2898

Orchard, S., Hickford, M. J. H., & Schiel, D. R. (2018b). Use of artificial habitats to detect spawning sites for the conservation of *Galaxias maculatus*, a riparian-spawning fish. *Ecological Indicators, 91*, 617-625.

Orchard, S., Hughey, K. F. D., Measures, R., & Schiel, D. R. (2020). Coastal tectonics and habitat squeeze: response of a tidal lagoon to co-seismic sea-level change. *Natural Hazards*. doi:10.1007/s11069-020-04147-w

QGIS Development Team. (2019). *QGIS Geographic Information System. Open Source Geospatial Foundation Project.* http://qgis.org.

Quigley, M. C., Hughes, M. W., Bradley, B. A., van Ballegooy, S., Reid, C., Morgenroth, J., . . . Pettinga, J. R. (2016). The 2010–2011 Canterbury Earthquake Sequence: Environmental effects, seismic triggering thresholds and geologic legacy. *Tectonophysics, 672-673*, 228-274. doi:10.1016/j.tecto.2016.01.044

Richardson, J., & Taylor, M. J. (2002). A guide to restoring inanga habitat. *NIWA Science and Technology Series, 50*, 1-29.

Taylor, M. J. (2004). *Inanga spawning grounds on the Avon and Heathcote rivers*. Aquatic Ecology Ltd. Christchurch.

Taylor, M. J., & Blair, W. (2011). *Effects of seismic activity on inaka spawning grounds on city rivers*. Aquatic Ecology Limited. Christchurch.