RDR Management Limited

Review of bio-acoustic fish fence effectiveness

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Rangitata Diversion Race Management Limited

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October 2015

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document version: 28/10/2015

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1. Introduction

1.1 Background

The Rangitata Diversion Race (RDR) is a 67km long canal that carries a maximum of 30.7m^3/sec (or cumecs) of water from an intake on the Rangitata River to the Rakaia River, crossing the Canterbury Plains in a north-easterly direction. Along its way the RDR supplies water to four irrigation schemes (Mayfield Hinds, Valetta, Ashburton Lyndhurst and Barrhill Chertsey) and two hydroelectric power stations (Montalto and Highbank).

The Rangitata River intake to the RDR is unscreened and therefore fish, including downstream migrating Chinook salmon (*Oncorhynchus tshawytscha*) fry, are diverted along with water from the Rangitata River into the RDR.

Past assessments (1998/99 irrigation season) estimated that about 200,000 salmon smolt from the Rangitata River were entrained to the RDR (Hamish Stevens, Fish and Game Officer, December 2007), and it was suggested that juvenile salmon entering the RDR may comprise 5-25% of Rangitata River migrants (Unwin *et al.* 2005). In response to these concerns, Rangitata Diversion Race Management Limited (RDRML) sought a method of screening juvenile salmon from the RDR, thereby allowing them to return safely to the Rangitata River.

1.2 Bio-acoustic fish fence (BAFF)

The RDR carries a large volume of water, which is often silt and sand laden, and the invasive algae Didymo (*Didymosphenia geminata*) is also present in the canal. These characteristics pose significant problems for a traditional physical mesh fish screen, which would quickly become blocked and ineffective. After evaluating alternative screening options a bio-acoustic fish fence (BAFF, Fish Guidance Systems, Southampton, United Kingdom) was installed in the RDR approximately 2km downstream of the intake in June 2007 (Figure 1). However, due to a number of issues affecting its operation, the BAFF was not considered commissioned until August 2008.

The BAFF consists of a combination of low-medium frequency sound and an air bubble curtain that concentrates the sound. This acts to repel fish travelling down the RDR, instead directing them towards a bypass that returns to the Rangitata River. As the BAFF is not a physical screen as such, algae does not clog it, although regular maintenance is required to ensure silt does not block the air bubble jets. The RDR BAFF remains the first of its type in New Zealand, although similar acoustic bubble curtains have been used to screen fish in Europe, North America and the United Kingdom with varying success depending on the species and site (reviews in DWA Topics 2006, O'Keeffe and Turnpenny 2005, United States Department of the Interior Bureau of Reclamation 2006, Welton *et al.* 2000). Deterrence rates of up to 80% or more have been reported for Chinook salmon smolt using BAFF technology (e.g., Bowen *et al*. 2009).

1.3 Consent conditions relating to the BAFF

Canterbury Regional Council consent CRC051180 authorises the discharge of water and associated sediment to the Rangitata River from a fish bypass channel associated with the RDR BAFF. Condition 7 of that consent has the following requirements:

(a) Within 18 months of the commencement of this consent, the consent holder shall implement a monitoring programme to determine how effective the fish bypass is in diverting salmon smolt, unharmed, back to a main braid of the Rangitata River.

(b) The monitoring programme shall be carried out for the duration of this consent.

(c) A copy of the monitoring programme shall be provided to the Canterbury Regional Council, Attention RMA Compliance & Enforcement Section, and Fish & Game New Zealand - Central South Island, not less than 20 working days prior to its implementation.

(d) Within three years of the commencement of this consent, and at five yearly intervals thereafter, the consent holder shall provide the Canterbury Regional Council, Attention RMA Compliance & Enforcement Section, and Fish & Game New Zealand - Central South Island with a report prepared by a suitably qualified and experienced person such as a freshwater fisheries scientist, which details how effective the fish bypass is in diverting salmon smolt, unharmed, back to a main braid of the Rangitata River, and makes recommendations as to how the effectiveness of fish bypass may be improved.

(e) Within 20 working days of the provision of every report prepared in accordance with clause (d), the consent holder shall advise the Canterbury Regional Council, Attention RMA Compliance & Enforcement Section, and Fish & Game New Zealand - Central South Island what actions will be taken to implement any recommendations made to improve the effectiveness of the fish bypass, and when those actions will be completed by.

A report was prepared by Goldsmith and Ryder (2010) to fulfil condition 7(d) and the requirement to prepare a report within three years of the commencement of this consent. RDRML has engaged Ryder Consulting to undertake a further review of the effectiveness of the RDR BAFF in fulfilment of consent condition 7(d) that reviews the performance of the fish bypass after a further five years of operation.

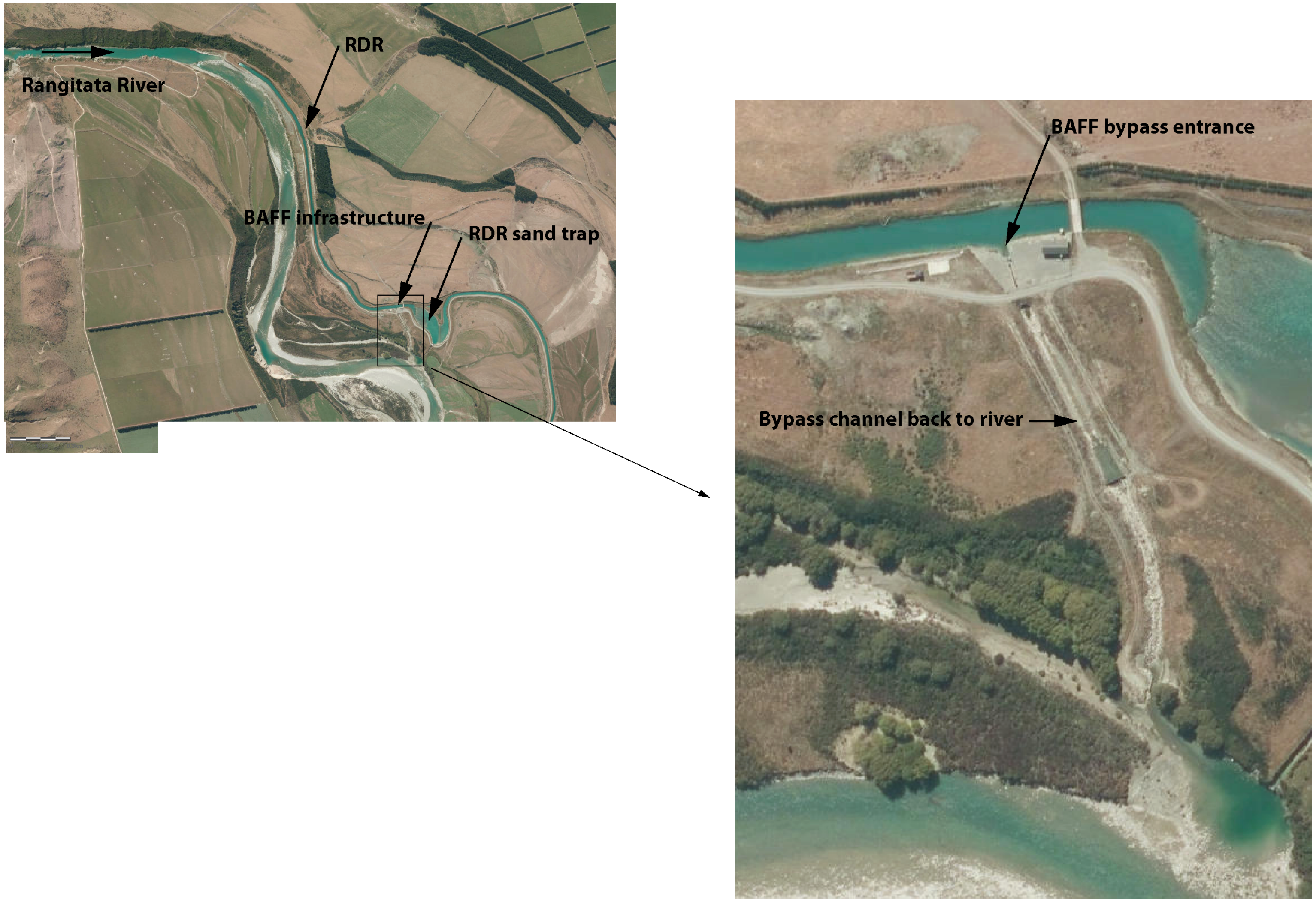

Figure 1. Aerial view of the RDR's BAFF system and associated return flow back to the Rangitata River.

2. Monitoring of BAFF effectiveness

2.1 Monitoring approach

The 'efficiency' of the BAFF has been defined as the number of fish diverted into the fish bypass relative to the number of fish passing downstream of the BAFF bubble curtain plus the number diverted into the BAFF fish bypass (expressed as a percentage).

Since the installation of the RDR BAFF, releases of marked salmon smolt have been undertaken to estimate its efficiency. Hatchery-reared salmon smolt are released upstream of the BAFF and a trap located in the bypass back to the Rangitata River, known as the BAFF trap (Figure 2) capture marked salmon that are diverted into the fish bypass channel. Up until the 2013-2014 season, a second trap, known as the ADC trap (Figure 2), situated further downstream (13km) of the BAFF, was used to capture marked salmon that had passed through the BAFF and moved further down the RDR.

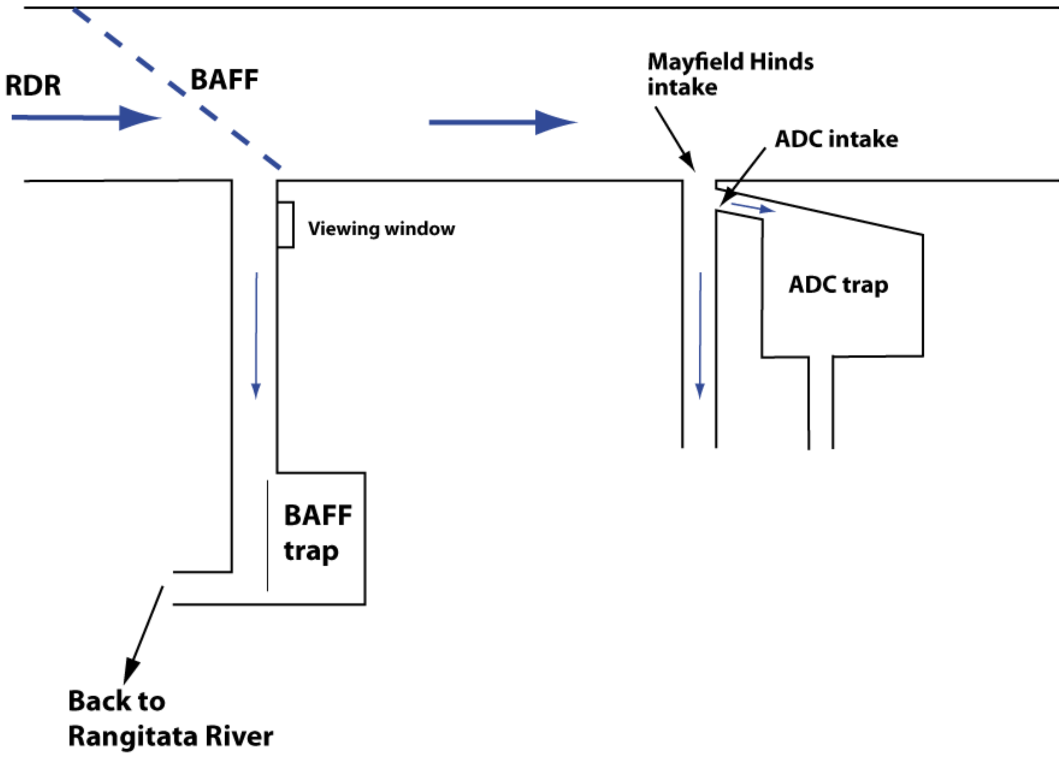

Figure 2. Schematic view of the RDR's BAFF and fish trap layouts.

Understanding the efficiency of both the BAFF bypass and ADC traps to retain fish, and therefore record the number of fish diverted or not by the BAFF, is critical to accurately assessing to the efficiency of the BAFF as a deterrent to fish moving further down the canal.

Wild salmon smolt trapping has also been undertaken mainly at the BAFF bypass trap.

Information gained from trapping wild smolt runs provides useful information on seasonal migration patterns in the Rangitata River.

Further, in September 2009, a DIDSON[1] camera was trialled for monitoring juvenile salmon in the RDR in order to better understand the effectiveness of the BAFF Quarterman (2009).

These monitoring trials are described below.

2.2 2008 – 2010 monitoring results for smolt trapping

Goldsmith and Ryder (2010) summarized the 2008 – 2010 mark-recapture monitoring trials undertaken by Central South Island Fish & Game on behalf of RDRML. These trials formed a part of condition 7(a) of consent CRC051180.

Between 68-94% of marked salmon released within the bypass channel immediately upstream of the BAFF trap were captured in the BAFF trap during these trials. The percentage of salmon captured varied depending on the time that had elapsed since release. In all three trials at least 40% of salmon were captured within 30 minutes of release, however it took up to 44 hours (range approximately 9-44 hours) for 80% of the marked salmon to be captured.

The ADC trap captured 100% of released salmon in the one trial of its effectiveness. Within 15 minutes of release 71% of salmon were captured and after approximately one hour 80% of salmon had been captured. However, it took approximately 24 hours for 100% of the salmon to be captured.

The effectiveness of the ADC trap to capture salmon released into the RDR above the intake to the ADC trap was also tested on five occasions. The release location varied from 400m to 1500m upstream of the ADC trap. Capture rates varied from 0.03% after seven hours for salmon released 1500m upstream to 1.3% after approximately two hours for salmon released 400m upstream. The average capture rate over the five trials was 0.3%.

The above monitoring indicated that the BAFF trap was only reasonably effective in capturing fish released at the trap intake. At least 40% of fish were shown to be captured within 30 minutes, however several days of monitoring were required to achieve capture rates of 80%. The duration of time required for some fish to reach the trap was surprising and may have been due to the presence of the stilling pond between the intake to the BAFF trap and the trap itself. The ADC trap was more effective at capturing fish once they entered the trap intake, however it appeared that on average only 0.3% of fish travelling down the RDR entered the intake to the ADC trap.

[1] Dual-Frequency Identification Sonar.

In 2008, the effectiveness of the BAFF to divert salmon was estimated by releasing marked salmon upstream of the BAFF and counting the number of fish captured in the BAFF and ADC traps. In October and November 2008, 526 and 3371 dyed salmon, respectively, were released 1.5km upstream of the BAFF. In the October trial, only 1.3% (7 fish) of the fish released had been captured in the BAFF trap within 137 hours, with 3 fish captured downstream of the BAFF in the ADC trap. Approximately seven hours elapsed between the time when the fish were released and when the first fish was captured in the BAFF trap. In the November trial, only 0.9% (30 fish) of the fish released were captured in the BAFF trap after 20 hours. Five fish were captured in the ADC trap.

Monitoring undertaken in 2008 therefore indicated that the effectiveness of the BAFF was low. However, the effectiveness of the BAFF and ADC traps in determining whether or not fish had been diverted or not was only moderate at best and required a long period of monitoring following release. An alternative method of monitoring was therefore sought by RDRML.

2.3 DIDSON monitoring

DIDSON camera monitoring upstream of the BAFF did not appear to be very effective in detecting juvenile salmon following two initial smolt releases, with only 10 of the 400 released salmon detected. However the DIDSON did detect a large number of what was probably 'natural run' salmon. Quarterman (2009) concluded that, as only 225 salmon were caught in the bypass trap over the monitoring period, an indication of the effectiveness of the BAFF to deflect juvenile salmon from the race to the bypass trap was approximately 4%. However, it should also be noted here, that Quarterman (2009) observed an efficiency of approximately 43% for salmon in the natural run, prior to any hatchery reared salmon releases.

2.4 2010 – 2011 monitoring results

Monitoring was undertaken again over the 2010-2011, 2011-2012, 2013-2014 and 2014-2015 irrigation seasons. The work was undertaken by Central South Island Fish & Game on behalf of RDRML and reported on by Webb (2011, 2014 and 2015). The details of these monitoring programmes are summarised below.

2.4.1 2010-2011 trap calibration

Prior to any assessment of BAFF efficiency, the traps have to be calibrated to determine their individual efficiency at capturing smolt. This is necessary because:

(i) the RDR bypass trap does not entrain the entire flow of water in the bypass channel and so only a proportion of the fish moving down the bypass can be caught – this may vary from trial to trial due to a range of factors including the amount of water being diverted down the bypass at the time of each trial;

(ii) while the entire flow of the ADC stock water off-take from the RDR can be trapped, its maximum flow is only 200-300 L/sec compared to the RDR flow of up to 33,000 L/sec, therefore the proportion fish caught in the trap is likely to be small relative to the number moving down the canal.

With respect to the RDR BAFF bypass, calibration trials in November 2010, February 2011, November 2011 and December 2011 indicated that an average of 12.3% of released fin-clipped smolt were captured by the BAFF bypass trap (Table 1).

Table 1. Summary of results from releases of salmon smolt into the BAFF bypass race to calibrate the bypass fish trap.

Date	Mean race flow (L/sec)	Number of fish released	Total recaptures	Proportion recaptured
24 – 28 Nov 2010	2,600	997	134	13.4%
1 – 5 Feb 2011	2,606	983	100	10.2%
29 – 20 Nov 2011	n/a	1,016	122	12.0%
5 – 6 Dec 2011	n/a	1,000	137	13.7%
Average				12.3%

With respect to the ADC trap, results of four trials since November 2008 are presented in Table 2.

Of 2,277 fish released downstream of the BAFF on 24 November 2010, only one fish was caught in the trap 43.75 hours after the release. This rate of capture was 7% of that expected based on the ratio of flow in the ADC off-take to that in the RDR. Webb (2011) also reports calibration results for the ADC trap for December 2010 and February 2011 (0% and 7.4% respectively).

I have less confidence in the calibration results for the ADC fish trap because they have more error associated with the estimates, as follows:

(i) the number of fish estimated to have moved downstream of the BAFF and thus be available for capture in the ADC trap are estimates of the total number of fin-clipped fish released above the BAFF and not entering the BAFF bypass;

(ii) the number of fish entering the BAFF bypass is an estimate based on the proportion of fish caught in the bypass trap which entrains only a proportion of the flow; thus adding further potential error to downstream estimates;

(iii) the release of fish for the trials has been from different locations (1,200 metres upstream of the BAFF for 13 December 2010 and 9 February 2011, and 5 metres downstream of the BAFF for the 24 November 2010 release);

(iv) the ADC intake has a very small flow relative to the flow in the RDR.

Table 2. Summary of four trials to assess ADC trap capture as a proportion of expected catch if fish were diverted relative to flow to provide an index of fish remaining in the RDR downstream of the BAFF.

Date	Fish released	Trap recaptures	Expected recapture	Actual catch as proportion of expected
19 – 22 Nov 2008	2,992	1	20	5.0%
24 – 26 Nov 2010	2,277	1	14	7.1%
13 – 14 Dec 2010	3,783	0	28	0.0%
9 – 11 Feb 2011	4,695	2	27	7.4%

2.4.2 2010-2011 BAFF efficiency estimates based on trapping of hatchery-released smolt

Trials of fin-clipped smolt releases in December 2010, February 2011 and December 2011 concluded that the BAFF bypass was attracting 23%, 15% and 98% respectively of the total number of smolt released upstream of the BAFF (Webb 2011) (Table 3). Webb (2011) noted that the Rangitata River was discoloured for part of the December 2010 trial and all of the February 2011 and December 2011 trials. As discussed in subsequent sections, this may have an influence on the efficiency of the BAFF.

Table 3. Summary of BAFF efficiency from release of fish upstream and their recapture in the bypass trap at assessed recapture rates.

Date	Fish released	Trap recaptures	Recapture efficiency	Estimated total fish diverted	BAFF efficiency
13 – 14 Dec 2010	4,910	151	13.4%	1,127	22.95%
9 – 14 Feb 2011	5,528	85	10.2%	833	15.1%
Average					19.01%
2 – 3 Dec 2011	5,352	672	12.9%	5,229	97.7%

2.4.3 2010-2011 BAFF bypass trapping of wild run smolt

The BAFF bypass trap captured 1,543 wild salmon smolt over 91 days during the 2010/2011 irrigation season. Based on the calibration trials, Webb (2011) estimated that this could equate to 13,076 fish in total diverted by the BAFF into the bypass channel back to the Rangitata River over those 91 days. Conversely, assuming the BAFF was 19% efficient at diverting wild salmon from the RDR into the bypass race, 55,745 would not have been diverted by the BAFF and continued down the RDR.

Webb (2011) estimated that, based on the ratio of the RDR abstraction rate to the flow in the Rangitata River (1 : 3.69), 185,130 smolt were not diverted in the RDR and remained in the Rangitata River over the 91 days of BAFF operation.

2.4.4 2010-2011 ADC intake trapping of wild run smolt

The ADC intake trap operated for 98 days over the 2010-2011 season. High river flows prevented the trap being operated on three occasions. The trap caught 52 fish.

Webb (2011) estimated that the expected catch in the ADC trap should have been 390 fish based on estimates of the BAFF efficiency and they were diverted into the ADC in proportion to the flow (0.72%). However, calibration of the ADC trap indicated an efficiency of about 7% of that expected based on the proportion of flow diverted.

2.5 2013 – 2014 monitoring results for smolt trapping

Methods used for assessing the efficiency of the BAFF over the 2013 – 2014 season were the same as used in the previous season. However, monitoring was not undertake in the ADC intake due to structural modification made to the ADC intake, which were thought to make this site even less effective as an indicator of BAFF efficiency.

Five calibration trials of the BAFF bypass trap were completed between December 2013 and February 2014. Calibration estimates for the trap ranged from 7.1% to 12.6%.

Three BAFF efficiency trials were undertaken where between 3,566 and 3,739 hatchery origin salmon smolt (fin-clipped) were released into the RDR upstream of the BAFF. Each trial was preceded and post ceded by calibration trials of the BAFF bypass trap as described above.

BAFF efficiency estimates for the three trials were 29.2%, 39.5% and 81.6% (Table 4).

Rangitata River mean daily flows ranged between 71 and 106 m^3/s over the trial period, although instantaneous flows peaked considerably higher than this range on occasions and may have affected water clarity in the RDR and bypass channel.

Table 4. Estimates of BAFF efficiency at diverting salmon from the RDR to the bypass channel from release of hatchery origin salmon into the RDR 1.2 km upstream in three trials over the 2013/14 season.

Release Date	Number Released	Total recaptures	Trap Efficiency	Estimated fish down bypass	BAFF Efficiency
1200 hrs 3 Dec 2013	3,739	355 after 22 hours	11.6%	3,051	81.6%
1120 hrs 23 Jan 2014	3,566	98 after 22.17 hours	9.4%	1,040	29.2%
2115 hrs 30 Jan 2014	3,686	147 after 37 hours	10.1%	1,456	39.5%

2.6 2014 – 2015 monitoring results for smolt trapping

Methods used for assessing the efficiency of the BAFF over the 2014 – 2015 season were the same as used in the previous two seasons. Trials were undertaken in two periods: 13-31 October 2014 and 3 -22 March 2014.

Six calibration trials of the BAFF bypass trap were undertaken. Calibration estimates for the trap ranged from 7.5% to 15.3%. The number of smolt released for these trials ranged from 720 to 839.

Four BAFF efficiency trials were undertaken where between 3,714 and 4,518 hatchery origin salmon smolt (fin-clipped) were released into the RDR upstream of the BAFF. Each trial was preceded and post ceded by calibration trials of the BAFF bypass trap.

BAFF efficiency estimates for the three trials were 6.5%, 14.3%, 25.4% and 32.5% (Table 5).

For the October 2014 group of trials, Rangitata River average mean daily flow was 72.3 m^3/sec (range 59-157 m^3/sec) and 69.9 m^3/sec for the March 2015 group of trials (range 47-156 m^3/sec). Flows were reported as being very stable over these periods, but some discolouration was likely, as discussed in section 3.2.

Table 5. Estimates of BAFF efficiency at diverting salmon from the RDR to the bypass channel from release of hatchery origin salmon into the RDR 1.2 km upstream in three trials over the 2013/14 season.

Release Date	Number Released	Total recaptures	Trap Efficiency	Estimated fish down bypass	BAFF Efficiency
2100 hrs 15 Oct 2014	3,714	31 after 109.67 hours	12.86%	241	6.5%
1120 hrs 23 Oct 2014	4,256	81 after 61 hours	13.29%	610	14.3%
2115 hrs 9 Mar 2015	4,518	136 after 39 hours	9.27%	1,467	32.5%
2100 hrs 17 Mar 15	4,480	102 after 63.17 hours	8.95%	1,140	25.4%

2.7 Summary of BAFF efficiency trials

Webb (2015) summarised the BAFF efficiency trials undertaken since they commenced in 2008 and these are presented in Table 6.

Table 6. Chronological order of estimates for BAFF efficiency utilizing wild natural run trap captures and hatchery origin salmon for mark-recapture and sonar trials.

Season	Date	BAFF estimated efficiency	Number released	Origin/Tag	Average length (mm)	Release point*
2008/09	Oct 2008	9.6%	270	wild, natural migration	> 40	
	Oct 2008	3.2%	226	wild, natural migration	< 40	
2009/10	Sep 2009	4%	4,600	dyed hatchery, Sonar tracked	35 to 50	
	Sep 2009	23%	150	wild, Sonar tracked	n/a	
2010/11	13 Dec 2010	23%	4,910	hatchery origin, fin clipped	80	L & R
	9 Feb 2011	15.1%	5,528	hatchery origin, fin clipped	149	L & R
2011/12	2 Dec 2011	97.7%	5,352	hatchery origin, fin clipped	82	R
	10 Jan 2012	25.0%	5,813	hatchery origin, fin clipped	92	L & R
2012/13	No hatchery fish available					
2013/14	3 Dec 2013	81.6%	3,739	hatchery origin, fin clipped	81	R
	23 Jan 2014	29.2%	3,566	hatchery origin, fin clipped	113	M
	30 Jan 2014	39.5%	3,686	hatchery origin, fin clipped	113	L
2014/15	15 Oct 2014	6.5%	3,714	hatchery origin, fin clipped	66	M
	23 Oct 2014	14.3%	4,256	hatchery origin, fin clipped	66	M
	9 Mar 2015	32.5%	4,516	hatchery origin, fin clipped	134	M
	17 Mar 2015	25.4%	4,480	hatchery origin, fin clipped	134	M

* L = true left side of canal, R = true right side of canal, M – mid channel

3. Factors affecting BAFF efficiency

There have been a number of internal and external factors that have changed throughout the course of the BAFF efficiency trials, and each of these may have affected the outcome of efficiency estimates.

3.1 BAFF modifications

RDRML and Central South Island Fish & Game have worked together to identify ways of improving the efficiency of the RDR BAFF and its associated monitoring programme to assess efficiency. These changes have been ongoing and are summarised in Table 7.

Table 7. Summary of main modifications to BAFF and associated structures and monitoring programme since 2008.

Season	Modification	Reason
End of 2008/09	BAFF repositioned to bring its downstream end nearer to the bypass entrance.	Encourage fish to move towards bypass intake.
	Baffles were removed.	To reduce silt accumulation around BAFF.
	Changes to the bypass entrance to decrease eddy effect and increase the velocity through the slide gate.	Encourage fish to move towards bypass intake.
September 2009	Monitoring trialled using DIDSON sonar.	To improve the effectiveness of determining the efficiency of the BAFF.
Prior to 2009/10 season	Increase BAFF bypass flow from 700 L/sec to 3,000 L/sec. Change BAFF bypass entrance from a culvert to an open race.	Create a greater attraction flow.
Prior to 2010/11 season	BAFF raised on pedestals.	To reduce silt accumulation around base of BAFF.
2010/11 season	Switch to fin-clipped smolt for trials (previously marked using a dye).	To reduce potential effect of dye on fish behaviour and mortality.
End of 2010/11 season	Routine maintenance.	Replacement of seals between the 22 BAFF units.
September 2011	Substantial changes to the made to the flow control structure on the ADC intake.	Nothing to do with salmon trapping efficiency. Likely to invalidate the site for future juvenile salmon monitoring.
Prior to 2013/14 season	Modifications to RDR canal walls and in-race structures near the BAFF.	To improve laminar flow conditions.
2013/14 season	Provision of a holding tank.	To assist in acclimatising fin-clipped hatchery fish prior to release. To enable releases to occur mid-channel and not just on the side where the intake entrance is located.

3.2 Estimating trap and BAFF efficiency

Some of the changes in trial methodology that may have affected or influenced efficiency estimates include tagging method (immersion in dye versus fin-clipping), average smolt size of hatchery-raised fish and release point of fish in the canal (left bank, right bank, middle).

Dye is thought to potentially induce some behavioural change to smolt and weaken them. Fin-clipping is a well proven method of tagging juvenile fish and recent moves in the RDR BAFF monitoring programme to retain a number of fin-clipped individuals for a period of time after the release of remainder has provided confidence in the method at least in terms of checking post-release mortality.

Smaller sized fish are thought to be weaker at resisting current and so less likely to be able to avoid passing through the BAFF bubble curtain. Webb (2011) noted that fish caught in the ADC trap were on average smaller than those caught upstream at the BAFF bypass and this may reflect a catch bias by larger fish actively avoiding diversion into the ADC intake. The use of difference average sized fish in the trials (Table 6) therefore introduces another variable. There is some suggestion from Table 6 that smaller fish (i.e., average of < 40 – 66 mm average length) have been associated with low efficiency estimates (typically less than 10%).

Two high efficiency estimates that were recorded in December 2011 (97.7%) and December 2013 (81.6%) were both associated with smolt releases at the true right side of the canal (the same side as the BAFF bypass intake), suggesting that a greater proportion of smolt on this side of the canal are more likely to find the bypass entrance. Releases from either the true left (opposite) bank, of in the middle of the channel, have been associated with lower efficiency estimates in recent years (6.5 – 39.5%, Table 6).

Despite these inconsistencies in the monitoring programme, it seems clear that some physical modifications since about December 2010 have improved the efficiency of the BAFF at deflecting smolt down the BAFF bypass and back to the Rangitata River.

Increasing the return flow in the BAFF bypass appears to have had a significant positive effect. The ratio of bypass flow to downstream flow in the RDR has improved significantly as a result of this change and it is not surprising that the efficiency has increased accordingly.

Other physical modifications in and around the BAFF appear to have resulted in consistency higher efficiency estimates.

Despite a general improvement, estimated efficiency remains quite variable, ranging between 6.5% and 97.7% (average 35.4%). Reasons for this inconsistency and, at times, still low efficiency, are somewhat speculative, but it seems clear that at times a considerable portion of juvenile salmon are not deterred by the BAFF and are able to pass through it and move further down the RDR.

This conclusion it not based only on the trials using hatchery-reared smolt. Trapping of wild salmon smolt has occurred at the ADC trap, located 13km downstream of the BAFF. Fifty two fish were caught in the trap over 98 days between October 2010 and March 2011. Webb (2011) suggested that this number was indicative of between 50,000 and 60,000 wild salmon smolt passing down the RDR during the 2010-2011 season. The effectiveness of the ADC intake trap and hatchery smolt in estimating BAFF efficiency are questionable, and are likely to introduce further 'error' in efficiency estimates and, consequently, the size of wild salmon runs.

The efficiency of the BAFF may also be affected by water clarity. Webb (2015) noted that there is weak evidence that the BAFF is more efficient in clear water than discoloured water. Water clarity is not routinely monitored during BAFF efficiency trials although the condition of the water is occasionally noted. Figure 3 shows the relationship between Rangitata River flow and water clarity during the last four trials. Clarity has been estimated using a clarity-flow relationship I developed for this river using historic data collected at the Arundel Bridge (Scarf & Waugh 2986). The figure indicates that a low efficiency estimate coincided with a low clarity flow event in the Rangitata River (and consequently in the RDR).

Figure 3. Recent estimates of BAFF efficiency (at deflecting salmon smolt) compares against Rangitata River flow and estimated water clarity during the trials.

4. Recommendation for further improvements

Consent condition 7(d) requires this report to make recommendations as to how the effectiveness of fish bypass may be improved. While not specifically mentioned in the consent condition, I assume this includes comment on the BAFF system itself.

4.1 Physical improvements

In its current location, there is probably little further that can be done physically to the BAFF to improve its effectiveness at deterring fish from passing through it. It may be possible to improve the effectiveness of the noise emissions and bubble curtain, but that would require advice from the BAFF suppliers.

Consideration should be given to the use of lighting in conjunction with the existing sound and bubble curtain system. Bowen *et al*. (2009) assessed the efficiency of a BAFF system at deflecting Chinook salmon smolt and concluded that the sound effectively deterred the fish and the bubble curtain contained the sound. Importantly, however, strobe lighting enabled the fish to identify the source of the sound (which may be beneficial in the RDR situation where low water clarity is relatively common). Bowen *et al*. (2009) concluded that the fish saw the barrier because of the strobe lights, and they heard the sound as they approached the BAFF. The strobe lighting used in that study were LED powered devices that created white light in a vertically orientated beam. The light arrays were used in the barrier and were aligned such that the beam projects onto the rising bubble curtain. This served to reflect the beam and improved visibility from the direction of approaching fish. The strobe light system was driven by a low voltage source (<25 V dc) at a flash rate of 360 per minute.

Webb (2009, pers comm. to RDRML) noted that the majority of salmon movement is at night. He suggested placing a light in the existing video window that illuminates through the bypass entry so that it would indirectly light the path before fish pass through the gate.

Consideration should also be given to other fish deterrent devices that may work in conjunction with the BAFF, to augment its effectiveness, such as louvers. Louvers are a form of behavioural device that have had reasonable success overseas. They consist of an array of vertical slats that are placed on a diagonal structure across a channel. Spacing between louver slats is typically larger than the width of the smallest fish that are being excluded. Louvers achieve fish exclusion by creating a series of elements that generate flow turbulence that the fish tend to avoid. Fish will maintain their position off the louver face while the sweeping flow (generated by the angled louver placement) guides the fish along the louver line to bypasses (Jamieson *et al*. 2007).

NIWA's Fish screening good practice guidelines for Canterbury (Jamieson *et al*. 2007) report documented exclusion efficiencies for louvers range from greater than 90% for juvenile Chinook salmon with fork length longer than 45 mm to efficiencies below

30% for juvenile Chinook salmon with fork length shorter than 30 mm. Louvers are suited to canal situations.

Further increasing the rate of water directed down the BAFF bypass may help improve its ability to attract smolt away from the main flow of the RDR. However, RDRML are constrained by their consent and the WCO as to the amount of water able to be abstracted into the RDR. There may also be additional constraints relating to the hydraulic capacity of the bypass entrance and channel.

4.2 Monitoring improvements

There remains a considerable level of uncertainty regarding the use of hatchery reared fish to assess BAFF efficiency. Wild smolt are likely to fitter than their hatchery counterparts and so may be able to be more successful at avoiding passing through the BAFF curtain. However the behaviour of wild fish around the BAFF has not been investigated thoroughly and observations using the DIDSON may have been hampered by the use of dyed fish. Basically, there is a general lack of knowledge of how wild salmon smolt behave and react in and around the BAFF and associated bypass entrance. Understanding this behaviour would provide greater confidence in the BAFF as a deterrent and how its efficiency may be improved.

Velocity profiling across and in front of the BAFF would assist in determining whether velocity 'hot spots' exist that may assist passage through the BAFF. Sonar monitoring of salmon smolt in front of the BAFF using a DIDSON found that most fish appeared to penetrate it about 3-4 metres from the true right bank. Quarterman (2009) suggested this section may also coincide with the highest velocities in the RDR cross-section.

Velocity profiling using an ADCP meter would enable 3D mapping of water velocities and water direction in the section of the RDR immediately upstream of the BAFF. Such an approach has been used successfully in the recently commissioned Highbank pumping station and its effect on fish movement (Goldsmith & Ryder 2013; Lintott 2013). Examples of the information generated from ADCP surveys are presented in figures 4 and 5.

Consideration should be given towards monitoring the behaviour of wild salmon smolt using acoustic telemetry. Bowen *et al*. (2009) used acoustic telemetry to track the movement and behaviour of juvenile Chinook salmon in and around a BAFF system on the San Joaquin River, California. The acoustic tag tracking system consisted of acoustic tags implanted in fish, hydrophones deployed underwater, and an on-shore receiver and data storage computer. Each acoustic tag transmitted an underwater sound signal or acoustic "ping" sending identification information about the tagged fish to hydrophones. The hydrophones were deployed at known locations within the array to maximize spacing of the hydrophones in two (or three) dimensions. For three dimensional tracking, tags needed to be received on at least four hydrophones, or on at least three hydrophones for two dimensional tracking. An example of the output data for one monitored fish is presented in Figure 6.

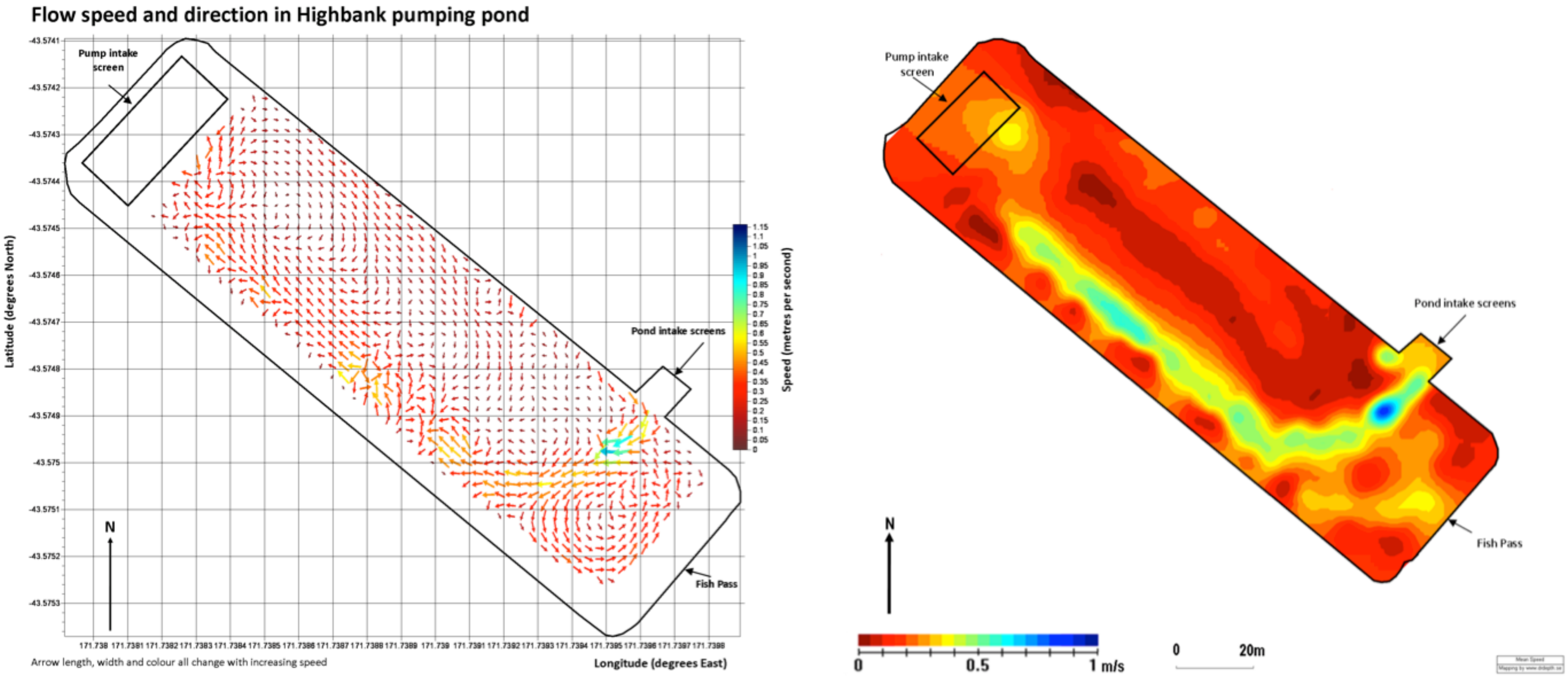

Figure 4. Highbank pond pumping station flow (velocity) direction and magnitude (left) and velocity magnitude (right). Redrawn from Lintott (2013).

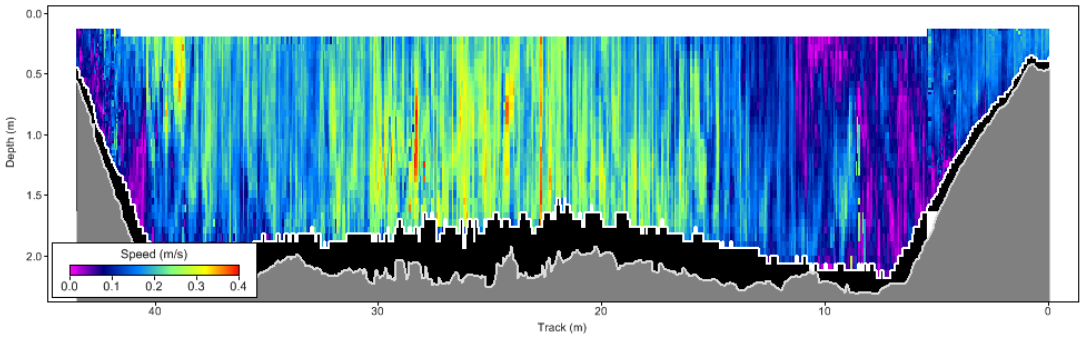

Figure 5. Example of a cross section showing current speeds throughout the water column using an ADCP.

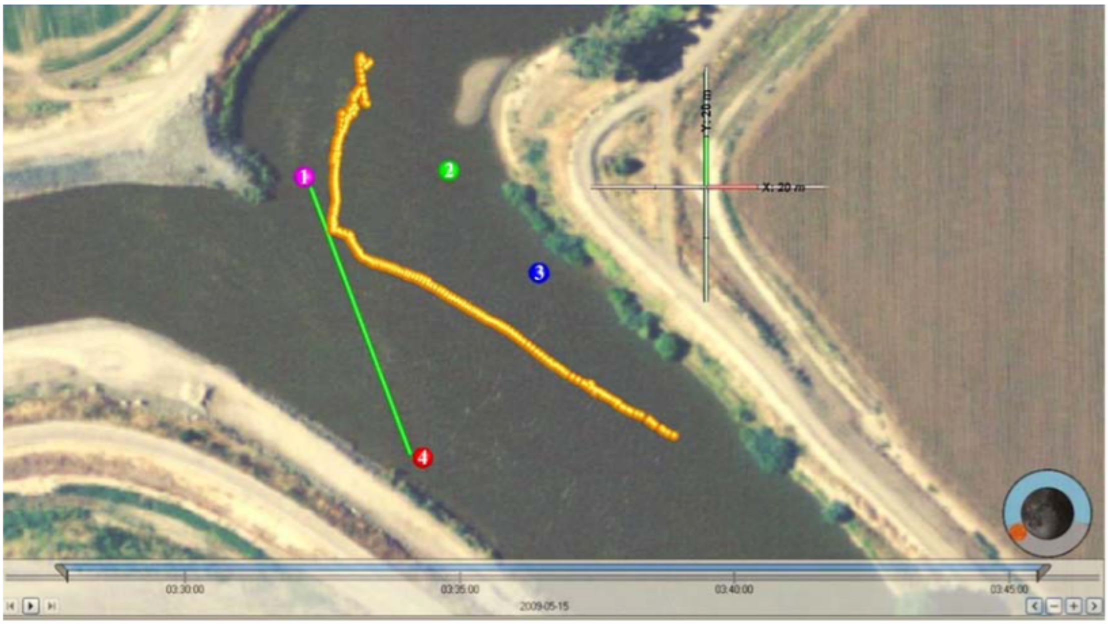

Figure 6. A juvenile Chinook salmon (tag # 5674) approaches the BAFF (green line). The tag exhibits a smolt-like trace: downstream quickly and no predator behavior. The colored circles indicate the location and number of the four hydrophones. Reproduced from Bowen et al. *(2009).*

Because acoustic tag technology enables individual fish movement to be identified and mapped (over a considerable distance in some situations), it would be possible to assess the effectiveness of the BAFF to wild salmon smolt of different sizes, and to determine whether they entered the BAFF bypass.

5. Conclusion

Comparisons of BAFF efficiency estimates over time are not strictly possible due to ongoing and varied changes in trial methodology and potentially the effects of environmental (external) variables such as river flow conditions. It seems clear, however, that efficiency at deflecting smolt down the BAFF and back to the Rangitata River has improved, with an average estimated efficiency of about 33% since the end of 2013. A low efficiency estimate within this period of 6.5% in October 2014 probably coincided with very low clarity river water, while a very high efficiency estimate of 81.6% in December 2013 was associated with release of hatchery fish on the same side of the RDR as the BAFF bypass, inferring possible bias in fish finding the bypass entrance.

An average efficiency estimate of 33% remains relatively low and so the issue of how to improve the level of efficiency is important.

Firstly, further improvements in deterring fish passage downstream the RDR should be investigated. One option is a louver screen immediately upstream and parallel to the BAFF bubble curtain. The other is the use of strobe lighting along the BAFF curtain as described in section 4.1. Both technologies have had success overseas with juvenile Chinook salmon (and other fish species).

Secondly, the accuracy of the BAFF efficiency estimates remains contentious due in part to the limitations of the trial methodology, some of which is largely unavoidable. The use of hatchery reared smolt in efficiency trials is questionable given their behaviour may differ significantly from wild smolt. The difficulties accessing wild smolt for trials are acknowledged, but consideration should be given towards using acoustic tag tracking to accurately observe individual smolt behaviour and movement around the BAFF. This, coupled with a better understanding of local water velocity and direction, would provide more definitive information on the effectiveness of the BAFF as a deterrent to wild fish. If the use of such a technique is not possible, then consideration should be given towards greater acclimatisation of hatchery reared fish prior to trials commencing, or the use of wild fish in the trials.

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