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Cross-channel movement of small migratory fish and shrimps in the Waikato River near Huntly thermal power station

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Cross-channel movement of small migratory fish and shrimps in the Waikato River near Huntly thermal power station

by

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SUMMARY

The ability of small migratory fish and shrimps to negotiate the thermal discharge from Huntly power station was studied during 1987 and 1988, prior to modification of the cooling water outfall structure.

Inanga (Galaxias maculatus), banded kokopu (G. fasciatus), common bullies (Gobiomorphus cotidianus), and freshwater shrimps (Paratya curvirostris) were batch marked by immersion in dye. The upstream migration of marked individuals was monitored by trapping at eight sites above and below the power station.

The migration of juvenile and spent adult inanga, and juvenile banded kokopu was curtailed on the power station side of the river by high water velocities at the station's outfall. Juvenile inanga migration was further interrupted in summer when temperatures in the thermal discharge plume reached 27°C. The migration of common bullies and shrimps also may have been curtailed by high plume temperatures. Under the current water right, a thermal barrier to migration should persist only in hot, dry summers.

Inanga and banded kokopu negotiated the thermal discharge by crossing to the ambient river margin. The proportion of migrants that did so could not be determined accurately because of the short-term nature of the marking method used. Nevertheless, it appeared that the migration of juvenile inanga could be delayed by the plume, at least temporarily. Spent adult inanga were able to negotiate the thermal discharge and they did so at a much faster rate than the juveniles.

In February 1987, common bullies reached the station's outfall by moving through a zone where water temperatures were up to 28.5°C. Further upstream migration did not occur along the true left bank of the river, but common bullies probably avoided the thermal discharge by moving on the bottom of the river channel.

Shrimps were the most thermally sensitive species marked. Like bullies, upstream migrating shrimps probably avoid high temperatures near the outfall by moving around them on the bottom of the river channel.

1. INTRODUCTION

Every year, juveniles of at least 10 native fish species, and the freshwater shrimp (Paratya curvirostris), migrate up the Waikato River from the sea or the estuary (Boubee et al. 1986). Immense numbers move into habitats upstream of Huntly, the site of New Zealand's largest thermal power station (Fig. 1).

Huntly power station is situated on the true left bank of the Waikato River, just downstream of the outlet of Lake Waahi and 15 km below the Waipa River confluence (Fig. 1). As the migration of many freshwater species is concentrated along the river margins (Stancliff et al. 1988a, Schicker et al. in press), there is concern that the bank-side discharge of condenser cooling water from the power station could disrupt migration and adversely affect recruitment to populations in the extensive habitats upstream.

Huntly power station is coal and gas fired, and utilises a "once through" cooling system. At full load (1000 MW), the station abstracts up to 38 m^3/s of water, which is returned to the river at 8-10°C above ambient temperature via a multi-port bank-side outfall. This results in a thermal plume which impinges on the left bank of the Waikato River.

Rutherford (1987) found that vertical mixing of the thermal plume is complete within 300-400 m of the outfall. He estimated that, at full load, condenser cooling water would mix with about 45% of the river's flow at a point 200 m downstream of the outfall. As the rate of transverse mixing is slow thereafter (transverse temperature gradients are still detectable 25 km downstream of Huntly), there is a corridor of ambient water along the right margin of the river which migratory fish and shrimps may use to avoid the thermal discharge.

The impacts of Huntly power station on fish and shrimp migration are not confined to thermal effects, as high water velocities at the outfall and discharges of pollutants from the power station also have the potential to disrupt migration on the true left side of the river.

In this study, inanga (Galaxias maculatus), banded kokopu (G. fasciatus), common bullies (Gobiomorphus cotidianus), and shrimps were marked with dye, to determine their ability to negotiate the thermal plume and to identify the migratory pathways involved.

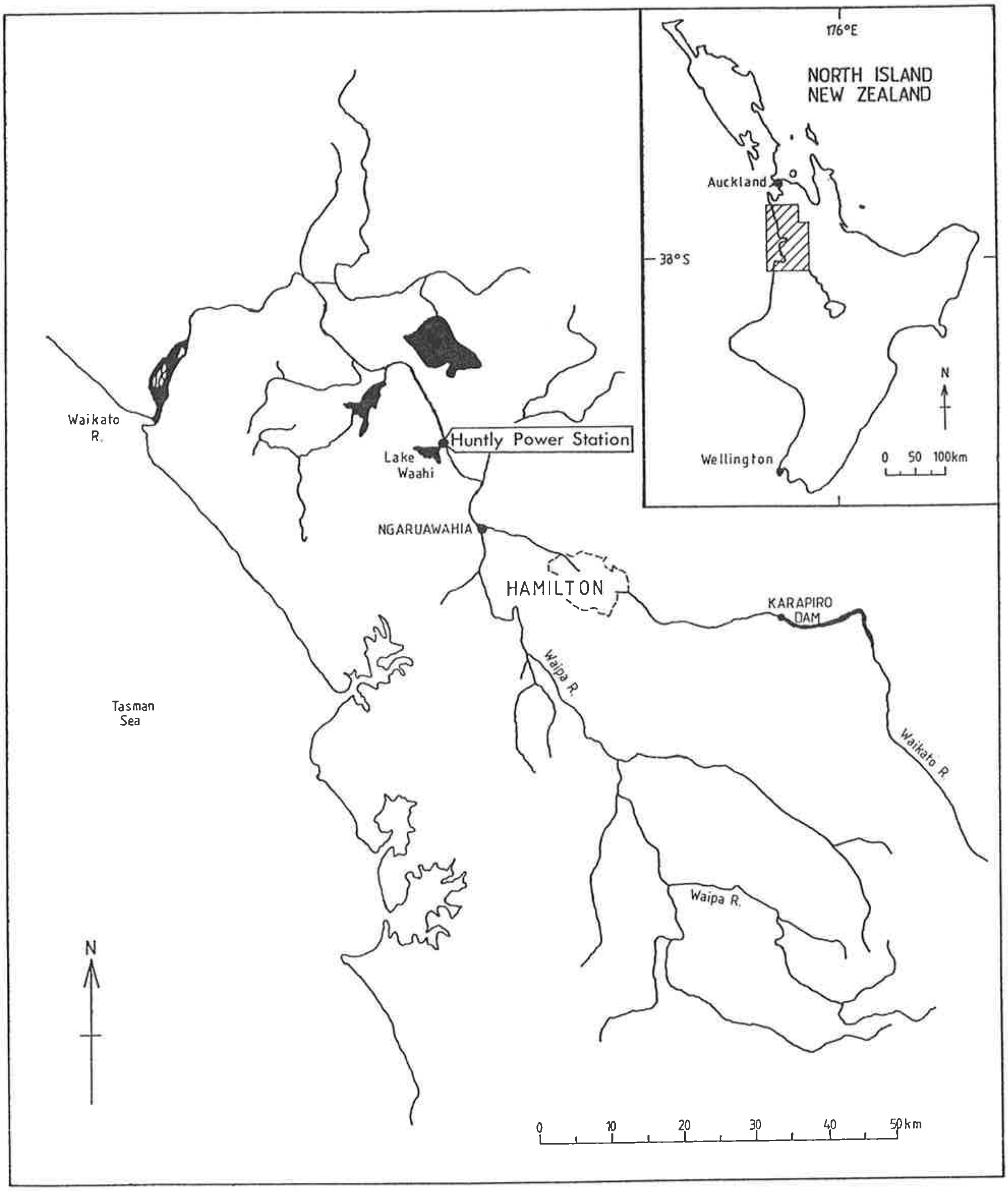

FIGURE 1. The lower Waikato River and Waipa catchment showing the location of Huntly thermal power station.

2. METHODS

Fish and shrimps were caught in 2-mm-mesh traps, set from eight solid wooden stands which blocked off the entire river margin (Stancliff et al. 1988a). Individuals were transferred to live-boxes and acclimated at release sites for 12-15 hours prior to marking.

Juveniles of inanga and banded kokopu, juvenile and adult common bullies, and spent adult inanga, were batch marked by immersion in 0.05 g/l neutral red or 0.15 g/l bismark brown for 8-10 minutes. Shrimps were marked by immersion in 0.15 g/l alcian blue for 10 minutes. The solutions were aerated continuously during the marking process.

Mortality was estimated from sub-samples kept in live-boxes for the duration of each experiment. The total numbers released were adjusted to account for mortality.

Marked fish and shrimps were recaptured in 2-mm-mesh traps, which sampled the top metre of the water column from each stand. Traps were checked hourly during the day, but left in position overnight. All recaptured fish and shrimps were counted and released about 20 m upstream of the recapture site. Trapping continued until marked individuals could no longer be identified, or few were caught. The trapping efficiency of three stands was evaluated using releases of marked juvenile inanga.

On two occasions in 1988, the movement of marked shrimps was monitored using eight 2-mm-mesh traps set along a transect across the river bottom, just upstream of the Huntly power station outfall (Fig. 2).

Rates of upstream migration were estimated for inanga and common bullies from the time taken for 50% of recaptures to travel from the release to the recapture site.

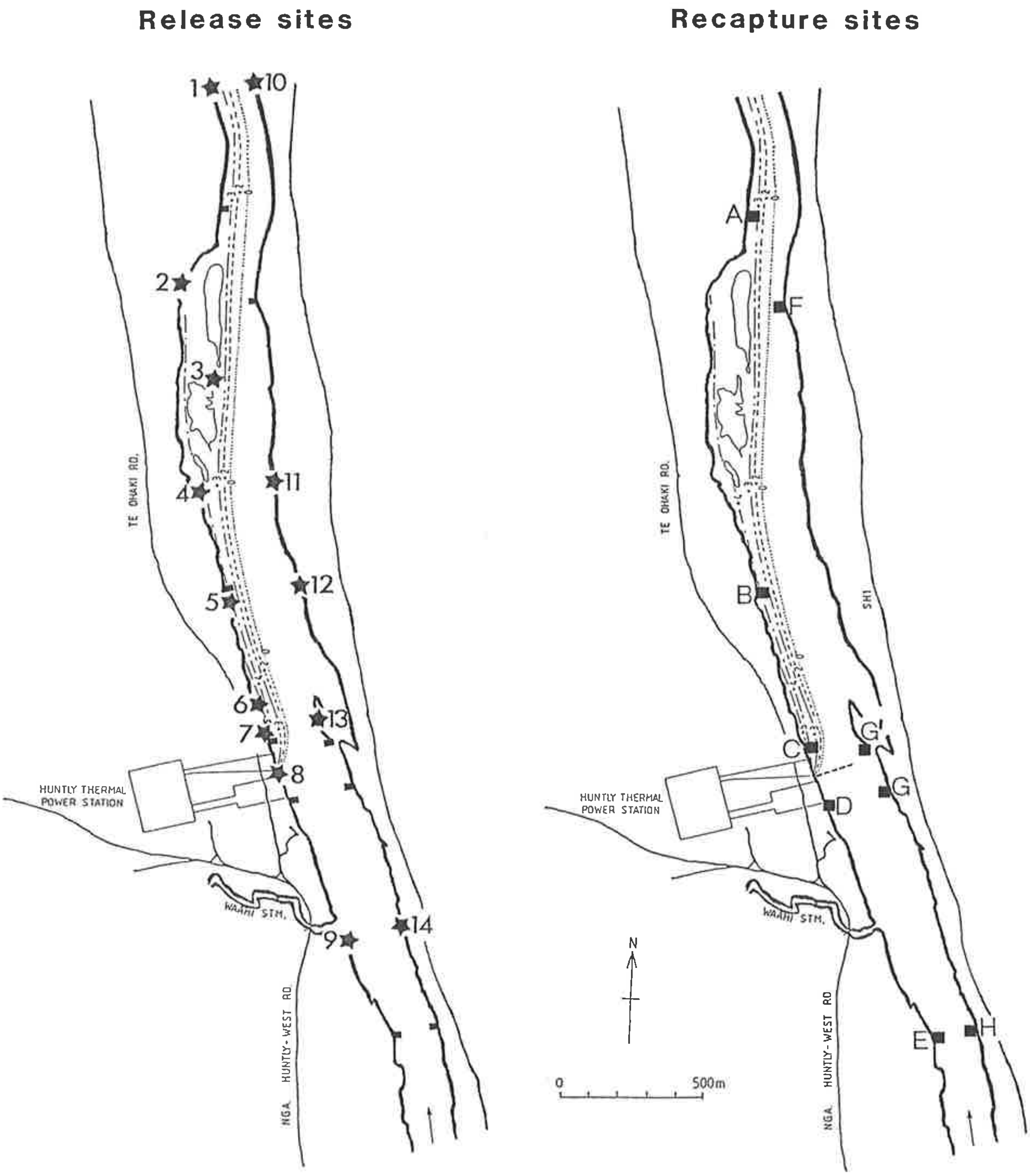

FIGURE 2. Location of release and recapture sites in the Waikato River near Huntly power station. The stand at site G1 was used only during the January and early February 1987 releases. The temperature (°C) by which the water in the thermal plume exceeded that of the ambient river water also is shown. --- = transect.

3. RESULTS

3.1 Mortality and Mark Retention

Mortality of marked juvenile inanga was usually less than 10%, although up to 50% mortality occurred on two occasions in January 1987, when ambient river temperatures were greater than 22°C. Mortalities of spent adult inanga, juvenile banded kokopu, common bullies, and shrimps were negligible.

Juvenile banded kokopu retained marks for about 24 hours, common bullies for 28-34 hours, and shrimps for about seven days. Marked juvenile inanga were recognised for up to 34 hours after release in summer (ambient temperatures were 21-23°C), but fading of the dye meant that identification was often difficult after 26 hours. Spent adult inanga retained marks for up to 70 hours in May, when ambient temperatures were only 13°C. Thus, mark retention time for inanga appeared to be inversely proportional to temperature.

3.2 Migration Pathways

3.2.1 Juvenile Inanga

On 7 and 8 January 1987, when Huntly power station was shut for maintenance, juvenile inanga were marked and released at sites 2 and 3, approximately 1500 m downstream of the station (Fig. 2). On average, 7.80% were recaptured along the left bank upstream of the station at sites D and E (Table 1). A further 1.23% were recaptured along the opposite margin.

On eight occasions between 11 January and 4 February 1987, when the power station was operating at 50% load, marked juvenile inanga were released within the thermal plume at sites 1-5 (Fig. 2). On average, only 0.21% were recaptured along the left bank upstream of the station, whereas 3.37% were recaptured along the opposite margin (Table 1).

Of the recaptures within the thermal plume (at sites A, B, and C), the highest percentages of marked juvenile inanga were taken at sites A and B, 2050 m and 550 m, respectively, downstream of the power station (Table 2). Most recaptures at site B occurred when water temperatures

TABLE 1. Percentage recapture (at sites outside the thermal plume) of marked juvenile inanga released downstream of Huntly power station when there was no generation and when the station was operating at 50% load (January-February 1987). (The location of the release and recapture sites is shown in Figure 2.)

				% recaptured				
				Along the left bank upstream of the station			Along the opposite margin	
Station generation	Date	Releases n	Site	D	E	F	G[1]	H
Nil	07.01.87	2190	2	8.30	0.80	0.50	NS	0.10
	08.01.87	2187	3	5.30	1.20	1.60	0.10	0.05
	Average			6.80	1.00	1.05	0.10	0.08
	Total			7.80			1.23	
450-550 MW	11.01.87	1027	1	0.40	0.00	1.40	0.20	0.50
	12.01.87	1530	2	0.00	0.00	1.00	0.07	0.20
	13.01.87	679	4	0.10	0.00	0.70	1.60	0.40
	16.01.87	4450	4	0.10	0.00	0.70	0.20	0.30
	20.01.87	1928	1	0.00	0.00	3.80	0.40	0.05
	30.01.87	2026	1	0.25	0.00	3.06	NS	1.40
	03.02.87	630	3	0.32	0.00	4.10	NS	1.40
	04.02.87	1040	5	0.48	0.00	0.10	NS	3.90
	Average			0.21	0.00	1.86	0.49	1.02
	Total			0.21			3.37	

n = number released.
NS = stand not trapped.

were between 26°C and 27°C. Only 1.6% of the marked inanga were recaptured at site C, 50 m from the outfall (Table 2), where water temperatures rose to between 27.0°C and 28.5°C.

TABLE 2. Percentage recapture (at sites within the thermal plume) of marked juvenile inanga released downstream of Huntly power station when it was operating at 50% load (11 January - 4 February 1987). (The location of the release and recapture sites is shown in Figure 2.)

Date	Releases n	Site	% recaptured A	B	C
11.01.87	1027	1	8.6	NS	NS
12.01.87	1530	2	*0.4	NS	NS
13.01.87	679	4	*0.0	NS	NS
16.01.87	4450	4	*0.0	NS	NS
20.01.87	1928	1	26.6	NS	NS
30.01.87	2026	1	14.6	NS	NS
03.02.87	630	3	*0.2	26.8	1.6
04.02.87	1040	5	*0.1	*0.2	1.6

n = number released.
NS = stand not trapped.
* = stands located downstream of the release site.

In September 1987, when the station was operating at 50-75% load, three further releases of marked juvenile inanga were made in the thermal plume at sites 5 and 6 (Fig. 2). On average, only 1.66% were recaptured (Table 3). Percentages recaptured along the left bank upstream of the station were low compared to those obtained from the ambient right margin.

On two occasions in October 1987, when the station was operating at 75% load, marked juvenile inanga were released concurrently along the left and right margins at sites 5 and 12 (Fig. 2). Percentages recaptured upstream of the station were much higher for right bank releases than for those made along the left bank (a total of 15.65% compared to 6.88%) (Table 4). Of the inanga released along the left bank, an average of 5.23% were recaptured at site C, 50 m downstream of the outfall, but only 0.83% were caught along the left bank upstream of the power station (Table 4).

TABLE 3. Percentage recapture of marked juvenile inanga released downstream of Huntly power station when it was operating at 50-75% load (September 1987). (The location of the release and recapture sites is shown in Figure 2.)

			% recaptured			
			Along the left bank upstream of the station		Along the opposite margin	
Date	Releases n	Site	D	E	G	H
03.09.87	400	5	0.00	0.00	4.25	0.00
09.09.87	3259	5	0.00	0.03	0.03	0.00
22.09.87	2067	6	0.10	0.00	0.58	0.00
Average			0.03	0.01	1.62	0.00
Total			0.04		1.62	

n = number released.

TABLE 4. Percentage recapture of marked juvenile inanga released concurrently along the left and right margins downstream of Huntly power station, when it was operating at 75% load (October 1987). (The location of the release and recapture sites is shown in Figure 2.)

				% recaptured				
				Below the station Left bank	Upstream of the station			
					Left bank		Right bank	
Margin	Date	Releases n	Site	C	D	E	G	H
Left	06.10.87	2049	5	0.05	0.10	0.05	6.70	0.00
	20.10.87	1333	5	10.40	1.40	0.10	5.20	0.20
	Average			5.23	0.75	0.08	5.95	0.10
	Total			5.23	0.83		6.05	
Right	06.10.87	702	12	0.00	0.30	0.30	17.40	2.10
	20.10.87	978	12	0.70	0.70	0.00	10.40	0.10
	Average			0.35	0.50	0.15	13.90	1.10
	Total			0.35	0.65		15.00	

n = number released.

The percentage of marked juvenile inanga that was recaptured along the opposite margin from their release site, and the proportion of the recaptures that crossed the river, were higher for releases made within the thermal plume than for releases made in ambient conditions (compare data in Tables 5 and 6).

TABLE 5. Cross-channel movement of marked inanga released in ambient river conditions at Huntly. (The location of the release sites is shown in Figure 2.)

Life stage	Releases Date	n	Site	% recaptured Directly upstream of release site	Along the opposite margin	% of recaptures crossing the river
Juvenile	07.01.87	2190	2#	9.10	0.60	6.1
	08.01.87	2187	3#	6.50	1.75	21.1
	30.01.87	1974	10	12.87	2.23	14.8
	06.10.87	702	12	19.50	0.60	2.8
	20.10.87	978	12	10.50	1.40	12.0
	Average % recaptured			11.69	1.32	11.4
Spent adult	25.05.87	982	11	16.50	0.61	3.6
	27.05.88	1416	13	27.05	2.68	9.0
	Average % recaptured			21.78	1.65	6.3

n = number released.
# = station shut down.

3.2.2 Spent Adult Inanga

Spent adult inanga were trapped as they returned to habitats upstream of Huntly, after spawning in the Waikato estuary.

In May 1987 and 1988, marked spent inanga were released concurrently along the left and right margins at four sites downstream of the power station, when it was operating at 50-75% load. Percentages recaptured upstream of the station were slightly higher for the left bank releases (a total of 28.71% compared to 23.43% for the right bank releases) (Table 7). Of the releases within the thermal plume (left bank releases at sites 4 and 7), only 0.81% were recaptured along the left bank upstream of the station, whereas 27.90% were recaptured along the ambient right margin (Table 7).

TABLE 6. Cross-channel movement of marked inanga released within the thermal plume below Huntly power station. Figures for station generation are the range of loads that occurred during daylight (the period when inanga migrate). (The location of the release sites is shown in Figure 2.)

Life stage	Releases Date	n	Site	Station generation (MW)	% recaptured Along the left bank upstream of the station	Along the opposite margin	% of recaptures crossing the river
Juvenile	11.01.87	1027	1	200-500	0.40	2.10	84.6
	12.01.87	1530	2	370-505	0.00	1.27	100.0
	13.01.87	679	4	370-505	0.10	2.70	94.7
	16.01.87	4450	4	370-505	0.10	1.20	93.0
	20.01.87	1928	1	490-507	0.00	4.25	100.0
	30.01.87	2026	1	524-757	0.25	4.46	94.7
	03.02.87	630	3	540-735	0.32	5.50	94.6
	04.02.87	1040	5	540-735	0.48	4.00	89.4
	03.09.87	400	5	743-750	0.00	4.25	100.0
	09.09.87	3259	5	629-650	0.03	0.03	50.0
	22.09.87	2067	7	499-753	0.10	0.58	85.7
	06.10.87	2049	5	690-740	0.15	6.70	97.9
	20.10.87	1333	5	668-746	1.50	5.40	78.3
	Average % recaptured				0.26	3.26	89.5
Spent adult	25.05.87	1200	4	408-694	1.17	15.50	93.0
	26.06.87	141	7	640-754	0.00	8.50	100.0
	27.05.88	926	7	688-753	0.43	40.28	98.9
	Average % recaptured				0.53	21.43	97.3

n = number released.

TABLE 7. Percentage recapture of marked spent adult inanga released concurrently along the left and right margins downstream of Huntly power station when it was operating at 50-75% load (May 1987 and 1988). (The location of the release and recapture sites is shown in Figure 2.)

				% recaptured					
				Below the station		Upstream of the station			
	Releases			Left bank		Left bank		Right bank	
Margin	Date	n	Site	B	C	D	E	G	H
Left	25.05.87	1200	4	3.43*	0.92*	0.92	0.25	6.60	8.90
	27.05.88	926	7	NS	NS	0.43	0.00	24.73	15.55
	Average					0.68	0.13	15.67	12.23
	Total					0.81		27.90	
Right	25.05.87	982	11	0.00	0.00	0.00	0.61	9.60	6.90
	27.05.88	1416	13	NS	NS	2.47	0.21	15.75	11.30
	Average					1.24	0.41	12.68	9.10
	Total					1.65		21.78	

n = number released.
* = stand trapped for only three hours.
NS = stand not trapped.

In May 1987, stands located within the thermal plume were trapped for only three hours (commencing 2-3 hours after inanga were released), but, in that time, 3.43% and 0.92% of the marked spent inanga were recaptured at sites B and C, 550 m and 50 m, respectively, downstream of the outfall (Table 7). Water temperatures in that zone were between 16°C and 17°C.

The percentage of marked spent inanga that was recaptured along the opposite margin from the release site, and the proportion of the recaptures that crossed the river, were much higher for releases made within the thermal plume than for releases made in ambient conditions (compare data in Tables 5 and 6).

3.2.3 Juvenile Banded Kokopu

On 22 September and 20 October 1987, when the station was operating at 50-75% load, a small number of juvenile banded kokopu were marked and released within the thermal plume at sites 5 and 7 (Fig. 2). None were recaptured at stands along the left bank upstream of the station, but an average of 11.1% were recaptured along the opposite margin (Table 8).

On 6 September 1987, 29 juveniles were released along the ambient right margin at site 12 (Fig. 2). The single recapture had crossed to the left bank.

3.2.4 Juvenile and Adult Common Bullies

On 3 and 4 February 1987, common bullies were marked and released within the thermal plume at sites 3 and 5 (Fig. 2). An average of 8.94% were recaptured 50 m downstream of the outfall at site C (Table 9), where water temperatures were between 27.5°C and 28.5°C. Very few were recaptured along the left bank upstream of the station or along the ambient right margin.

3.2.5 Shrimps

On four occasions between 9 February and 17 March 1987, an average of 11 100 marked shrimps were released near the left bank at site 6, 150 m downstream of the outfall (Fig. 2). On average, only 0.05% were recaptured 100 m further upstream at site C, where water temperatures were between 26.0°C and 28.5°C. None were recaptured at the other stands.

On 10 February and 15 March 1988, an average of 23 650 marked shrimps also were released at site 6. Only 0.03% were recaptured in traps set along a transect across the river bottom. A further 0.08% and 0.01% were trapped upstream of the station, at sites D and G respectively (Fig. 2).

3.3 Trapping Efficiency of Stands

On 4 November 1987, 2225 and 2751 marked juvenile inanga were released upstream of the power station at sites 9 and 14 respectively (Fig. 2). Similar percentage recaptures (24.18% and 20.72%) were made at Sites E and H, respectively, directly upstream of the release sites. In addition, 1776 marked juvenile inanga were released at site 8, along

TABLE 8. Percentage recapture of marked juvenile banded kokopu released downstream of Huntly power station when it was operating at 50-75% load (September-October 1987). (The location of the release and recapture sites is shown in Figure 2.)

			% recaptured			
			Along the left bank upstream of the station		Along the opposite margin	
Date	Releases n	Site	D	E	G	H
22.09.87	25	7	0.00	0.00	0.00	4.00
20.10.87	11	5	0.00	0.00	18.20	0.00
Average			0.00	0.00	9.10	2.00
Total			0.00		11.10	

n = number released.

TABLE 9. Percentage recapture of marked common bullies released downstream of Huntly power station when it was operating at 50% load (February 1987). (The location of the release and recapture sites is shown in Figure 2.)

			% recaptured					
			Along the left bank below the station		Along the left bank upstream of the station		Along the opposite margin	
Date	Releases n	Site	B	C	D	E	G	H
03.02.87	829	3	10.10	5.80	0.12	0.00	0.12	0.00
04.02.87	1480	5	NS	12.07	0.67	0.00	0.00	0.00
Average				8.94	0.40	0.00	0.06	0.00
Total					0.40		0.06	

n = number released.
NS = stand not trapped.

the sheet-piling between the station's outfall and the intake forebay. A total of 62.11% was recaptured at site D, on the left bank just upstream of the station.

3.4 Rates of Upstream Migration

The upstream migration rates of juvenile inanga were highest (0.074-0.133 m/s) within the thermal plume, where water temperatures were between 2.6°C and 4.4°C above ambient (Table 10). Migration rates were usually slowest when juvenile inanga crossed the river. However, those released at site 1 on 20 and 30 January 1987, crossed from the left to the right margin of the river, and moved upstream, at a similar rate to those that moved only along the right margin on those days. (Site 1 was located in a section of the river where there were no well-defined channels.) The fast migration rate (0.07 m/s) exhibited by marked juvenile inanga released at site 5 and recaptured at site H suggests that river crossing can occur rapidly.

Large, spent adult inanga moved upstream at a faster rate than the juveniles, indicating that their swimming ability was superior. Common bullies had the slowest rate of migration (Table 10).

4. DISCUSSION

4.1 Juvenile Inanga

4.1.1 Thermal and Velocity Barriers to Migration

When Huntly power station restarted after a maintenance shutdown in January 1987, the percentage of marked juvenile inanga recaptured along the left bank upstream of the station decreased from 7.8% to 0.2%. Similarly, the proportion of the total catch of unmarked inanga that was taken along that bank decreased from 30.4% to 6.1% (Boubee et al. in prep. a). Thermal discharges from the station were therefore impeding juvenile inanga migration along the left margin.

The migration of juvenile inanga was curtailed between 550 m and 50 m downstream of the outfall. At that time, plume temperatures within 550 m of the station often reached or exceeded 27°C, with late

TABLE 10. Upstream migration rates of juvenile and spent adult inanga, and common bullies released within the thermal plume and in ambient zones of the Waikato River at Huntly, January-May 1987. Rates were estimated by determining the time taken for 50% of the recaptures to travel from the release to the recapture sites.

Date	Ambient temperature	Releases Site	Releases Δt	Recaptures Site	Recaptures Δt	Number recaptured	Upstream gain†	Migration pathway*	Migration rate (m/s)
Juvenile inanga									
07.01.87	22.0	2	0.0	D	0.0	183	1870	l	0.087
08.01.87	22.0	3	0.0	D	0.0	117	1600	l	0.076
20.01.87	22.0	10	0.0	F	0.0	74	1250	r	0.050
30.01.87	21.4	10	0.0	F	0.0	245	1250	r	0.047
20.01.87	22.0	1	2.6	A	3.0	513	750	l	0.098
30.01.87	21.4	1	2.6	A	3.0	296	750	l	0.074
03.02.87	22.2	3	3.6	B	4.4	168	830	l	0.133
04.02.87	22.8	5	3.8	C	4.4	17	450	l	0.122
20.01.87	22.0	10	0.0	A	3.0	31	750	r-l	0.032
30.01.87	21.4	10	0.0	A	3.0	38	750	r-l	0.033
20.01.87	22.0	1	2.6	F	0.0	74	1250	l-r	0.046
30.01.87	21.4	1	2.6	F	0.0	62	1250	l-r	0.043
04.02.87	22.8	5	3.8	H	0.0	41	1960	l-r	0.070
Spent adult inanga									
25.05.87	13.0	11	0.0	G	0.0	94	1200	r	0.163
25.05.87	13.0	11	0.0	H	0.0	68	2450	r	0.149
25.05.87	13.0	4	2.0	G	0.0	79	1200	l-r	0.069
25.05.87	13.0	4	2.0	H	0.0	107	2450	l-r	0.106
Common bullies									
30.01.87	21.4	10	0.0	F	0.0	14	1250	r	0.031
30.01.87	21.4	1	2.6	A	3.0	116	750	l	0.032
03.02.87	22.2	3	3.6	B	4.4	84	830	l	0.034
04.02.87	22.8	5	3.8	C	4.4	179	450	l	0.029

Δt = temperature (in °C) by which the water in the thermal plume exceeds that of the ambient river water.

† = distance (in m) between the release and recapture sites, as measured along the river bank.

* Migration pathway: l = true left margin.
r = true right margin.
l-r = crossed from the left to the right margin.
r-l = crossed from the right to the left margin.

afternoon temperatures as high as 29.5°C being recorded 50 m below the outfall.

Simons (1986) estimated that the upper temperature limit for the long-term survival of inanga was 26-27°C. It is therefore expected that inanga would strongly avoid temperatures of 27°C or higher. Although the temperatures that elicit avoidance responses in inanga have not been determined in the laboratory, Boubee et al. (in prep. b) have found that inanga avoided water 5°C warmer than ambient, when ambient temperatures were 18°C or higher. As water temperatures near the outfall were often 5-6°C above ambient in January and early February 1987, high temperature was the likely cause of the avoidance observed at that time.

A thermal barrier to migration, which may extend for several hundred metres below the outfall, will therefore be present at times when plume temperatures reach 27°C. Juvenile inanga that arrive at Huntly from mid December onwards are most likely to be affected.

The upstream migration of marked juvenile inanga also was curtailed on the true left bank of the river in September and October 1987. At that time, ambient river temperatures were low (12.8-16.5°C) and plume temperatures 50 m from the outfall were only 3.4-4.3°C above ambient. Although marked inanga moved to within 50 m of the outfall in October, few were caught along the left bank above the power station. Similarly, 31.2% of the total catch of unmarked inanga in September and October was trapped 50 m downstream of the outfall, but only 8.0% was trapped along the left bank upstream of the station (Boubee et al. in prep. a).

Since juvenile inanga migrated to within 50 m of the outfall in September and October, and temperatures there were similar to those occurring closer to the outfall, high temperature probably did not cause the curtailment of migration observed in those months. High water velocities are more likely to have discouraged further upstream migration in September and October, as velocities averaging 2.24 m/s were measured against a concrete abutment at the downstream edge of the outfall, when the cooling water flow rate was high (31.9 m^3/s). Such high velocities are well beyond the maximum, short burst, swimming speeds of juvenile inanga (up to 1.25 m/s) (Mitchell in press).

On the six occasions (mostly in November and December) when substantial numbers of juvenile inanga were recorded moving upstream past the outfall with the station running, the cooling water flow rate was less than 23.3 m^3/s. Migration was always curtailed when the flow rate exceeded 27 m^3/s (Boubee et al. in prep. a). A cooling water flow rate of between 23 m^3/s and 27 m^3/s is therefore sufficient to disrupt juvenile inanga migration past Huntly power station. Inanga migration could be affected adversely at even lower flow rates when river levels fall below about 107.20 m (Moturiki Datum), owing to increased jetting from the outfall ports.

Under the current water right for Huntly power station, water velocities at the existing outfall could be high enough to interrupt the entire annual migration of juvenile inanga along the Waikato River's left bank. Juvenile inanga migration usually occurs at Huntly from September to early February each year (Stancliff et al. 1988b).

4.1.2 Migration Pathways Past the Thermal Plume

The upstream migration of juvenile inanga is confined largely to the margins (Stancliff et al. 1988a), but some river crossing does take place. On two occasions when marked juvenile inanga were released in ambient conditions, nearly 15% of the recaptured fish had crossed to the opposite margin within 4 km of the release site. Thus, most of the inanga that negotiated the thermal discharge at Huntly probably did so by crossing to the ambient right margin. Indeed, in January 1987, a higher percentage of marked juvenile inanga crossed the river when the station was running, than when it was shut down. Catches of unmarked inanga along the right bank upstream of the station also increased in relation to the other stands when the station re-started (Boubee et al. in prep. a).

Although the Waikato River at Huntly is only about 250 m wide, juvenile inanga are unlikely to cross directly to the right margin, because water velocities in the channels adjacent to each margin are higher than the sustainable swimming speeds of these fish. Juvenile inanga probably cross the river by utilising areas of lower water velocity near the bottom of the river and in the lee of sandbars in the middle of the river (Stancliff et al. 1988a).

River crossing can result in a net movement downstream, as most of the inanga that crossed to the right margin on 6 and 8 January 1987 were recaptured 200-300 m below the left bank release sites. This downstream movement probably occurs when juvenile inanga negotiate the channels, which carry a large proportion of the river's flow and contain hard-packed sediments with few resting places. As well-defined channels were absent from the section of river where marked juvenile inanga crossed the river at a similar rate to those that moved only along the margins, it appears that the ease of river crossing is dependent on the river profile.

4.1.3 Percentage of Fish that Negotiated the Thermal Plume

The very low percentage of fish recaptured from the September 1987 releases (1.7%), suggests that there may be little stimulus for juvenile inanga to move out of the thermal plume when ambient temperatures are low. Neill and Magnusson (1974) found that temperature preference and food abundance can influence the distribution of fish. In September, plume temperatures of 16-17°C were close to the preferred temperature of inanga (B. Penlington pers. comm.), and food supplies may have been abundant in the plume at that time.

In January 1987, the percentage of marked juvenile inanga recaptured at sites upstream of the station, and along the ambient right margin, decreased from a total of 9.0% when the station was shut down, to 3.6% when the station was generating at 50% load. The most likely explanation for the decrease is that a proportion of the marked inanga did not negotiate the thermal plume. However, lower overall trapping efficiency of right bank stands and faster fading of marks in the thermal plume also could have produced this decrease.

Although the left and right bank stands (E and H) furthest upstream from the station had similar efficiencies, those adjacent to the station (D and G^1) differed. The left bank stand (D) was located on a main bank and was very effective. When the station was shut down in early January 1987, 75% of the recaptured fish were trapped there. In contrast, the right bank stand (G^1) was situated on an island during the January and early February 1987 releases, and some inanga probably evaded capture by moving into the shallow, weed-choked channel behind it.

Furthermore, as mark retention time appeared to be inversely proportional to temperature (owing to a more rapid turnover of epidermal mucus at high temperature, A.S. Meredith pers. comm.), juvenile inanga released within the thermal plume may have lost marks at a faster rate than those liberated when the station was shut down. Using their estimated migration rates (Table 10), half the marked juvenile inanga released in the plume 2800 m below the station would take more than 25 hours to cross the river and reach the most upstream stand on the right bank. Thus, many slower migrants could have lost their marks before being recaptured.

If marked juvenile inanga released within the thermal plume were able to move easily past the station by crossing the river, then the total percentages of fish recaptured upstream of the station should have been the same as those obtained for releases made concurrently along the unaffected right margin. In October 1987, an average of only 6.9% of marked inanga liberated within the plume were recaptured upstream of the station, compared to 15.7% for releases made along the right margin. This implies that less than half of the juvenile inanga migrating along the left bank managed to move upstream past the station in the 24 hours for which releases were monitored.

Thus, although the short-term marking of juvenile inanga did not allow an accurate determination of the proportion of the migrants that negotiated the thermal plume, it showed that the migration of juvenile inanga can be delayed, at least temporarily, by the thermal discharge from Huntly power station.

4.2 Spent Adult Inanga

Few marked spent inanga moved upstream past the outfall of Huntly power station via the left margin. Similarly, only 2-5% of the unmarked spent inanga caught upstream of the station were trapped along the left bank (Boubee *et al.* in prep. a).

Some marked inanga moved to within 50 m of the outfall in May 1987, but the percentage that did so could not be quantified because traps were set in the plume for only three hours. During that time, however, 866 unmarked inanga were caught and released at site B, 550 m downstream of the station, but only 74 were trapped at site C, 50 m from the station (Boubee et al. in prep. a). Spent inanga may therefore have been avoiding the plume before they reached the outfall.

The avoidance responses observed in May 1987 could have been caused by a substantial discharge of coal stockpile runoff, which entered the river 70 m downstream of the outfall. Storm water discharges were absent in May 1988, when similar numbers of spent inanga were caught at sites B and C (Boubee et al. in prep. a).

High plume temperatures should not have curtailed migration on the true left bank of the river on either occasion, as temperatures at the outfall were only 3-4°C above ambient, and spent inanga moved past the outfall at Meremere power station when temperatures were up to 7°C above ambient (MAFFish unpublished data). High cooling water flow rates (28-33 m^3/s) during the 1987 and 1988 releases probably impeded the migration of spent inanga that reached the outfall.

The high percentage of marked spent inanga that crossed to the ambient right margin confirmed that most of the spent inanga that negotiated the thermal discharge at Huntly did so by crossing the river. Because the percentages of fish recaptured upstream of the station were at least as high for releases within the thermal plume as for releases along the ambient margin, spent inanga migrating along the left margin must have been able to cross the river quickly and continue on upstream. Spent inanga are larger than juveniles, and migrated upstream at a much faster rate. Their greater swimming ability probably allowed them to move past the station more easily than juvenile inanga.

4.3 Juvenile Banded Kokopu

The migration of juvenile banded kokopu appeared to be curtailed on the true left bank of the river, as none of the marked individuals released within the thermal plume were recaptured along the left bank upstream of the station. However, 9.5% of the total catch of unmarked banded kokopu was trapped there (Boubee et al. in prep. a). Although this was substantially less than the proportion trapped 50 m below the outfall (22.6% of the total catch), it indicates that some banded kokopu managed to move past the station. The considerable climbing ability of juvenile kokopu (McDowall 1978) may have facilitated this movement.

Plume temperatures were probably not high enough to curtail the migration of banded kokopu on the true left bank of the river, as most of these fish reach Huntly from September to early November, when ambient temperatures are low (<18°C) (Stancliff et al. 1988b), and avoidance responses did not occur when temperatures near the outfall were up to 21°C. High water velocities at the outfall are more likely to have impeded migration (cooling water flow rates were between 27 m^3/s and 33 m^3/s).

Releases of marked banded kokopu showed that this species can negotiate the thermal discharge at Huntly by crossing to the ambient margin; the proportion that do so could not be determined.

4.4 Juvenile and Adult Common Bullies

Few marked common bullies were recaptured along the left bank above the station in early February 1987, but many moved as far upstream as the station's outfall. The same migration pattern was shown by unmarked bullies along the left bank at that time, as 24.1% of the total catch was trapped 50 m below the outfall, but only 6.3% was caught above the station (Boubee et al. in prep. a).

Common bullies migrated through the plume when its temperature was as high as 28.5°C. Bullies therefore tolerated higher temperatures than juvenile inanga, which is in agreement with Simons (1984), who found that bullies had higher critical thermal maxima than juvenile inanga.

The low catch of common bullies above the station in early February 1987 could have been caused by temperatures higher than 28.5°C at the outfall, or by high water velocities (cooling water flow rates were between 31 m^3/s and 32 m^3/s). Although migration along the left margin was not impeded from September 1987 to March 1988, when plume temperatures were lower, water velocities also may have been lower at that time (Boubee et al. in prep. a). The exact cause of the migration curtailment therefore remains uncertain.

Common bullies are probably able to avoid the thermal discharge at Huntly by moving upstream along the bottom of the river channel. As substantial numbers of bullies normally migrate upstream along the river bottom (Stancliff et al. 1988a), many marked bullies may not have returned to the margins quickly enough to be caught at the stands above the station. Those that returned to the margins may still have eluded capture, as common bullies move throughout the water column when migrating along the margins (Stancliff et al. 1988a) and only the uppermost metre of the water column was trapped.

4.5 Shrimps

Shrimps differ from the other species discussed, in that their migration occurs mostly at night (Stancliff et al. 1988a). Shrimps are more temperature sensitive than inanga or common bullies (Simons 1984), and significant mortality can occur in summer when they are exposed continuously to temperatures of 27.5°C (Town 1982). In this study, shrimps were marked and released during the day, in a zone of high temperature (25.0-28.5°C). Exposure to high temperatures, at a time when shrimps are normally inactive, could explain why very few marked individuals were recaptured.

Plume temperatures high enough to prevent shrimps from moving past the station can occur in summer, but may not persist in every summer. In January and February 1987, when the temperature of the cooling water usually exceeded 25°C at night, only 6.6% of the total shrimp catch was trapped along the left bank upstream of the station (Boubee et al. in prep. a). This increased to 12.7% in March of that year, when cooling water temperatures were lower (23°C - 24°C between 0100 h and 0600 h).

In contrast, 35.2% of the shrimp catch was taken along the left bank upstream of the station in the period September 1987 to March 1988 (Boubee et al. in prep. a), when cooling water temperatures were usually between 17°C and 24°C at night. Cooling water flow rates of 27-33 m^3/s were apparently not high enough to interfere with shrimp migration during that period.

As large numbers of shrimps normally migrate upstream over the entire river bottom (Stancliff et al. 1988a), they probably avoid areas of high temperature and velocity along the river margins by moving around them on the bottom of the river channel.

5. CONCLUSION

The existing outfall at Huntly power station can produce both thermal and velocity barriers to small migratory fish and shrimps. The addition of orifice plates and extensions to the outfall ports should reduce these impacts.

It is likely that all juvenile inanga held up by the thermal discharge are eventually able to continue their upstream migration by crossing to the opposite margin. However, we were unable to prove that this occurs, owing to the short-term nature of the marking method used.

Mark-recapture experiments did not demonstrate that common bullies and shrimps moved past the station, but these species can probably negotiate thermal and velocity barriers adjacent to the margins by moving along the bottom of the river channel.

The avoidance responses observed in spent adult inanga in May 1987 emphasise the need for adequate treatment of wastes before discharge to the river.

The existing outfall at Huntly power station has probably reduced recruitment to populations of inanga and banded kokopu in Lake Waahi and its catchment, because fish access is via Waahi Stream, which enters the river just upstream of the station. Natural cross-channel movement should minimise impacts to other upstream populations, such as those in the Waipa catchment, but this needs to be confirmed by field studies.

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