Effects of irrigation water abstraction from the Ashburton River on chinook salmon passage, fish and invertebrate habitat, and water temperature

CBER Contract Report 36

Confidential client report prepared for
Kingett Mitchell Ltd,
Christchurch

by

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6 December 2004

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Executive summary

The Ashburton River is subject to abstractions for irrigation, the largest of which is the intake for the Rangitata Diversion Race. This report uses the data previously collected at three representative reaches to model the effects of reducing flows on upstream passage of adult salmonids, habitat availability for brown trout and native fish, food production, and water temperatures. The program RHYHABSIM 3.31 was used to model habitat suitability, and WAIORA was used to model water temperature.

This report examines the previous assumed minimum depth for upstream migration of adult chinook salmon of 0.24 m, and suggests from previous research the minimum depth for passage is likely to be 0.20 m, the approximate maximum body depth of chinook salmon in New Zealand. Also important for passage is water velocity; if velocity exceeds 1 m/s, the maximum velocity for sustained swimming, salmon are unlikely to negotiate the longest riffles (up to 30 m). At low flows in the Ashburton River, some critical cross sections provide passage in only a small proportion of the cross section. Salmon might take 6-63 days to reach the RDR siphon, 63 km upstream from the sea, assuming passage rates that vary from 1-10 km/day. Passage rates are likely to be slowest during times of low flow and high temperatures.

With a minimum depth requirement is 0.20 m and a maximum velocity of 1.0 m/s upstream passage of adult chinook salmon is likely to be blocked by low flows at some critical points in the Ashburton River. At Wakanui, flows of ≥1.0 m^3/s provided salmon passage. At Ollivers, passage was possible at flows ≥1.5 m^3/s. At Valetta, salmon passage was possible at flows of ≥1.25 m^3/s, which agrees approximately with Hudson's riffle crest analysis. I assumed that flows that provided upstream passage for adult chinook salmon also provided passage for the smaller adult brown trout.

The modelled reaches have limited suitability for adult brown trout, and for their feeding and spawning, but are more suitable for juvenile brown trout. Within the range of modelled flows, the available habitat for juvenile brown trout increases with increasing flow.

The Ashburton River is more suitable for native fish than for salmonids, and is especially suitable for Canterbury (common river) galaxias, longfin eels <300 mm, and upland and common bullies. The habitat is relatively unsuitable for longfin eels >300 mm, inanga, and juvenile lamprey. At Valetta and Ollivers, there was little change in native fish habitat with flows >1.5 m^3/s except for a slight increase in torrentfish habitat with flow. At Wakanui, the habitat changed little with as flows increased to > 3 m^3/s except for and torrentfish and longfin eels <300 mm.

The habitat suitability for food production is quite high, especially for the horny cased caddis *Olinga feredayi* and *Deleatidium* spp. mayflies. The habitat becomes more suitable for all taxa modelled as flows increase.

Daily mean and maximum water temperatures modelled for January with WAIORA 2.0 decreased with increasing flow. Over the flow range 1.5-2.5 m^3/s, maximum daily temperatures range dropped 25.0 to 24.4°C at Valetta, from 26.6 to 24.8°C at Ollivers, and from 27.7 to 27.0°C at Wakanui. Though maximum daily temperatures may persist for only an hour or two on any

day, the temperature extremes show that the Ashburton River is more suitable for native fish species than for salmonids.

The daily mean temperatures at low flows exceed 20°C in all reaches, but especially in the most downstream reach (Wakanui), which suggests that chinook salmon migration might not be possible under low flows in January and other warm months, at least during the day. The highest modelled temperatures suggest that daily maxima are likely to restrict salmon passage and cause mortalities.

Introduction

The Ashburton River flows east from the foothills of the Southern Alps to the sea across the alluvial gravels of the South Canterbury plains (Fig. 1). The Rangitata Diversion Race abstracts irrigation water from the North Branch Ashburton River that also drives two power stations. The purpose of this report is to evaluate a the effect of range of flows on upstream passage of adult salmonids, brown trout habitat, native fish habitat, food production, and the thermal regime.

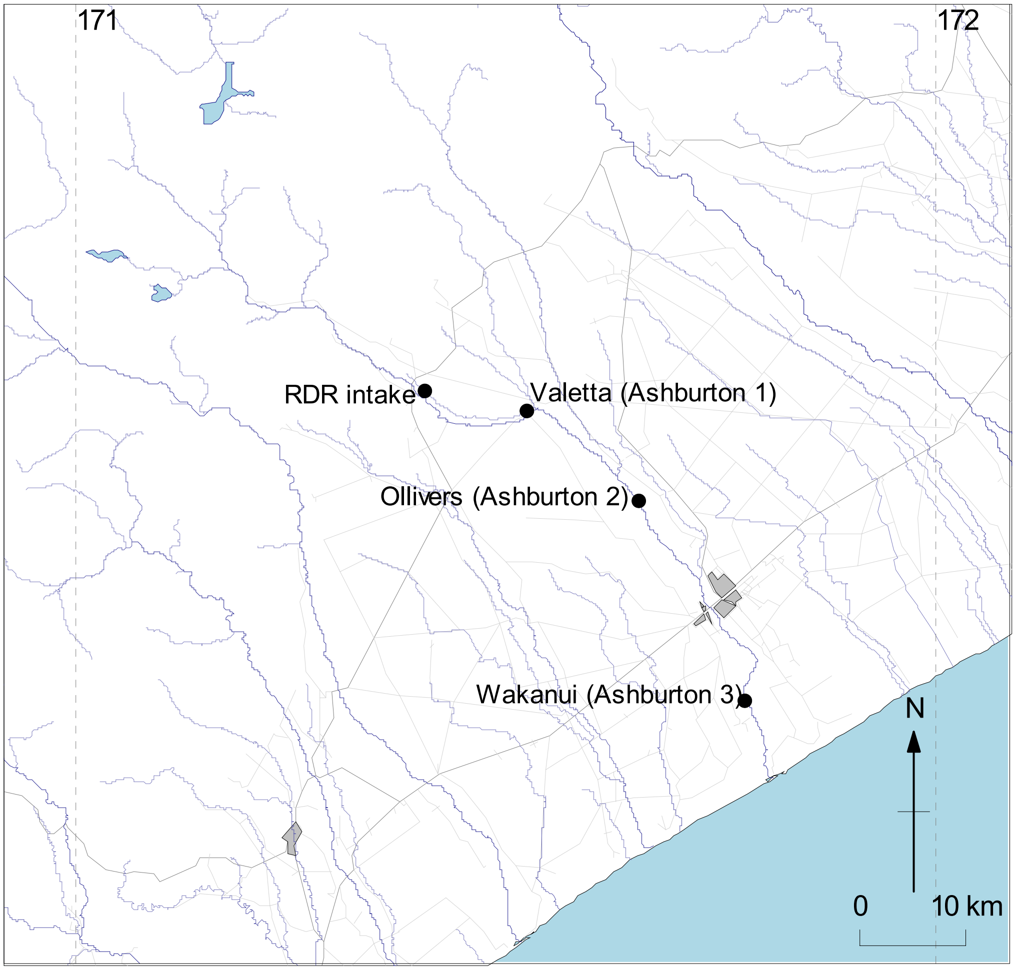

Figure 1. Location of the cross sections and Rangitata Diversion Race (RDR) intake on the Ashburton River. Drawn with Freshwater Fish Database Assistant version 5.0, I. Jowett, NIWA, Hamilton.

Several key statements that have been brought out in evidence or correspondence bear repeating here by way of introduction:

"… if flow abstractions do not alter the mean annual minimum or median flow, then I believe they will have little effect on trout stocks - which are already limited by natural flow regime."

(I. Jowett 30 April 1993, letter to Malcom Miller, Regional Planning Officer, Canterbury Regional Council.)

"…. I still have reservations about the prediction of velocity distribution at high flows in unconfined channels. In the Ashburton, I have more confidence in predictions made for the upper reaches (Valetta and Olivers) [sic] than for the downstream reach (Wakanui) where the river is spread out over a wide gravel bed as the flow increases."

(I. Jowett 10 February 1995, letter to Malcom Miller, Canterbury Regional Council.)

"Based on the morphology of the river, I would be surprised if the Ashburton River could ever become a high quality trout fishery, no matter what the flow."

(I. Jowett 10 February 1995, letter to Malcom Miller, Canterbury Regional Council.)

Low flows in the Ashburton River have the right velocities for drift-feeding adult brown trout (0.4-0.5 m/s) but in general are too shallow (<1 m deep). Water depth increases with increasing flow, but then the velocities become too high. This problem is common to gravel-bedded rivers that are unconfined and lack any well-defined pool-riffle structure. However, such rivers provide good habitat for species that require moderate depths and high velocities.

This report attempts to encompass the minimum flow criteria outlined in Table 1.

Table 1. Flow scenarios modelled for the Ashburton River below the Rangitata Diversion Race.

Site	Magnitude	Flow (m^3/s)	
		Scenario 1	Scenario 2, 3 & 4
Abstraction pt	Minimum	2.458	2.454 or 2.300
Abstraction pt	Median	4.193	2.479
Abstraction pt	Mean	7.266	5.983
Valetta ****	Minimum	1.5	1.5 or 1.353
Valetta ****	Median	3.1	1.52
Valetta ****	Mean	6.0	4.8
Ollivers *	Minimum	No flow record info	No flow record info
Ollivers *	Median	No flow record info	No flow record info
Ollivers *	Mean	No flow record info	No flow record info
Wakanui **	Minimum	1.978	1.978 ***
Wakanui **	Median	13.141	13.141 ***
Wakanui **	Mean	19.108	19.108 ***

* no reliable relationship to calc flows for this site

** SH1 data assumes no loss or gain between SH1 and Wakanui

*** No way to calc difference between scenario 1 and 2, 3, & 4

**** Regression for Valetta flow (de Joux): Valetta = 0.94*Abstraction pt - 800 L/s

Salmonids

In New Zealand, mature adult chinook salmon begin to migrate into freshwater around late November, and the peak of the migration generally occurs at the river mouths in March (McDowall 1990). However, there is considerable variation in the timing of the upstream migration. The run into the Rangitata River peaks in January, seven weeks earlier than the run into the Waitaki River, which peaks in March (Quinn et al. 2001). The median date of entry into headwater spawning tributaries varies little, occurring in late April or early May (Deans et al. 2004). Quinn et al. (2001) concluded that chinook salmon in New Zealand had evolved from their parent stock, and that within at most 30 generations since the time of their initial release, some character traits had diverged genetically to suit local conditions.

The Ashburton River is not among the 40 most fished rivers and lakes in New Zealand (Deans et al. 2004). Salmon runs in rivers of the East Coast of the South Island are at an all-time low (Table 1). The longer term record for the Glenariffe Stream shows just how serious this decline is (Fig. 2). The evidence of Don Jellyman, reported in Henry Hudson's evidence (p31), documents the decline in chinook salmon caught in the Ashburton River:

Year	**Number of salmon**
1952	>600 at the mouth
1967	1,400
1968	2,300
late 1980s	50-150
2003	~15

Chinook salmon have relatively high site fidelity, with most fish (up to 97%) returning to their natal streams to spawn. As runs in small streams are usually very variable, the prospect of periodic extinction of the natal race is quite likely, leaving strays from other rivers the primary source of returning adults. Chinook salmon may stray into the Ashburton River from other rivers from time to time, but given the parlous current state of stocks in other rivers, the local run is possibly extinct. Despite this, the run in has always been erratic, and it is likely to recover, even if only from strays from other rivers in years of strong runs. Thus habitat for chinook salmon should be considered in habitat modelling.

Table 2. Annual runs of chinook salmon in the four main salmon rivers between 1993 and 2003. For the first three rivers the table shows the total run and angler catch, and the angler catch as a percentage of the total. For the Waitaki River, data shown are the estimated Hakataramea River spawning run (number of fish), and the catch for Central South Island anglers. Source: Deans et al. (2004).

	Waimakariri River		Rakaia River		Rangitata River		Waitaki River	
Year	Total run	Angler catch	Total run	Angler catch	Total run	Angler catch	Hakataramea spawning run	Angler catch
1993	2400	1100 (47%)	3900	1100 (26%)			1173	
1994	4100	1600 (39%)	19900	7900 (40%)	11400	3300 (29%)	6301	3400
1995	10400	4400 (42%)	11600	3100 (27%)	8500	3200 (38%)	1183	7100
1996	13500	6000 (45%)	22600	9000 (40%)	16600	5400 (33%)	5962	2200
1997	9100	3900 (43%)	18500	8500 (46%)	15800	5800 (37%)	934	3100
1998	5800	2800 (48%)	6100	2600 (42%)	600	2600 (40%)	367	2300
1999	7100	4700 (66%)	6500	2600 (39%)	7800	3500 (45%)	829	1900
2000	3500	2600 (72%)	4900	3000 (61%)	4400	2100 (49%)	282	1100
2001	1900	1100 (56%)	1600	800 (53%)	1000	300 (32%)	12	500
2002	3300	1100 (34%)	2500	600 (23%)	1000	200 (24%)	79	600
2003	3600	1800 (49%)	3100	1700 (55%)	1600	700 (45%)	12	800

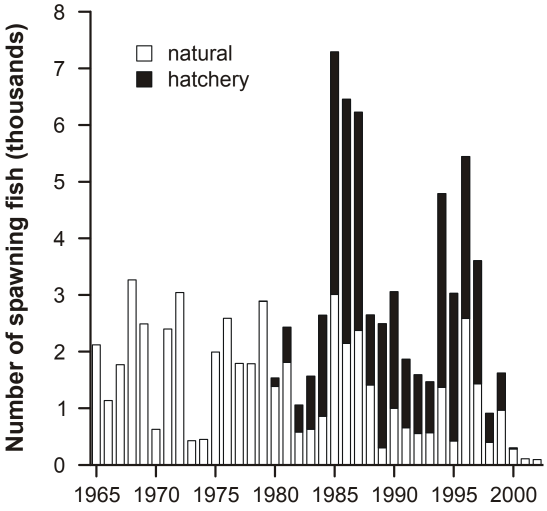

Figure 2. Chinook salmon spawning runs in Glenariffe Stream, 1965-2002, by origin (natural or hatchery) and year. Source: Deans et al. (2004).

Mouth closure

The barrier bar is likely to block the mouth at flows <4 m^3/s, and flows of ≥6 m^3/s are required to keep the bar open when the mouth is displaced northwards. A flow of ≥90 m^3/s is required to breach the bar once it is closed (Todd 1992, in EMG 2001, p17). This has implications for entry of migratory fish such as salmon and many native species.

Abstractions reduce the discharge at SH1 by 9.4 m^3/s under median conditions and a maximum of 13.1 m^3/s (EMG 2001, p22). A maximum water temperature of 30^oC has been recorded below the SH1 bridge, but 95% of the measurements were <18^oC (EMG 2001). However, spot water temperatures recorded at the mouth did not exceed 23.8^oC.

Methods

Habitat suitability curves of Raleigh et al. (1986a) were used to predict the effect of reducing flows on upstream passage of adult chinook salmon. These curves predict that depths of ≥0.15 m at velocities of <0.61 m/s are optimal for successful passage. According to these curves, depths ≤0.091 m cannot be negotiated by salmon. Substrate type was assumed not to be limiting. Water temperatures are assumed to be >2.0^oC and <16.0^oC (Raleigh et al. 1986a). Some earlier work has assumed that a greater minimum depth (~0.24 m) is required for salmon passage (Thompson 1972; in Hayes 1997, p10).

Water temperatures were modelled using the water temperature module contained in the programme WAIORA version 2.0, which is essentially the same routine used in RHYHABSIM 3.31 (I. Jowett, pers. comm.), but has improved graphical output, and includes data files to help select appropriate parameters. The model is a mechanistic, one-dimensional heat transport model that predicts the daily mean and maximum water temperatures as a function of stream distance and environmental heat flux. Net heat flux is calculated as the sum of heat to or from long-wave atmospheric radiation, direct short-wave solar radiation, convection, conduction, evaporation, streamside vegetation (shading), streambed fluid friction, and the water's back radiation. The heat flux model includes the incorporation of groundwater influx. The heat transport model tracks heat and water fluxes down stream. It assumes that all input data, including meteorological and hydrological variables, can be represented by 24-hour averages or sinusoidal variation about the average.

Water temperatures are modelled downstream of a section of river, and previous depth, velocity, and substrate measurements (Jowett 1992) were used to determine variability of temperature with flow. Water flowing downstream will the increase or decrease in temperature until the incoming radiation equals the heat lost from the river through radiation and evaporation. The temperature at which incoming energy equals the outgoing energy and there is no further increase in water temperature is known as the equilibrium temperature.

The change in water temperature is calculated as the water flows downstream using the initial water temperature at the beginning of the reach. The magnitude of the change will depend on meteorological conditions such as radiation and air temperature and the flow (RHYHABSIM 3.31 help file).

The simulations used the cross sectional data collected by Jowett (1992) and assumptions listed in Table 3. Data for which WAIORA is the source are monthly averages for the period 1971-2000 for Christcurch (WAIORA 2.0, NIWA, Hamilton).

Table 3. Parameters assumed for Ashburton River water temperature modelling with WAIORA 2.0 (NIWA, Hamilton).

Parameters assumed across all reaches	Value	Unit	Source
Mean daily air temperature	17.4	^{o}C	Waiora
Maximum daily air temperature	22.5	^{o}C	Waiora
Mean daily solar radiation	22	MJ/m^{2}	Waiora
Time of maximum temperature	14:00	h	Assumed
Wind velocity	0.5	m/s	Assumed
Possible sun hours	90	%	Assumed
Mean relative humidity	73	%	Waiora
Shade (proportion of 180^{o} sky arc)	0.1		Assumed
Latitude	45	^{o}S	Map
River bed temperature at 1 m below the river	17	^{o}C	Assumed
Stream shade - topographic angle	10	^{o}	Assumed
Stream shade - canopy	10	^{o}	Assumed
Stream shade - fraction through canopy	0.5		Assumed
Stream bed - bed conductivity	10	J/m/s/^{o}C	Assumed
Stream bed - bed thickness	1	m	Assumed
Stream bed - bed temperature	17	^{o}C	Assumed

Parameters that varied between reaches	Valetta	Ollivers	Wakanui	Unit	Source
Mean elevation above sea level of segment	205	104	50	m	RHYHABSIM files
Upstream mean water temperature	equilibrium	20.6	21	^{o}C	
Upstream maximum water temperature	equilibrium	25.1	24.6	^{o}C	
Index flow	700	1300	2500	L/s	

Results

A search of the Freshwater Fish Database on 17 November 2004 revealed 69 records for the Ashburton River and its tributaries (catchment number 688.000) collected between Sept 1961 and April 2004 (Table 4).

Table 4. Fish species recorded in the Ashburton River and its tributaries. Source: Freshwater Fish Database, NIWA, Hamilton, 21 May 2004.

Common name	Scientific name	Frequency
Upland bully	*Gobiomorphus breviceps*	39
Brown trout	*Salmo trutta*	25
Canterbury galaxias	*Galaxias vulgaris*	18
Longfin eel	*Anguilla dieffenbachii*	9
Chinook salmon	*Oncorhynchus tshawytscha*	6
Torrentfish	*Cheimarrichthys fosteri*	4
Canterbury mudfish	*Neochanna burrowsius*	4
Alpine galaxias	*Galaxias paucispondylus*	3
Bluegill bully	*Gobiomorphus hubbsi*	3
Koaro	*Galaxias brevipinnis*	3
Common bully	*Gobiomorphus cotidianus*	3
Perch	*Perca fluviatilis*	3
Trout	*Salmo* spp.	3
Freshwater crayfish	*Paranephrops*	2
Brook char	*Salvelinus fontinalis*	2
Shortfin eel	*Anguilla australis*	2
Giant bully	*Gobiomorphus gobioides*	1
Black flounder	*Rhombosolea retiaria*	1
Goldfish	*Carassius auratus*	1

Hydraulic reach analysis

The sites of the measured cross sections (Jowett 1992) vary in distance from the sea, elevation, and mean flow (Table 5).

Table 5. Distance from the sea, elevation, and catchment area river segments of the Ashburton River at the sites of the RDR intake siphon and the cross section reaches used in the IFIM analysis.

River	Site	SSI number	Stream order	Distance from the sea (km)	Elevation (m)	Catchment area (km^2)	Mean flow (m^3/s)
South Branch Ashburton	RDR intake siphon	13052607	6	62.8	352	558.4	12.8
South Branch Ashburton	Valetta Bridge	13053614	6	50.5	252	574.8	12.9
South Branch Ashburton	Ollivers	13056510	6	34.8	159	1280.5	26.5
Ashburton	Wakanui	13060319	6	9.2	50	1548.3	28.7

The bed gradient downstream of each of the representative reaches chosen for the cross sections was 0.006-0.007 m/m (Table 6).

Table 6. Bed gradient downstream of each of the representative reaches in the Ashburton River as measured from 1:50,000 NZMS 260 maps.

Elevation of contour line (m)	Latitude (°S)	Longitude (°E)	Distance between contour lines (m)	Bed gradient (m/m)
Ashburton 1 (Valetta)				
260	43.74416	171.51702		
250	43.74091	171.53051	1388	0.007
240	43.74070	171.54256	1205	0.008
230	43.74804	171.56052	1940	0.005
220	43.75555	171.57102	1291	0.008
Segment			5824	0.007
Ashburton 2 (Ollivers)				
160	43.81663	171.65312		
150	43.83074	171.66313	1730	0.006
140	43.84042	171.66720	1050	0.010
130	43.85313	171.68018	1817	0.006
120	43.86630	171.69830	2240	0.004
Segment			6837	0.006
Ashburton 3 (Wakanui)				
50	43.98981	171.77787		
40	44.00113	171.78462	1318	0.008
30	44.01559	171.79462	1758	0.006
20	44.03090	171.79931	1601	0.006
Segment			4677	0.006

This comprehensive data set includes depths, velocities, and substrate at 20 cross sections at Valetta (Table 7), 23 cross sections at Ollivers (Table 8), and 16 cross sections at Wakanui (Table 9) (Jowett 1992).

Table 7. Reach hydraulic geometry of the cross sections at Valetta (Ashburton 1, reach length 193 m) measured at a mean flow for the reach of 2.20 m^3/s.

Section	Flow (m^3/s)	Width (m)	Depth (m)	Velocity (m/s)	Area (m^2)	Froude no.	Pool (%)	Run (%)	Riffle (%)	Habitat type
XSECT-1	2.30	27.20	0.24	0.28	6.6	0.18	49.1	39.9	11.0	pool
XSECT-2	2.25	21.52	0.28	0.28	6.1	0.16	48.4	51.6	0.0	run
XSECT-3	2.11	10.26	0.48	0.40	4.9	0.18	26.9	73.1	0.0	run
XSECT-4	2.07	8.00	0.82	0.26	6.6	0.09	100.0	0.0	0.0	pool
XSECT-5	2.40	7.60	0.81	0.29	6.1	0.09	100.0	0.0	0.0	pool
XSECT-6	2.20	8.20	0.47	0.38	3.9	0.15	58.2	41.8	0.0	pool
XSECT-7	2.06	13.65	0.24	0.57	3.3	0.36	18.0	45.4	36.6	run
XSECT-8	2.49	31.50	0.11	0.50	3.6	0.50	9.5	32.5	57.9	riffle
XSECT-9	2.75	35.50	0.12	0.50	4.2	0.49	16.2	30.3	53.5	riffle
XSECT-10	1.74	30.50	0.12	0.37	3.8	0.34	9.0	54.9	36.1	run
XSECT-11	2.03	31.00	0.13	0.44	4.1	0.39	8.1	62.1	29.8	run
XSECT-12	2.68	30.00	0.15	0.48	4.5	0.40	8.3	49.2	42.5	run
XSECT-13	2.43	20.00	0.20	0.55	4.0	0.38	7.5	38.8	53.8	riffle
XSECT-14	2.11	16.30	0.22	0.53	3.6	0.34	7.1	59.2	33.7	run
XSECT-15	2.14	14.80	0.24	0.53	3.6	0.33	7.8	68.6	23.7	run
XSECT-16	2.01	11.10	0.31	0.48	3.4	0.26	18.5	81.5	0.0	run
XSECT-17	1.99	9.40	0.34	0.52	3.2	0.27	19.2	76.6	4.3	run
XSECT-18	2.13	9.00	0.29	0.70	2.6	0.40	10.0	41.1	48.9	riffle
XSECT-19	1.95	10.00	0.23	0.73	2.3	0.48	13.0	20.0	67.0	riffle
XSECT-20	2.19	10.80	0.22	0.74	2.4	0.49	9.3	17.6	73.2	riffle
Reach	2.20	15.709	0.26	0.48	4.1	0.33	20.6	49.5	29.9	

Table 8. Reach hydraulic geometry of the cross sections at Ollivers (Ashburton 2, reach length 263 m) measured at a mean flow for the reach of 2.02 m^3/s.

Section	Flow (m^3/s)	Width (m)	Depth (m)	Velocity (m/s)	Area (m^2)	Froude no.	Pool (%)	Run (%)	Riffle (%)	Habitat type
XSECT-01	2.15	19.40	0.25	0.34	4.84	0.21	17.8	82.2	0.0	run
XSECT-02	2.02	16.10	0.34	0.32	5.49	0.17	50.6	49.4	0.0	pool
XSECT-03	1.97	14.10	0.34	0.36	4.75	0.19	50.4	49.7	0.0	pool
XSECT-04	1.83	14.00	0.24	0.43	3.39	0.25	36.4	46.4	17.1	run
XSECT-05	1.77	13.90	0.18	0.60	2.49	0.43	6.5	40.7	52.9	riffle
XSECT-06	1.90	18.40	0.16	0.48	2.88	0.36	23.4	31.7	45.0	riffle
XSECT-07	1.73	19.00	0.19	0.40	3.57	0.28	20.8	61.1	18.2	run
XSECT-08	1.80	18.00	0.33	0.31	5.92	0.20	43.1	56.9	0.0	run
XSECT-09	1.52	12.85	0.48	0.18	6.22	0.07	100.0	0.0	0.0	pool
XSECT-10	1.78	10.40	0.48	0.27	5.04	0.11	80.8	19.2	0.0	pool
XSECT-11	1.86	9.10	0.60	0.27	5.46	0.10	83.5	16.5	0.0	pool
XSECT-12	2.78	13.09	0.47	0.37	6.20	0.20	46.3	40.0	13.8	pool
XSECT-13	2.42	32.60	0.13	0.45	4.15	0.39	9.5	56.4	34.1	run
XSECT-14	2.55	33.60	0.11	0.58	3.63	0.55	7.0	21.0	72.0	riffle
XSECT-15	2.52	29.70	0.12	0.58	3.61	0.52	15.2	38.2	46.6	riffle
XSECT-16	1.91	29.50	0.12	0.47	3.44	0.41	28.0	17.0	55.1	riffle
XSECT-17	1.91	25.30	0.14	0.45	3.65	0.36	11.5	49.0	39.5	run
XSECT-18	1.77	20.70	0.17	0.41	3.50	0.31	12.6	66.9	20.5	run
XSECT-19	1.97	21.50	0.15	0.36	3.32	0.27	27.9	48.8	23.3	run
XSECT-20	1.87	24.20	0.18	0.28	4.27	0.18	68.0	11.4	20.7	pool
XSECT-21	2.04	26.50	0.29	0.29	7.64	0.18	59.4	14.9	25.7	pool
XSECT-22	2.10	24.70	0.22	0.41	5.35	0.29	42.9	24.7	32.4	pool
XSECT-23	2.24	29.50	0.16	0.43	4.73	0.36	33.1	10.2	56.8	riffle
Reach	2.02	19.68	0.24	0.37	4.80	0.26	41.1	35.5	23.4	

Table 9. Reach hydraulic geometry of the cross sections at Wakanui (Ashburton 3, reach length 275 m) measured at a mean flow for the reach of 3.42 m^3/s.

Section	Flow (m^3/s)	Width (m)	Depth (m)	Velocity (m/s)	Area (m^2)	Froude no.	Pool (%)	Run (%)	Riffle (%)	Habitat type
XSECT-1	3.40	43.20	0.19	0.32	8.32	0.21	36.1	46.5	17.4	run
XSECT-2	2.94	33.25	0.24	0.26	7.83	0.15	56.4	43.6	0.0	pool
XSECT-3	2.94	30.30	0.22	0.27	6.78	0.15	64.0	29.4	6.6	pool
XSECT-4	3.64	35.30	0.14	0.41	4.82	0.31	31.0	24.4	44.6	riffle
XSECT-5	3.49	33.30	0.15	0.54	4.99	0.41	24.5	10.5	65.0	riffle
XSECT-6a	3.86	35.70	0.21	0.43	7.56	0.28	34.3	30.5	35.2	riffle
XSECT-6	3.86	35.70	0.21	0.43	7.56	0.28	34.3	30.5	35.2	riffle
XSECT-7	3.55	33.70	0.21	0.23	6.94	0.12	71.1	24.5	4.5	pool
XSECT-8	3.67	23.35	0.24	0.54	5.56	0.34	6.5	53.2	40.3	run
XSECT-9	3.33	20.20	0.26	0.47	5.30	0.27	28.0	47.3	24.8	run
XSECT-10	3.62	15.40	0.35	0.57	5.31	0.30	25.3	51.3	23.4	run
XSECT-11	3.30	23.20	0.24	0.53	5.64	0.36	24.1	33.0	42.9	riffle
XSECT-12	2.99	30.20	0.14	0.48	4.26	0.37	23.7	28.3	48.0	riffle
XSECT-13	3.15	26.90	0.18	0.52	4.72	0.38	25.1	16.9	58.0	riffle
XSECT-14	3.42	20.10	0.25	0.64	5.11	0.40	11.9	23.6	64.4	riffle
XSECT-15	3.53	34.70	0.20	0.43	6.83	0.29	45.8	21.3	32.9	pool
XSECT-16	3.49	27.80	0.26	0.42	7.26	0.31	40.7	16.2	43.2	riffle
Reach	3.42	28.69	0.21	0.43	6.11	0.28	36.2	31.0	32.8	

Upstream salmonid passage

When shallow water depth is combined with high water velocities and temperature, passage of salmonids can be impeded. Problems of upstream passage of adult salmonids may be caused by hydraulic features of the habitat, such as high water velocity, inadequate water depth, or extreme turbulence (Scottish Executive Consultations 2004).

The evidence of Henry Hudson for the 2003 consent hearing considers upstream passage for chinook salmon in the Ashburton River (p38), and concludes that

"The North Branch dries up in summer, even without water abstractions, thus impeding passage to spawning grounds."

Hudson considers that trout passage is not generally impeded in the main channel at low flow, but that whether the RDR siphon structure is a barrier remains to be investigated. In regard of salmon passage, Hudson maintains, without giving his sources of information, that

"Trout passage is generally not impeded in the main channel at low flow (minimum depth 15 cm for trout vs. 24 cm for salmon) (e.g. Figure 27)."

Hudson uses an interesting technique for evaluating salmon passage, measuring depth at riffle crests (Fig. 3 in this report, Fig. 27 in Hudson). Using 0.24 m as the minimum depth for upstream passage of chinook salmon, Fig. 3 shows that passage is not possible at Valetta at flows of 1.50 m^3/s or less.

However, there are two major problems with this analysis, firstly the minimum depth for passage, and secondly the maximum velocity. The blanket acceptance of 0.24 m as the minimum depth for salmon passage is problematic, which Hayes (1997) also quotes, and requires evaluation. Though the source is not given in Hudson's evidence, it seems likely that the 0.24 m minimum depth for chinook passage is from Thompson (1972), as given in Hayes (1997). However, a later reference suggests that chinook salmon in North America are capable of migrating in depths of 0.15 m (Raleigh et al. 1986a). This is based on the work of Sautner et al. (1984). Jowett (1999) adopted a minimum depth of 0.25 m in his modelling of chinook salmon passage.

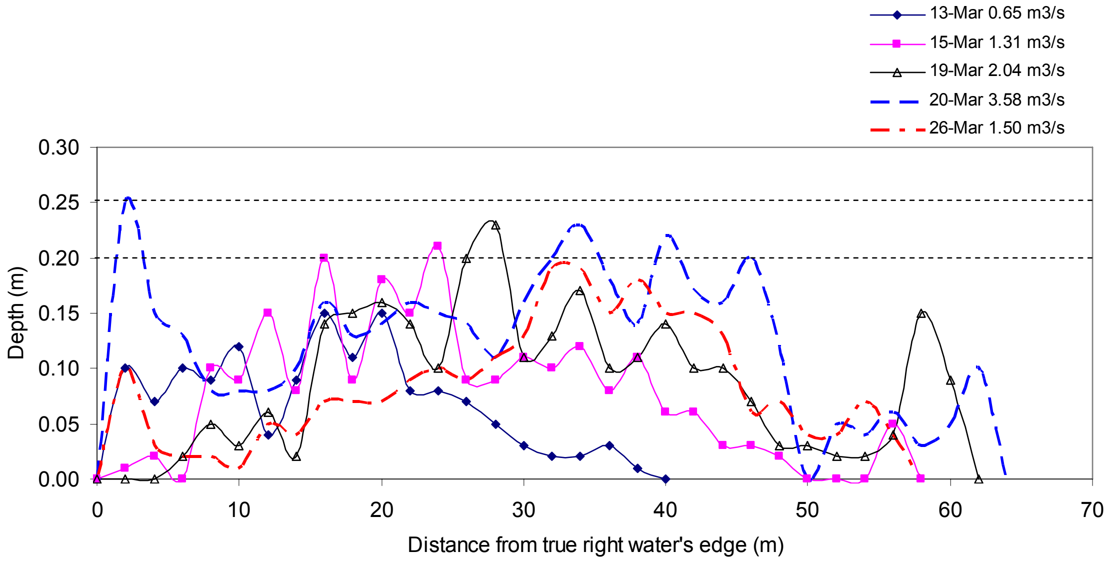

Figure 3. Riffle crest water depths in the South Branch Ashburton River at Valetta (cross-section 07) at a range of river flows. After Figure 27, Henry Hudson's evidence.

In fact, the 0.24 m minimum has never been formally tested for chinook salmon, should not be adopted without considering water velocity, water temperature, and the length over which any minimum depth might apply. Riffle crests may sometimes be the shallowest part of a river, but they are also short. The maximum length of riffles in the three reaches of the Ashburton River surveyed by Jowett (1992) was 30 m (Jowett 1999).

At issue is the minimum depth and maximum velocity requirements for upstream passage of adult chinook salmon and brown trout. It appears that the only specific study that has attempted to physically determine minimum depths for passage of adult salmon during their spawning migration was conducted by Powers and Orsborn (1985). Success of passage for chum salmon (average length 76 cm) and coho salmon (average length 61 cm) through a 2.4-m long chute was evaluated. Based on these results, the authors suggested that the minimum water depths required for passage are 0.12 m for coho salmon (mean weight 2.8 kg) and 0.15 m for chum (mean weight 4.6 kg). Further, these authors suggested that the minimum water depth should be equal to the maximum depth of the fish's body (T. Payne, Thomas R. Payne & Associates, Arcata, California, USA, pers. comm.). In New Zealand, the mean body depth of chinook salmon is 0.15-0.20 m (Docherty 1979).

In the Pacific northwest of America, chinook salmon frequently defend territories in spawning tributaries in depths of about 0.10-0.12 m, about half their body depth, swimming about with apparent ease with the uppermost half of their bodies above the water line. Under optimum temperatures, the sustained swimming velocity of adult chinook salmon 1 m/s, but in above optimum temperature swimming ability may be reduced by up to 50% (Bell 1973).

Anecdotal evidence from the Hurunui River on 8 March 1978, when maximum water temperature was 21°C, shows that riffles up to 30 m long with maximum depths of ≤0.15 m prevented upstream passage of adult chinook salmon despite repeated attempts by salmon to negotiate the riffles (Docherty 1979). Thus I adopted the more conservative depth of 0.20 m as the shallowest depth for both chinook salmon and brown trout passage, with an optimum depth of ≥0.25 m, and 1.0 m/s as the upper water velocity that allowed passage. (see Appendix 1 for the habitat suitability file used for the RHYHABSIM habitat modelling).

In Hudson's cross section 07 at Valetta in the North Branch Ashburton River, the lowest flow given (0.65 m^3/s or 650 L/s) in Fig. 3 would have presented upstream salmon passage, assuming a minimum suitable depth of 0.20 m. However, passage is possible at 1.31 m^3/s, where two points have depths of ≥0.20 m. The higher flows of 2.04 and 3.58 m^3/s also permit salmon passage, but 1.50 m^3/s did not, which seems anomalous. Any depth and velocity suitable for chinook salmon passage was considered to be suitable for brown trout passage.

The second problem that Hudson does not appear to consider is velocity associated with shallow depths. Assuming that the velocity criteria in Raleigh et al. (1986a) apply, then velocity should be considered with depth in any analysis of salmon passage. Jowett (1999) appeared also not to consider velocity in his analysis of salmon passage. It is possible to consider both minimum depth and maximum velocity with RHYHABSIM, and is the approach that I took.

As Hudson (p38) points out, salmon migrations occur at times of high flow, which will increase water depth and reduce water temperature. However, flows can recede quickly in New Zealand rivers, and once in the river, salmon could become trapped in pools by falling depths at critical points in the river, normally riffles. Median rates of travel of 10-40 km/day have been measured in the Columbia River and its tributaries (USA), and passage rates were inversely related to discharge. Some rates were as low as 4 km/day (Keefer et al. 2004). In the Hurunui River, North Canterbury, one salmon moved only 1 km/day on average (Docherty 1979). Given the potential variability in rates of upstream migration shown for adult chinook salmon, and the possibility that warm water temperatures might slow passage compared to the USA, it seems appropriate to consider the potential blocks presented by riffles at low flows in the Ashburton River. Salmon might take 6-63 days to reach the RDR siphon, 63 km upstream from the sea, assuming passage rates that vary from 1-10 km/day. Passage rates are likely to be slowest during times of low flow and high temperatures.

Salmon passage was modelled with RHYHABSIM version 3.31 using the habitat data from Jowett (1992) for the Ashburton River. Passage through the riffles is possible, but limited (Fig. 4). Weighted usable area is not the only way to look at passage requirements, but does show graphically the most critical cross sections, combines depth and velocity, and give a simple comparison of the effects of flows on the possibility of upstream passage. Another method of analysing salmon passage is to examine the point habitat suitability at individual cross sections. Jowett (1999) does caution, however, that the cross sections used for the Ashburton River in-stream habitat surveys were selected to be representative of average river conditions, and might not include the shallowest sections in the river.

Salmon passage at Valetta

In the Valetta reach, salmon passage was most limited at low flows in the runs represented by cross sections 10 and 11 (Fig. 4). Cross section 8 was the shallowest, with a mean depth of 0.11 m (Table 7), cross section 11 was more limiting, however, with no passage at flows of ≤1.0 m^3/s (Fig. 5). As flows increased to ≥1.25 m^3/s, there was always one point in the cross section that met the depth and velocity criteria for salmon passage (Appendix 1A). Using a minimum depth of 0.25 m, but no velocity criteria, the graphs (Fig. 14) of Jowett (1999) suggest that flows >2.0 m^3/s were required to enable salmon passage at Valetta.

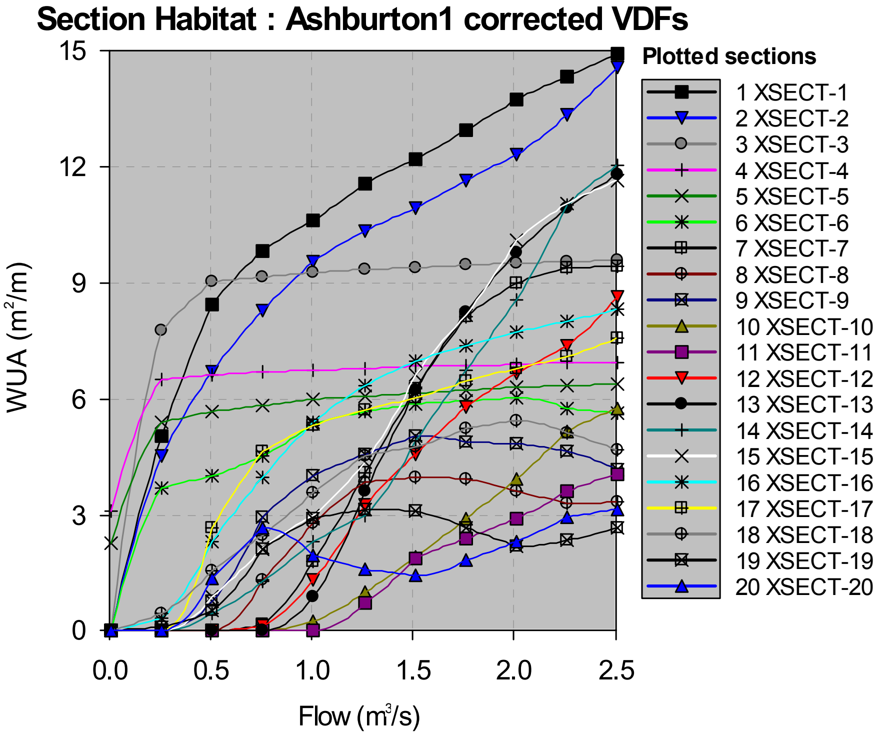

Figure 4. Effect of reducing flows on upstream passage of chinook salmon at Valetta (Ashburton 1) on the South Branch Ashburton River. Section habitat modelled using RHYHABSIM 3.31 and the data of Jowett (1992).

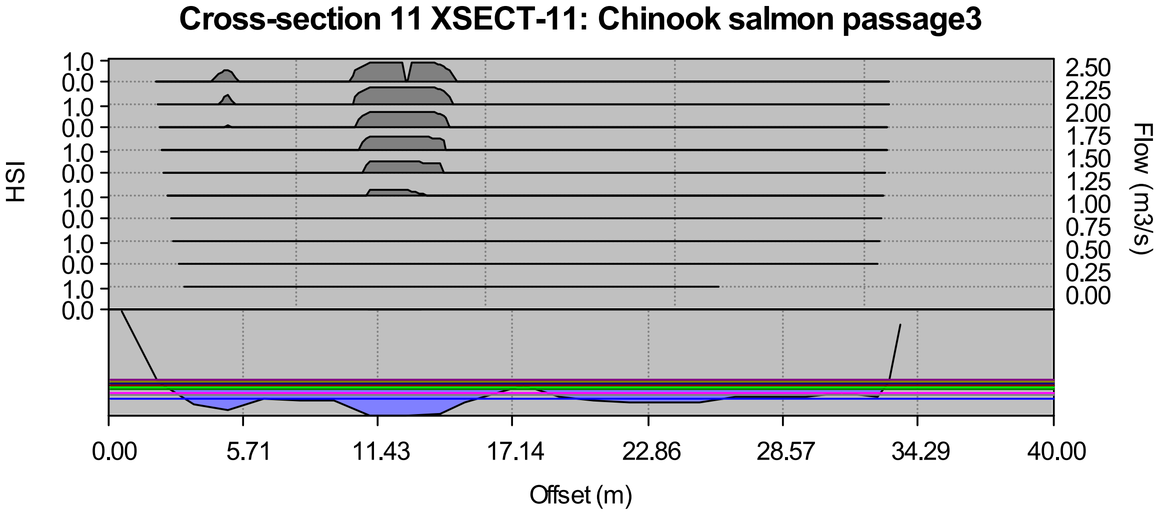

Figure 5. Change of habitat suitability for upstream passage of adult chinook salmon with flow at the critical run cross section 11 in the Valetta reach of the North Branch Ashburton River. Point habitat modelled using RHYHABSIM 3.31 and the data of Jowett (1992).

Salmon passage at Ollivers

At Ollivers, adult salmon and trout can migrate upstream at flows ≥1.5 m^3/s even through the shallowest cross sections (Fig. 6). The riffle at cross section 16 did not permit passage at flows <1.5 m/s (Fig. 7), and passage was very limited through cross section 14 at all flows modelled between 1 and 3 m^3/s (Appendix 1B). Cross section 14 had the shallowest depths of any cross sections (mean depth 0.11 m, Table 8). The graphs of Jowett (1999) suggest that flows >2.6 m^3/s enabled salmon passage at Ollivers.

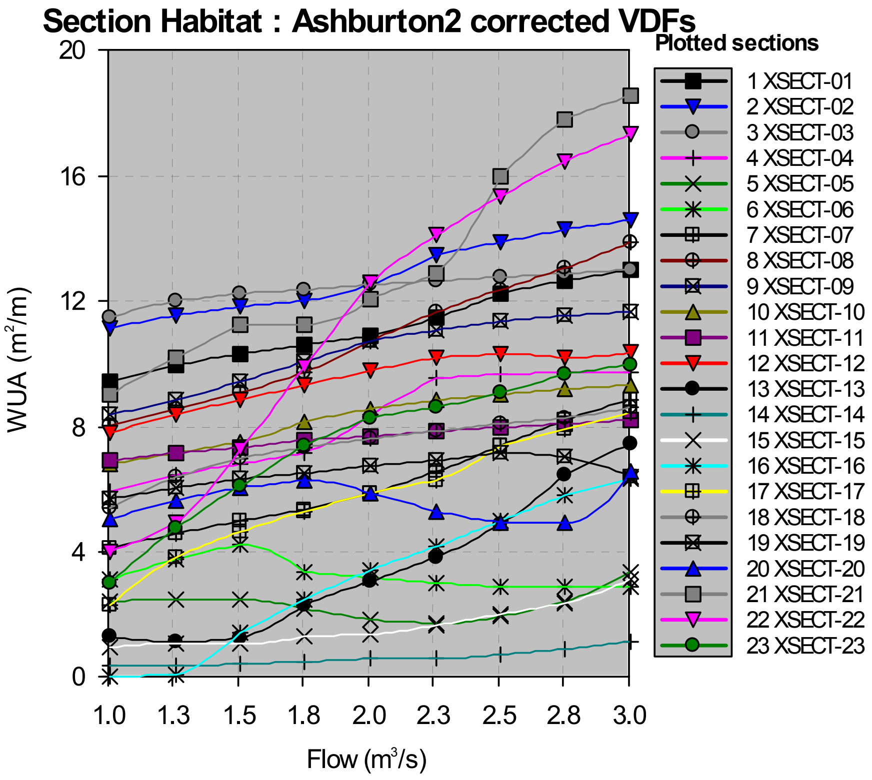

Figure 6. Effect of reducing flows on upstream passage of adult chinook salmon at Ollivers (Ashburton 2) on the South Branch Ashburton River. Section habitat modelled using RHYHABSIM 3.31 and the data of Jowett (1992).

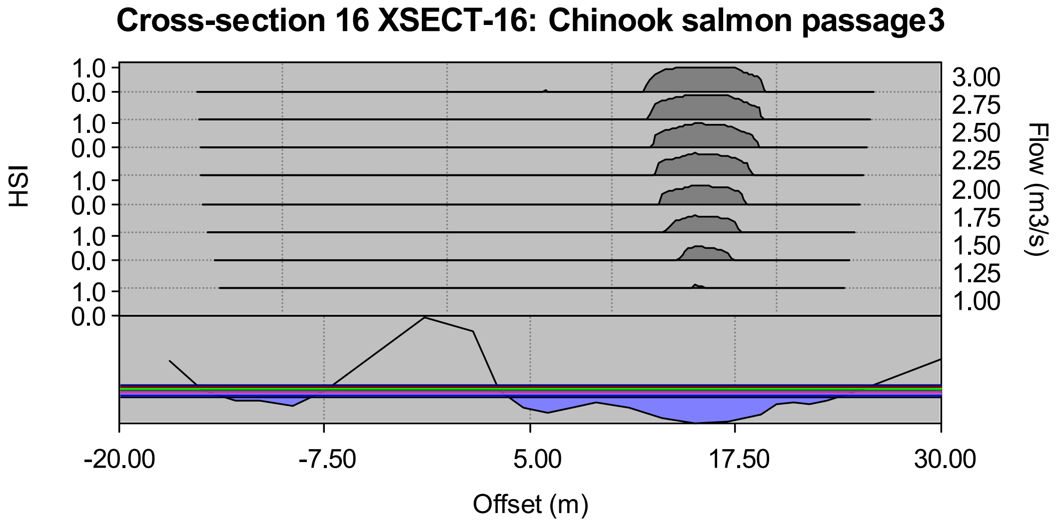

Figure 7. Change of depth and velocity with flow at riffle cross section 16 in the Olliver's reach of the North Branch Ashburton River. Point habitat modelled using RHYHABSIM 3.31 and the data of Jowett (1992).

Salmon passage at Wakanui

At Wakanui, adult salmon and trout can just migrate upstream at all modelled flows ≥1.0 m^3/s through even the most critical cross sections (Fig. 8). Cross sections 4 and 12 had the shallowest depths of any cross sections (mean depth 0.14 m, Table 9), but cross section 12 had the least available habitat for upstream salmon passage (Fig. 8). The graphs of Jowett (1999) suggested that flows >1.6 m^3/s allowed salmon passage at Wakanui.

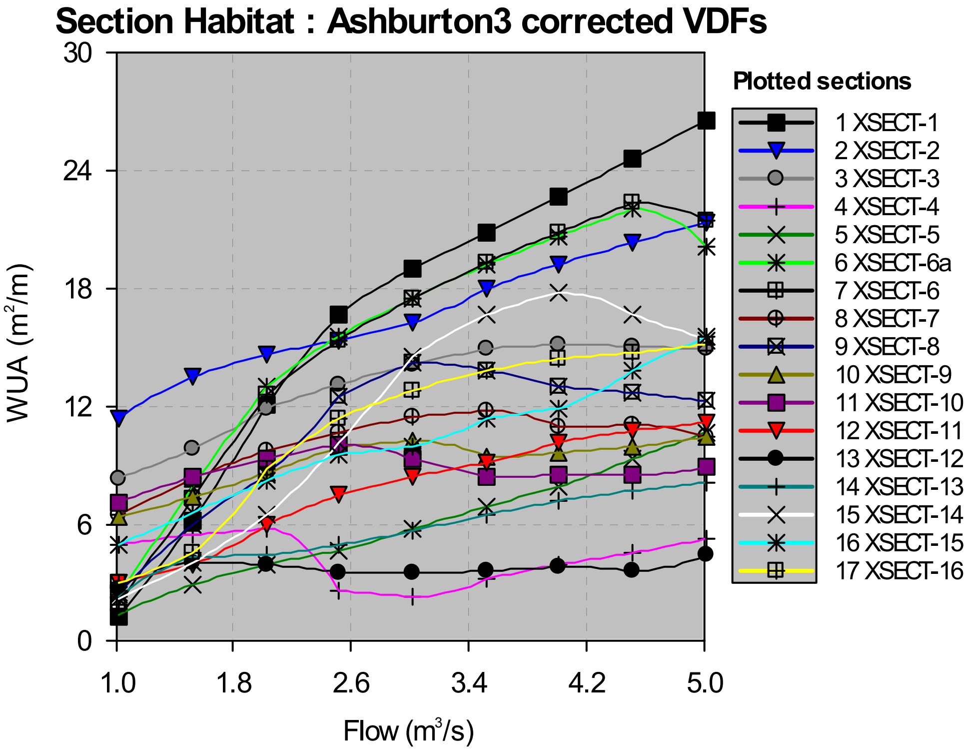

Figure 8. Effect of reducing flows on salmon passage at Wakanui (Ashburton 3) on the main stem of the Ashburton River. Section habitat modelled using RHYHABSIM 3.31 and the data of Jowett (1992).

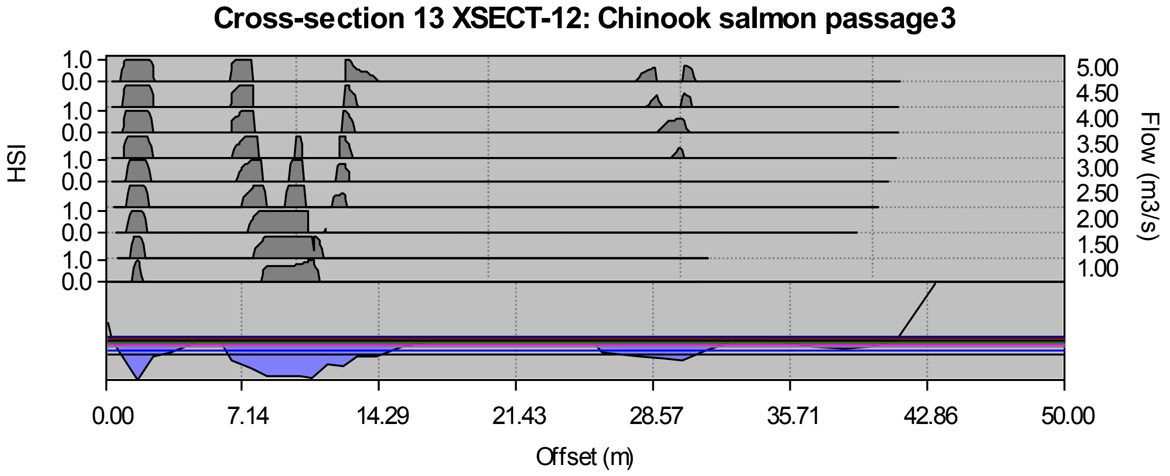

Figure 9. Change of depth and velocity with flow at cross section 12 in the Wakanui reach of the main stem of the Ashburton River. Point habitat modelled using RHYHABSIM 3.31 and the data of Jowett (1992).

Habitat for resident fish

Brown trout at Valetta

At flows >1.0 m^3/s, there was little change in the amount of habitat for the life stages of brown trout was shown except for juvenile habitat, which increases with flow (Fig. 10). Given the average width of the reach (15.7 m, Table 7), only a small proportion is suitable for brown trout adults or for feeding or spawning. Table 10 gives the data for Fig. 10, and the habitat suitability index (HSI) shows the proportional value of the reach for each life stage.

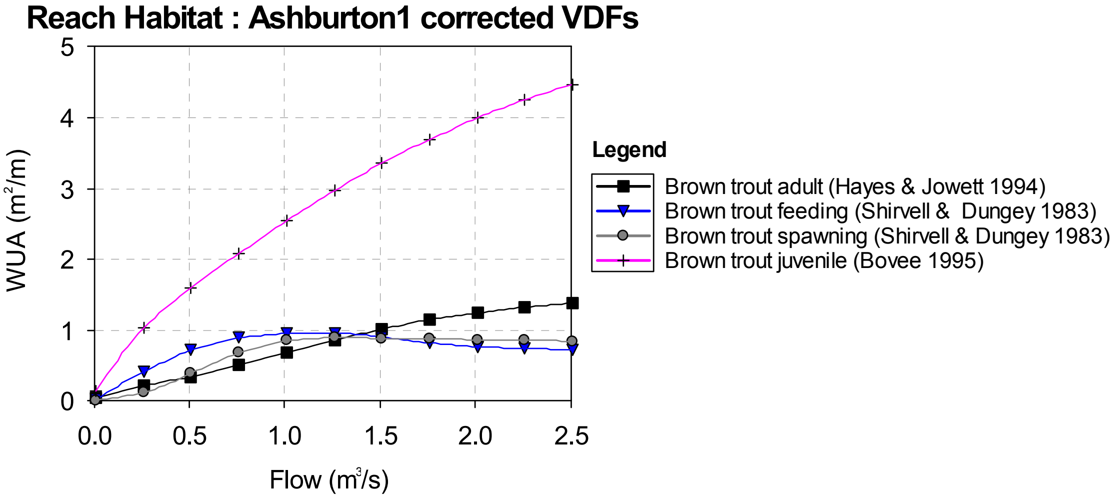

Figure 10. Relation of habitat for brown trout at Valetta with flows between 0 and 2.5 m^3/s.

Table 10. Data for Fig. 10. WUA = weighted usable area, and HIS = habitat suitability index.

Reach length :   193.12 m

1:- Brown trout adult (Hayes & Jowett 1994)
2:- Brown trout feeding (Shirvell & Dungey 1983)
3:- Brown trout spawning (Shirvell & Dungey 1983)
4:- Brown trout juvenile (Bovee 1995)

Flow (m3/s)	1 WUA (m2/m)	1 HSI	2 WUA (m2/m)	2 HSI	3 WUA (m2/m)	3 HSI	4 WUA (m2/m)	4 HSI
0.00	0.03	0.03	0.02	0.02	0.00	0.00	0.14	0.12
0.25	0.22	0.02	0.41	0.05	0.11	0.01	1.03	0.11
0.50	0.34	0.03	0.71	0.07	0.38	0.04	1.58	0.15
0.75	0.50	0.04	0.89	0.08	0.68	0.06	2.08	0.18
1.00	0.67	0.05	0.95	0.08	0.85	0.07	2.55	0.20
1.25	0.85	0.06	0.95	0.07	0.89	0.07	2.97	0.22
1.50	1.01	0.07	0.89	0.06	0.88	0.06	3.35	0.23
1.75	1.14	0.08	0.81	0.05	0.88	0.06	3.68	0.25
2.00	1.25	0.08	0.76	0.05	0.86	0.06	3.98	0.26
2.25	1.323	0.08	0.731	0.05	0.846	0.05	4.251	0.27
2.50	1.371	0.09	0.712	0.04	0.831	0.05	4.465	0.28

Brown trout at Ollivers

At Ollivers (mean reach width 19.7 m, Table 8), slightly more habitat was available for brown trout spawning than at Valetta, but there was no increase spawning or feeding habitat with flow over the range 1.0 and 3.0 m^3/s (Fig. 11, Table 11). As at Valetta, habitat for juveniles increased with flow, and there was small change in habitat for brown trout adults from 5 to 9%. However, only a small proportion of the reach was suitable for brown trout.

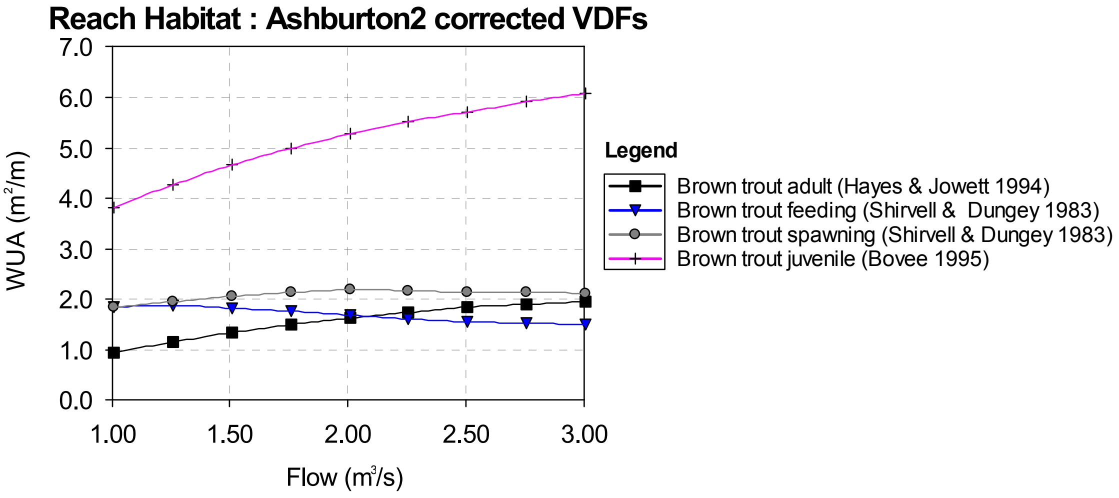

Figure 11. Relation of habitat for brown trout at Ollivers with flows between 1 and 3 m^3/s.

Table 11. Data for Fig. 11. WUA = weighted usable area, and HIS = habitat suitability index.

Reach length : 262.65 m
1:- Brown trout adult (Hayes & Jowett 1994)
2:- Brown trout feeding (Shirvell & Dungey 1983)
3:- Brown trout spawning (Shirvell & Dungey 1983)
4:- Brown trout juvenile (Bovee 1995)

Flow (m3/s)	1 WUA (m2/m)	1 HSI	2 WUA (m2/m)	2 HSI	3 WUA (m2/m)	3 HSI	4 WUA (m2/m)	4 HSI
1.00	0.92	0.05	1.84	0.11	1.83	0.11	3.80	0.23
1.25	1.14	0.06	1.86	0.11	1.94	0.11	4.27	0.24
1.50	1.32	0.07	1.82	0.10	2.05	0.11	4.66	0.25
1.75	1.49	0.08	1.75	0.09	2.14	0.11	4.99	0.26
2.00	1.63	0.08	1.67	0.09	2.17	0.11	5.27	0.27
2.25	1.74	0.09	1.60	0.08	2.16	0.11	5.50	0.28
2.50	1.83	0.09	1.55	0.08	2.13	0.11	5.71	0.28
2.75	1.89	0.09	1.52	0.07	2.12	0.10	5.91	0.29
3.00	1.93	0.09	1.49	0.07	2.10	0.10	6.07	0.29

Brown trout at Wakanui

At Wakanui (mean reach width 28.7m, Table 9), more habitat was available for brown trout spawning than at the upstream reaches, but there was less habitat for brown trout adults and for feeding (Fig. 12, Table 12). There was little or no increase of habitat with flow except for brown trout juvenile habitat within the range of flows 1.5 and 5.0 m^3/s. Only a very small proportion of the reach was suitable for brown trout adults and for feeding (about 3%).

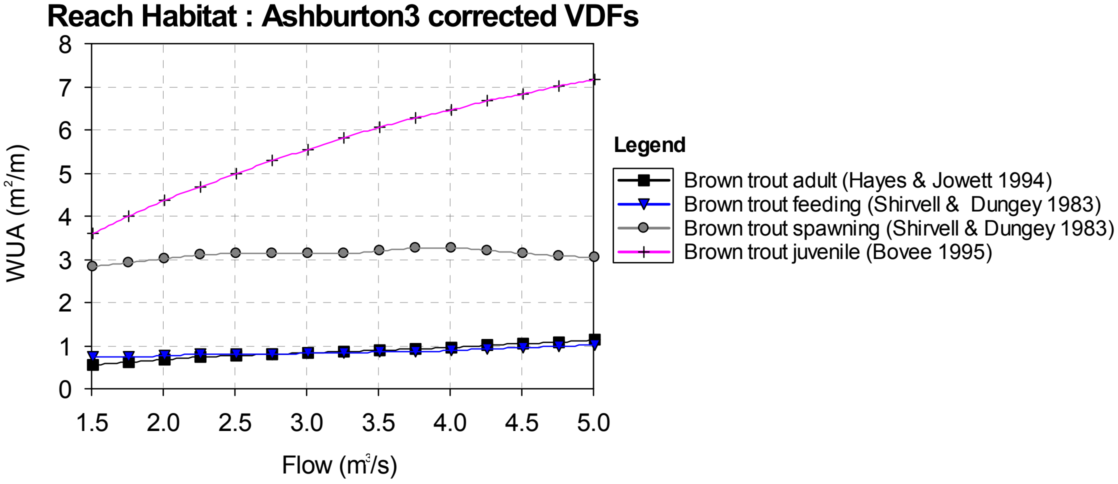

Figure 12. Relation of habitat for brown trout at Wakanui with flows between 1.5 and 5.0 m^3/s.

Table 12. Data for Fig. 12. WUA = weighted usable area, and HIS = habitat suitability index.

Reach length : 274.60 m
1:- Brown trout adult (Hayes & Jowett 1994)
2:- Brown trout feeding (Shirvell & Dungey 1983)
3:- Brown trout spawning (Shirvell & Dungey 1983)
4:- Brown trout juvenile (Bovee 1995)

Flow (m3/s)	1 WUA (m2/m)	1 HSI	2 WUA (m2/m)	2 HSI	3 WUA (m2/m)	3 HSI	4 WUA (m2/m)	4 HSI
1.50	0.55	0.03	0.74	0.04	2.83	0.14	3.61	0.18
1.75	0.63	0.03	0.75	0.04	2.93	0.14	4.00	0.19
2.00	0.68	0.03	0.77	0.03	3.02	0.13	4.36	0.19
2.25	0.73	0.03	0.79	0.03	3.12	0.13	4.69	0.20
2.50	0.77	0.03	0.80	0.03	3.15	0.13	5.00	0.20
2.75	0.80	0.03	0.81	0.03	3.13	0.12	5.28	0.20
3.00	0.83	0.03	0.83	0.03	3.14	0.12	5.55	0.21
3.25	0.86	0.03	0.84	0.03	3.14	0.11	5.80	0.21
3.50	0.90	0.03	0.86	0.03	3.21	0.11	6.05	0.21
3.75	0.93	0.03	0.88	0.03	3.26	0.11	6.27	0.21
4.00	0.97	0.03	0.90	0.03	3.26	0.11	6.47	0.21
4.25	1.01	0.03	0.92	0.03	3.21	0.10	6.67	0.22
4.50	1.05	0.03	0.95	0.03	3.15	0.10	6.85	0.22
4.75	1.09	0.03	0.98	0.03	3.09	0.10	7.02	0.22
5.00	1.13	0.04	1.01	0.03	3.03	0.09	7.18	0.22

Native fish habitat at Valetta

There was little change in native fish habitat with flows >1.5 m^3/s at Valetta except for a slight increase in torrentfish habitat with flow (Fig. 13, Table 13). Between 0.5 and 1.5 m^3/s, habitat for all species declined except for upland bullies. The reach was most suitable for Canterbury (common river) galaxias, and this habitat declined slightly with increasing flows >2.0 m^3/s. The reach was also suitable for small longfin eels, and their habitat increased slightly with flow, but the reach was unsuitable for larger longfin eels. For some species that was a clear point of inflexion about 0.25-0.50 m^3/s.

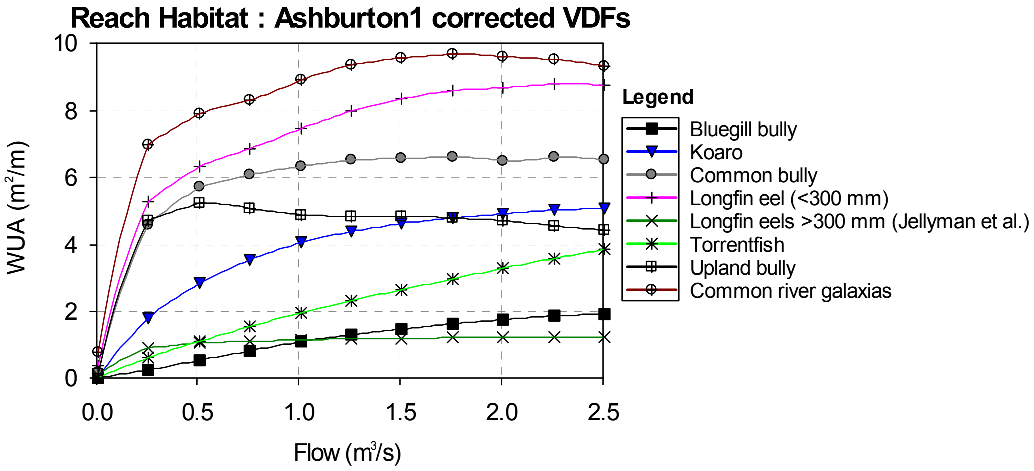

Figure 13. Relation of habitat for native fish at Valetta with flows between 0 and 2.5 m^3/s.

Table 13. Data for Fig. 13. WUA = weighted usable area, and HIS = habitat suitability index.

Reach length : 193.12 m
1:- Bluegill bully
2:- Koaro
3:- Common bully
4:- Longfin eel (<300 mm)

Flow (m3/s)	1 WUA (m2/m)	1 HSI	2 WUA (m2/m)	2 HSI	3 WUA (m2/m)	3 HSI	4 WUA (m2/m)	4 HSI
0.00	0.00	0.00	0.01	0.01	0.16	0.13	0.38	0.33
0.25	0.26	0.03	1.79	0.20	4.58	0.50	5.25	0.58
0.50	0.55	0.05	2.82	0.27	5.73	0.55	6.33	0.60
0.75	0.82	0.07	3.54	0.31	6.06	0.53	6.84	0.60
1.00	1.08	0.09	4.04	0.32	6.31	0.50	7.47	0.59
1.25	1.29	0.09	4.38	0.32	6.51	0.48	7.99	0.58
1.50	1.47	0.10	4.62	0.32	6.56	0.46	8.33	0.58
1.75	1.63	0.11	4.79	0.32	6.61	0.44	8.58	0.57
2.00	1.75	0.11	4.90	0.32	6.50	0.42	8.68	0.56
2.25	1.845	0.12	5.012	0.32	6.596	0.42	8.768	0.56
2.50	1.909	0.12	5.055	0.32	6.501	0.41	8.762	0.55

5:- Longfin eels >300 mm (Jellyman et al.)
6:- Torrentfish
7:- Upland bully
8:- Common river galaxias

Flow (m3/s)	5 WUA (m2/m)	5 HSI	6 WUA (m2/m)	6 HSI	7 WUA (m2/m)	7 HSI	8 WUA (m2/m)	8 HSI
0.00	0.10	0.08	0.01	0.01	0.12	0.11	0.77	0.65
0.25	0.89	0.10	0.59	0.07	4.70	0.52	6.96	0.77
0.50	1.05	0.10	1.08	0.10	5.24	0.50	7.88	0.75
0.75	1.10	0.10	1.52	0.13	5.08	0.45	8.30	0.73
1.00	1.12	0.09	1.94	0.15	4.85	0.38	8.89	0.70
1.25	1.16	0.08	2.31	0.17	4.81	0.35	9.36	0.68
1.50	1.19	0.08	2.65	0.18	4.81	0.34	9.55	0.67
1.75	1.21	0.08	2.97	0.20	4.79	0.32	9.66	0.65
2.00	1.22	0.08	3.27	0.21	4.70	0.31	9.60	0.62
2.25	1.216	0.08	3.57	0.23	4.547	0.29	9.496	0.6
2.50	1.21	0.08	3.827	0.24	4.411	0.28	9.312	0.58

Native fish habitat at Ollivers

There was little change in native fish habitat with flow at Ollivers except for an increase in torrentfish habitat with flow (Fig. 14, Table 14). This reach was also most suitable for small longfin eels and Canterbury (common river) galaxias. Upland bully habitat decreased with increasing flow. The reach was least suitable for longfin eels >300 mm.

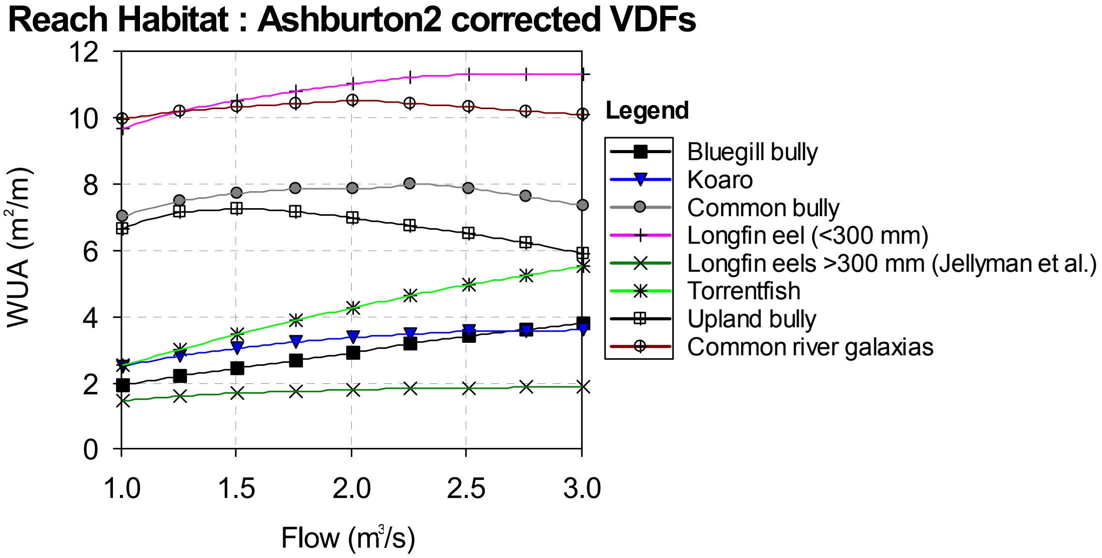

Figure 14. Relation of habitat for native fish at Ollivers with flows between 1.0 and 3.0 m^3/s.

Table 14. Data for Fig. 14. WUA = weighted usable area, and HIS = habitat suitability index.

Reach length : 262.65 m
1:- Bluegill bully
2:- Koaro
3:- Common bully
4:- Longfin eel (<300 mm)

Flow (m3/s)	1 WUA (m2/m)	1 HSI	2 WUA (m2/m)	2 HSI	3 WUA (m2/m)	3 HSI	4 WUA (m2/m)	4 HSI
1.00	1.93	0.11	2.50	0.15	7.02	0.42	9.68	0.58
1.25	2.20	0.12	2.80	0.16	7.46	0.42	10.19	0.58
1.50	2.44	0.13	3.04	0.17	7.73	0.42	10.50	0.57
1.75	2.68	0.14	3.22	0.17	7.82	0.41	10.78	0.57
2.00	2.92	0.15	3.35	0.17	7.85	0.40	11.03	0.56
2.25	3.17	0.16	3.47	0.17	8.00	0.40	11.23	0.56
2.50	3.39	0.17	3.53	0.17	7.83	0.39	11.29	0.56
2.75	3.60	0.18	3.57	0.17	7.60	0.37	11.30	0.55
3.00	3.79	0.18	3.60	0.17	7.34	0.35	11.29	0.54

5:- Longfin eels >300 mm (Jellyman et al.)
6:- Torrentfish
7:- Upland bully
8:- Common river galaxias

Flow (m3/s)	5 WUA (m2/m)	5 HSI	6 WUA (m2/m)	6 HSI	7 WUA (m2/m)	7 HSI	8 WUA (m2/m)	8 HSI
1.00	1.46	0.09	2.54	0.15	6.65	0.40	9.94	0.59
1.25	1.60	0.09	3.01	0.17	7.13	0.40	10.20	0.58
1.50	1.68	0.09	3.46	0.19	7.25	0.40	10.32	0.56
1.75	1.73	0.09	3.87	0.20	7.13	0.38	10.42	0.55
2.00	1.78	0.09	4.25	0.22	6.94	0.35	10.50	0.54
2.25	1.81	0.09	4.63	0.23	6.72	0.34	10.44	0.52
2.50	1.84	0.09	4.95	0.24	6.47	0.32	10.32	0.51
2.75	1.87	0.09	5.24	0.25	6.19	0.30	10.20	0.50
3.00	1.88	0.09	5.50	0.26	5.88	0.28	10.07	0.48

Native fish habitat at Wakanui

There was an increase in native fish habitat with flow at Wakanui except for koaro, longfin eels >300 mm, inanga, and juvenile lamprey, for which there was almost no habitat (Fig. 15, Table 15). This reach was also most suitable for shortfin eels, small longfin eels, and Canterbury (common river) galaxias. The reach was least suitable for inanga feeding and juvenile lamprey.

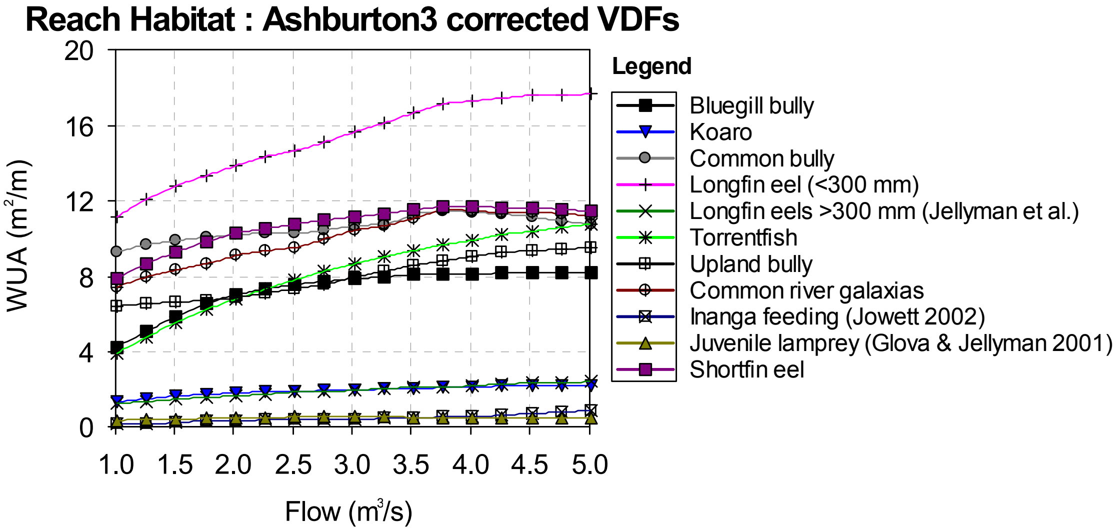

Figure 15. Relation of habitat for native fish at Wakanui with flows between 1.5 and 3.0 m^3/s.

Table 15. Data for Fig. 15. WUA = weighted usable area, and HIS = habitat suitability index.

Reach length : 274.60 m
1:- Bluegill bully
2:- Koaro
3:- Common bully
4:- Longfin eel (<300 mm)

Flow (m3/s)	1 WUA (m2/m)	1 HSI	2 WUA (m2/m)	2 HSI	3 WUA (m2/m)	3 HSI	4 WUA (m2/m)	4 HSI
1.00	4.16	0.24	1.32	0.08	9.22	0.54	11.10	0.65
1.25	5.07	0.27	1.49	0.08	9.67	0.51	12.04	0.64
1.50	5.88	0.29	1.62	0.08	9.90	0.49	12.74	0.64
1.75	6.53	0.31	1.71	0.08	10.03	0.47	13.30	0.62
2.00	7.02	0.31	1.79	0.08	10.17	0.45	13.88	0.61
2.25	7.35	0.31	1.85	0.08	10.26	0.43	14.33	0.61
2.50	7.55	0.31	1.89	0.08	10.29	0.42	14.65	0.60
2.75	7.72	0.30	1.93	0.07	10.44	0.40	15.12	0.59
3.00	7.85	0.29	1.97	0.07	10.67	0.39	15.65	0.58
3.25	7.95	0.28	2.00	0.07	10.77	0.38	16.07	0.57
3.50	8.07	0.28	2.06	0.07	11.29	0.39	16.63	0.57
3.75	8.11	0.27	2.10	0.07	11.44	0.38	17.09	0.57
4.00	8.13	0.27	2.13	0.07	11.39	0.37	17.30	0.57
4.25	8.15	0.26	2.16	0.07	11.27	0.36	17.46	0.56
4.50	8.17	0.26	2.18	0.07	11.10	0.35	17.56	0.56
4.75	8.18	0.26	2.20	0.07	10.92	0.34	17.61	0.56
5.00	8.21	0.26	2.21	0.07	10.74	0.34	17.64	0.55

5:- Longfin eels >300 mm (Jellyman et al.)
6:- Torrentfish
7:- Upland bully
8:- Common river galaxias

Flow (m3/s)	5 WUA (m2/m)	5 HSI	6 WUA (m2/m)	6 HSI	7 WUA (m2/m)	7 HSI	8 WUA (m2/m)	8 HSI
1.00	1.23	0.07	3.89	0.23	6.35	0.37	7.43	0.43
1.25	1.36	0.07	4.76	0.25	6.53	0.35	7.97	0.42
1.50	1.48	0.07	5.54	0.28	6.59	0.33	8.32	0.42
1.75	1.57	0.07	6.19	0.29	6.70	0.31	8.67	0.41
2.00	1.66	0.07	6.78	0.30	6.87	0.30	9.11	0.40
2.25	1.75	0.07	7.30	0.31	7.09	0.30	9.35	0.40
2.50	1.84	0.07	7.79	0.32	7.31	0.30	9.52	0.39
2.75	1.90	0.07	8.23	0.32	7.58	0.29	9.95	0.39
3.00	1.96	0.07	8.65	0.32	7.92	0.29	10.42	0.39
3.25	2.03	0.07	9.01	0.32	8.25	0.29	10.68	0.38
3.50	2.08	0.07	9.36	0.32	8.55	0.29	11.08	0.38
3.75	2.14	0.07	9.66	0.32	8.82	0.29	11.50	0.38
4.00	2.19	0.07	9.92	0.32	9.07	0.30	11.45	0.37
4.25	2.25	0.07	10.16	0.33	9.23	0.30	11.39	0.37
4.50	2.30	0.07	10.37	0.33	9.35	0.30	11.33	0.36
4.75	2.35	0.07	10.56	0.33	9.43	0.30	11.27	0.36
5.00	2.40	0.07	10.73	0.33	9.47	0.30	11.21	0.35

9:- Inanga feeding (Jowett 2002)
10:- Juvenile lamprey (Glova & Jellyman 2001)
11:- Shortfin eel

Flow (m3/s)	9 WUA (m2/m)	9 HSI	10 WUA (m2/m)	10 HSI	11 WUA (m2/m)	11 HSI
1.00	0.17	0.01	0.31	0.02	7.83	0.46
1.25	0.19	0.01	0.36	0.02	8.64	0.46
1.50	0.23	0.01	0.41	0.02	9.29	0.46
1.75	0.28	0.01	0.44	0.02	9.83	0.46
2.00	0.31	0.01	0.48	0.02	10.27	0.45
2.25	0.35	0.01	0.50	0.02	10.53	0.45
2.50	0.39	0.02	0.52	0.02	10.70	0.44
2.75	0.43	0.02	0.53	0.02	10.93	0.42
3.00	0.42	0.02	0.53	0.02	11.14	0.41
3.25	0.46	0.02	0.53	0.02	11.26	0.40
3.50	0.46	0.02	0.47	0.02	11.53	0.40
3.75	0.51	0.02	0.47	0.02	11.66	0.39
4.00	0.57	0.02	0.47	0.02	11.64	0.38
4.25	0.64	0.02	0.46	0.01	11.62	0.38
4.50	0.71	0.02	0.46	0.01	11.58	0.37
4.75	0.78	0.02	0.45	0.01	11.53	0.36
5.00	0.85	0.03	0.45	0.01	11.48	0.36

Food production

Food production at Valetta

Habitat for the most common and widespread aquatic insects increased with flow, as did the area for food production (invertebrates) generally (Fig. 16, Table 16). Habitat was most suitable for *Olinga feredayi*, and least suitable for *Aoteapsyche*. For *Olinga feredayi* and Hydrobiosidae there was point of inflexion at about 0.5 m^3/s; habitat decreased faster with decreasing flows below this point.

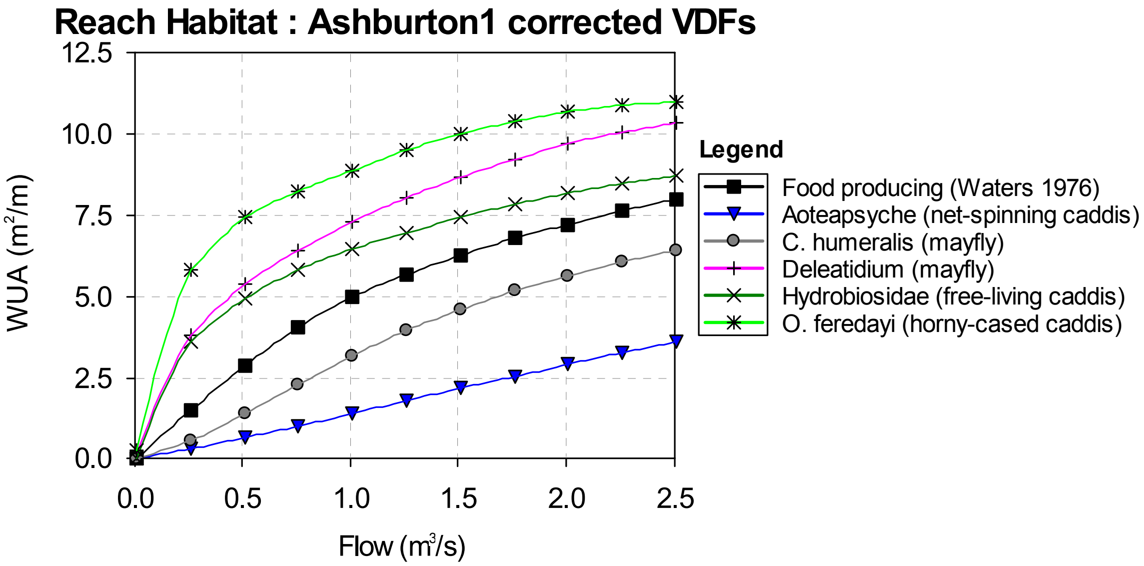

Figure 16. Relation of habitat for food production and aquatic insects at Valetta with flows between 0 and 2.5 m^3/s.

Table 16. Data for Fig. 16. WUA = weighted usable area, and HIS = habitat suitability index.

Reach length : 193.12 m
1:- Food producing (Waters 1976)
2:- Aoteapsyche (net-spinning caddis)
3:- C. humeralis (mayfly)
4:- Deleatidium (mayfly)

Flow (m3/s)	1 WUA (m2/m)	1 HSI	2 WUA (m2/m)	2 HSI	3 WUA (m2/m)	3 HSI	4 WUA (m2/m)	4 HSI
0.000	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.12
0.250	1.50	0.17	0.30	0.03	0.54	0.06	3.79	0.42
0.500	2.86	0.27	0.63	0.06	1.40	0.13	5.38	0.51
0.750	4.01	0.35	0.99	0.09	2.27	0.20	6.42	0.56
1.000	4.96	0.39	1.37	0.11	3.15	0.25	7.27	0.58
1.250	5.68	0.42	1.76	0.13	3.93	0.29	8.01	0.59
1.500	6.27	0.44	2.15	0.15	4.59	0.32	8.66	0.60
1.750	6.77	0.45	2.53	0.17	5.14	0.34	9.23	0.62
2.000	7.20	0.47	2.89	0.19	5.62	0.37	9.68	0.63
2.250	7.61	0.48	3.26	0.21	6.05	0.38	10.06	0.64
2.500	7.96	0.50	3.60	0.23	6.41	0.40	10.32	0.64

5:- Hydrobiosidae (free-living caddis)
6:- O. feredayi (horny-cased caddis)

Flow (m3/s)	5 WUA (m2/m)	5 HSI	6 WUA (m2/m)	6 HSI
0.000	0.00	0.00	0.23	0.20
0.250	3.58	0.39	5.82	0.64
0.500	4.94	0.47	7.44	0.71
0.750	5.81	0.51	8.22	0.72
1.000	6.44	0.51	8.87	0.70
1.250	6.96	0.51	9.48	0.69
1.500	7.42	0.52	9.99	0.70
1.750	7.82	0.52	10.40	0.69
2.000	8.16	0.53	10.67	0.69
2.250	8.48	0.54	10.87	0.69
2.500	8.72	0.55	10.96	0.68

Food production at Ollivers

Aquatic insect habitat increased with flow, as did the area for food production generally (Fig. 17, Table 17). As at Valetta, habitat was most suitable for *Olinga feredayi*, and least suitable for *Aoteapsyche*. There was a general decline of habitat with decreasing flows, with no points of inflection that might indicate a threshold flow for the reach.

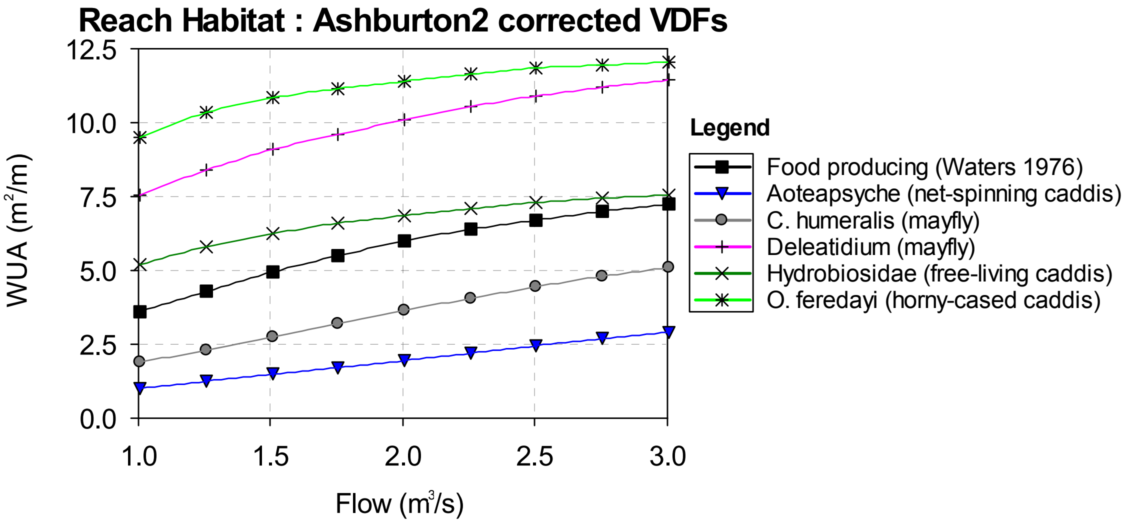

Figure 17. Relation of habitat for food production and aquatic insects at Ollivers with flows between 1 and 3 m^3/s.

Table 17. Data for Fig. 17. WUA = weighted usable area, and HIS = habitat suitability index.

Reach length : 262.65 m
1:- Food producing (Waters 1976)
2:- Aoteapsyche (net-spinning caddis)
3:- C. humeralis (mayfly)
4:- Deleatidium (mayfly)

Flow (m3/s)	1 WUA (m2/m)	1 HSI	2 WUA (m2/m)	2 HSI	3 WUA (m2/m)	3 HSI	4 WUA (m2/m)	4 HSI
1.000	3.58	0.21	0.99	0.06	1.89	0.11	7.53	0.45
1.250	4.29	0.24	1.24	0.07	2.32	0.13	8.41	0.48
1.500	4.95	0.27	1.48	0.08	2.76	0.15	9.08	0.50
1.750	5.52	0.29	1.72	0.09	3.21	0.17	9.62	0.51
2.000	6.00	0.31	1.97	0.10	3.64	0.19	10.10	0.51
2.250	6.39	0.32	2.22	0.11	4.07	0.20	10.54	0.53
2.500	6.72	0.33	2.46	0.12	4.46	0.22	10.90	0.54
2.750	7.01	0.34	2.68	0.13	4.81	0.23	11.21	0.55
3.000	7.24	0.35	2.91	0.14	5.12	0.25	11.47	0.55

5:- Hydrobiosidae (free-living caddis)
6:- O. feredayi (horny-cased caddis)

Flow (m3/s)	5 WUA (m2/m)	5 HSI	6 WUA (m2/m)	6 HSI
1.000	5.22	0.31	9.52	0.57
1.250	5.82	0.33	10.34	0.59
1.500	6.27	0.34	10.83	0.59
1.750	6.61	0.35	11.14	0.59
2.000	6.86	0.35	11.42	0.58
2.250	7.10	0.36	11.67	0.58
2.500	7.28	0.36	11.85	0.58
2.750	7.43	0.36	11.97	0.58
3.000	7.56	0.36	12.04	0.58

Food production at Wakanui

Aquatic insect habitat increased with flow, as did the area for food production generally (Fig. 18, Table 18). The habitat was most suitable for *Deleatidium* and *Olinga feredayi*, and least suitable for *Aoteapsyche*. There was a general decline of habitat with decreasing flows, with no points of inflexion that might indicate a threshold flow for the reach.

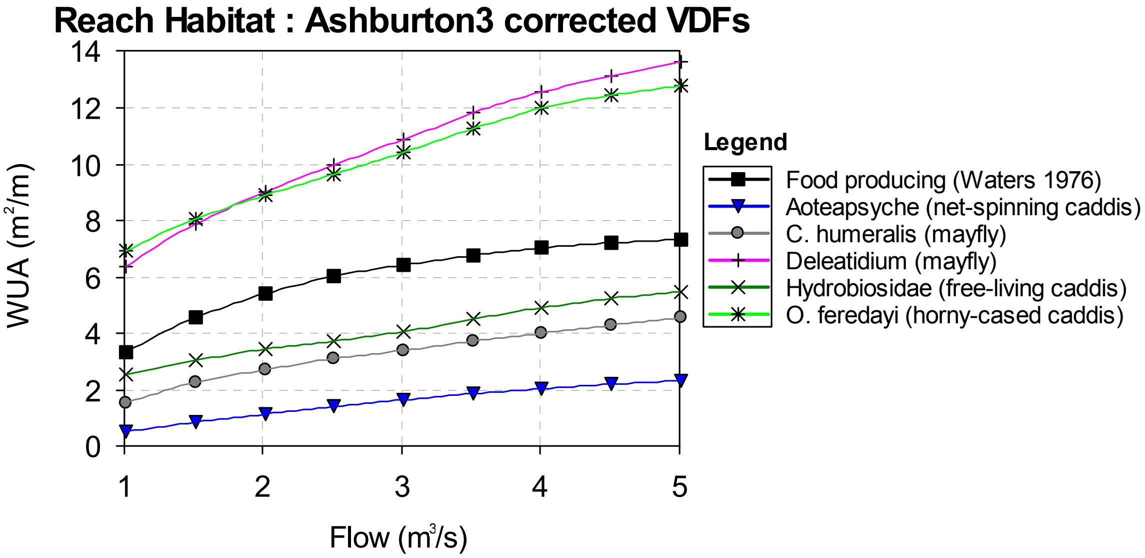

Figure 18. Relation of habitat for food production and aquatic insects at Wakanui with flows between 1.5 and 3.0 m^3/s.

Table 18. Data for Fig. 18. WUA = weighted usable area, and HIS = habitat suitability index.

Reach length : 274.60 m
1:- Food producing (Waters 1976)
2:- Aoteapsyche (net-spinning caddis)
3:- C. humeralis (mayfly)
4:- Deleatidium (mayfly)

Flow (m3/s)	1 WUA (m2/m)	1 HSI	2 WUA (m2/m)	2 HSI	3 WUA (m2/m)	3 HSI	4 WUA (m2/m)	4 HSI
1.000	3.34	0.19	0.52	0.03	1.50	0.09	6.37	0.37
1.250	4.00	0.21	0.68	0.04	1.88	0.10	7.14	0.38
1.500	4.54	0.23	0.84	0.04	2.23	0.11	7.85	0.39
1.750	5.00	0.23	0.99	0.05	2.49	0.12	8.44	0.40
2.000	5.39	0.24	1.13	0.05	2.70	0.12	8.97	0.40
2.250	5.72	0.24	1.26	0.05	2.89	0.12	9.47	0.40
2.500	5.99	0.24	1.40	0.06	3.07	0.12	9.93	0.40
2.750	6.22	0.24	1.52	0.06	3.23	0.13	10.37	0.40
3.000	6.41	0.24	1.63	0.06	3.38	0.13	10.86	0.40
3.250	6.56	0.23	1.74	0.06	3.53	0.13	11.32	0.40
3.500	6.76	0.23	1.84	0.06	3.69	0.13	11.79	0.41
3.750	6.90	0.23	1.94	0.06	3.85	0.13	12.20	0.40
4.000	7.02	0.23	2.02	0.07	4.00	0.13	12.55	0.41
4.250	7.13	0.23	2.11	0.07	4.15	0.13	12.86	0.42
4.500	7.21	0.23	2.18	0.07	4.30	0.14	13.13	0.42
4.750	7.29	0.23	2.26	0.07	4.43	0.14	13.38	0.42
5.000	7.33	0.23	2.33	0.07	4.55	0.14	13.61	0.42

5:- Hydrobiosidae (free-living caddis)
6:- O. feredayi (horny-cased caddis)

Flow (m3/s)	5 WUA (m2/m)	5 HSI	6 WUA (m2/m)	6 HSI
1.000	2.54	0.15	6.94	0.40
1.250	2.81	0.15	7.54	0.40
1.500	3.03	0.15	8.06	0.40
1.750	3.23	0.15	8.50	0.40
2.000	3.41	0.15	8.89	0.39
2.250	3.58	0.15	9.28	0.39
2.500	3.74	0.15	9.64	0.39
2.750	3.89	0.15	10.00	0.39
3.000	4.07	0.15	10.42	0.39
3.250	4.26	0.15	10.83	0.39
3.500	4.49	0.15	11.26	0.39
3.750	4.70	0.16	11.64	0.39
4.000	4.90	0.16	11.95	0.39
4.250	5.08	0.16	12.22	0.39
4.500	5.24	0.17	12.43	0.40
4.750	5.37	0.17	12.62	0.40
5.000	5.48	0.17	12.78	0.40

Water temperature

Freshwater fish have clear temperature preferenda, and there is generally a clear relationship between preferred and upper lethal temperature (Jobling 1981). For wild brown trout, optimal growth occurs at about 13°C (range 10-15.5°C), and diminishes with increasing temperature to zero at some temperature between 19.5 and 23°C (Jobling 1981; Lobón-Cerviá and Rincón 1998). Others cite slightly higher values, with optimal temperature requirements for good growth and survival of brown trout of 12 to 19°C (Frost and Brown 1967; Mills 1971; Tebo 1975). Preferred temperatures range from 12.2 to 17.6°C, and upper lethal temperatures have been reported as 23-26.4°C (Jobling 1981; Eaton et al. 1995). Wild brown trout were found in streams in the Rocky Mountains, USA, in areas with July (summer) air temperature 19-22°C (Rahel and Nibbelink 1999). Raleigh et al (1986b) quote Needham's (1969) finding that the upper limiting, near-lethal water temperature for brown trout is 27.2°C, at which naturally reproducing, viable stream populations would not be maintained.

For adult migrating chinook salmon, the preferred temperature in one study was 11.7°C (Jobling 1981); Raleigh et al. (1986a) reported a preferred range during migration of 7-13°C. Bell (1973) considered that the optimum temperature was 11-14°C, with an upper lethal limit of 25°C. In the northern hemisphere, northern stocks may have lower temperature optima than southern stocks, and the values cited in Raleigh et al. (1986a) are for chinook salmon in Alaska. Optimal growth occurred at 15.5°C, and the upper lethal temperature was 25.1°C (Jobling 1981). In the San Joaquin River, California, 20°C is used as the upper limit for water temperatures during chinook salmon migrations (Friant Water Users Authority), and this is probably more applicable to chinook salmon in New Zealand than the Alaskan values.

Catches of chinook salmon in February and early March by anglers at the mouth the Hurunui River, North Canterbury, show temperature limitations on river entry in New Zealand. Catches increased when water temperatures fell below 22°C, and were reduced by temperatures ≥23°C. Mortalities of chinook salmon in the Hurunui River were observed on a day when the maximum temperature was 23°C. High water temperatures may also delay in-river migration rates. One tagged salmon was caught 49 days after tagging 50 km from its initial release site, which equates to a average migration rate of 1 km/day. In North America, a migration rate of 8 km/day was regarded as slow (Docherty 1979).

The temperature preferenda of New Zealand's native fish are generally higher than for salmonids. Eels have the highest preferred and lethal temperatures, and common smelt and banded kokopu the lowest (Fig. 19).

Water temperatures in rivers of the South Canterbury plains have considerable annual variation that follows a sinusoidal pattern, as shown by annual temperature variation in the Orari River, which is just south of the Rangitata River (Fig. 4 below; data for site 69506 in Mosley 1982). Otago and Canterbury rivers showed a high amplitude in temperature variation, but mean temperatures were 7-18°C (Mosley 1982, p9). Mosley (1992, p9) characterises these sites as follows:

"Generally clear skies promote rapid heating and cooling of the water both during the day and over the year, and many of these water courses tend to be wide and braided, which again promotes rapid heating and cooling."

This is a description typical of the Ashburton River in its reaches below the abstraction point.

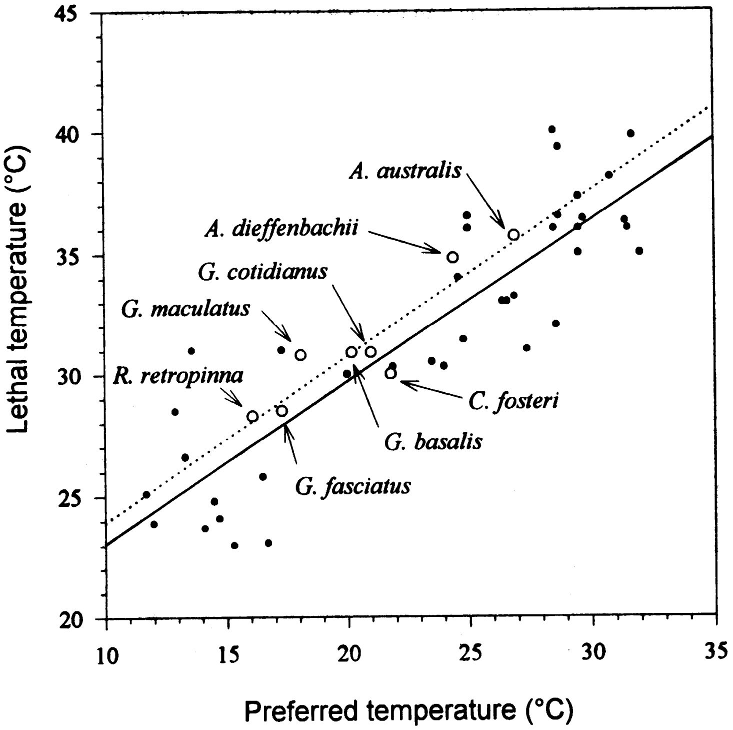

Figure 19. Relationship between lethal and preferred temperatures for eight New Zealand native fish species (open circles, dashed line) and 38 other species developed by Jobling (1981; closed circles, solid line). Source: Richardson et al. (1994).

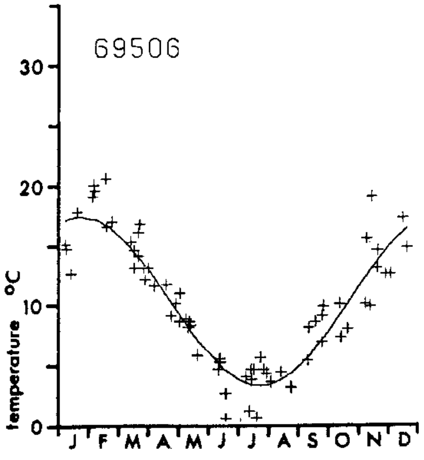

Figure 20. Annual temperature variation in the Orari River. Source: Mosley (1992), p53.

Modelling

Modelled water temperature showed that maximum daily temperature in the reach of the North Branch Ashburton River downstream of Valetta was highly dependent on flow when the discharge fell below about 1000 L/s, but above 1000 L/s was relatively insensitive to incremental increases in flow (Fig. 21). For instance, a flow decrease from 3,500 L/s to 1,561 L/s increased the maximum daily temperature from 24.1 to 25.0°C, and to 25.1°C at 1,358 L/s (Table 19). For this segment, a power curve adequately describes the relation of daily maximum water temperature with flow between 350 and 3,500 L/s ($r^2 = 0.9996$), such that

$$\text{Daily maximum water temperature}_{\text{Valetta}} = 33.446\ Q^{-0.04} \text{ (Equation 1),}$$

where Q is river flow in L/s. According to this equation, there is no difference in daily maximum or mean water temperature when flow is reduced from 2,458 to 2,300 L/s (24.5°C). Though no hydraulic modelling has been attempted for the abstraction point of the RDR, and not habitat measurements are available, the temperature change with flow could be approximated by assuming that the reach morphology was similar to the Valetta reach, and that Equation 1 above applies.

In the segment of the North Branch Ashburton River downstream of Ollivers, daily maximum temperature was highly subject to flow when the discharge fell below about 2,800 L/s, but above this was relatively insensitive to incremental increases in flow (Fig. 22). For instance, a flow decrease from 3,809 L/s to 2,815 L/s increased the maximum daily temperature from 23.4 to 24.4°C, and to 25.2°C at 2,288 L/s (Table 19).

For the segment downstream of Ollivers, a line equation adequately describes the relation of daily maximum water temperature with flow between about 1,200 and 2,700 L/s ($r^2 = 0.9991$), such that

$$\text{Daily maximum water temperature}_{\text{Ollivers}} = -0.0018\,Q + 29.374 \text{ (Equation 2).}$$

NBAR contributes a 7-day duration MALF of 3,690 L/s at its confluence with the North Branch Ashburton River 24.3 km from the sea (EMG 2001, Appendix 3). This initially cools the Ashburton River, but eventually as the river progresses downstream the river gains heat (Fig. 23).

In the segment from Wakanui to the sea, the reduction in daily maximum temperature is progressive with increasing flows. A reduction in flow of 1000 L/s results in a temperature increase of 0.4-0.5^{o}C at almost any initial discharge (Fig. 24, Table 19).

For the segment downstream of Wakanui, a line equation adequately describes the relation of daily maximum water temperature with flows between about 2,000 and 5,500 L/s ($r^2 = 0.9981$), such that

$$\text{Daily maximum water temperature}_{\text{Wakanui}} = -0.0004\,Q + 27.996 \text{ (Equation 3).}$$

According to Equation 3, daily maximum water temperature would increase from 27.1 to 27.2^{o}C when flow is reduced from 2,300 to 1,978 L/s.

The scenarios modelled here represent the extremes of water temperature for cloudless days in January, when solar radiation is at its maximum. The mean daily temperatures show that on any given day the maximum temperature does not last for long, and is followed by a cooling phase as the sun sets. In addition, there are additions from ground water and tributaries that have not been included in the modelling, with the exception of the North Branch Ashburton River. The WAIORA model assumes that the river is fully mixed laterally, and this is not always true of braided rivers, as temperature have been shown to vary across the braids. There can be an 8^{o}C variation that offers cold water refugia in places (Mosley 1983, in EMG 2001, p24).

While these temperatures at their maximum might compromise salmonid survival, they do not in general exceed the lethal temperatures for native fish, the most sensitive of which can survive temperatures >27^{o}C (Fig. 3), at least for short periods. Jowett et al. (2004, p53) suggest a daily maximum of 26^{o}C is appropriate if trout are absent but native fish are present.

The results of the temperature modelling have implications for chinook salmon migrations. The daily mean temperature at low flows exceeds 20^{o}C in all reaches, but especially in the most downstream reach (Wakanui), which suggests that chinook salmon migration might not be possible in January.

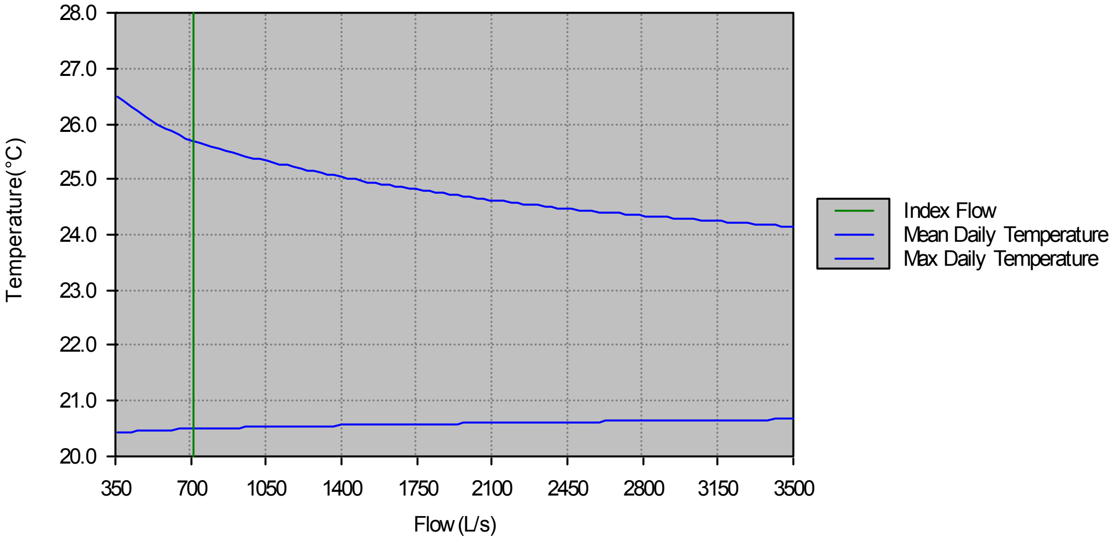

Figure 21. The influence of river flow on mean and maximum daily temperatures for the South Branch Ashburton River modelled with WAIORA 2.0 for the 15.7-km segment between Valletta and Ollivers based on the IFIM data of Jowett (1992).

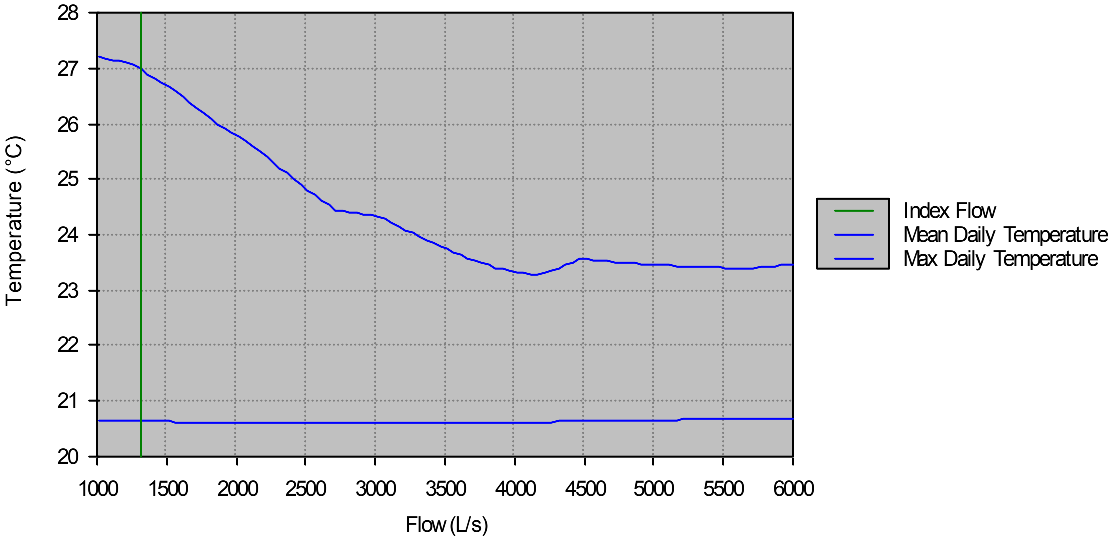

Figure 22. The influence of river flow on mean and maximum daily temperatures for the South Branch Ashburton River and Ashburton River main stem modelled with WAIORA 2.0 for the 25.6-km segment between Ollivers and Wakanui based on the IFIM data of Jowett (1992).

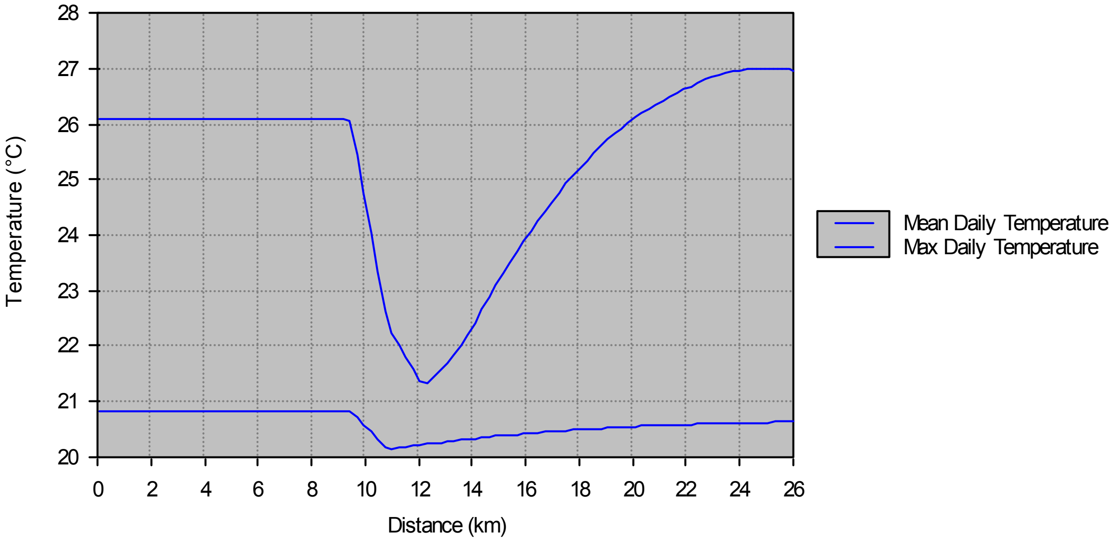

Figure 23. The influence of North Branch Ashburton River (NBAR) on the maximum and mean daily temperatures on the Ashburton River main stem modelled with WAIORA 2.0 for the 25.6-km segment between Ollivers and Wakanui based on the IFIM data of Jowett (1992). Assumed contribution of the NBAR is the 7-day mean annual low flow of 3,690 L/s from EMG 2001, Appendix 3, Table 3B.

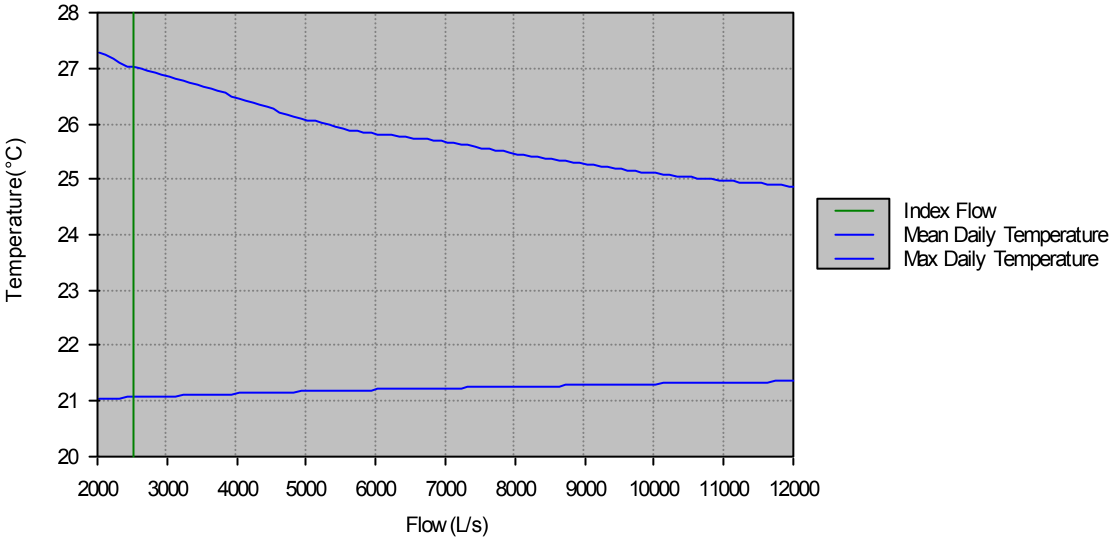

Figure 24. The influence of river flow on mean and maximum daily temperatures for the South Branch Ashburton River and Ashburton River main stem modelled with WAIORA 2.0 for the 9.2-km segment between Wakanui and the sea based on the IFIM data of Jowett (1992).

Table 19. Water temperature three reaches in the North Branch Ashburton River and main stem Ashburton River modelled for a range of flows with WAIORA 2.0.

	15.7 km segment below Valetta			25.6 km segment below Ollivers			9.2 km segment below Wakanui	
Flow (L/s)	Mean daily temperature (°C)	Maximum daily temperature (°C)	Flow (L/s)	Mean daily temperature (°C)	Maximum daily temperature (°C)	Flow (L/s)	Mean daily temperature (°C)	Maximum daily temperature (°C)
350	20.4	26.5	650	20.7	26.8	1250	21.0	27.9
382	20.4	26.4	709	20.6	26.9	1363	21.0	27.8
413	20.5	26.3	767	20.6	27.0	1475	21.0	27.7
445	20.5	26.2	826	20.6	27.1	1588	21.0	27.6
476	20.5	26.1	884	20.6	27.1	1700	21.0	27.5
508	20.5	26.0	943	20.6	27.2	1813	21.0	27.4
539	20.5	26.0	1001	20.6	27.2	1925	21.0	27.3
571	20.5	25.9	1060	20.6	27.2	2038	21.0	27.3
602	20.5	25.9	1118	20.6	27.1	2150	21.1	27.2
634	20.5	25.8	1177	20.6	27.1	2263	21.1	27.1
665	20.5	25.7	1235	20.6	27.1	2375	21.1	27.1
697	20.5	25.7	1294	20.6	27.0	2488	21.1	27.0
728	20.5	25.7	1352	20.6	26.9	2600	21.1	27.0
760	20.5	25.6	1411	20.6	26.8	2713	21.1	26.9
791	20.5	25.6	1469	20.6	26.7	2825	21.1	26.9
823	20.5	25.6	1528	20.6	26.6	2938	21.1	26.9
854	20.5	25.5	1586	20.6	26.5	3050	21.1	26.8
886	20.5	25.5	1645	20.6	26.4	3163	21.1	26.8
917	20.5	25.5	1703	20.6	26.3	3275	21.1	26.7
949	20.5	25.4	1762	20.6	26.2	3388	21.1	26.7
980	20.5	25.4	1820	20.6	26.0	3500	21.1	26.7
1012	20.5	25.4	1879	20.6	26.0	3613	21.1	26.6
1043	20.5	25.3	1937	20.6	25.9	3725	21.1	26.6
1075	20.5	25.3	1996	20.6	25.8	3838	21.1	26.5
1106	20.5	25.3	2054	20.6	25.7	3950	21.1	26.5
1138	20.5	25.2	2113	20.6	25.6	4063	21.1	26.4
1169	20.5	25.2	2171	20.6	25.5	4175	21.1	26.4
1201	20.5	25.2	2230	20.6	25.3	4288	21.1	26.3
1232	20.5	25.2	2288	20.6	25.2	4400	21.2	26.3
1264	20.6	25.1	2347	20.6	25.1	4513	21.2	26.3
1295	20.6	25.1	2405	20.6	25.0	4625	21.2	26.2
1327	20.6	25.1	2464	20.6	24.9	4738	21.2	26.2
1358	20.6	25.1	2522	20.6	24.8	4850	21.2	26.1
1390	20.6	25.0	2581	20.6	24.7	4963	21.2	26.1
1421	20.6	25.0	2639	20.6	24.5	5075	21.2	26.0
1453	20.6	25.0	2698	20.6	24.4	5188	21.2	26.0
1484	20.6	25.0	2756	20.6	24.4	5300	21.2	26.0
1516	20.6	25.0	2815	20.6	24.4	5413	21.2	25.9
1547	20.6	24.9	2873	20.6	24.4	5525	21.2	25.9
1579	20.6	24.9	2932	20.6	24.4	5638	21.2	25.9
1610	20.6	24.9	2990	20.6	24.3	5750	21.2	25.8
1642	20.6	24.9	3049	20.6	24.3	5863	21.2	25.8
1673	20.6	24.9	3107	20.6	24.2	5975	21.2	25.8
1705	20.6	24.8	3166	20.6	24.1	6088	21.2	25.8
1736	20.6	24.8	3224	20.6	24.1	6200	21.2	25.8
1768	20.6	24.8	3283	20.6	24.0	6313	21.2	25.8
1799	20.6	24.8	3341	20.6	23.9	6425	21.2	25.8

continued on the next page………

Table 19. (continued)

	15.7 km segment below Valetta		25.6 km segment below Ollivers			9.2 km segment below Wakanui		
Flow (L/s)	Mean daily temperature (^{o}C)	Maximum daily temperature (^{o}C)	Flow (L/s)	Mean daily temperature (^{o}C)	Maximum daily temperature (^{o}C)	Flow (L/s)	Mean daily temperature (^{o}C)	Maximum daily temperature (^{o}C)
1831	20.6	24.8	3400	20.6	23.8	6538	21.2	25.7
1862	20.6	24.7	3458	20.6	23.8	6650	21.2	25.7
1894	20.6	24.7	3517	20.6	23.7	6763	21.2	25.7
1925	20.6	24.7	3575	20.6	23.7	6875	21.2	25.7
1957	20.6	24.7	3634	20.6	23.6	6988	21.2	25.7
1988	20.6	24.7	3692	20.6	23.5	7100	21.2	25.6
2020	20.6	24.7	3751	20.6	23.5	7213	21.2	25.6
2051	20.6	24.6	3809	20.6	23.4	7325	21.2	25.6
2083	20.6	24.6	3868	20.6	23.4	7438	21.2	25.6
2114	20.6	24.6	3926	20.6	23.4	7550	21.3	25.6
2146	20.6	24.6	3985	20.6	23.3	7663	21.3	25.5
2177	20.6	24.6	4043	20.6	23.3	7775	21.3	25.5
2209	20.6	24.6	4102	20.6	23.3	7888	21.3	25.5
2240	20.6	24.6	4160	20.6	23.3	8000	21.3	25.5
2272	20.6	24.5	4219	20.6	23.3	8113	21.3	25.4
2303	20.6	24.5	4277	20.6	23.4	8225	21.3	25.4
2335	20.6	24.5	4336	20.6	23.4	8338	21.3	25.4
2366	20.6	24.5	4394	20.6	23.5	8450	21.3	25.4
2398	20.6	24.5	4453	20.7	23.6	8563	21.3	25.3
2429	20.6	24.5	4511	20.7	23.5	8675	21.3	25.3
2461	20.6	24.5	4570	20.7	23.5	8788	21.3	25.3
2492	20.6	24.4	4628	20.7	23.5	8900	21.3	25.3
2524	20.6	24.4	4687	20.7	23.5	9013	21.3	25.3
2555	20.6	24.4	4745	20.7	23.5	9125	21.3	25.2
2587	20.6	24.4	4804	20.7	23.5	9238	21.3	25.2
2618	20.6	24.4	4862	20.7	23.5	9350	21.3	25.2
2650	20.6	24.4	4921	20.7	23.5	9463	21.3	25.2
2681	20.6	24.4	4979	20.7	23.5	9575	21.3	25.2
2713	20.6	24.4	5038	20.7	23.5	9688	21.3	25.1
2744	20.6	24.4	5096	20.7	23.4	9800	21.3	25.1
2776	20.6	24.3	5155	20.7	23.4	9913	21.3	25.1
2807	20.6	24.3	5213	20.7	23.4	10025	21.3	25.1
2839	20.6	24.3	5272	20.7	23.4	10138	21.3	25.1
2870	20.6	24.3	5330	20.7	23.4	10250	21.3	25.1
2902	20.6	24.3	5389	20.7	23.4	10363	21.3	25.1
2933	20.6	24.3	5447	20.7	23.4	10475	21.3	25.0
2965	20.6	24.3	5506	20.7	23.4	10588	21.3	25.0
2996	20.6	24.3	5564	20.7	23.4	10700	21.3	25.0
3028	20.7	24.3	5623	20.7	23.4	10813	21.3	25.0
3059	20.7	24.3	5681	20.7	23.4	10925	21.3	25.0
3091	20.7	24.3	5740	20.7	23.4	11038	21.3	25.0
3122	20.7	24.2	5798	20.7	23.4	11150	21.3	25.0
3154	20.7	24.2	5857	20.7	23.4	11263	21.3	24.9
3185	20.7	24.2	5915	20.7	23.5	11375	21.3	24.9
3217	20.7	24.2	5974	20.7	23.4	11488	21.3	24.9
3248	20.7	24.2	6032	20.7	23.4	11600	21.4	24.9
3280	20.7	24.2	6091	20.7	23.4	11713	21.4	24.9
3311	20.7	24.2	6149	20.7	23.4	11825	21.4	24.9
3343	20.7	24.2	6208	20.7	23.4	11938	21.4	24.9
3374	20.7	24.2	6266	20.7	23.4	12050	21.4	24.9
3406	20.7	24.2	6325	20.7	23.4	12163	21.4	24.9
3437	20.7	24.2	6383	20.7	23.4	12275	21.4	24.8
3469	20.7	24.2	6442	20.7	23.4	12388	21.4	24.8
3500	20.7	24.1	6500	20.7	23.4	12500	21.4	24.8

Acknowledgements

I acknowledge the use of the Freshwater Fish Database that is held and maintained by NIWA. I thank Ian Jowett for useful discussions on the operation of RHYHABSIM and WAIORA. I also acknowledge the data freely provided by Henry Hudson.

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Appendix 1. Point habitat analysis by cross sections for upstream passage of adult chinook salmon for the from Jowett's (1992) habitat data.

Assumptions:

1. All substrates are equally suitable.
2. Minimum depth permitting passage 0.20 m (= maximum body depth of adult chinook salmon), with a suitability of 0.5. Depths ≥0.25 m are fully suitable (suitability = 1.0).
3. Passage is possible at water velocities ≤1.0 m/s, the cruising velocity of chinook salmon.

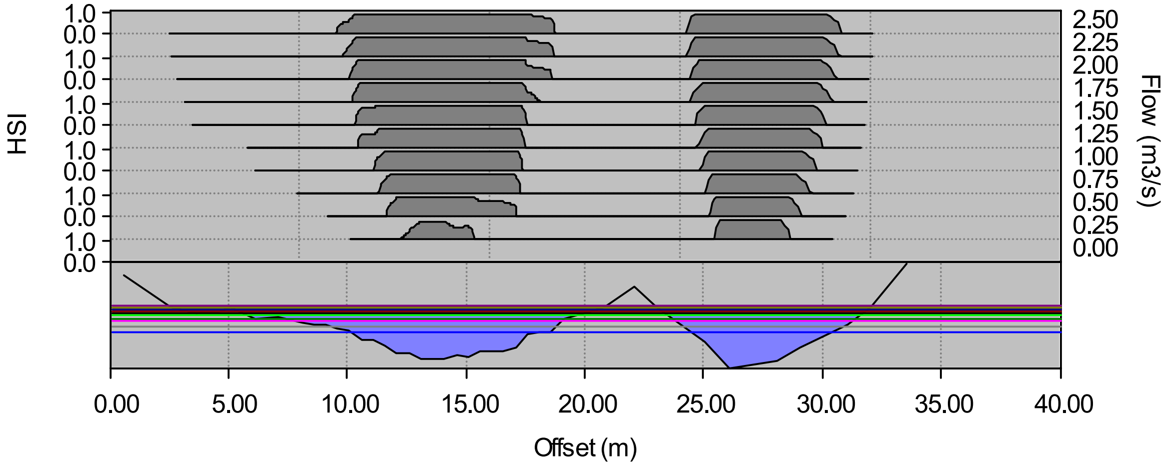
Habitat preference file

'Chinook salmon passage3'

VELOCITY	0	1	1.01	3				
WEIGHT	1	1	0	0				
DEPTH	0	0.19	0.2	0.25	10			
WEIGHT	0	0	0.5	1	1			
SUBSTRATE	1	2	3	4	5	6	7	8
WEIGHT	1	1	1	1	1	1	1	1

A. Valetta

Cross-section 1 XSECT-1: Chinook salmon passage3



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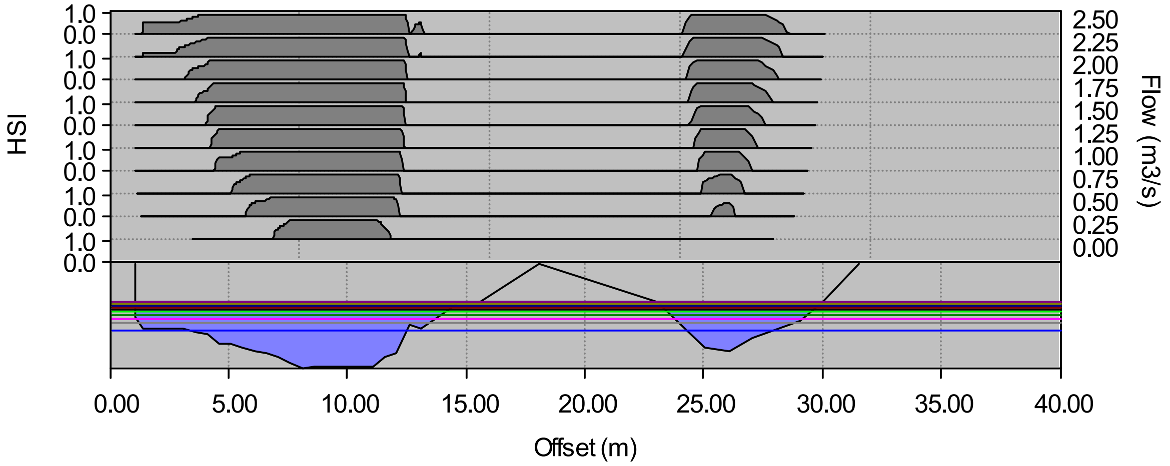

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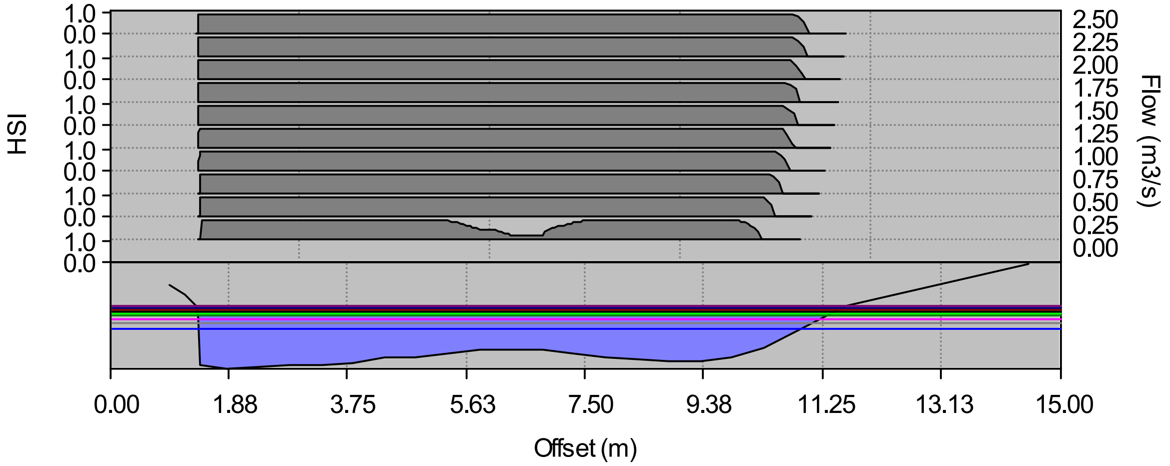

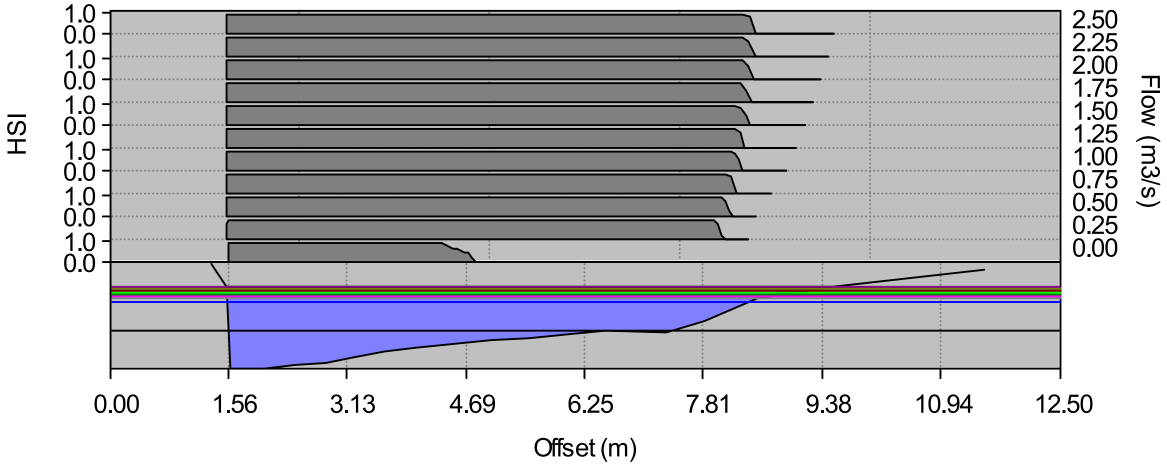

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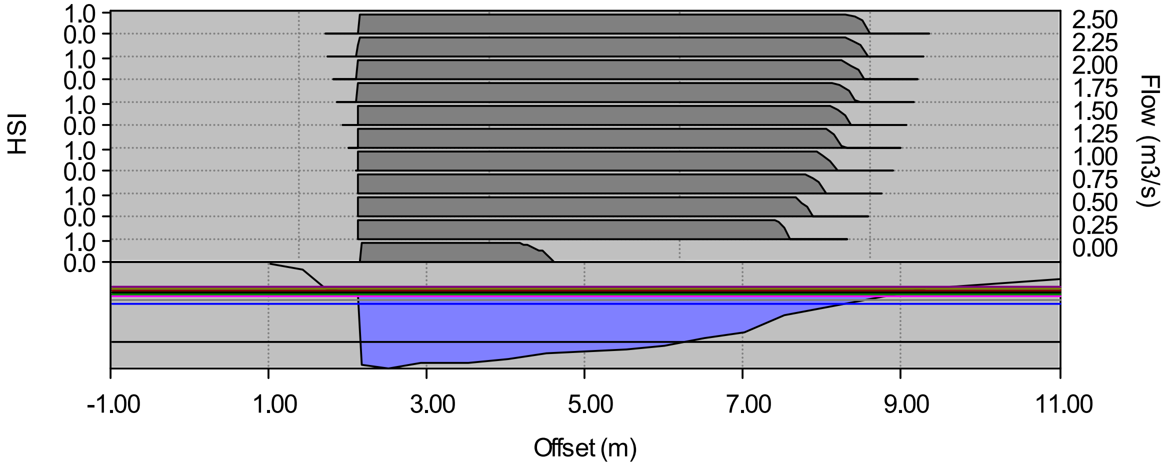

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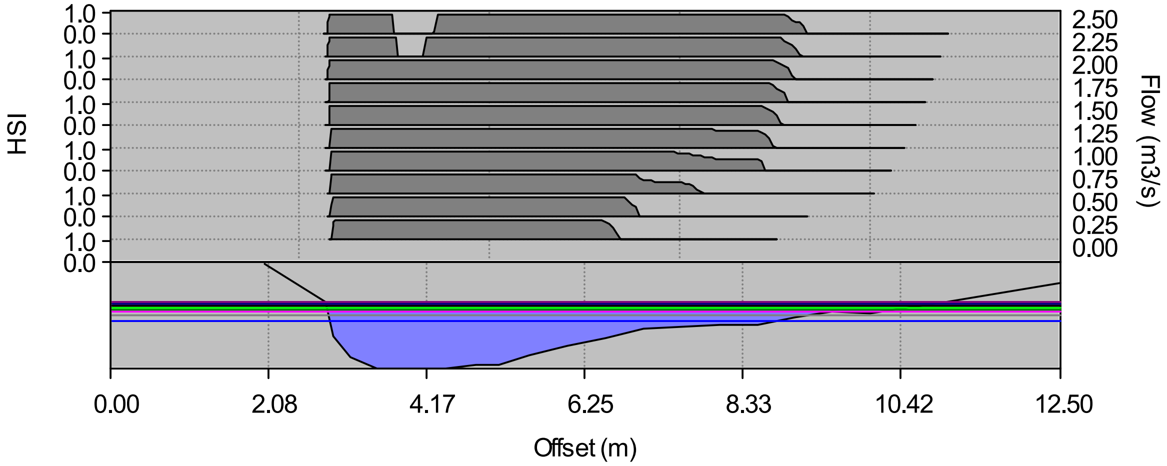

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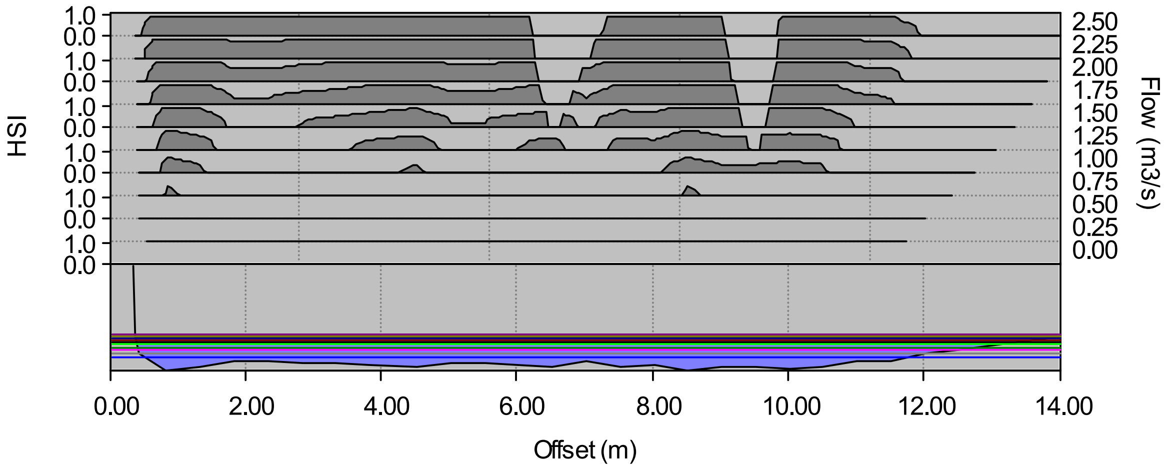

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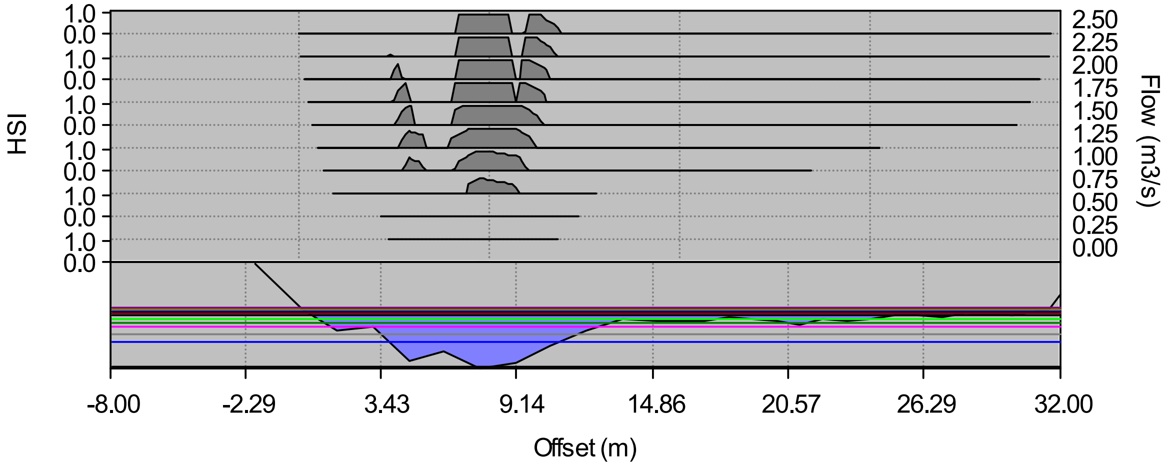
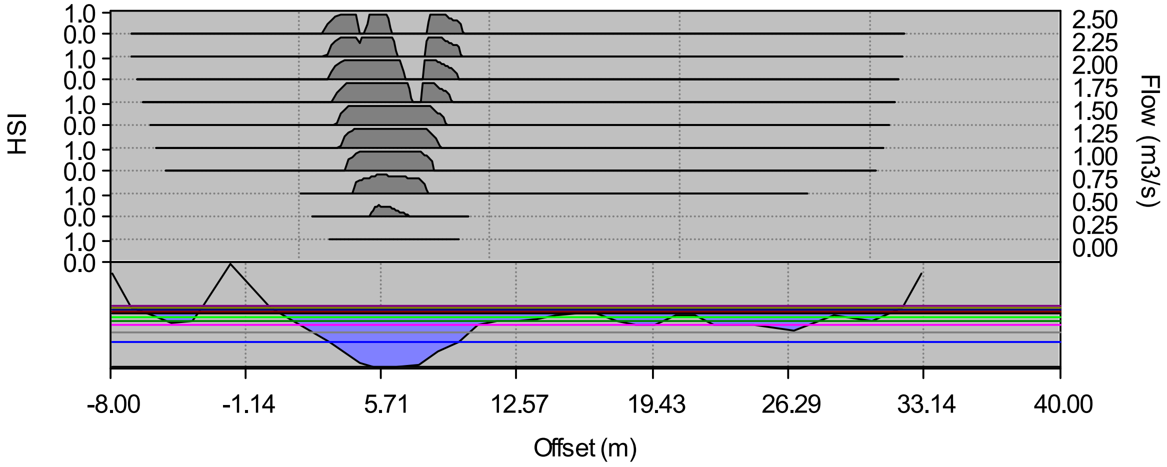
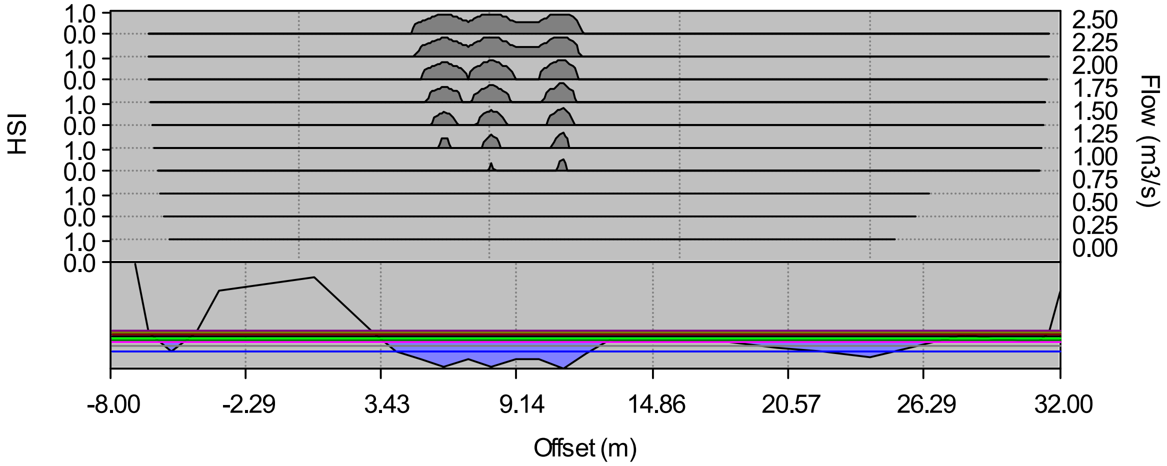


Cross-section 8 XSECT-8: Chinook salmon passage3

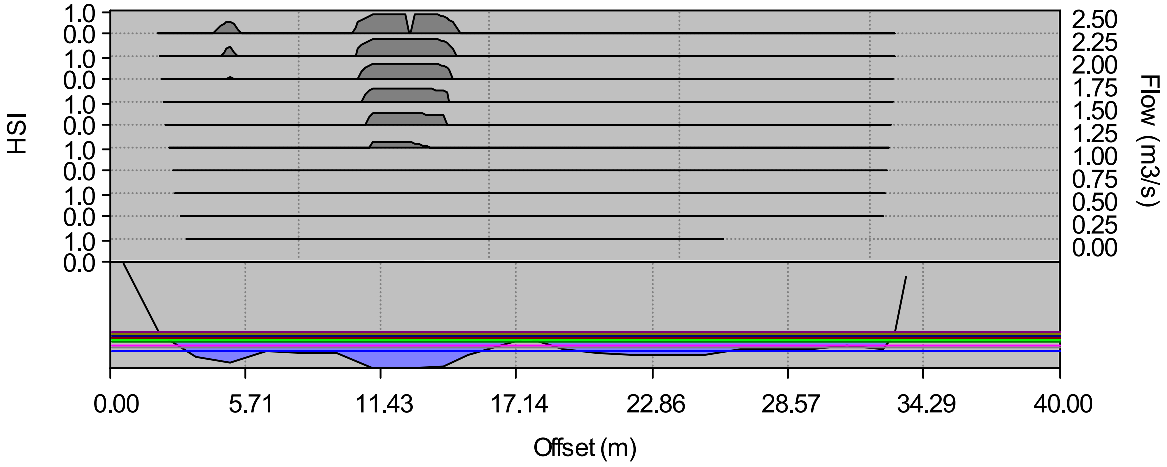


Cross-section 9 XSECT-9: Chinook salmon passage3

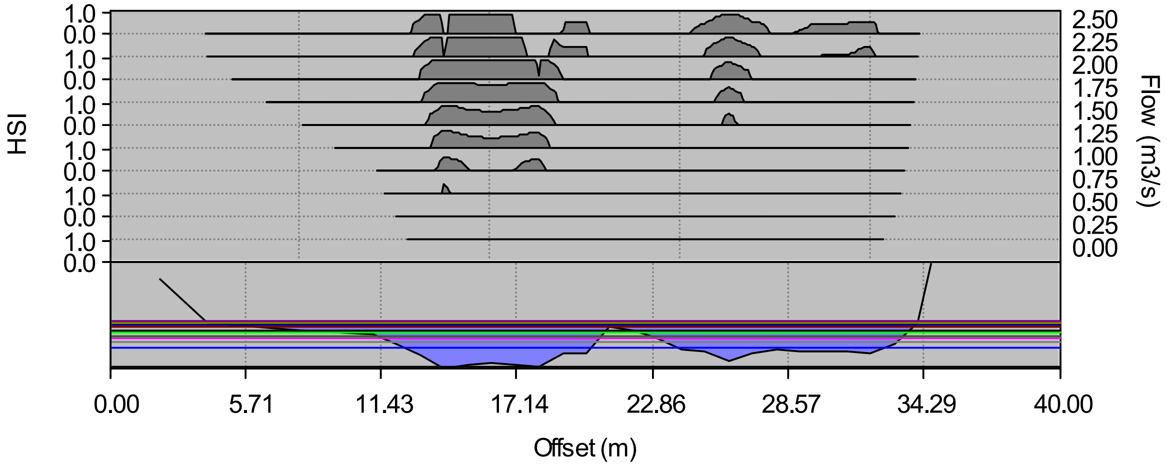
Cross-section 10 XSECT-10: Chinook salmon passage3



Cross-section 11 XSECT-11: Chinook salmon passage3



Cross-section 12 XSECT-12: Chinook salmon passage3



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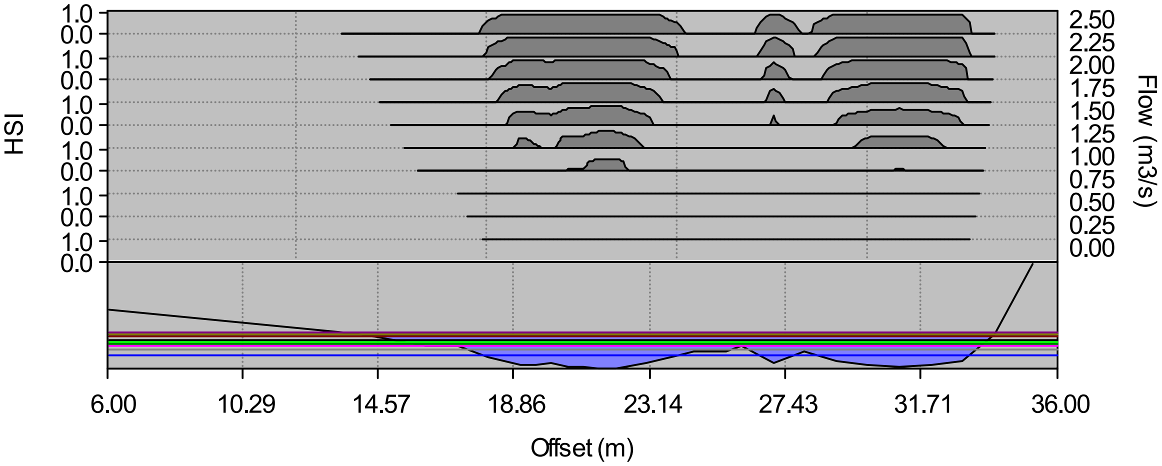

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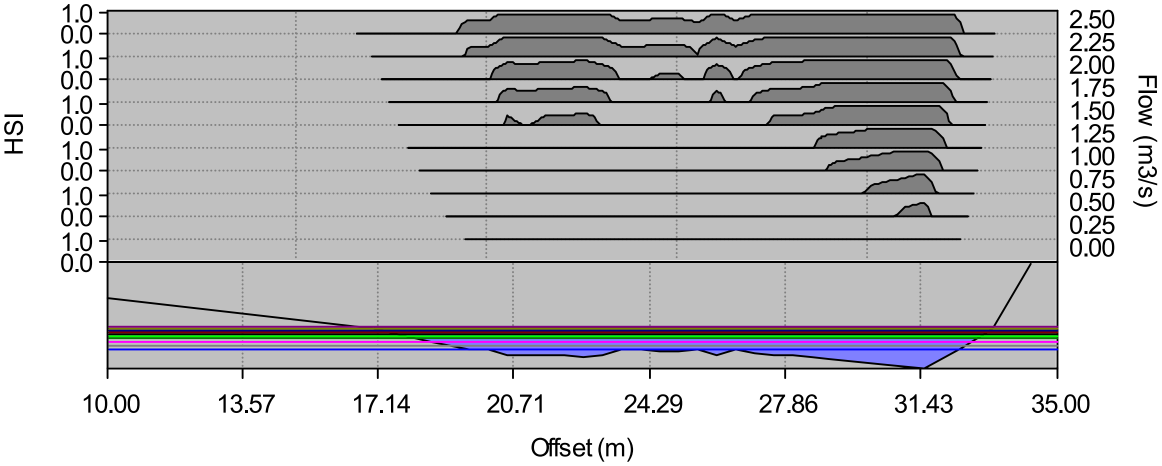

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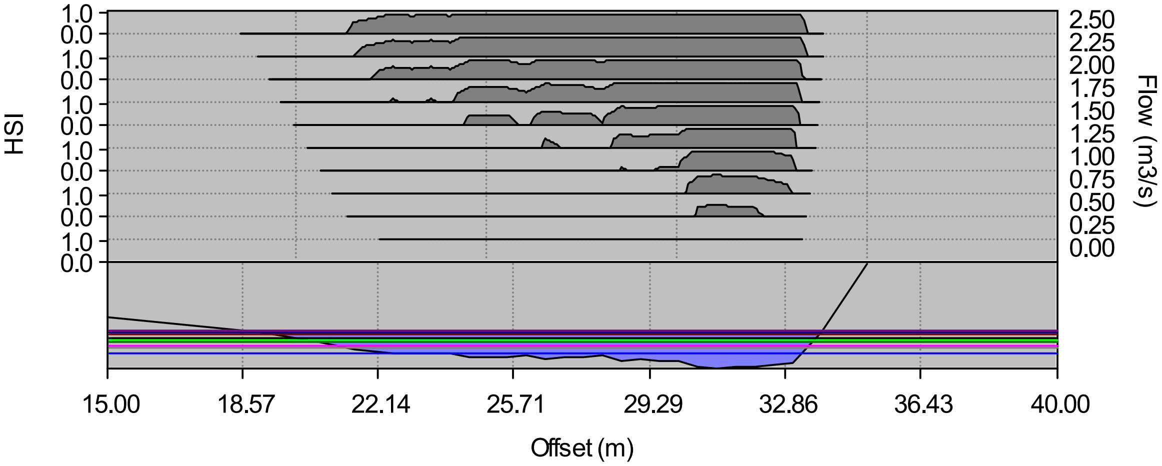

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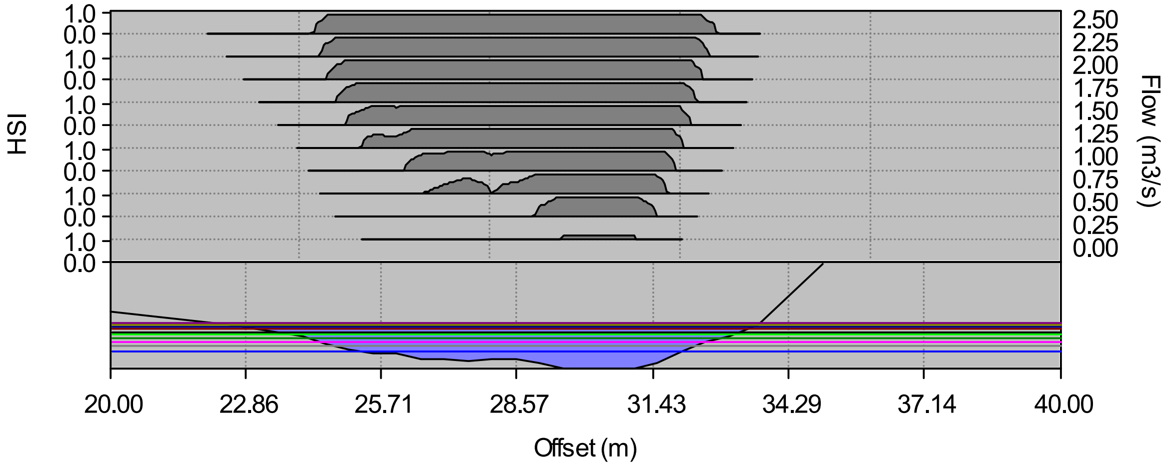

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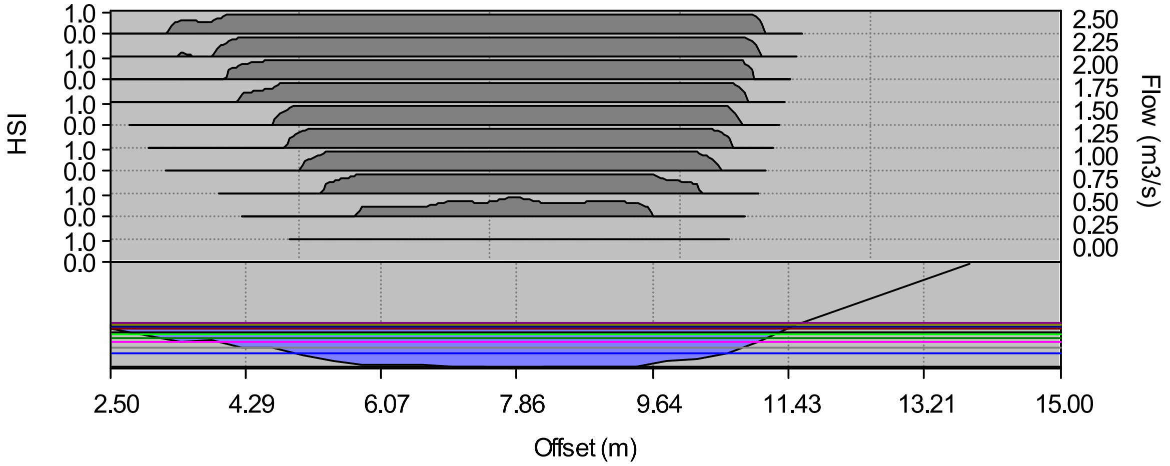

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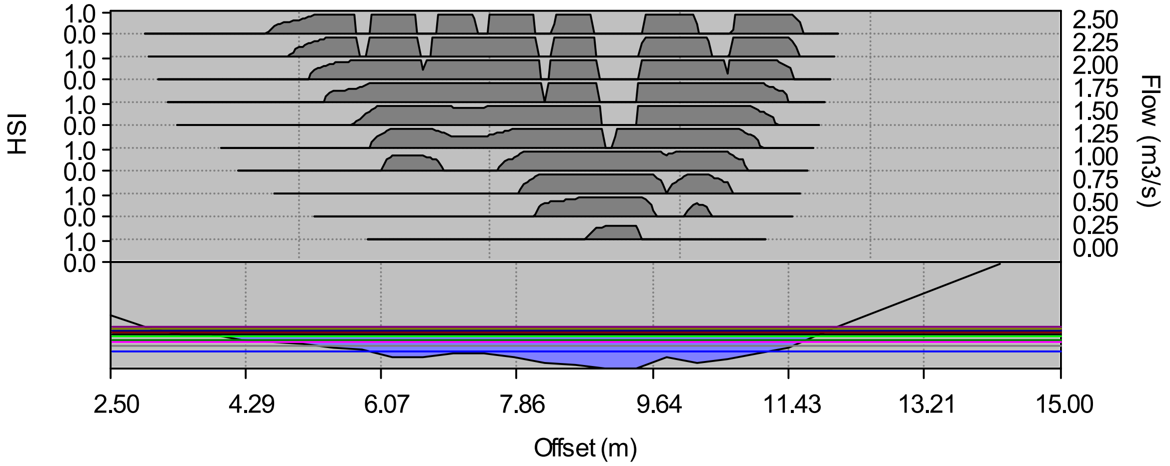

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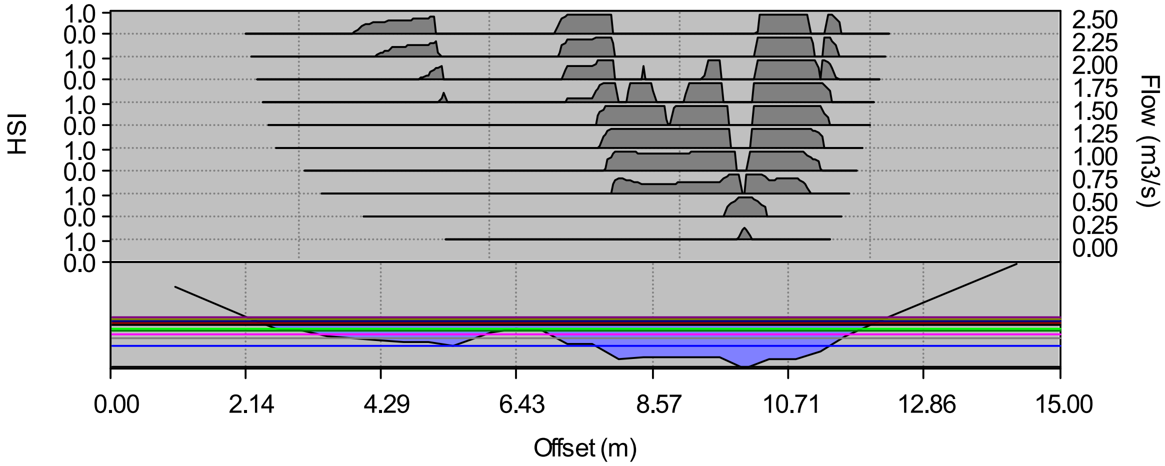

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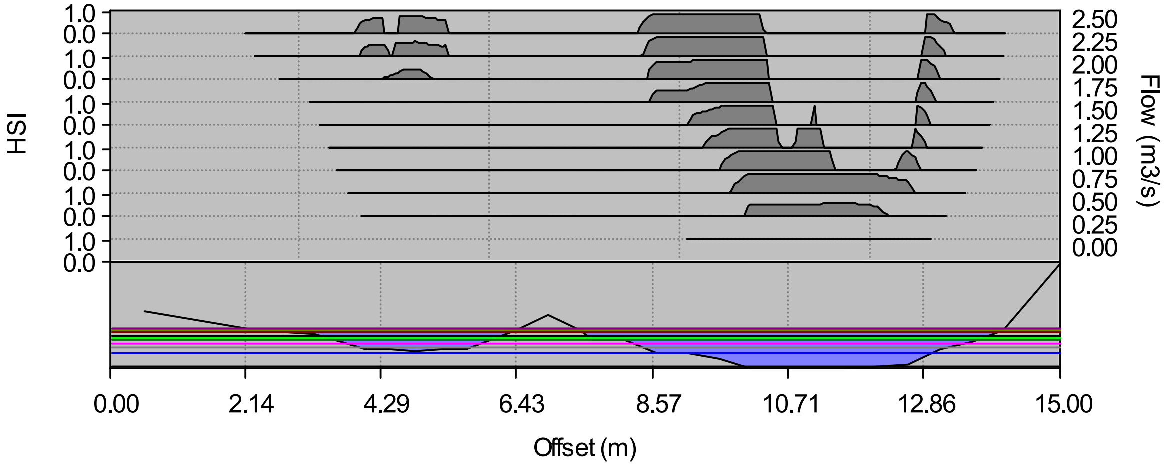
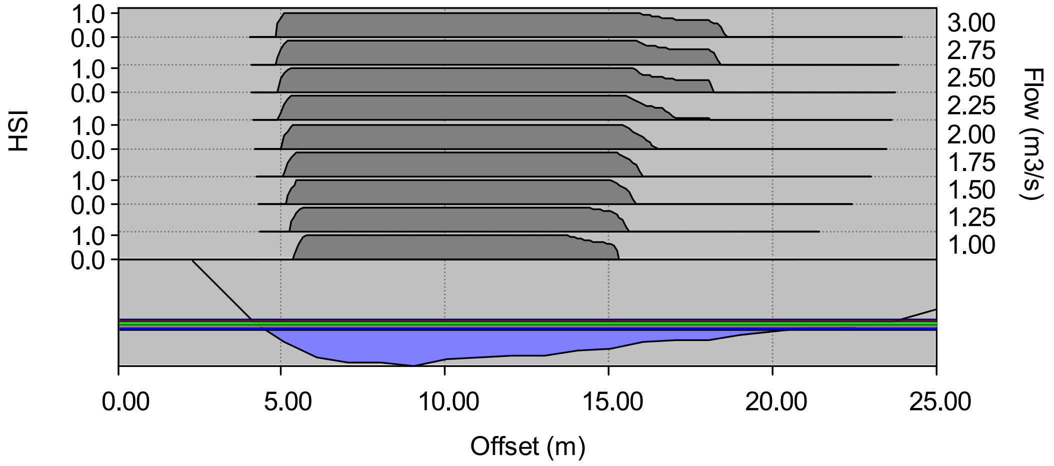


B. Ollivers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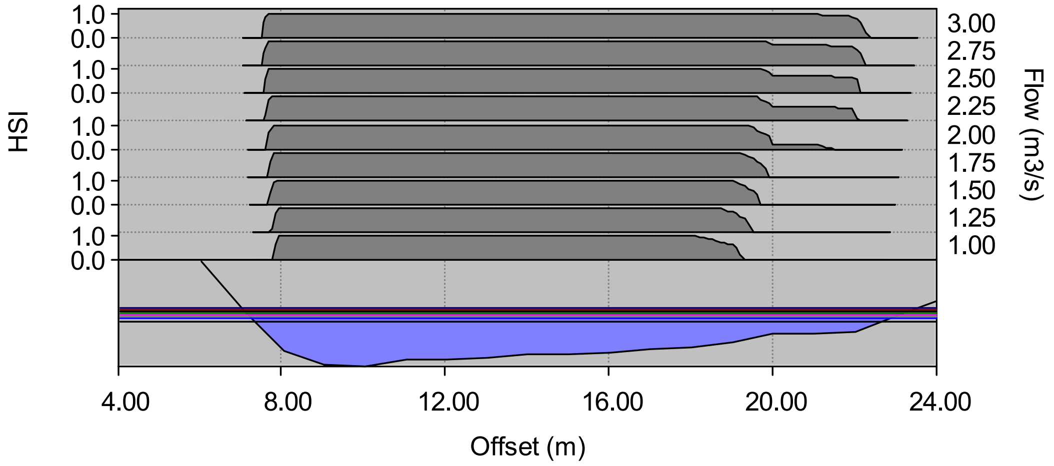
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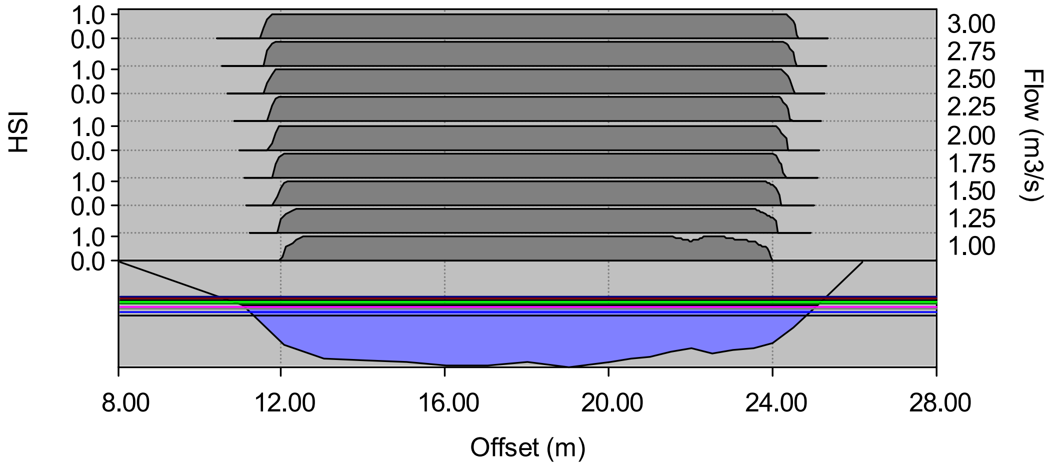
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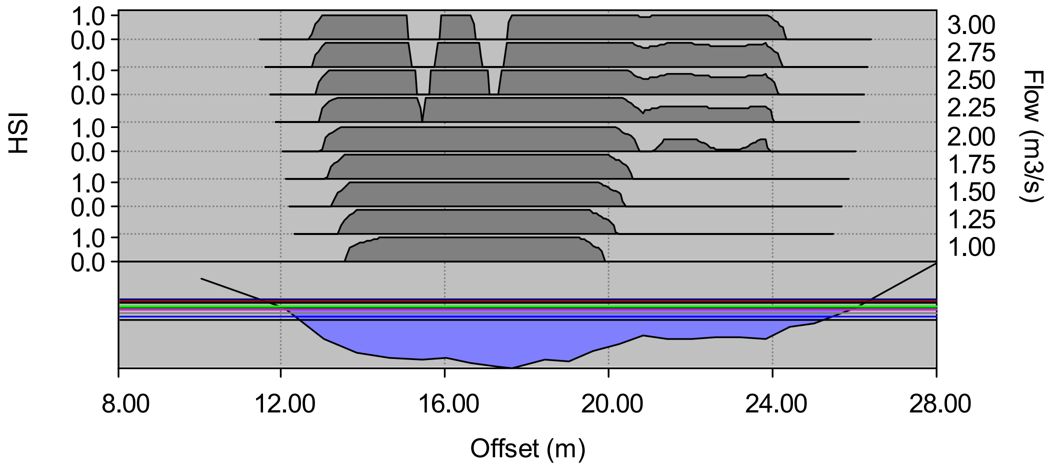

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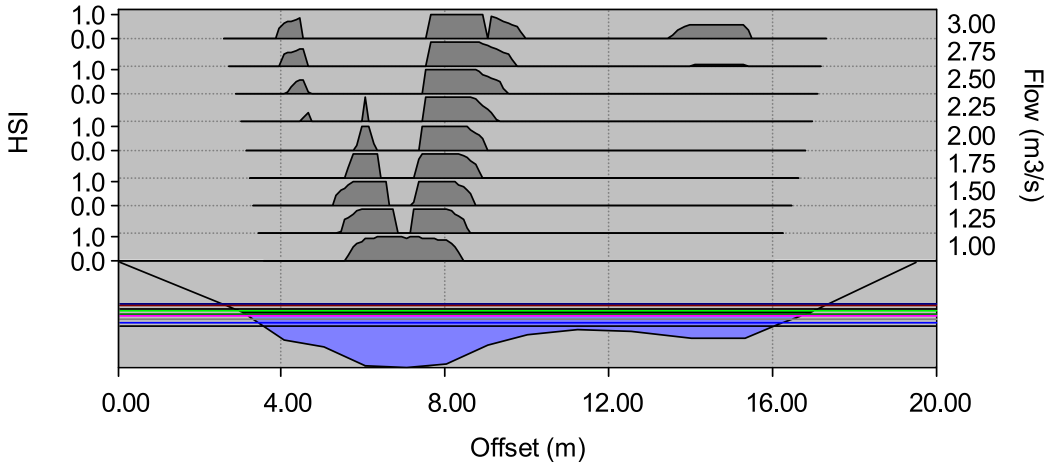

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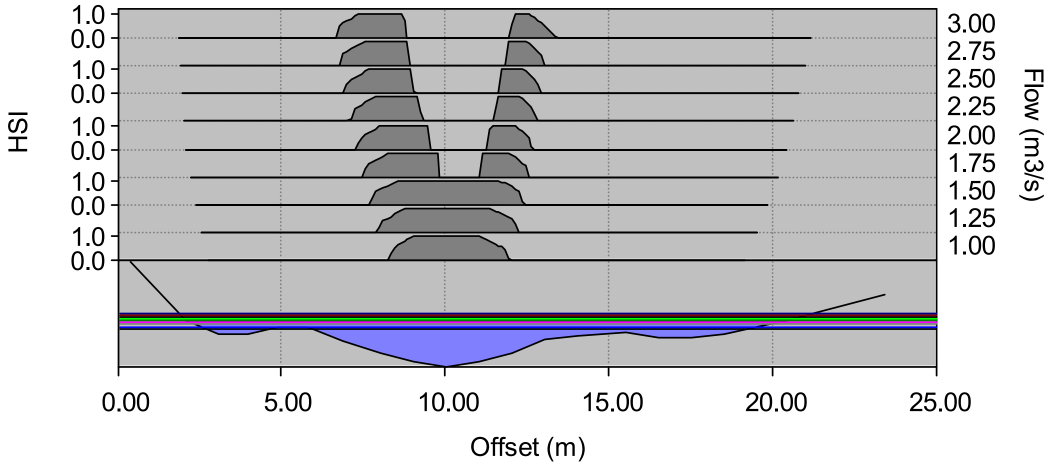
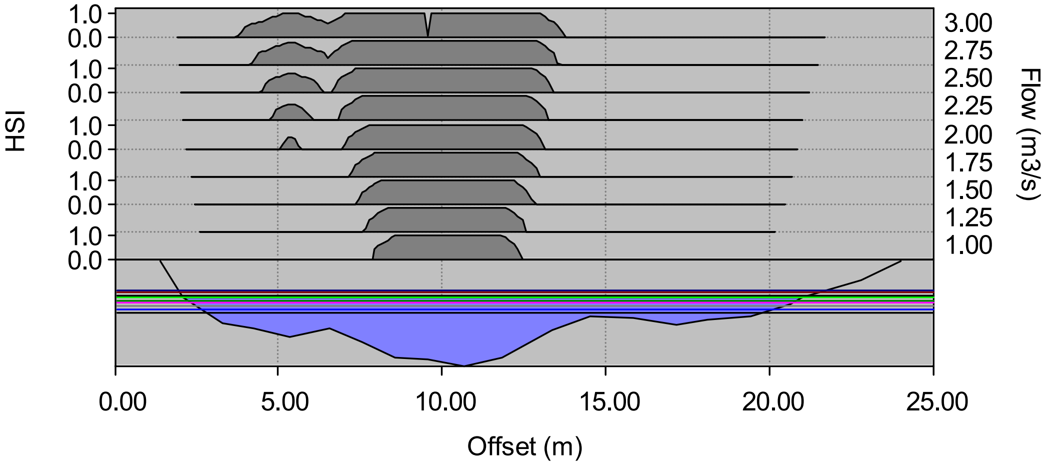


Cross-section 6 XSECT-06: Chinook salmon passage3

Cross-section 7 XSECT-07: Chinook salmon passage3



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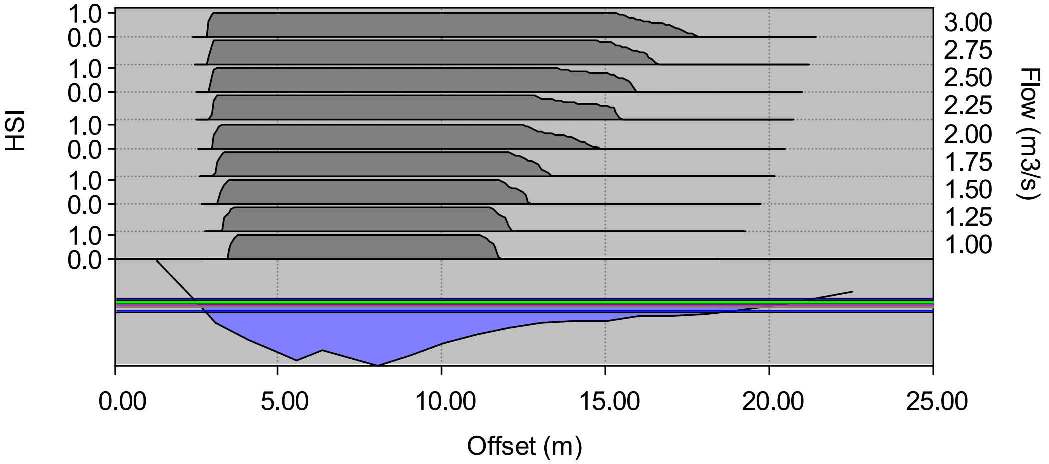

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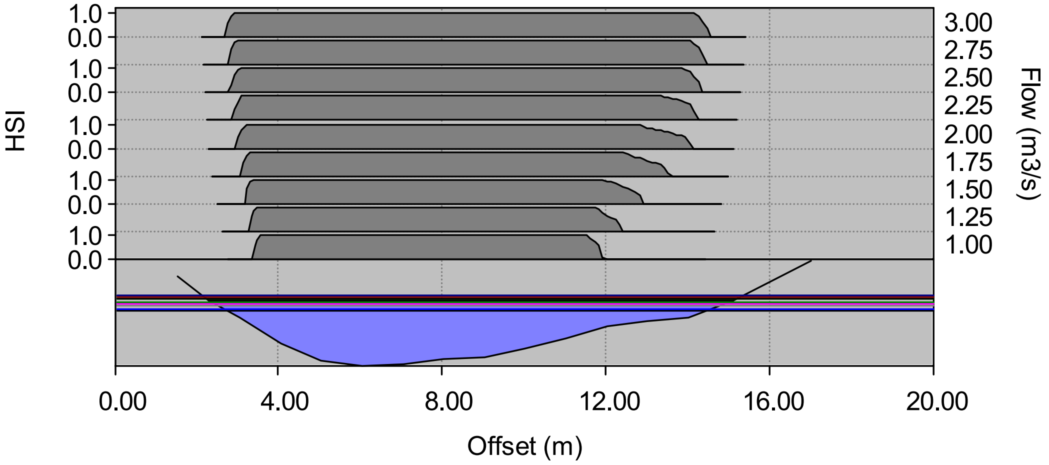

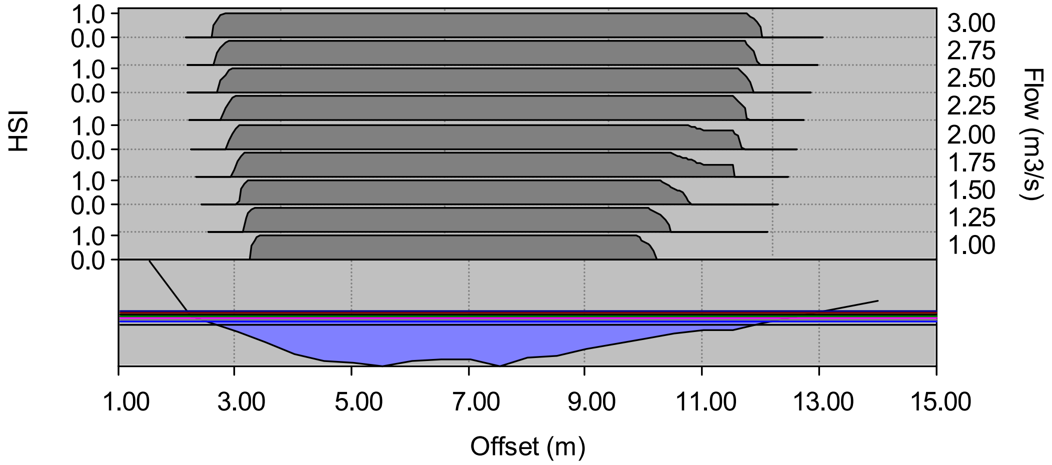
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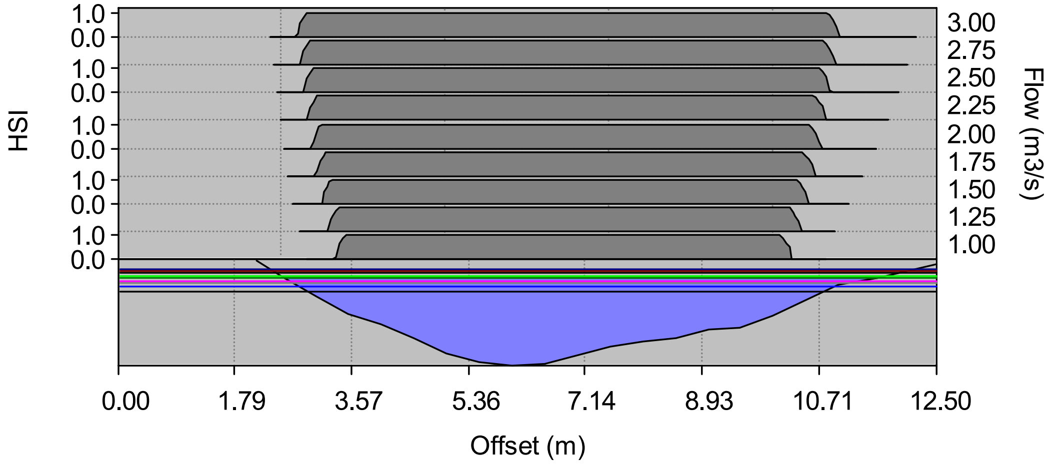
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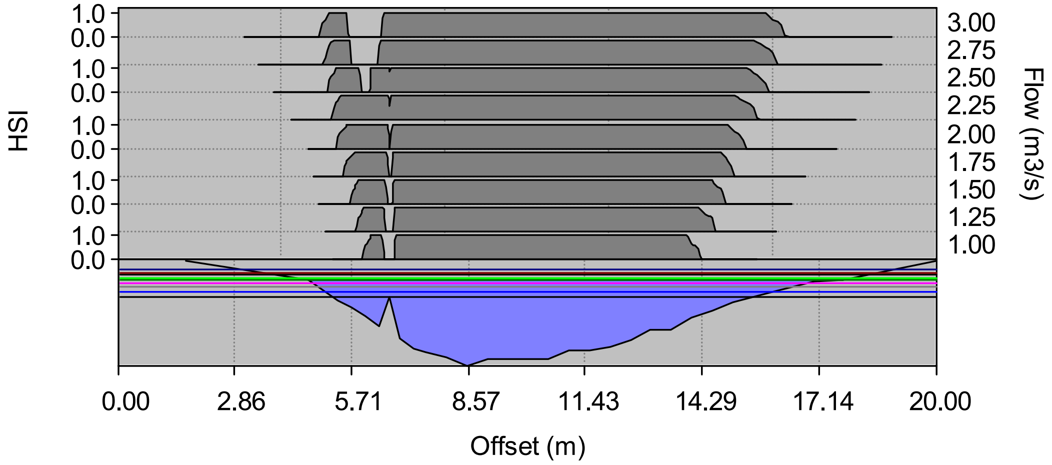
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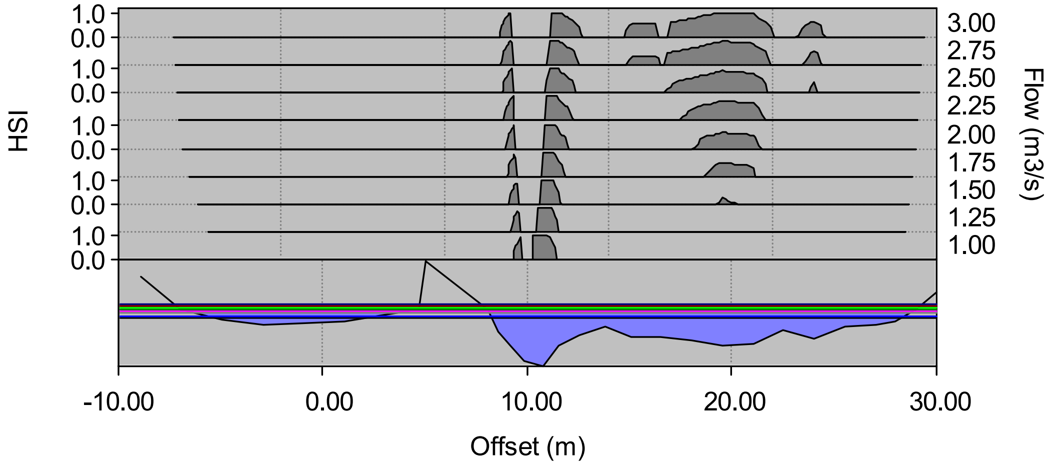

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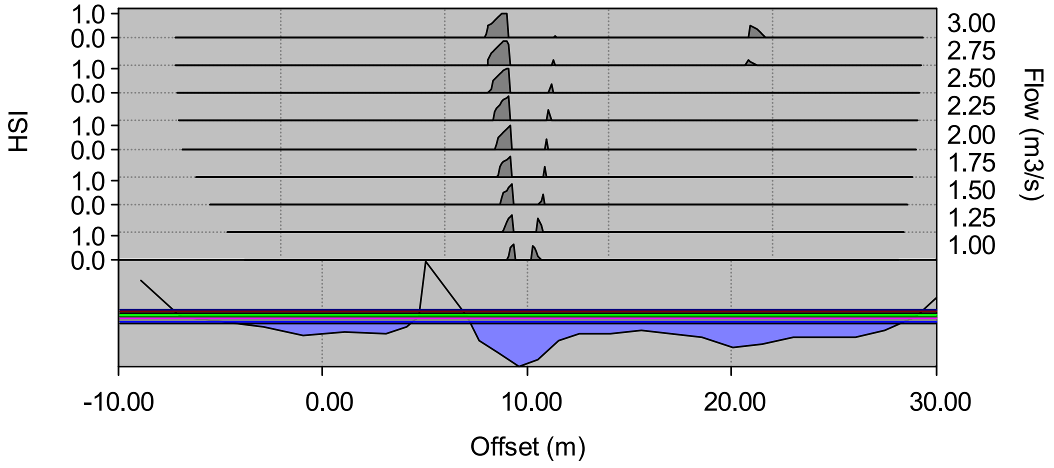

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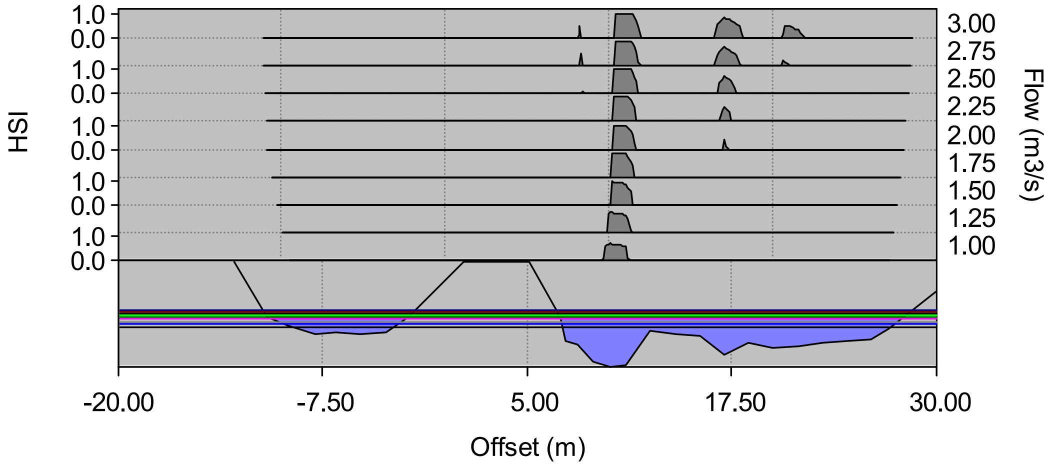

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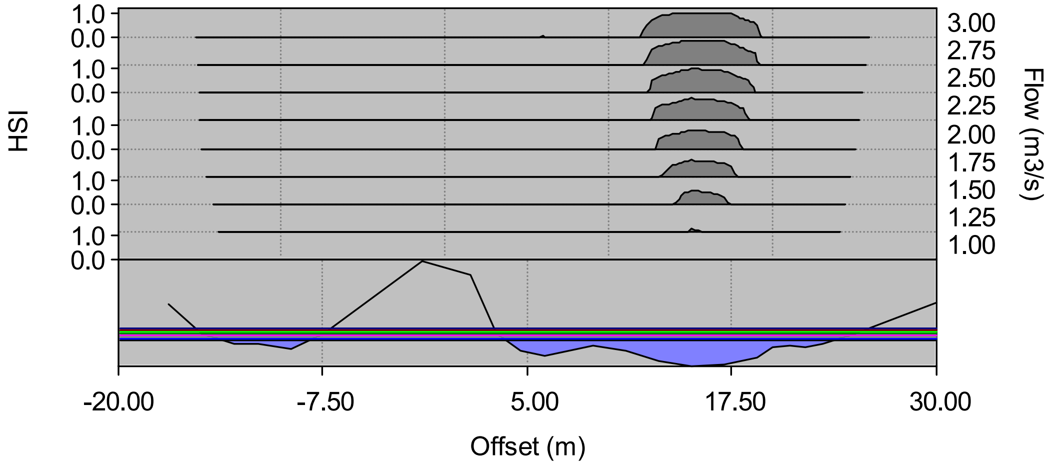
Cross-section 16 XSECT-16: Chinook salmon passage3



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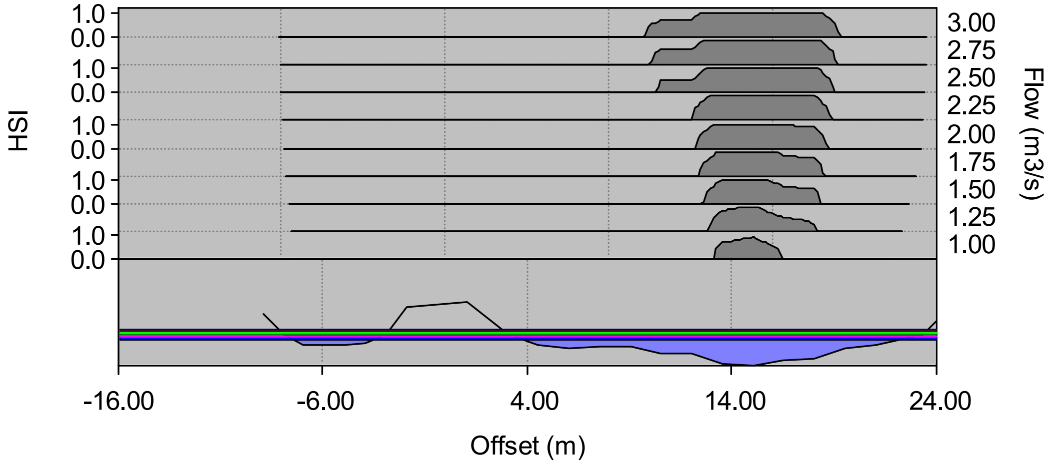

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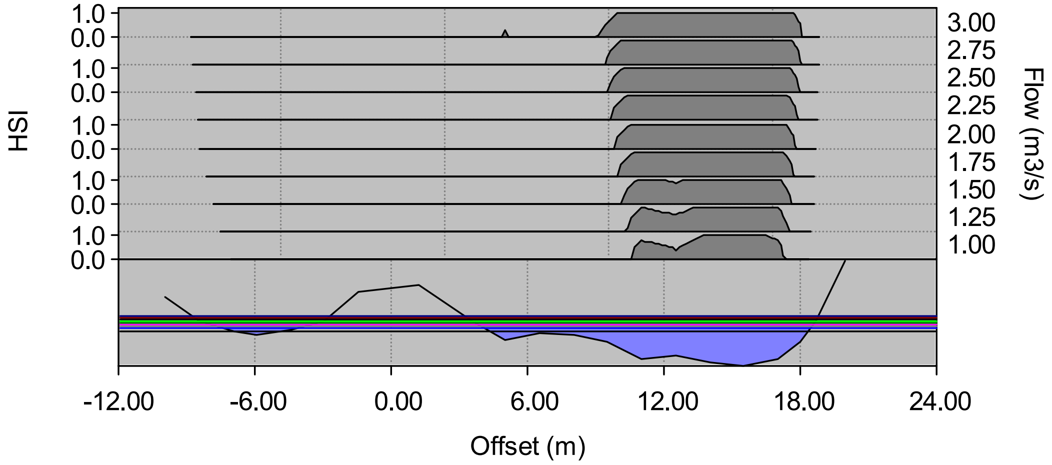

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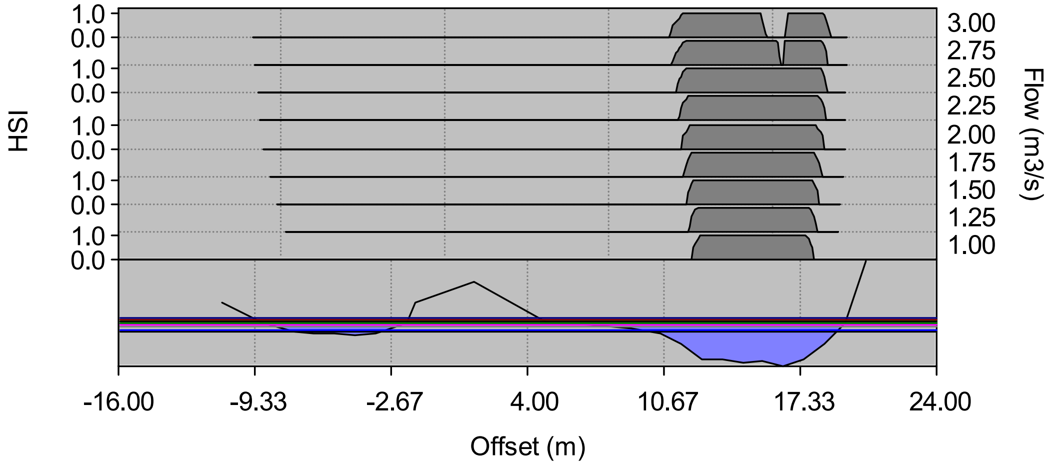

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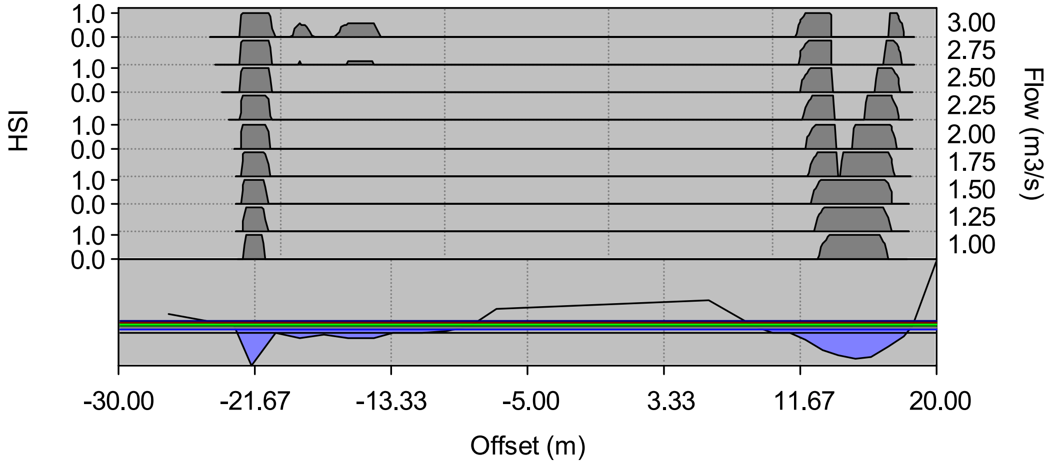

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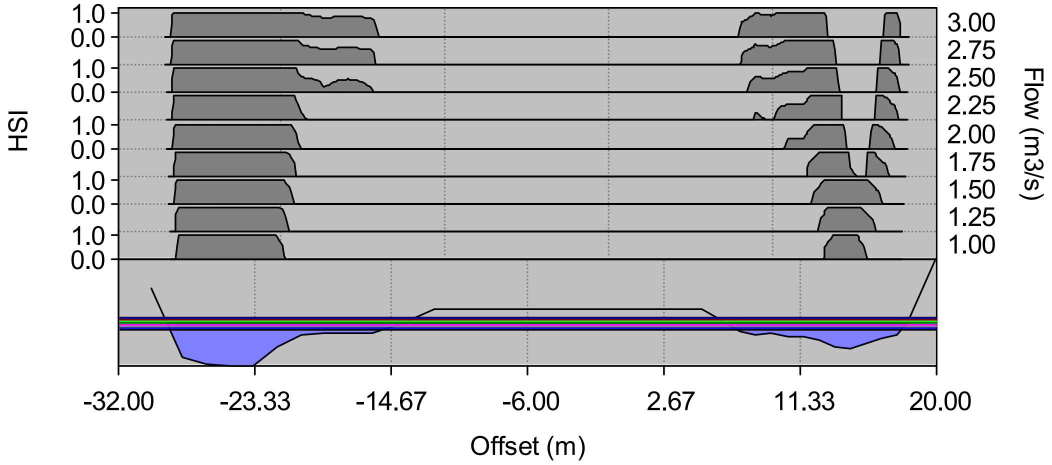

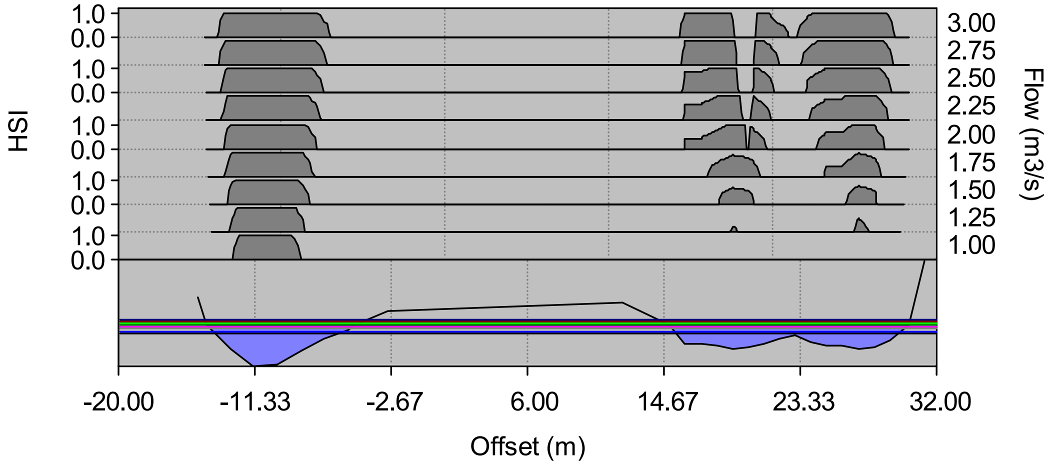

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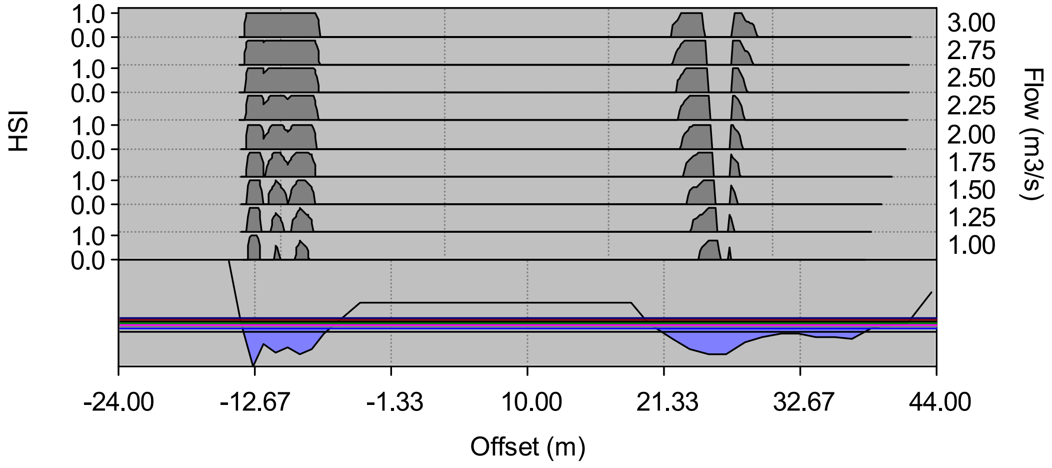
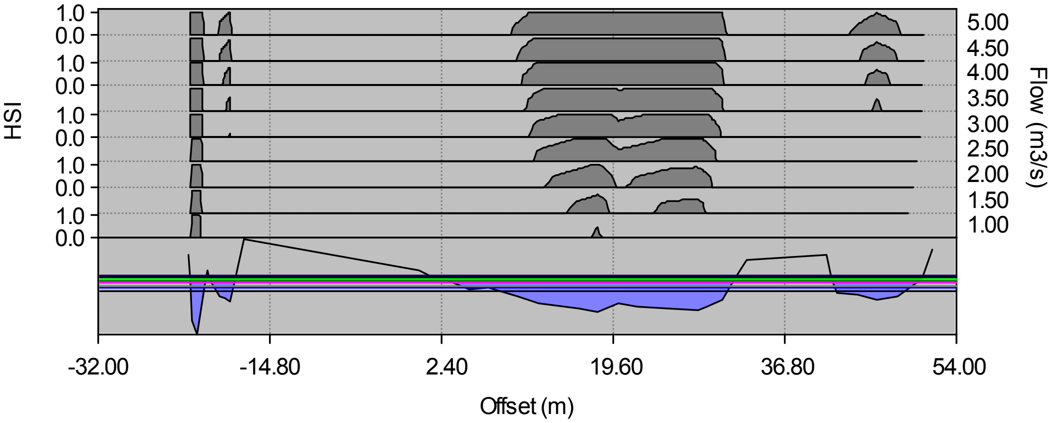


Cross-section 23 XSECT-23: Chinook salmon passage3

C. Wakanui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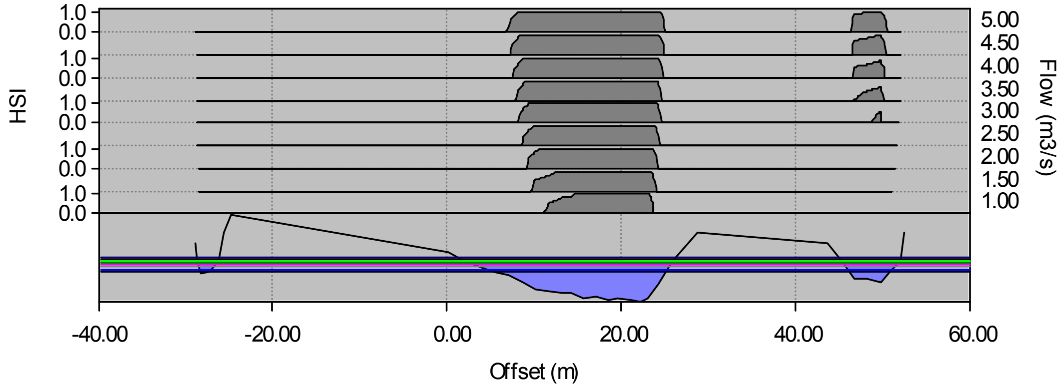
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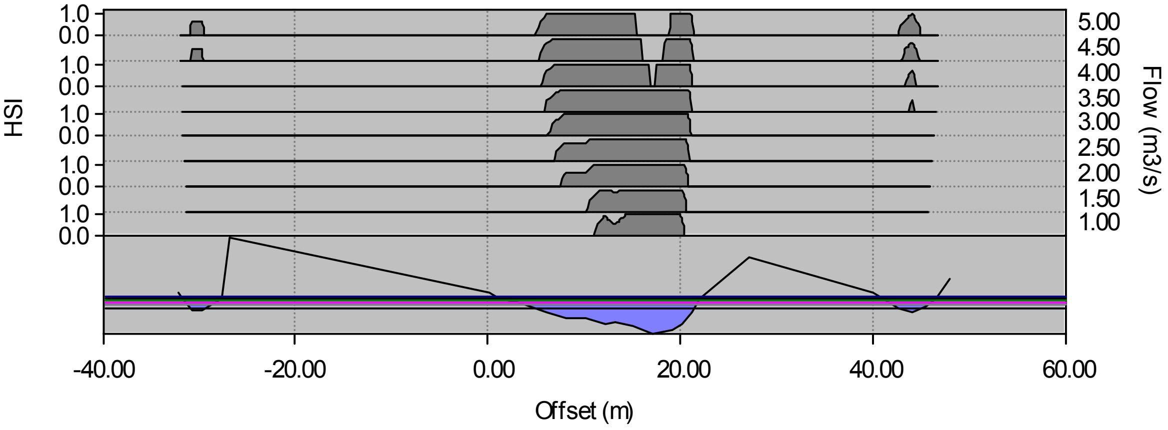
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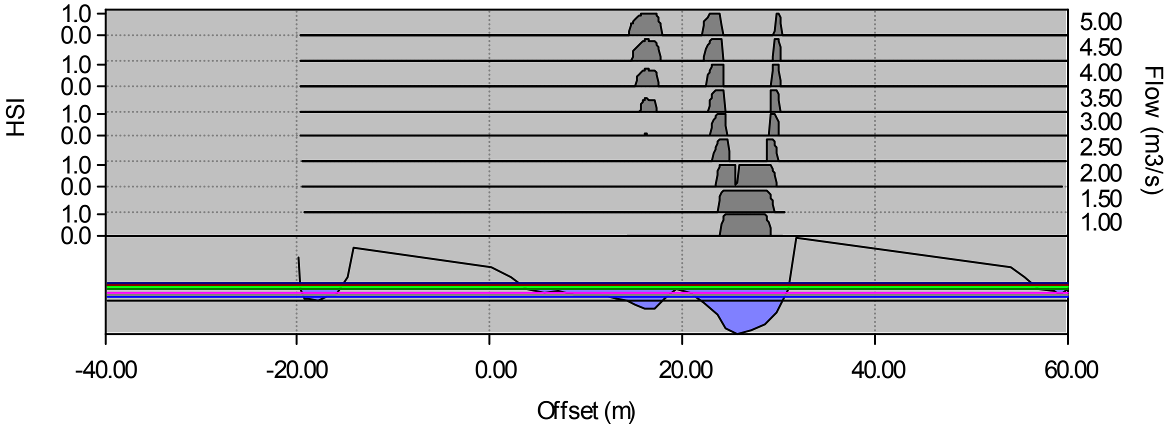

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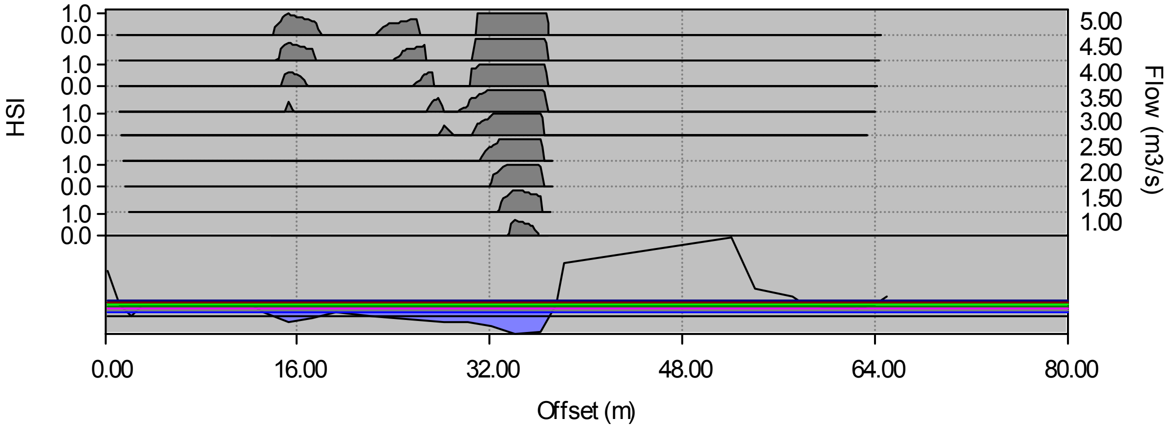

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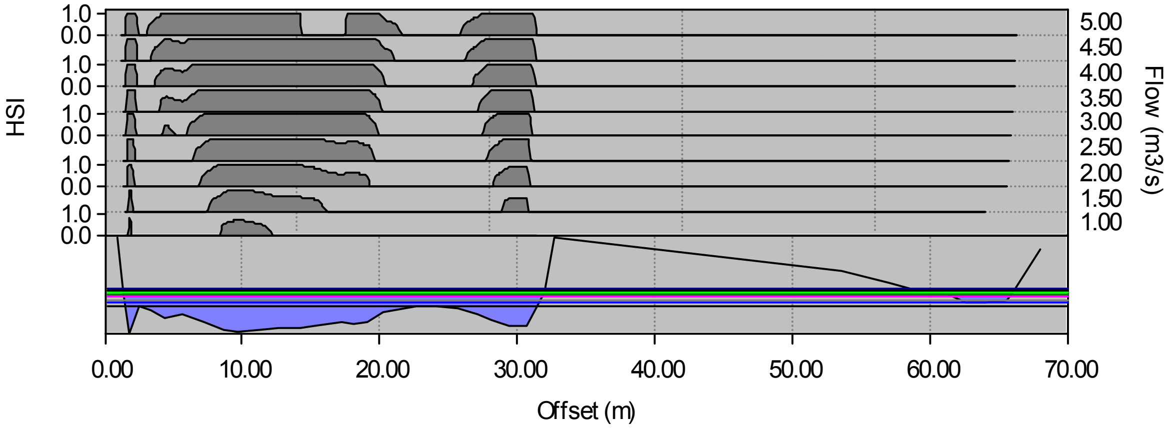

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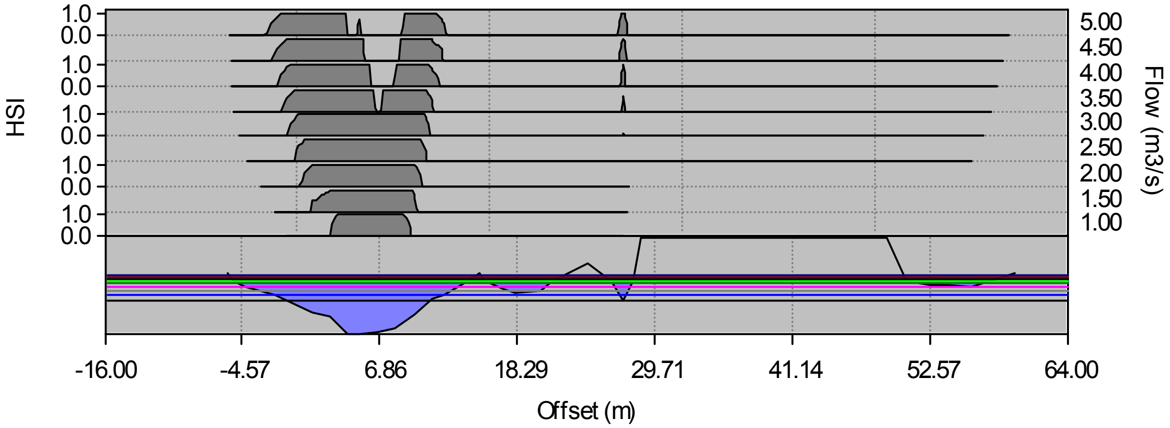

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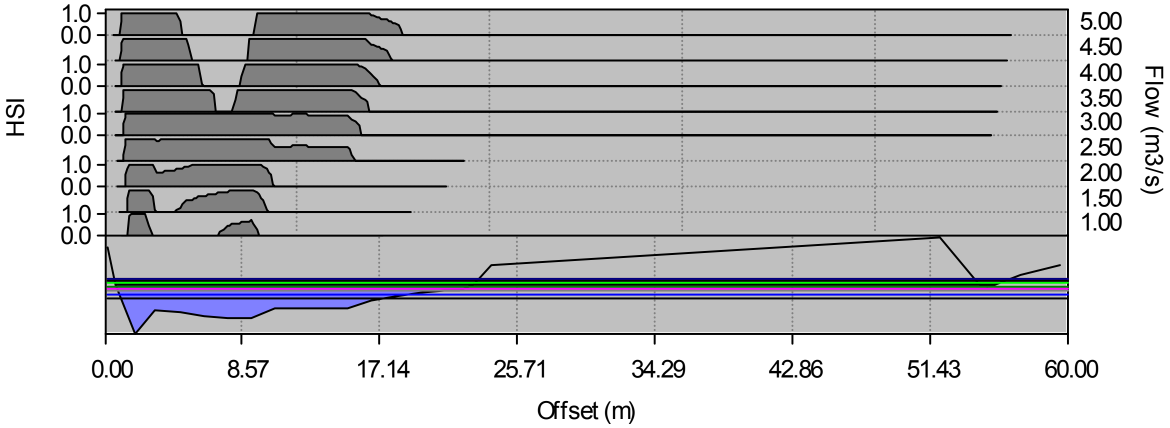

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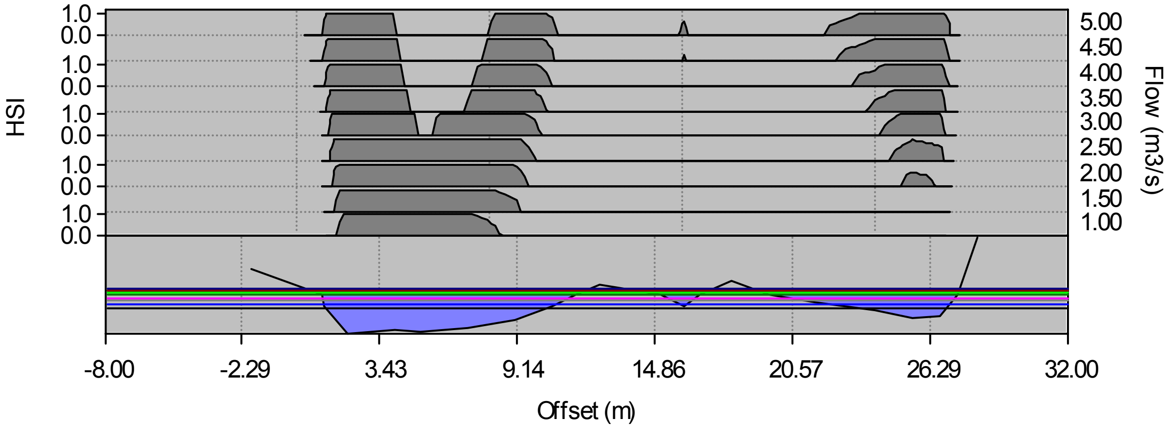

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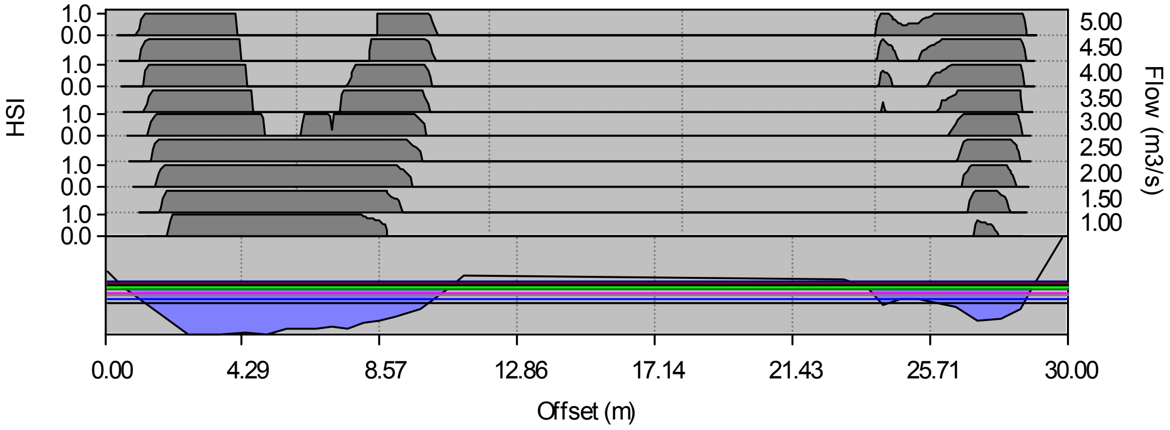

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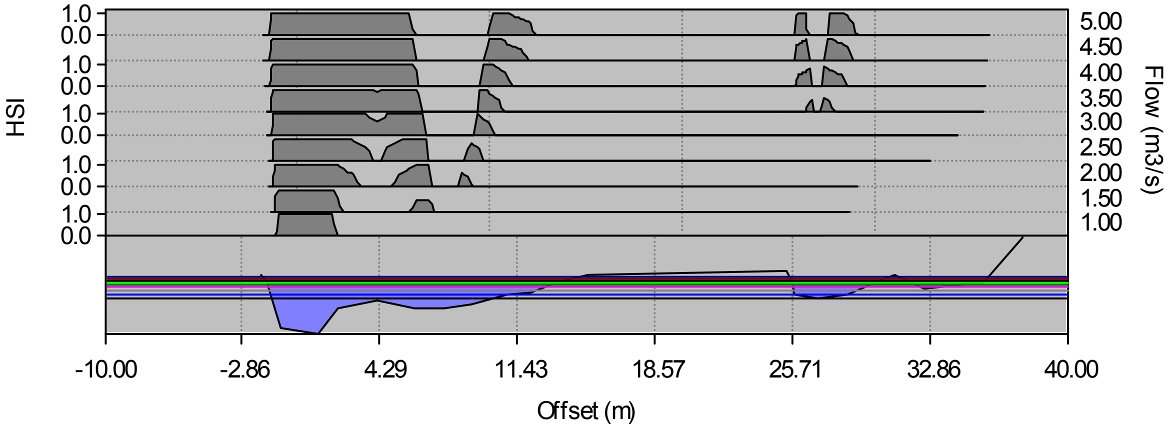
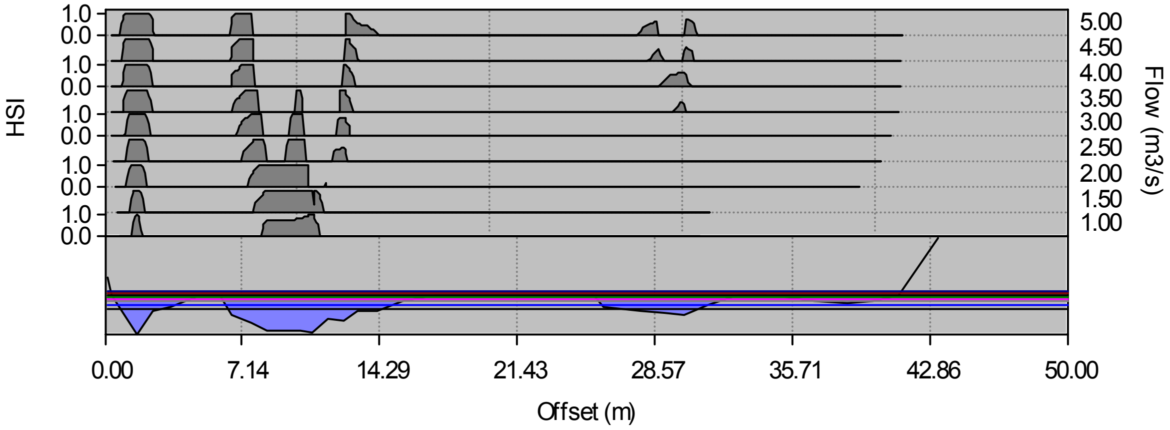
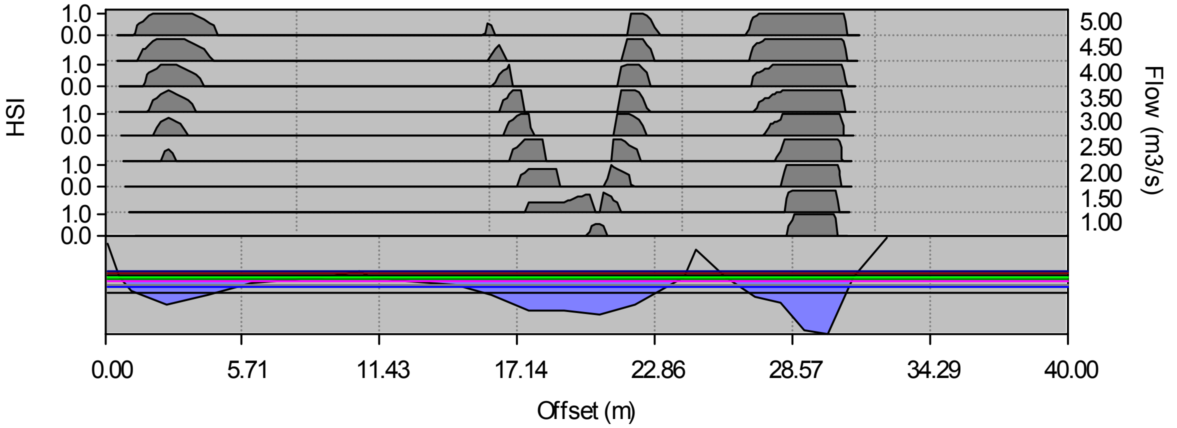


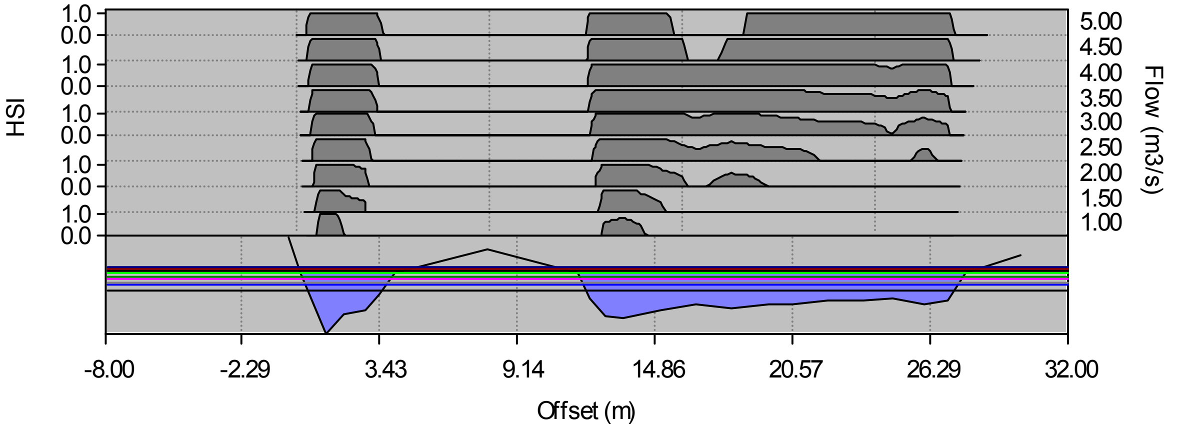
Cross-section 13 XSECT-12: Chinook salmon passage3



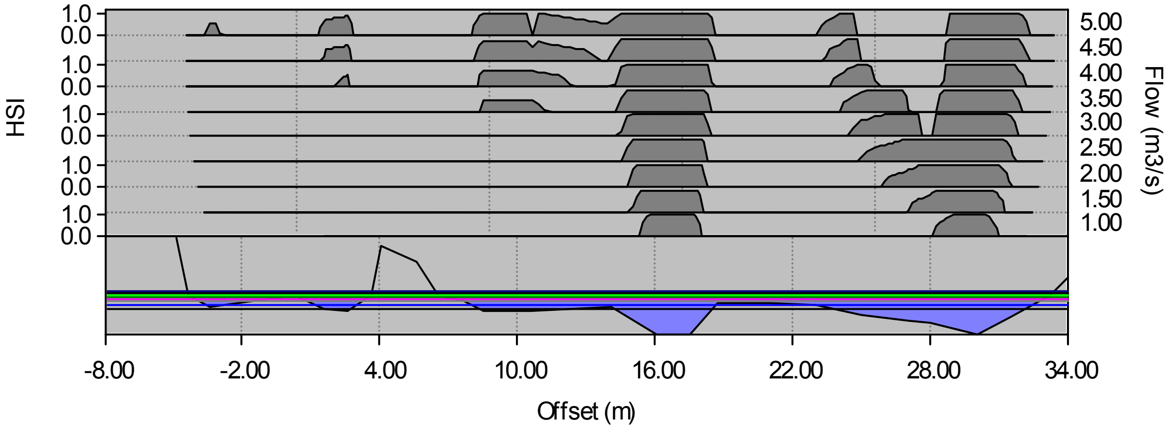
Cross-section 14 XSECT-13: Chinook salmon passage3



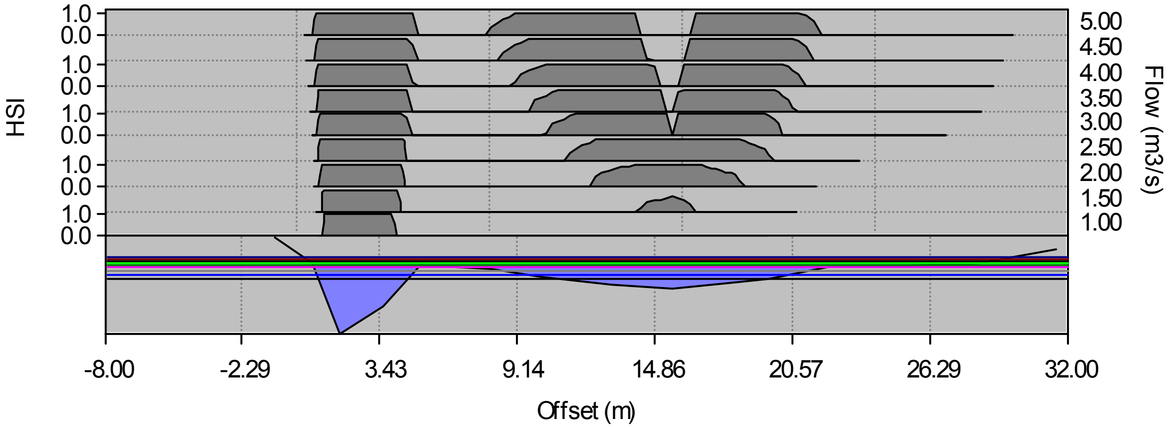
Cross-section 15 XSECT-14: Chinook salmon passage3



Cross-section 16 XSECT-15: Chinook salmon passage3

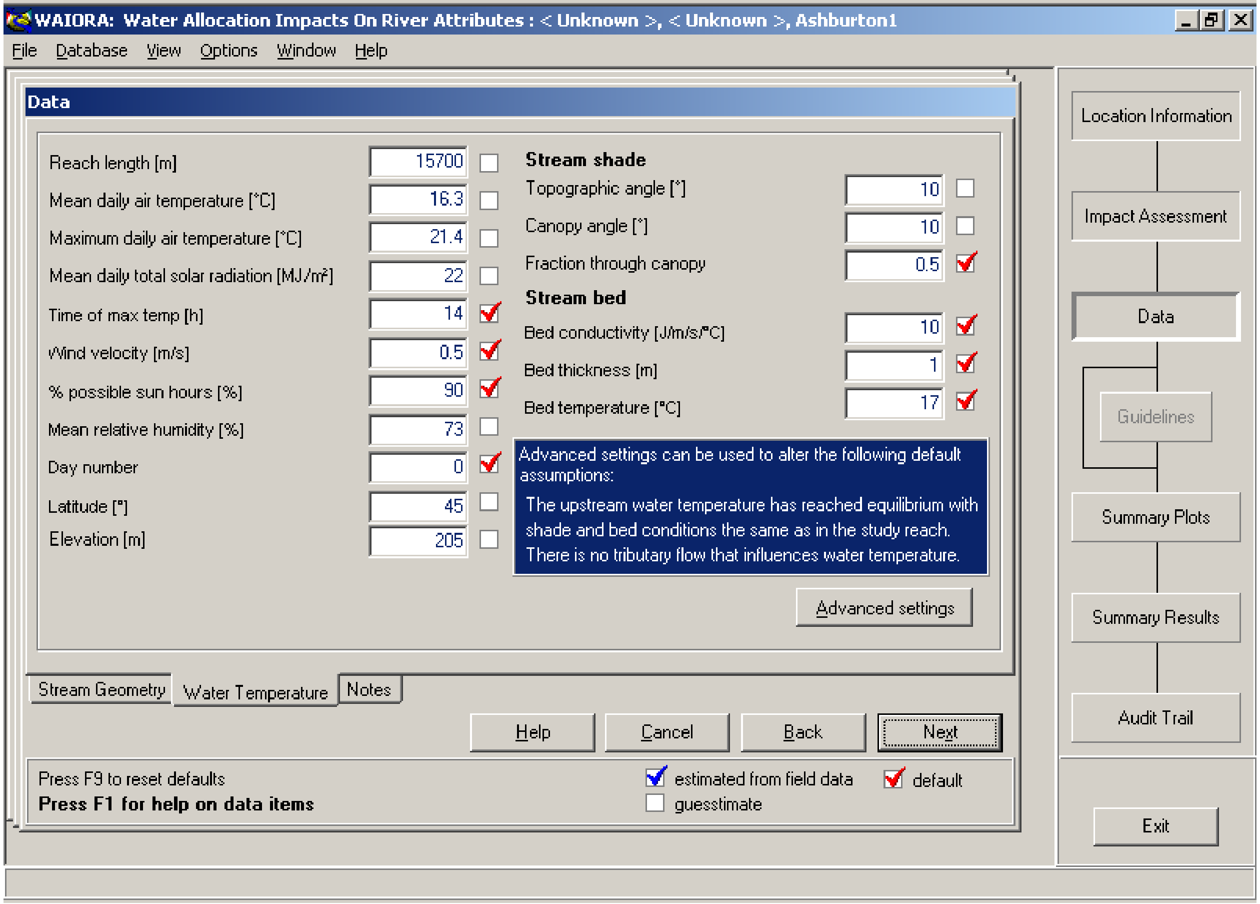


Cross-section 17 XSECT-16: Chinook salmon passage3



Appendix 2. Parameter settings for temperature modelling with Wairoa 2.0.

Ashburton1 (Valetta)



Reach length [m] 15700 ☐
Mean daily air temperature [°C] 16.3 ☐
Maximum daily air temperature [°C] 21.4 ☐
Mean daily total solar radiation [MJ/m²] 22 ☐
Time of max temp [h] 14 ☑
Wind velocity [m/s] 0.5 ☑
% possible sun hours [%] 90 ☑
Mean relative humidity [%] 73 ☐
Day number 0 ☑
Latitude [°] 45 ☐
Elevation [m] 205 ☐

Stream shade
Topographic angle [°] 10 ☐
Canopy angle [°] 10 ☐
Fraction through canopy 0.5 ☑

Stream bed
Bed conductivity [J/m/s/°C] 10 ☑
Bed thickness [m] 1 ☑
Bed temperature [°C] 17 ☑

Advanced settings can be used to alter the following default assumptions:

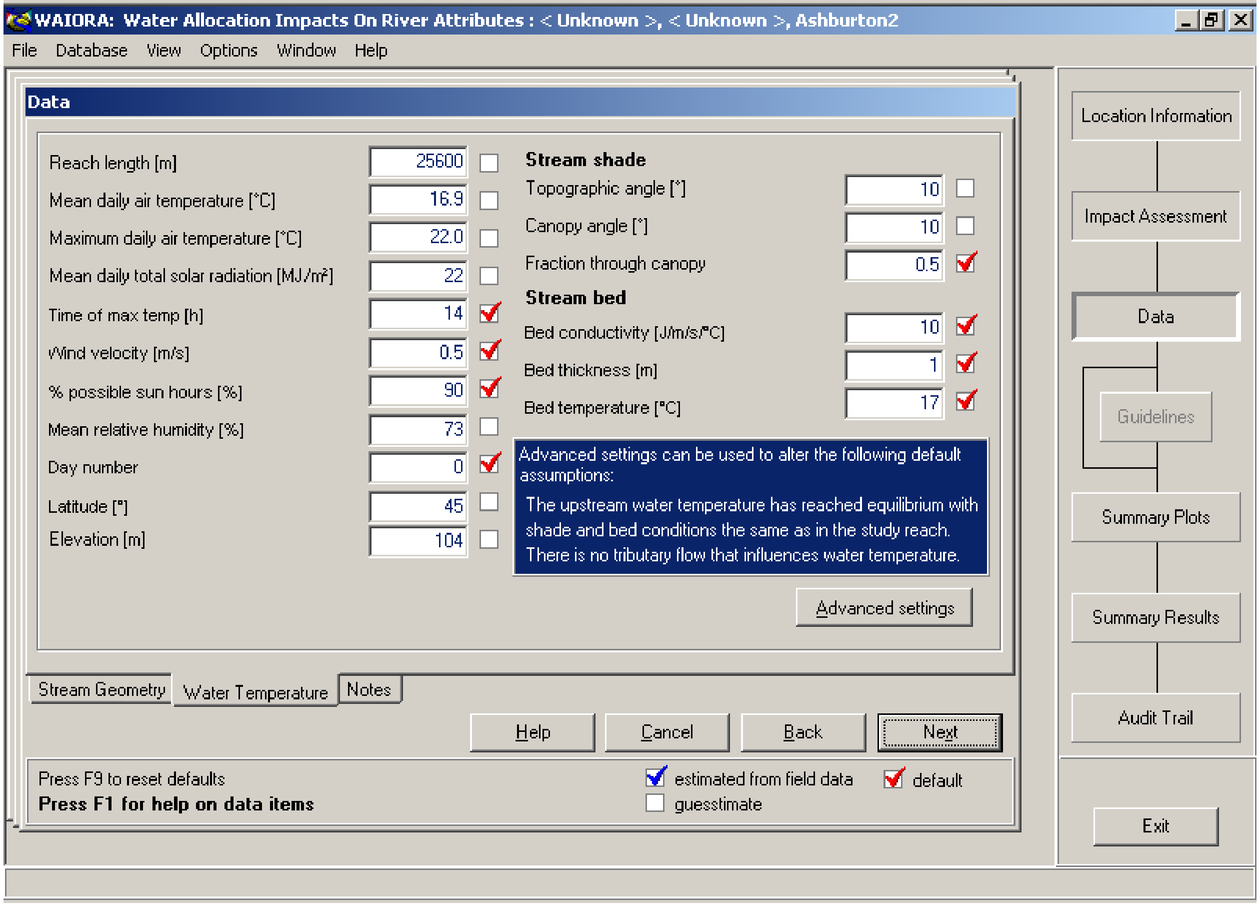
The upstream water temperature has reached equilibrium with shade and bed conditions the same as in the study reach.
There is no tributary flow that influences water temperature.

Press F9 to reset defaults
Press F1 for help on data items

☑ estimated from field data ☑ default
☐ guesstimate

Upstream water temperature - used equilibrium temperature

Ashburton2 (Ollivers)



Data

Reach length [m]	25600	☐
Mean daily air temperature [°C]	16.9	☐
Maximum daily air temperature [°C]	22.0	☐
Mean daily total solar radiation [MJ/m²]	22	☐
Time of max temp [h]	14	☑
Wind velocity [m/s]	0.5	☑
% possible sun hours [%]	90	☑
Mean relative humidity [%]	73	☐
Day number	0	☑
Latitude [°]	45	☐
Elevation [m]	104	☐

Stream shade

Topographic angle [°]	10	☐
Canopy angle [°]	10	☐
Fraction through canopy	0.5	☑

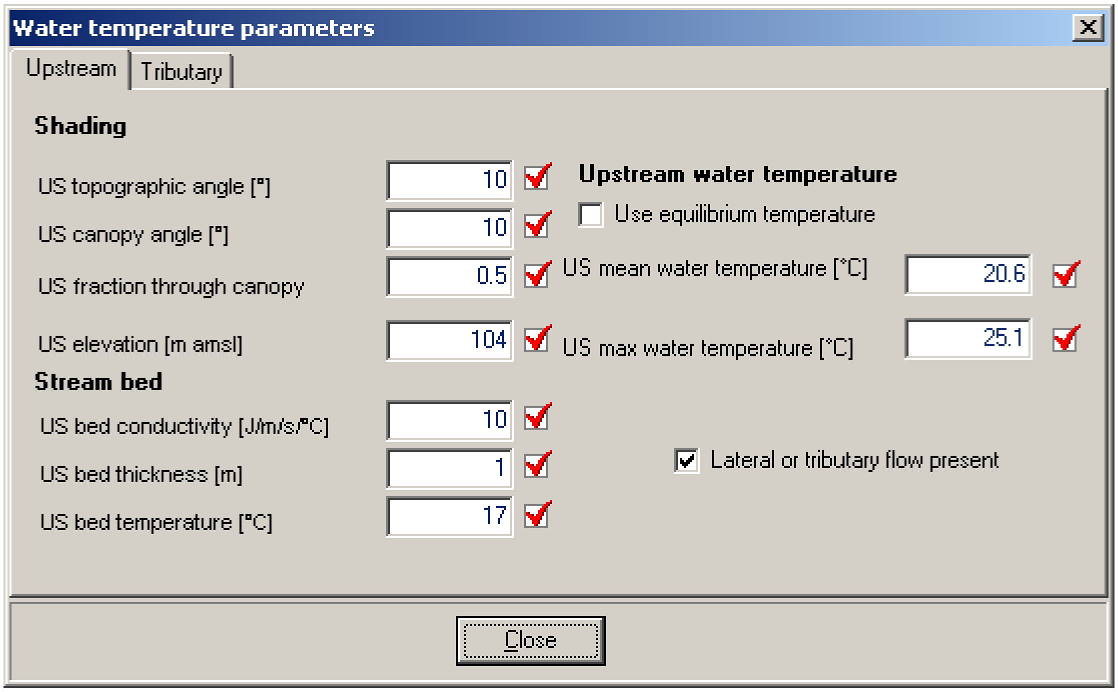
Stream bed

Bed conductivity [J/m/s/°C]	10	☑
Bed thickness [m]	1	☑
Bed temperature [°C]	17	☑

Advanced settings can be used to alter the following default assumptions:
The upstream water temperature has reached equilibrium with shade and bed conditions the same as in the study reach.
There is no tributary flow that influences water temperature.

Press F9 to reset defaults
Press F1 for help on data items

☑ estimated from field data ☑ default
☐ guesstimate



Shading

US topographic angle [°]	10	☑
US canopy angle [°]	10	☑
US fraction through canopy	0.5	☑
US elevation [m amsl]	104	☑

Stream bed

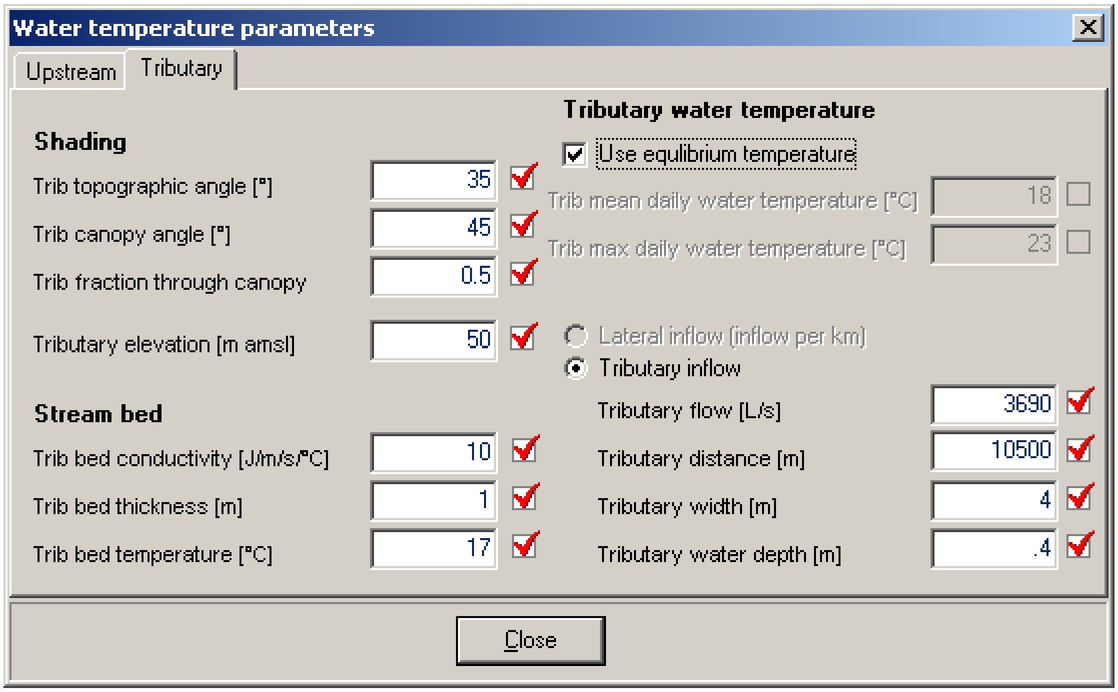
US bed conductivity [J/m/s/°C]	10	☑
US bed thickness [m]	1	☑
US bed temperature [°C]	17	☑

Upstream water temperature

☐ Use equilibrium temperature

US mean water temperature [°C]	20.6	☑
US max water temperature [°C]	25.1	☑

☑ Lateral or tributary flow present



Shading

Trib topographic angle [°] 35 ☑

Trib canopy angle [°] 45 ☑

Trib fraction through canopy 0.5 ☑

Tributary elevation [m amsl] 50 ☑

Stream bed

Trib bed conductivity [J/m/s/°C] 10 ☑

Trib bed thickness [m] 1 ☑

Trib bed temperature [°C] 17 ☑

Tributary water temperature

☑ Use equlibrium temperature

Trib mean daily water temperature [°C] 18 ☐

Trib max daily water temperature [°C] 23 ☐

○ Lateral inflow (inflow per km)

● Tributary inflow

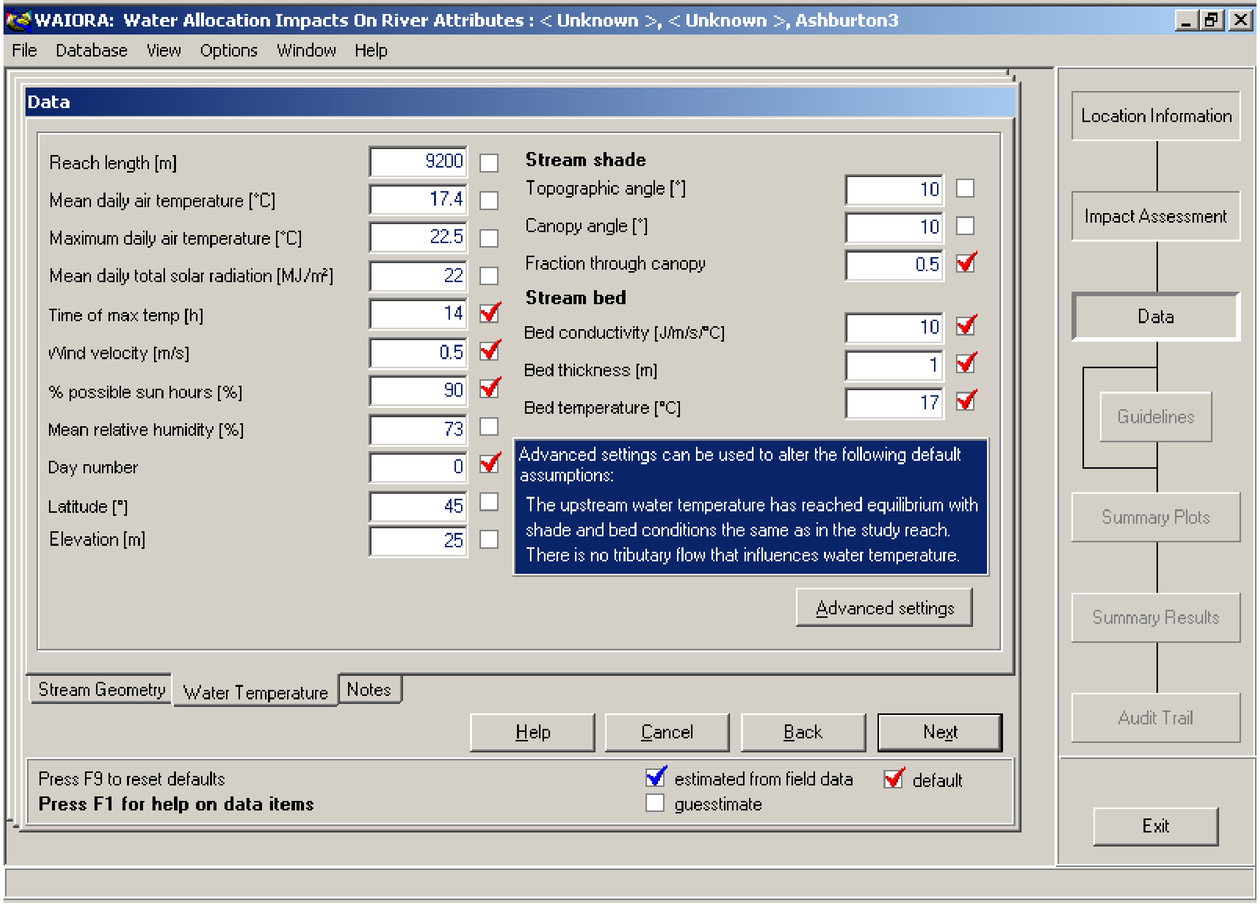
Tributary flow [L/s] 3690 ☑

Tributary distance [m] 10500 ☑

Tributary width [m] 4 ☑

Tributary water depth [m] .4 ☑

Ashburton3 (Wakanui)



Reach length [m] 9200 ☐

Mean daily air temperature [°C] 17.4 ☐

Maximum daily air temperature [°C] 22.5 ☐

Mean daily total solar radiation [MJ/m²] 22 ☐

Time of max temp [h] 14 ☑

Wind velocity [m/s] 0.5 ☑

% possible sun hours [%] 90 ☑

Mean relative humidity [%] 73 ☐

Day number 0 ☑

Latitude [°] 45 ☐

Elevation [m] 25 ☐

Stream shade

Topographic angle [°] 10 ☐

Canopy angle [°] 10 ☐

Fraction through canopy 0.5 ☑

Stream bed

Bed conductivity [J/m/s/°C] 10 ☑

Bed thickness [m] 1 ☑

Bed temperature [°C] 17 ☑

Advanced settings can be used to alter the following default assumptions:

The upstream water temperature has reached equilibrium with shade and bed conditions the same as in the study reach.

There is no tributary flow that influences water temperature.

Press F9 to reset defaults

Press F1 for help on data items

☑ estimated from field data ☑ default

☐ guesstimate

Upstream water temperature - used equilibrium temperature