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CONTENTS

TABLES

FIGURES

SUMMARY

Chinook salmon (*Oncorhynchus tshawytscha*) redd characteristics were measured at three locations in the glacially-sourced mainstem and two locations in small rainfed tributaries of the lower Waitaki River. Mean redd size was 17.5 m^2; lengths of redds ranged from 2.4 to 10 m and their widths ranged from 1.2 to 9.5 m. Water depth (mean 0.37 m, s.d. 0.09) and water velocity (mean 0.68 m, s.d. 0.27) were significantly different between two of the mainstem locations but we assume this was a result of differences in site conditions rather than any distinct preference by salmon. Substrate permeability, water flow rate through the substrate (termed apparent velocity) and oxygen were high in all redds and any "stress" to early fish life stages would likely result from excessive permeabilities (>5500 cm/hr) and apparent velocities (>150 cm/hr) rather than inadequate water circulation in the substrate. While salmon did not use all available spawning habitat at any location, *in situ* redd conditions generally favoured good development and high survival rates.

1. INTRODUCTION

Proposed hydro-electric development of the lower Waitaki River (Graynoth *et al.* 1981; McColl and Natusch 1982) will clearly change riverine characteristics including the alteration of discharge patterns which will affect water depth, velocity and sediment transport properties (Langford 1983). The small particle size (0.019 mm) of silt carried by the Waitaki River could settle more readily, which could pose problems for early development and survival of progeny from anadromous or resident fish spawning in the system. In fact, one-third of the wetted area of the lower Waitaki River where water velocities were low and depths were shallow had surficial silt deposits (Jowett pers. comm.). Einstein (1968) showed that even when water velocities were high enough to preclude surface accumulation, fine sediment settled within clean gravels.

While fishery managers recognise that successful spawning is critical to stock maintenance, physical characteristics of salmonid spawning sites have generally received only limited attention (Crisp and Carling 1989). In New Zealand, chinook salmon redds have been counted on foot or by air (West and Goode 1986, James and Deverall 1987, as examples) to estimate numbers of spawning salmon; however, characteristics of these redds are only partially known from measurements made in stranded redds (Hawke 1978) or from redds made by fish transplanted to a normally inaccessible stream (Dougherty and Little 1971). Conditions within salmon redds have not been examined. To gain insight into the properties of chinook salmon redds and to enhance our ability to predict the success of salmon spawning in a lower Waitaki system modified for hydro-electric power, redds were examined in mainstem areas where glacial silt was present, and in tributaries where it was absent. At the mainstem sites, redd size was determined and water depth and velocity were measured. Flow rate, termed apparent velocity (Carling and Boole 1986) were also measured as was dissolved oxygen and temperature of the water flowing through a subset of redds. These data were compared with similar measurements made in two nearby rainfed tributaries. Finally, survival of embryos in redds was estimated in five redds and compared to published relations between apparent velocity and survival (Wickett 1954; Cooper 1965).

2. STUDY AREA

The Hakataramea and Maerewhenua Rivers are tributaries of the Waitaki River (Fig. 1), the fourth largest river in New Zealand. Hydrological regimes are similar and there are no great differences in topography or geology (Jowett and Richardson 1989). Study sites for the lower Waitaki River were in the "demonstration channels" which were interconnected channels physically similar to braids of the mainstem (Palmer 1990). Each demonstration channel contained a different but stable flow (5, 10, 15 m^3/s) maintained by headworks structures that were constructed in 1981/82 and demolished in 1988.

The five redd study areas (three demonstration channels, two tributaries) differed in flow, channel width, gradient and substrate (Table 1). However, all areas contained habitat in which quinnat salmon spawned successfully (James and Deverall 1987, Palmer 1990).

3. METHODS

Salmon redds are oval areas of disturbed river bed with a depression upstream (pit) and a mound of gravel downstream (tailspill). They were located by foot surveys, and were identified by their difference in colour from the undisturbed riverbed, the shape of the disturbance, the alteration in river bed profile, and, in some cases, the presence of spawning salmon. Redds were marked with stakes and their location plotted on a sketch map. Because some of the wooden stakes were

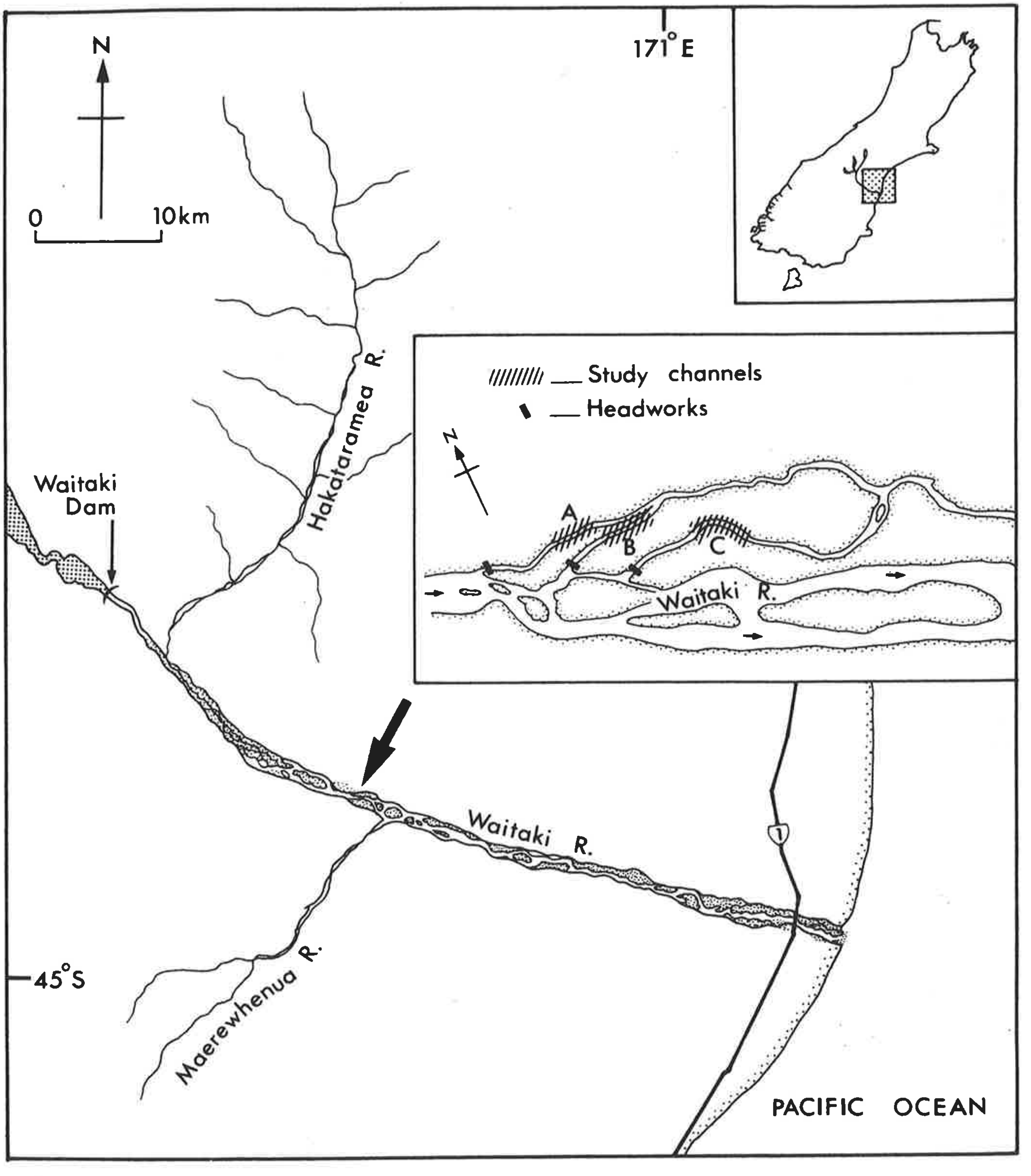

FIGURE 1. Location map.

washed or knocked out in 1982, steel rods were driven upstream in the undisturbed gravel in 1983. Two surveys were made in the 10 m^3/s channel, one on 18-19 May 1982 and the other on 25 June 1982. One survey was made in the 15 m^3/s channel on 15 June 1982, and three surveys were made in the 5 m^3/s channel on 26 and 29 May and 30 June 1982. In 1983, water clarity was poor and redd surveys were made only in the 5 m^3/s channel on 15 May and 8 June.

Water depth, water velocity and redd dimensions (maximum length and width) were measured for 49 redds in the three mainstem channels. An approximate area was calculated by treating individual redds as an

TABLE 1. Flow, channel width, gradient and substrate characteristics for the demonstration channels and the Hakataramea, Maerewhenua and Waitaki Rivers.

		Demonstration channels				
	Waitaki	5 m³/s	10 m³/s	15 m³/s	Hakataramea	Maerewhenua
Flow m³/s Nov 1983 mean	617**	1.2	3.4	10.2	5.9*	2.9*
Mean channel width	370+	16.4	21.3	25.4	14*	15*
% Gradient (m/km)	3.3†	2.9	1.1	1.5	6.5†	6.5†
Substrate						
% Gravel	1†	44	20	59	84†	66†
% Sand	99†	24	65	24	15†	34†
% Cobble	-	32	15	17	-	-

* = data from Jowett and Richardson (1989).
† = data from McColl and Natusch (1982).
** = data from Freestone (1990).
+ = data from Graybill *et al.* (1988).

ellipse and multiple redds (two or more adjoining redds) as rectangles. Water depths and velocities were measured immediately upstream of the disturbed river bed. Velocity was measured using a "Gurley" current meter at 0.6 depth measured from the surface. These measurements of water depth and velocity were presumed to be typical of conditions at the redd site prior to construction by the female salmon.

Permeability, which is directly related to porosity, and water flow rate through the substrate, termed apparent velocity, were determined for 21 redds in the 5 m³/s (9 redds) and 10 m³/s (5) channels and the Hakataramea (6) and Maerewhenua (1) Rivers, towards the end of the egg incubation period in 1982 and 1983. At this time, permeabilities and apparent water velocities were expected to be at or near their lowest because flows were declining. The procedures, equations and assumptions outlined in Terhune (1958) were used with a standpipe built to his specifications. In brief, a groundwater standpipe with perforations near the point was driven about 25 cm into the gravel. When permeability was high (>5000 cm/hr), a minimum value was approximated and apparent velocity was estimated from the maximum rate at which water could be withdrawn from the standpipe. The dye used to determine apparent velocity was a 50:50 mixture of "Greggs" blue (green s) and yellow (tartrazine) food colourings. A specific gravity of 1 g/cm³ was obtained by mixing 71% green food colouring with 29% ethyl alcohol.

Oxygen concentration in five salmon redds in the 5 m³/s channel and Hakataramea River was measured in the standpipe using a Beckman oxygen meter. The meter was first calibrated with a saturated stream of surface water. The probe was then lowered to the bottom of the standpipe and gently agitated until a stable reading was obtained.

Two redds in the Hakataramea River, one in the 10 m³/s channel, and another in the Maerewhenua River, selected for their low (<30 cm/hr) apparent velocities, were excavated using a shovel. Eggs and alevins were collected in a fine-meshed hand net held downstream of the redd. The number of dead and live specimens were counted.

We tested for statistical differences only between redds in the 5 and 10 m³/s channels as insufficient data were available from the other three study sites. Statistical analyses were performed using SYSTAT (Wilkinson 1988).

4. RESULTS

4.1 Redd dimensions, water depth and velocity

In 1982 the 5, 10 and 15 m³/s demonstration channels contained 27, 87 and 8 identifiable redds, respectively. Only ten redds were located in the 5 m³/s channel in 1983. Redds were concentrated in riffle areas but not all riffles contained redds. No redds were found in pools. Redds were constructed across the width of the channel but none were close (<1.5 m) to the bank. Some redds were superimposed on other, presumably older redds. How much this occurred in 1983 was difficult to determine because water clarity was low. The area of disturbed gravel comprising an individual salmon redd ranged, overall, from 3 to 50 m² (Table 2).

The mean size of 49 redds for which all measurements were made in the three demonstration channels was 17.5 m² (s.d. = 10.1).

Redds occurred in water depths ranging from 0.20 to 0.68 m (overall mean = 0.37 m, s.d. = 0.09, Table 2). Analysis of variance indicated that there was a significant difference ($F = 27.6$, $P < 0.05$) between the depths of redds in the 5 and 10 m³/s channels. Depth of redds in the 5 m³/s demonstration channel (mean = 0.38 m) was slightly greater than in the 10 m³/s channel (0.35 m).

Water velocity measured immediately upstream of 45 redds ranged from 0.27 to 1.43 m/s with a mean velocity of 0.68 m/s (s.d. = 0.27). There was a significant difference ($F = 16.9$, $P<0.05$) in the velocities measured at redds in the two demonstration channels. The mean water velocity at salmon redds was greater in the 10 m³/s (0.75 m/s) channel than in the 5 m³/s (0.58 m/s) channel (Table 2).

4.2 Conditions within redd substrates

Permeabilities (Table 3) within redd substrates ranged from 1000 to >6400 cm/hr in the 5 m³/s channel, 1000 to >9000 cm/hr in the 10 m³/s channel, and from 1200 to 8400 cm/hr in the Hakataramea and Maraewhenua Rivers. The preponderance of high, estimated permeabilities precluded statistical tests.

Apparent velocities within redds ranged from 60 to >160 cm/hr in the 5 m³/s channel, 20 to >170 cm/hr in the 10 m³/s channel, and from 12 to >150 cm/hr in the Hakataramea and Maerewhenua Rivers (Table 3). Only four redds had apparent velocities less than 50 cm/hr and most (77%) had apparent velocities greater than 100 cm/hr.

Water removed from the standpipe during redd permeability measurements was noticeably more turbid from redds in the demonstration channels than from redds in the Hakataramea and Maerewhenua Rivers. In the latter two streams, turbidity became negligible after removal of 2-3 L of water from the standpipe whereas in the demonstration channels turbidity persisted as water was removed from the standpipe. While the permeabilities and apparent velocities were similar among the five sites, the amount of silt deposition was clearly different.

TABLE 2. Water depths and velocity measured immediately upstream of chinook salmon redds in three demonstration channels and redd characteristics measured in New Zealand and elsewhere. Means and ranges are in parenthesis.

Location (source)	No. of redds	Depth (m)	Velocity (m/s)	Width (m)	Length (m)	Area (m²)
5 m³/s demonstration channel (1982)	19	0.38 (0.24-0.56)	0.58 (0.27-1.17)	2.9 (1.2-6.9)	5.6 (2.4-10.0)	16.3 (3.0-50.0)
10 m³/s demonstration channel (1982)	26	0.35 (0.20-0.56)	0.75 (0.37-1.43)	4.03 (2.0-9.5)	7.1 (3.6-7.1)	18.7 (7.0-34.5)
15 m³/s demonstration channel (1982)	4	0.56 (0.45-0.68)	0.93 (0.89-0.99)	2.9 (2.5-3.5)	6.7 (5.5-9.0)	13.6 (8.7-23.7)
Mathias River (Hawke 1978)	7	(0.18-0.42)				
Glenariffe (Dougherty and Little 1971)	5	0.34 (0.23-0.38)	0.28 (0.30-0.61)			
Unknown (Field-Dodgson 1985)				2.5	6.3	15.4
Oregon spring chinook (Smith 1973)	142	0.31	0.43			
Oregon fall chinook (Smith 1973)	50	0.39	0.49			

TABLE 3. Permeabilities at 10°C and apparent velocities of quinnat salmon redds in the 5 m^3/s and 10 m^3/s channels, and Hakataramea and Maerewhenua Rivers, 1982 and 1983.

Year	Redd no.	Permeability (cm/hr)	Apparent velocity (cm/hr)
5 m^3/s channel			
1982	8	>6400	>150*
	9	>5400	>150*
	21	>5300	>150*
1983	1	>5800	140
	9	>5060	>160*
	8	>5700	100
	6	1000-2000	60-70
	3	4500	150
	10	3900	150
10 m^3/s channel			
1982	6	>9000	-
	32	1000	20
	33	-	>170*
	36	7800	120
	53	6700	>170*
Hakataramea			
1982	1	1200	12
	2	8400	30
	3	>8000	-
1983	1	4000	100
	2	2400	>150*
	3	1800	>150*
Maerewhenua			
1982	1	3500	25

* = too high to be accurately measured with equipment used.

If substrate permeability and apparent velocities were insufficient for adequate water circulation within redds, one would expect temperature and oxygen in redds to be different from the stream ambient. Dissolved oxygen (Table 4) within redds was similar to ambient in two redds, approximately 1 mg/L lower in two redds and approximately 3 mg/L lower in one redd with a low apparent velocity (<20 cm/hr). Consequently, only about 10% of the total number of redds (Tables 2 and 3) could be expected to exhibit significant (i.e. >3 mg/L) oxygen decreases. Water temperature within redds constructed in the demonstration channels was slightly higher than ambient stream temperature in six of eight redds and slightly lower in the other two (Table 5). All temperature differences were under 1°C. Water temperatures in redds constructed in the Hakataramea River followed a similar pattern as two of four redds had water temperatures similar to ambient. When water temperature differed between the redd and stream, it was also <0.5°C.

TABLE 4. Oxygen concentration of water from stream surface and within five salmon redds in the 5 m^3/s channel and the Hakataramea River and 1983.

Location	Oxygen concentration of stream surface (mg/L)	Oxygen concentration of groundwater (mg.L)	Apparent velocity (cm/hr)
5 m^3/s channel	*	12.0	>150
5 m^3/s channel	12.7	9.2	15-18
Hakataramea River	12.0	11.0	100
Hakataramea River	12.1	11.7	>150
Hakataramea River	11.6	11.5	>150

* = not recorded.

TABLE 5. Comparison of water temperature at stream surface and within redds in the Hakataramea River and the 5 m^3/s and 10 m^3/s channels, 1982 and 1983.

		Temperature (°C)	
Year	Location	stream	groundwater in redds
1982	5 m^3/s channel	6.5	7.0
	5 m^3/s channel	7.0	7.5
	5 m^3/s channel	6.0	7.0
	10 m^3/s channel	7.5	7.0
	10 m^3/s channel	8.0	7.5
	Hakataramea River	8.0	8.0
1983	5 m^3/s channel	7.0	7.5
	5 m^3/s channel	6.1	6.5
	5 m^3/s channel	7.0	6.7
	Hakataramea River	6.5	6.0
	Hakataramea River	7.0	7.0
	Hakataramea River	7.8	8.0

The four redds with apparent velocities not exceeding 30 cm/hr (Table 3) were excavated to determine the viability of embryos and alevins. A redd with an apparent velocity within the substrate of 12 cm/hr in the Hakataramea River contained only 18% live eyed eggs. The remaining three redds contained 75-98% live eyed eggs or alevins.

5. DISCUSSION

Chinook salmon redds in the demonstration channels, the Hakataramea River and the Maerewhenua River, were typical in distinctive shape and similar to those described by Hawke (1978), Field-Dodgson (1985), and summarised by McDowall (1990) for salmon in New Zealand (Table 2). Mean redd size estimated in the three demonstration channels (17.5 m²), was similar to that estimated by Field-Dodgson (1985), 15.4 m², and approximated the 13.6 m² from Hawke's (1978) data. These New Zealand redds generally correspond with Burner's (1951) suggested average of 20 m² and with Chapman *et al.* (1986) who estimated an average of 17 m² per chinook spawning in the Columbia River. Any site differences might result from differences in the size of spawning females as Crisp and Carling (1989) found redd dimensions are correlated with female fish length. Because none of the New Zealand redd measurements were accompanied by data on fish size, and because some site-to-site differences occur, further comparison among rivers and authors is of limited value.

Mean water depths and velocities for the demonstration channels were within the ranges summarised by Graynoth *et al.* (1981), but significant differences existed for water depths and velocity measured for redds in the two demonstration channels that contained the greater number of redds. Because gradients, flows, morphometry and likely velocity differed among the study sites (Table 1), it is reasonable to expect site-to-site differences within a range of conditions suitable for spawning. Chinook salmon were expected to construct redds within a range of stream conditions similar to those summarised by Smith (1973) for Oregon, North America, i.e., depths of >0.18 m and water velocities between 0.21 and 0.76 m/s. In this study redd depths were found to be between 0.18 and 0.68 m but velocities ranged from 0.27 to 1.17 m/s. Recently, however, Swan (1989) found chinook salmon spawning in the mainstem Columbia River (USA) at velocities over 3 m/s and depths up to 11 m. It appears likely, then, that once minimum conditions are found, redd construction by the female will occur over a wide range of conditions.

The frequencies of water depths and velocities at our study sites (Fig. 2) closely resemble probability of use curves for fall chinook salmon reported by Bovee (1978). As a result, Bovee's curves should be useful when calculating "weighted usable area" (WUA) for salmon spawning in New Zealand. Palmer (1990) used these curves to estimate WUA for chinook salmon spawning in the demonstration channels and these values were compared to the 1982 total redd count made in each demonstration channel (Table 6). The number of

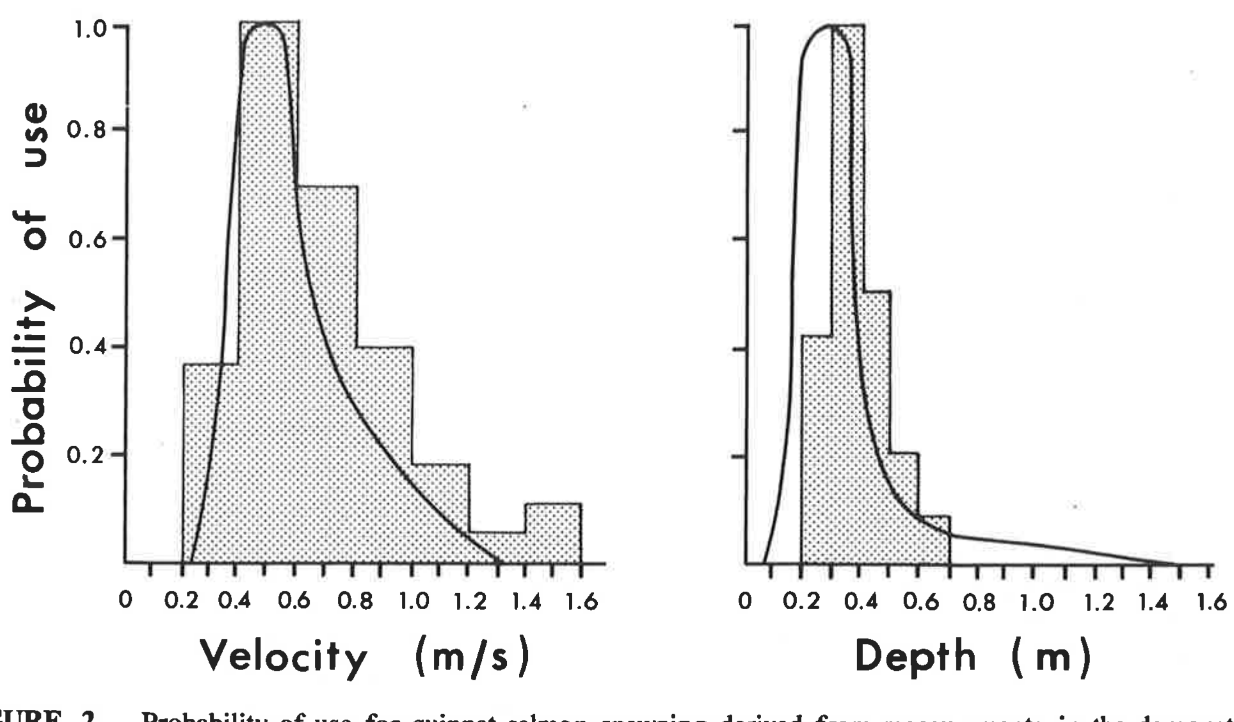

FIGURE 2. Probability of use for quinnat salmon spawning derived from measurements in the demonstration channels (histograms) and from Bovee (1978a) (curves).

TABLE 6. Weighted usable area (WUA) for quinnat salmon spawning, number of redds, and amount of WUA/redd (1982).

Channel	WUA (m^2)	No. of redds	WUA/redd (m^2/redd)
5 m^3/s	3229	27	120
10 m^3/s	6616	87	76
15 m^3/s	976	8	122

salmon redds clearly followed the order predicted by the WUA calculation and in roughly the proportion suggested by comparing WUAs among channels. There was no apparent relation between channel discharge and use (as reflected by number of redds) by spawning salmon.

While riffle areas provided good conditions for successful spawning, redds in some areas were in close proximity while no redds were found in other areas. Closely spaced redds were found in the Hakataramea River and late spawners were observed destroying redds formed earlier. There were also year-to-year differences in redd location, particularly in the 5 m^3/s demonstration channel. These observations indicate either that spawning salmon may not make full use of available space or that factors which we did not measure affected choice of spawning sites.

Apparent velocity, permeability, and oxygen levels in redds at all sites were high and exceeded conditions deemed necessary for "good" survival (Wickett 1954; Cooper 1965). No redd had apparent velocities or oxygen levels below critical limits as described by Wickett (1954) and temperature was not appreciably different from ambient. Shumway *et al.* (1964) showed that reduced oxygen and low apparent velocities in redd substrates probably caused reduced size of emergent coho salmon fry. In this study, few redds had apparent velocities or oxygen levels approaching those measured by Shumway *et al.* and only one redd had low survival. All factors collectively indicate that water movement within redd substrates of the lower Waitaki River demonstration channels and two tributaries were adequate for successful spawning and egg development.

Conversely, the high permeabilities and apparent velocities we measured could adversely affect embryo development. Brannon (1965) showed that at permeabilities >5500 cm/hr, fewer chinook salmon alevins survived to yolk absorption and that survivors were generally smaller than alevins incubated at lower velocities. We found permeabilities as high as 9000 cm/hr and almost half the redds had permeabilities >5500 cm/hr. Consequently, developing embryos may be more likely to be stressed by excessive velocities and scouring in the redd than from siltation, inadequate oxygen levels or altered thermal regimes.

While the viability of eyed eggs was low in one excavated redd with the lowest permeability and apparent velocity, we expect that over 90% of redds should have high egg survival. Although deposited silt was present in water removed from redds, flushing was adequate or silt deposition rates were sufficiently low such that interstitial spaces in the substrate were not occluded to the point of reducing embryo survival. Substrate permeability in the Waitaki watershed was high and is undoubtedly related to the abundance of coarse substrate (Table 1) which provides large interstitial spaces. It is unknown what sediment load, either from hydroelectric dam construction and operation or contribution from tributaries (especially the Hakataramea River) might result in occlusion of these large instertial spaces. Although chinook salmon did not necessarily make the best use of available spawning areas in the demonstration channels and tributaries, conditions in the substrate generally favoured good development rates and high survival of embryos. Conversely, it is possible that high apparent velocities in New Zealand streams might adversely affect early embryo development. If a residual river is created or watershed conditions altered, it would be important to monitor sedimentation rates closely to ensure that high survival rates of embryos are maintained.

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