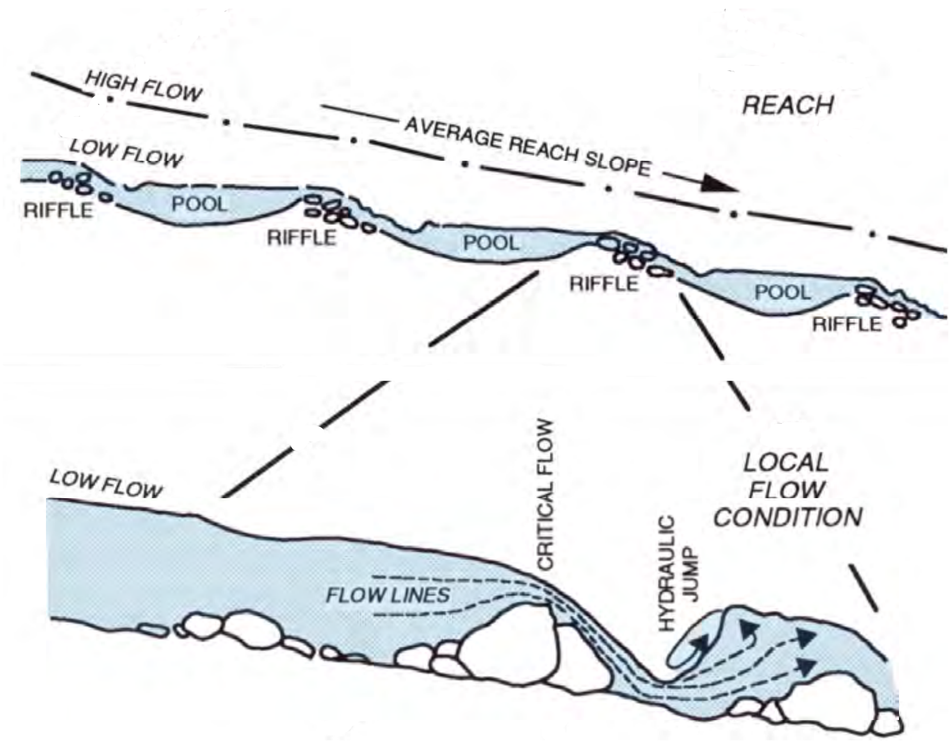
Stream Restoration Hydraulics
Part 2: Applications

A selection of Canadian stream restoration projects and studies based on traditional one-dimensional steady flow hydraulic equations and natural channel reference sites are collected as case studies in this volume. The projects were undertaken between 1976 and 2016 and continue to function, often with new features created by subsequent flood flows and riparian zone recovery.



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web edition Part 2 of 2

Continued from Volume 1/2 Theory

Chapter 5: Projects Restoring Pool and Riffle Channels

Designing channels with gradient controls to slow the flow and reduce erosion is an ancient practice found in early Sumerian and Andean channels. Modern practice uses a variety of vertical control structures, ranging from flax straw weirs to concrete spillways with control gates (USCE 1987). The structures are generally widely spaced to minimize their costs. In meandering and pool and riffle streams the riffles act as regularly spaced minor drop structures. The natural spacing of the riffles varies from 3 to 12 times the channel width with an average of approximately 2π times the channel width (Chang 1988).

Three pool and riffle construction projects were chosen to illustrate the designs for streams at either end of the pool and riffle gradient spectrum with similar design discharges (13 to 17 m^3/s). The average slope of the Mink Creek walleye spawning channel is 0.3%, the slope of the boulder-filled Oulette Creek salmon spawning channel is 3.0% and the slope of the lower Dickson Brook stepped channel for brook trout is 1.1%. Other step-pool projects for specific problems (alluvial fan head-cutting, pipeline crossings and pool creation) are summarized at the end of the chapter.

Design Example 1: Pool and Riffle 0.3% Gradient Stepped Channel for Walleye Spawning and Fry Returns to Downstream Lakes (Mink Creek MB 1985).

1. Background: With the advent of diesel-driven earth moving machinery, many streams in the North American mid-west were straightened and confined to gain the use of rich floodplain lands and improve the efficiency of agricultural drainage. Typical channelized reaches are apparent on a map of escarpment-fed streams as they leave a national park and enter the agricultural zone surrounding Lake Dauphin MB (Figure 5.1).

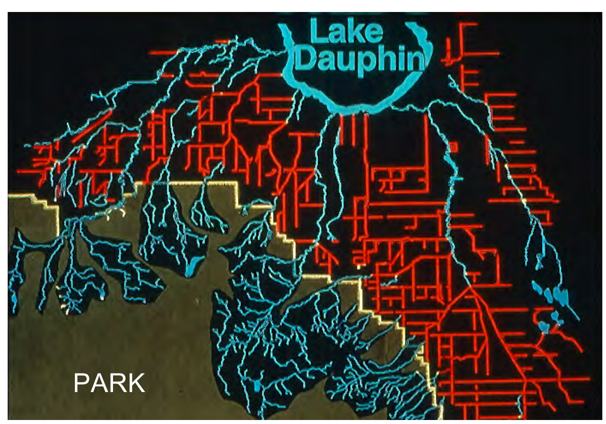


Figure 5.1: Many streams leaving the park are moved and channelized into 99-foot wide public road allowances surrounding farmlands.

The Mink Creek project (1985) was built and monitored with the help of the Manitoba Habitat Heritage Corp. and the Manitoba Fisheries Branch (M. Gaboury, R. Janusz).

For example, the meandering channel of Mink Creek, one of the western tributaries of Lake Dauphin, was straightened and channelized in 1951 (Figure 5.2, plans A and B). Natural walleye spawning riffles and connecting pools were destroyed by the uniform grading (Figure 5.3). The elimination of the pools and riffles stranded walleye fry in the channel in low flow years. They were unable to drift back to their rearing habitat in Lake Dauphin downstream leading to the closure of the commercial walleye fishery.

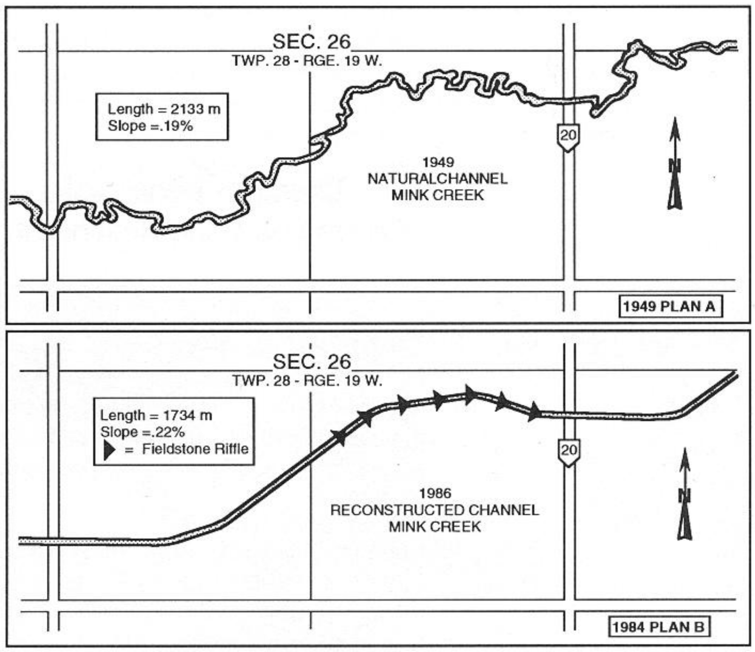


Figure 5.2: The naturally meandering reaches of Mink Creek (Plan A) were straightened and dyked in 1951 to improve the drainage from flat-lying agricultural lands. In 1986 pools and riffles were restored to this section of the channel (Plan B).

Figure 5.3: A channelized reach of Mink Creek in 1984 prior to pool and riffle restoration (see Figure 5.14).

2. Channel Conveyance Calculations: From surveys undertaken before channelization (Figure 5.4, Table 5.1), the pre-channelization bankfull capacity in the restoration reach was estimated to be 17 m^3/s. This corresponds to the median annual flood peak based on nearby gauging records adjusted exponentially for the drainage area tributary to the reach (Figure 5.5). After five decades of down-cutting followed by re-excavation and maintenance, the enlarged bankfull capacity was 76 m^3/s, equivalent to a 1 in 12 year flood. The accumulating spoil materials were used to dyke the edges of the channel right-of-way.

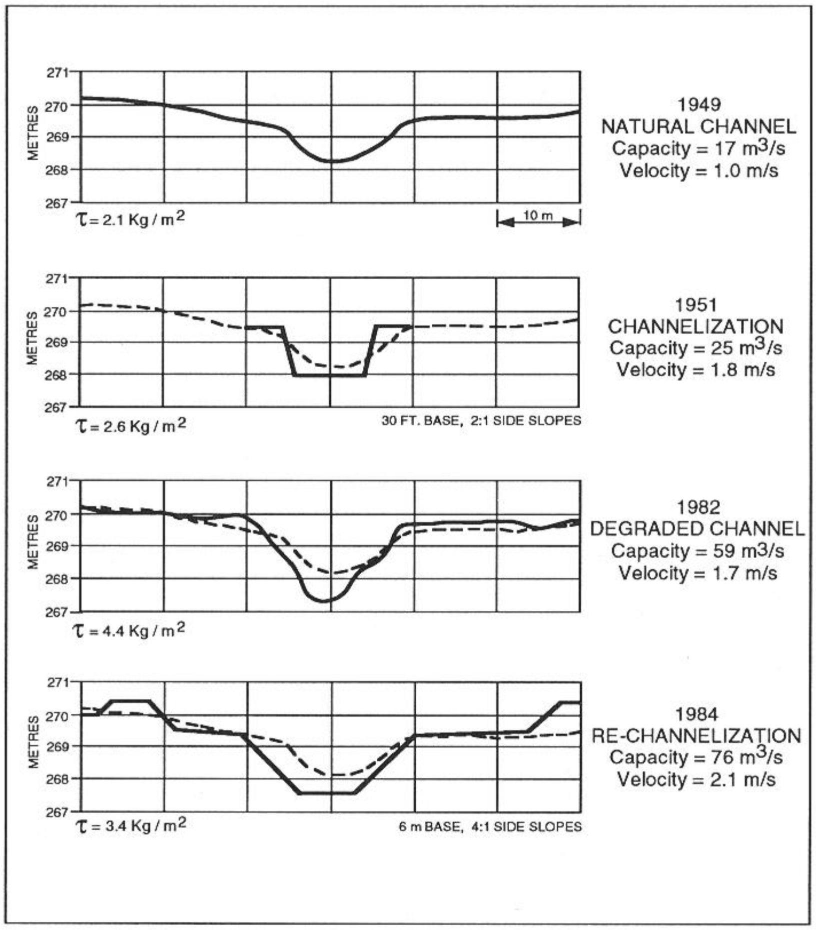


Figure 5.4: The down-cutting and re-grading history in a typical cross-section of channelized streams entering Lake Dauphin MB (Mink Creek MB).

In Mink Creek the tractive force at the bankfull stage increased from 2.0 kg/m^2 to 3.4 kg/m^2 exceeding the movement threshold of the previously stable bed materials. The eroded bed and bank materials formed new deltas in Lake Dauphin reducing shoreline spawning habitats as well (Figure 5.6).

	Natural	Channelized
bankfull width	15.0 m	22.0 m
bankfull depth	1.1 m	1.6 m
average bed slope	.0019	.0022
median bed paving	----	2 cm
bankfull roughness est	.045	.03
bankfull velocity	1.0 m/s	2.1 m/s
bankfull tractive force	2.1 kg/m²	3.4 kg/m²
bankfull Froude number	0.31	0.54
bankfull discharge	17 m³/s	76 m³/s

Table 5.1: Average dimensions and channel capacity in the Mink Creek restoration reach before and after channelization.

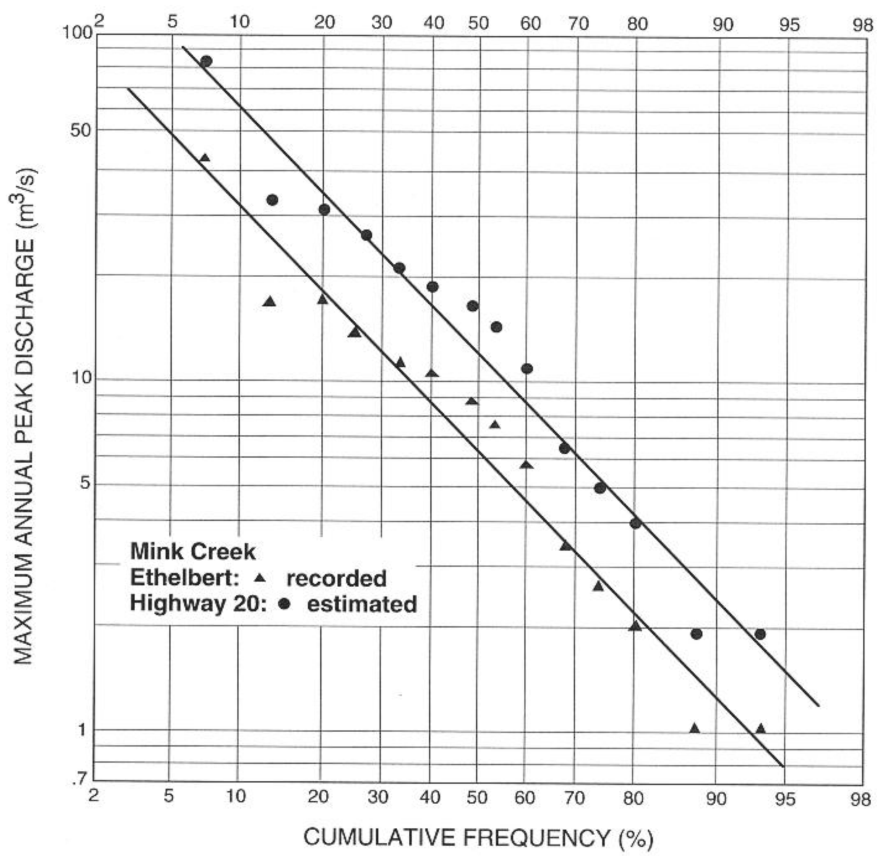


Figure 5.5: The annual flood frequency curve for Mink Creek near the Highway 20 restoration reach based on a nearby Water Survey of Canada station at Ethelbert MB (05LJ019).

Figure 5.6: Eroded bed and bank materials from channelized streams accumulate in new deltas on the Lake Dauphin shoreline (Edwards Creek MB delta accumulation from 1950 to 1962).

A pre-channelization roughness value was determined by surveys in nearby natural streams (Figure 5.7). The pre-channelization bankfull velocity and discharge estimates are
V = $1.1^{2/3}$ ($.0019^{1/2}$)/ .045 = 1.03 m/s and **Q** = 1.03 x 1.1 x 15.0 = 17.0 m^3/s.

Figure 5.7: A Manning's "n" estimate of 0.045 for the pre-channelized Mink Creek reach was based on observations made in Wilson Creek MB in a similar sub-escarpment reach and on Hicks and Mason reference channel 40708 (1991).

3. Design Goals and Constraints: To determine the minimum flows required for successful spawning, the discharges during the spring and early summer hatching periods were compared to the success of the same year-class commercial catch 3 years later in Lake Dauphin. It was found that poor year-class strengths corresponded to drought years in the stream when pools dried out before the fry had drifted back to the lake, for example in the 1980-1982 period (Figure 5.8).

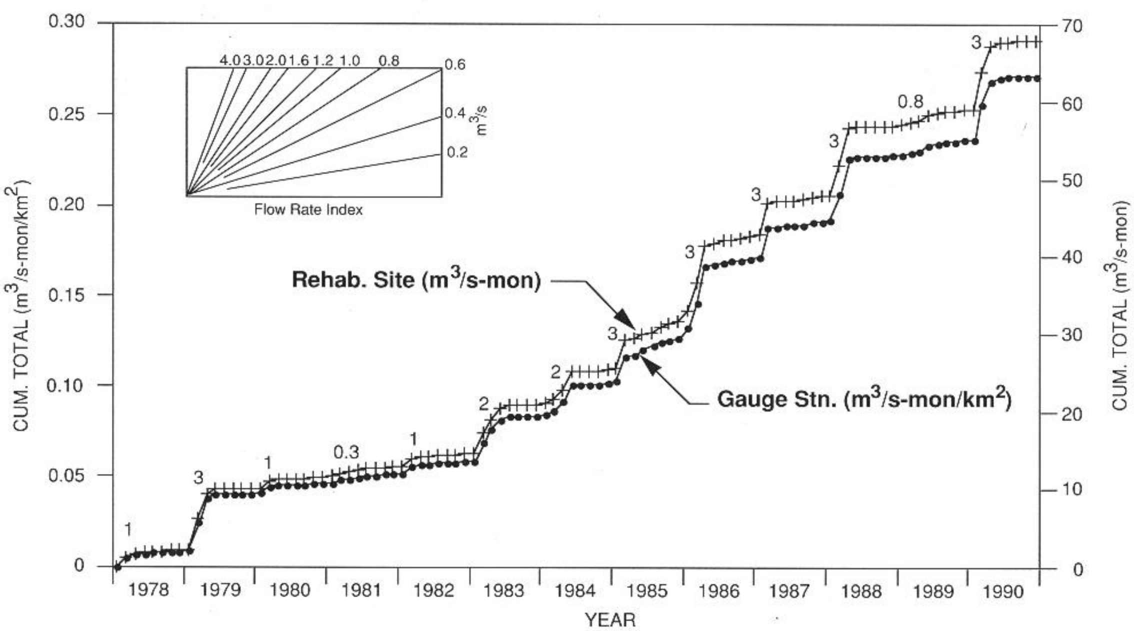


Figure 5.8: A mass curve of monthly flows for the Mink Creek restoration reach. Poor year-class catches in 1983-85 were attributed to low spawning and fry return flows. The dewatered channel prevented walleye fry from returning to the lake in 1980-82.

Natural Riffles: Walleye spawning riffles in similar but unaltered streams were surveyed to determine the dimensions of riffles that could be added to the channelized reaches. The profile of a typical walleye spawning riffle in the Valley River was found to rise 0.3 m above the bed in a steep 2:1 slope (Figure 5.9). The downstream face tapered back to the streambed at a shallow 20:1 slope (Figure 5.10). The pool depth at the downstream toe of the riffle varied from 0.2 to 0.3 m. Mid-summer surveys found the cross-section of the riffle to be slightly v-shaped, allowing a central channel to be maintained between pools under low flow conditions (Figure 5.11).

Figure 5.9: A natural spawning riffle on the Valley River MB during the high-flow Spring spawning period.

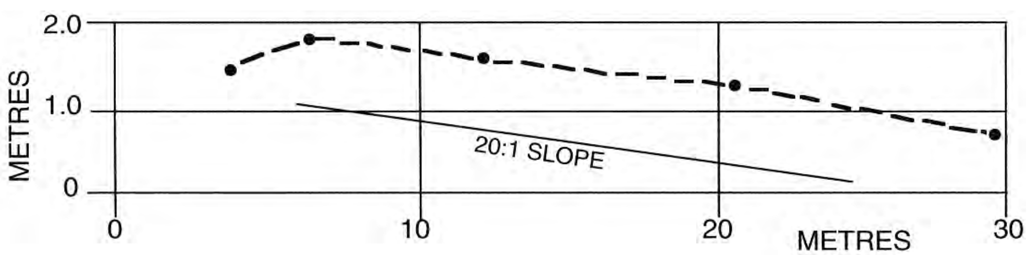


Figure 5.10: The bed profile surveyed on a typical Valley River MB spawning riffle (Figure 5.9). The surveyed riffles were found to be approximately as long as they were wide.

Figure 5.11: Mid-summer surveys found the cross-section of the rocky riffle to be slightly v-shaped, allowing a central channel to be maintained between pools under low flow conditions.

4. Riffle Design and Construction: A bankfull depth of 1.1 m at a median flood discharge of 17 m^3/s was re-established to protect the central channel from excessive shear forces during higher floods. Greater than bankfull floods are conducted in the combined channel and floodplains inside the dykes. No additional setback was required to conduct the 500 year flood. The specific energy curve for the design flow of 17 m^3/s was plotted for the 22 m wide present channel (Table 5.2, Figure 5.12).

Depth m	specific energy m
0.1	3.13
0.2	0.96
0.3	0.64
0.4	0.59
0.5	0.62
0.6	0.68
0.7	0.76
0.8	0.84
0.9	0.94
1.0	1.03
1.1	1.13
1.5	1.51
2.0	2.01

Table 5.2: Mink Creek specific energy at 17 m^3/s.

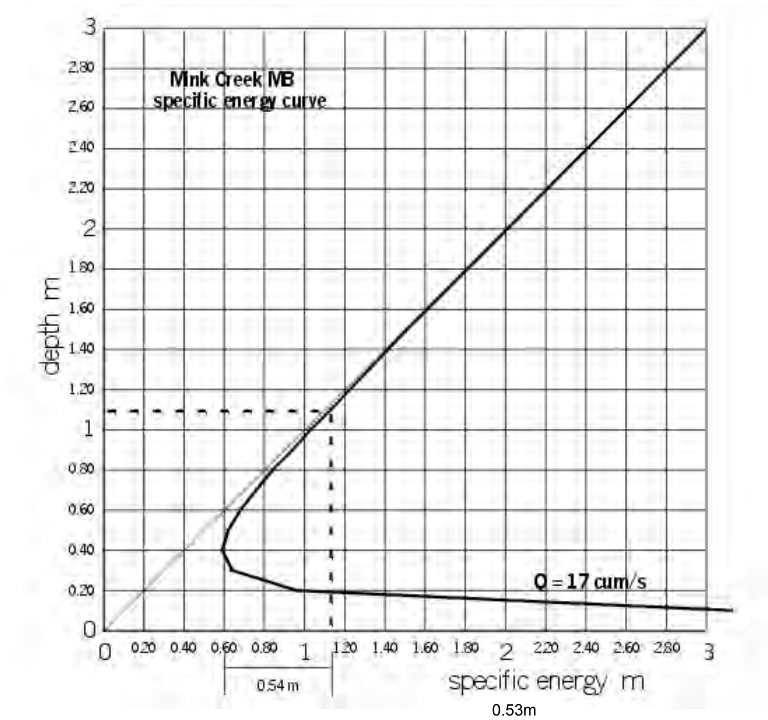


Figure 5.12: Mink Creek specific energy diagram for the design discharge of 17 m^3/s.

The specific energy of the 1.1 m deep bankfull flow is 1.13 m. The specific energy required to pass the design discharge over the riffle crest at critical velocity is 0.60 m. The 0.53 m difference in specific energies is the riffle height that would form a bankfull pool at the design flow (Figure 5.13). The riffle calculations are summarized in Table 5.3.

	RIFFLE HEIGHT		Mink Creek MB
Q	design discharge m^3/s		17
D	depth of flow approaching riffle m		1.1
W	average width of flow m		22
V	approaching velocity m/s	Q / W D	0.7
$V^2/2g$	velocity head of approaching flow m		0.03
H	specific energy of approaching flow m	$D + V^2/2g$	1.13
D_c	critical depth of flow on riffle crest m	$D_c = (Q^2 / gW^2)^{1/3}$	0.40
$v_c^2/2g$	critical velocity head m	$D_c / 2$	0.20
H_c	critical specific energy m	$H_c = D_c + v_c^2/2g$	0.60
R_H	riffle height above channel bed m	$H – H_c$	0.53
	DIMENSIONS		
S_B	channel slope		.003
S_{RU}	slope of upstream riffle face		0.5 (2:1)
S_{RD}	slope of downstream riffle face		0.05 (20:1)
R_U	distance of heel to crest m	$R_U = R_H / (S_{RU} + S_B)$	1.05
R_D	distance of crest to toe m	$R_D = R_H / (S_{RD} – S_B)$	11.27
Y_D	height of bed at the crest above toe m	$Y_D = R_D (S_B)$	0.03
	total drop in chute m	$Y_D + R_H$	0.56
	SPACING		
L	pool length with no back-flooding m	$L = R_H / S_B$	176.5
B_F	height of back-flooding on upstream riffle m		0.27
I_{step}	interval between crests with back-flooding m	$I_{step} = L – (B_F / S_B) + R_D$	97.8
I_{run}	interval between crests with run and pool m	$I_{run} = L + R_D + run$	na

Table 5.3: Summary of Mink Creek riffle and reach calculations.

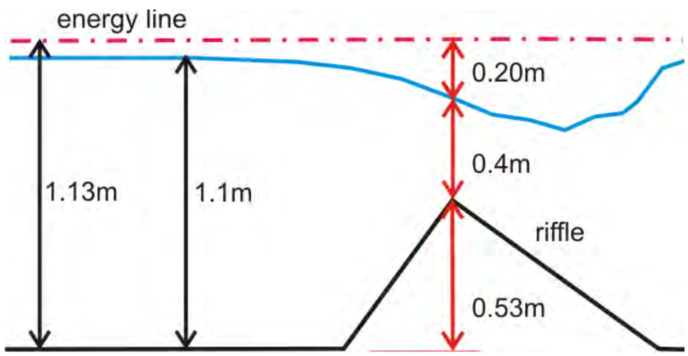


Figure 5.13: Idealized flow conditions predicted by the specific energy curve for a Mink Creek riffle at the bankfull discharge of 17 m^3/s.

The final construction profile for one of the restored segments is shown in Figure 5.14. The v-shaped crest was built to a height of 0.6 m to allow for settlement. Construction in this reach was undertaken in mid-winter 1985 (Figure 5.15).

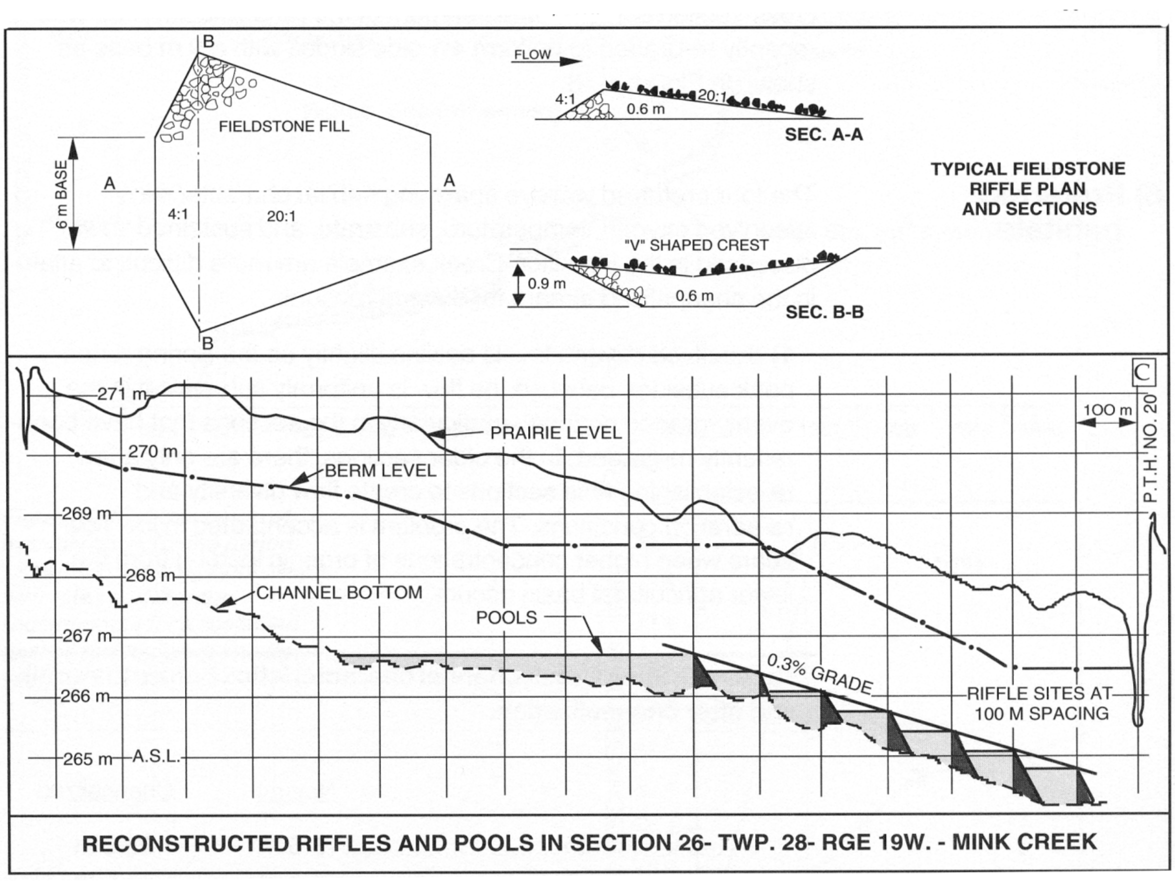


Figure 5.14: Pool and riffle profile design constructed in a typical reach of Mink Creek for walleye spawning and fry survival. The riffles crests were spaced at 100 m on average.

Figure 5.15: The Mink River riffles were built in the winter of 1985 using local fieldstone hauled to the site once the fields were frozen. Elevations were increased by 10 cm to allow for settling in the Spring.

Fish Passage: The velocity on the crest at the design discharge is $V_c = (g\ D_c)^{1/2}$ or $V = (9.8 \times 0.4)^{1/2} = 1.98$ m/s. The burst speed based on the size of adult walleye would allow fish passage (Figure 3.21). At greater than the bankfull stage, the riffles are submerged and opportunities exist for passage over, around and through gaps in the rugged crest.

Riffle Rock Sizing: Minimum stable rock sizes for the riffles were estimated using the maximum tractive force that would occur below the riffle crest at the bankfull stage assuming that the flow could rapidly achieve a slope of 20:1. The predicted cobble size at incipient motion was therefore: $D_{mean} = 1000 \times 0.4 \times .05 = 20$ cm. Larger rock was placed in and on top of the 20 cm materials to form low-flow channels and to provide a margin of safety. At greater than bankfull flows, the slope of the water surface decreases rapidly as the riffles become submerged. The increase in depth is limited in the larger cross-section that now includes the floodplains. No cut-off walls or filters were used in the riffle core but the riffle was sealed by packing the materials in layers with the machine treads and infilling the front slope with shale gravels scraped from the upstream pond. A reach of constructed riffles is shown in Figure 5.16.

Figure 5.16: The Mink Creek pool and riffle reach in 1988, three years after construction (see pre-construction Figure 5.3).

5. Monitoring: The project was re-surveyed and sampled for five seasons following construction. After pools were eroded in the soft shale bed below the riffles in the first year, the riffle and pool profile did not change in spite of a flood peaks with a forty year return period (Figure 5.17).

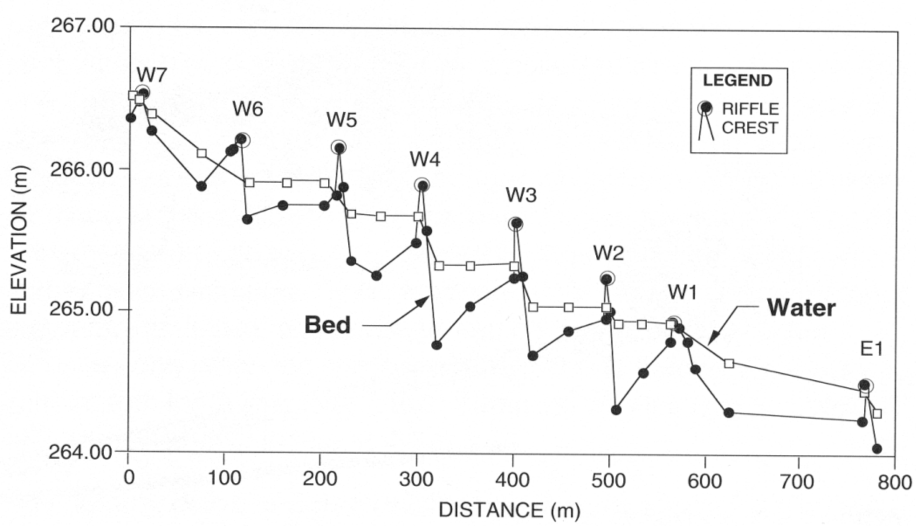


Figure 5.17: The pool and riffle profile of the Mink River restoration reach three years after construction. The initial flood flows formed pools in the soft shale gravel bed.

Walleye egg densities and fry drifting to Lake Dauphin were sampled following each spring spawning period (Figures 5.18 and 5.19). Fry production and drift in the reach was similar to that observed in natural reaches (Newbury and Gaboury 1994). Other species, suckers and pike in particular, were observed spawning on the riffles and on the rapidly re-generating reeds growing in the new pools (Figure 5.20)

Figure 5.18: Walleye eggs deposited in the built riffles are being sucked from between the rocks with a diaphragm pump after the spring spawning period. The eggs are filtered and examined to determine their survival (M. Gaboury, L. and R. Janusz).

Figure 5.19: Drift traps in the pools were used to sample fry movement back to Lake Dauphin (L. Janusz).

Surveys undertaken nine and fifteen years after construction found no riffle failures. The small deep pools and continuous low flow water connections have been naturally maintained. Riparian grasses and reeds all but obscured the riffles. Figure 5.20 was taken nine years and Figure 5.21 twenty eight years after construction in the reach.

Figure 5.20 (1994): Pools and constructed riffles in Mink Creek nine years after construction (D. Roseboom).

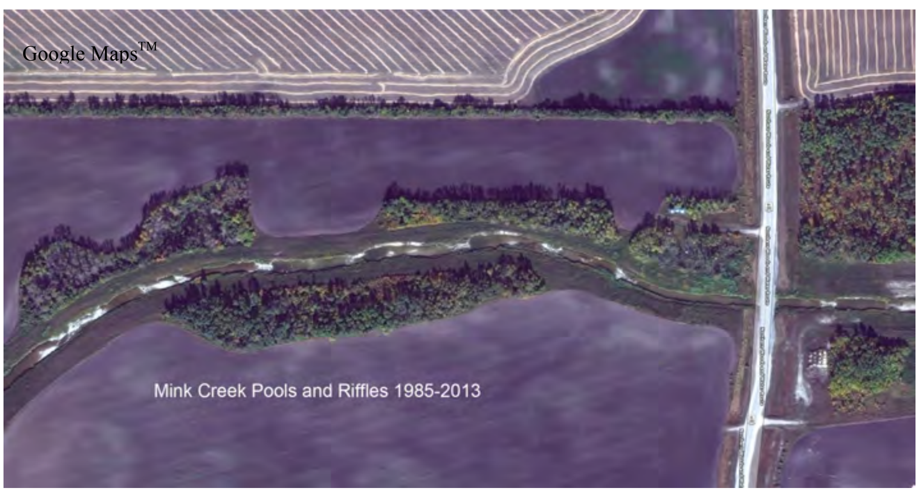


Figure 5.21 (2013): The pool and riffle profile was maintained and shifted a few metres downstream in twenty eight years (Google Earth Image 2013).

In the ensuing years (1986-2001), similar pool and riffle reaches were added to over 20 km of channelized streams tributary to Lake Dauphin. The walleye fishery has been re-established (pers. com. Martin Erickson, Manitoba Fisheries Branch). Similar monitoring has been undertaken in many locations since 1985 (White et al. 2010, Waukegan River video,).

Design Example 2: Pool and Riffle 3% Gradient Channel for Pacific Salmon Spawning and Over-wintering Habitats (Oulette Creek BC 1998).

1. Background: The meandering channel of Oulette Creek was straightened and diverted in 1978 to create a large dry-land log sorting yard in Howe Sound BC on the alluvial fan of the stream. The new 600 m long trapezoidal diversion channel was stepped with alternating single log and single row boulder drop structures every 30.5 m (Figure 5.22). The additional shear stress in the shortened channel rapidly eroded the fan materials. The bed elevation stabilized with boulder lag deposits 1.1 m below the constructed grade in two seasons, collapsing or under-cutting the drop structures (Figure 5.23). Coho salmon spawning riffles and rearing pools were destroyed. Pink and chum spawning platforms in the lower reaches were in-filled with large cobbles transported by the steeper channel (Figure 5.24).

Figure 5.22: The new Oulette Creek diversion channel immediately after construction in 1978.

The Oulette Creek project was funded, built and monitored with the help of Rob Lidden (Terminal Forest Products Ltd.), Grant McBain and Jim Wilson (Fisheries and Oceans Canada) and Dave Bates (FSCI Consultants).The methods were worked out with assistance and immense tolerance from Ken Sneddon on Sechelt Creek Contracting sites.

In 1979 a small hatchery was built at the site as habitat loss compensation but fish returns to the cobble-bed stream were insignificant.

Figure 5.23: The Oulette diversion channel in 1982, four years after construction. Single "digger" log and rock drop structures contributed to the rapid down-cutting.

Figure 5.24: The uniform boulder and cobble channel of Oulette Creek in 1993 fifteen years after construction prior to the addition of pools and riffles.

In 1998, rock riffles were constructed at each of the former drop structure locations in the now hardened channel (Figure 5.25). The riffles were designed to form a stepped channel that would restore access to the floodplains at the median annual flood discharge of 17 m^3/s. This option reduced the shear stress in the channel as greater than median flood flows could now access the floodplain. Cobbles and spawning size gravels accumulated in the lower ends of the new pools.

Figure 5.25: A large boulder riffle under construction in the Oulette Creek diversion channel in 1994 (P. Husband, G. McBain).

2. Channel Conveyance Calculations: Surveys undertaken in 1994 in the reach immediately above the diversion indicated that the pre-project channel average width and trim-line depth were 7 m and 0.7 m (Table 5.4). The diverted reach had stabilized at a width of 9 m with an average depth of 1.8 m after down-cutting ceased. There was no evidence of flood flows reaching the level of the elevated floodplain in the diverted reach.

drainage area		5.6 km²
mean annual rainfall		2590 mm
reach gradient		3 %
bankfull discharge		17 m³/s
bankfull width	natural	7 m
	diverted reach	9 m
bankfull depth	natural	0.7 m
	diverted reach	1.8 m
minimum flow		0.05 m³/s

Table 5.4: Oulette Creek BC survey summary. The natural channel measurements were made in the natural reach immediately upstream from the diversion.

The natural bankfull velocity and discharge calculated using a Manning's coefficient of 0.04 are:

$$\mathbf{V} = (0.7)^{2/3}\,(0.03)^{1/2} / 0.04 = 3.4 \text{ m/s}$$

$$\mathbf{Q} = 7 \times 0.7 \times 3.4 = 17 \text{ m}^3/\text{s}$$

The bankfull discharge estimate is approximately equal to the median annual flood peak based on a nearby gauging station frequency curve adjusted exponentially for the difference in drainage areas (Figure 5.26). The roughness characteristics were estimated from the reference channel shown in Figure 5.27.

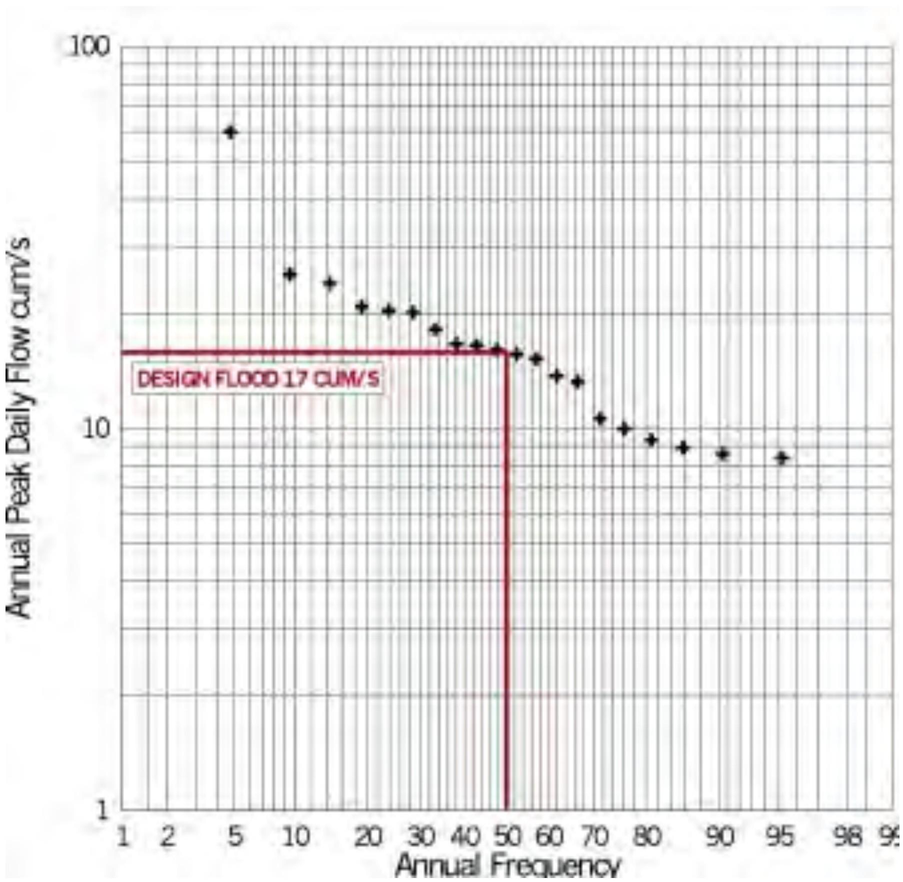


Figure 5.26: The annual flood frequency curve for Oulette Creek BC based the nearby WSC gauging station (Rainy River 08GA020). The depth of the median annual flood corresponds to the vegetation trim line elevation in the natural channel upstream.

Figure 5.27: Surveys in Chapman Creek BC at the trim-line flood stage were used to predict a Manning's "n" estimate of 0.04 for the natural channel of Oulette Creek (similar to Hicks and Mason reference channel number 9065 (1991)).

3. Design Goals and Constraints: The loss of spawning and overwintering areas due to floodplain developments occurs on the alluvial fans of many Strait of Georgia streams. Oulette Creek was one of the first rebuilt restoration projects. The habitat goals for the channelized streams identified by Canada Department of Fisheries and Oceans fisheries biologists were:

1. Coho spawning riffles must have sufficient head loss to allow water movement through the gravels deposited at the end of the pool approaching the riffle crest,

2. pools greater than 1 m deep must be maintained during low-flow periods for over-wintering Coho fry,

3. back eddies with large wood and boulder covers in pools are required for safe fry habitat, and

4. shallow spawning platforms with smaller gravel sizes are required for Chum and Pink salmon in the readily accessible lower reaches.

To re-establish access to the floodplain, riffle crests were designed to raise pool elevations to the original 1978 floodplain level at the median annual flood of 17 m^3/s (Figure 5.28).

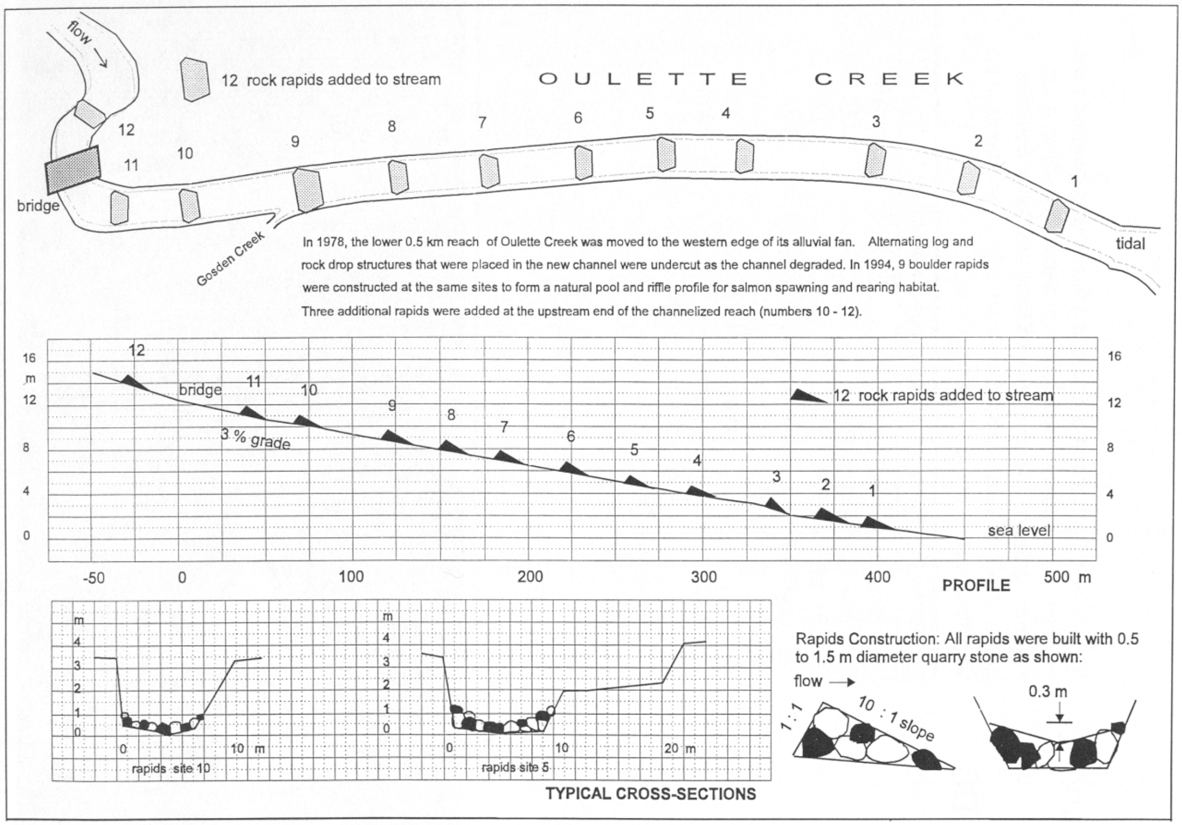


Figure 5.28: Pool and riffle plan constructed in the diverted reach of Oulette Creek BC.

In 1997 the upper riffle crests were re-constructed to deepen and narrow the flow so that a central torrent was formed to scour 1.0 to 1.5 m deep section in the upper pool for Coho fry (Figure 5.29). The broad crest of the lower two riffles was not modified to maintain shallow spawning areas above and below the riffles for Chum and Pink salmon (Figure 5.30).

By the year 2000, large cobbles and boulders in the bed load from the steep upstream reach above the fan (10% gradient) began to fill the upper pool in the restored reach. This upper fan deposition would normally cause an avulsion of the stream into a new channel. However as this channel must remain confined between the diversion dykes the deposition is removed from the upper pool when it is filled. This has occurred once in the first 15 years of the project.

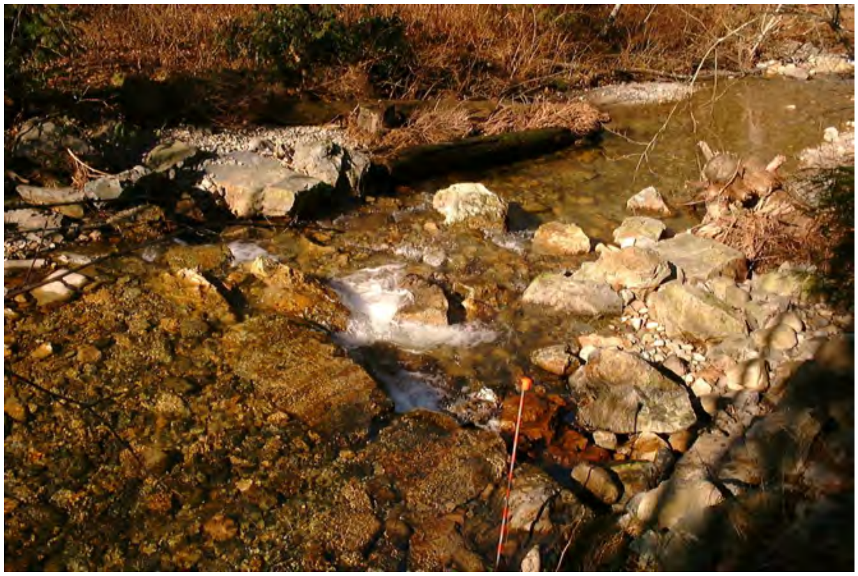


Figure 5.29: The upper Oulette Creek riffles were deepened and narrowed to concentrate the flow and scour a deep central pool that is used by Coho and Steelhead fry as over-wintering habitat.

Figure 5.30: The lower Oulette Creek riffles with level crests have formed spawning platforms used by Pink and Chum salmon in the shallow upstream pool. The shallow exit flows do not form a scour hole below the riffle. Spawning Chum salmon are near the riffle crest and in the upper left portion of the photograph.

4. Riffle Design

Flood Capacity and Height: Calculation of the allowable riffle height was determined by setting the median flood elevation in the pool immediately above the riffle equal to the floodplain elevation. In effect it is an artificially forced "bankfull flow" approaching the riffle in the 1.8 m deep channel. The velocity of the approaching flow is Q / (w x d) = 17 / (9 x 1.8) = 1.05 m/s. The specific energy is $1.8 + (1.05)^2 / 2\,(9.81) = 1.86$ m. As the flow accelerates over the 9 m wide riffle crest, the critical depth of flow is

$$D_{c9} = (Q^2 / gW^2)^{1/3} = ((17^2) / 9.81(9)^2)^{1/3} = 0.72 \text{ m}$$

The specific energy of the critical flow is 1.5 x 0.72 = 1.08m. Disregarding small contraction losses, the target height of the 9 m wide riffle is equal to the difference in the specific energy of the pool and riffle crest or 1.86 – 1.08 = 0.78 m. This forces the median flood to just reach the floodplain level as shown in Figure 5.31 taken during a 17 m^3/s design flood event.

Figure 5.31: Oulette Creek flowing at 17 m^3/s over a 9 m wide riffle. The upstream pool just approaches the floodplain level.

When the upper riffles were narrowed to 6 m to form a central torrent, the critical depth on the riffle crest increased to 0.94 m where

$$D_{c6} = (Q^2 / gW^2)^{1/3} = ((17^2) / 9.81(6)^2)^{1/3} = 0.94 \text{ m}$$

The specific energy of the narrowed flow is 1.5 x Dc =1.41 m. The allowable height of the central crest was therefore 1.86 – 1.41 = 0.45 m, assuming again that the maximum depth in the 9 m wide channel approaching the crest just meets the bankfull depth. The critical velocity in the central torrent = $(9.81 \times 0.94)^{1/2}$ = 3.04 m/s. Graphical solutions for both riffle types are plotted in the specific energy diagram shown in Figure 5.32.

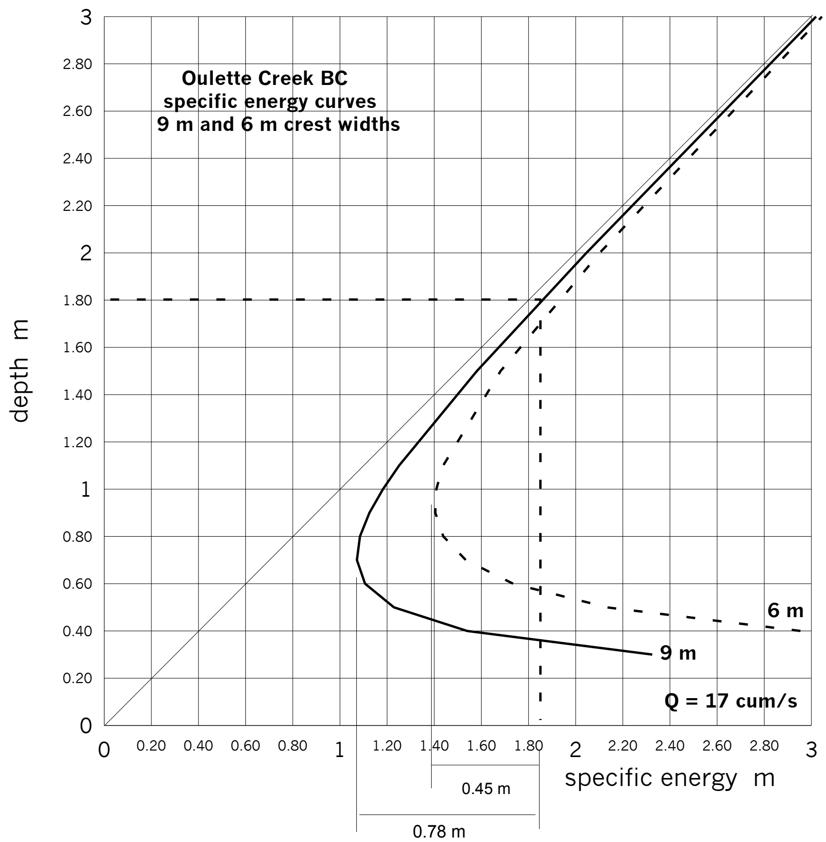


Figure 5.32: Specific energy curves for the Oulette Creek channelized reach (9m width, solid line and 6m wide, dashed line). The corresponding riffle heights are 0.78 and 0.46 m resp.

The Reynolds number of the central torrent at the design discharge is V D / ν or 3.0 x 0.94 / 1.3 x 10^{-6} = 2.17 x 10^6 (10°C water). Torrents with similar Reynolds numbers entering pools have been observed to cause fully-developed back eddy circulation and local gravel deposits (Figure 3.11).

Geometry and Spacing: The geometry calculations and dimensions of the Oulette pools and 9 m wide riffles designed with a 0.2 m backflood on the toe are summarized in Table 5.5

	RIFFLE HEIGHT		Oulette Creek BC
Q	design discharge m^3/s		17
D	depth of flow approaching riffle m		1.8
W	average width of flow m		9
V	approaching velocity m/s	$Q / W D$	1.05
$V^2/2g$	velocity head of approaching flow m		0.06
H	specific energy of approaching flow m	$D + V^2/2g$	1.86
D_c	critical depth of flow on riffle crest m	$D_c = (Q^2 / gW^2)^{1/3}$	0.72
$v_c^2/2g$	critical velocity head m	$D_c / 2$	0.36
H_c	critical specific energy m	$H_c = D_c + v_c^2/2g$	1.08
R_H	riffle height above channel bed m	$H - H_c$	0.78
	DIMENSIONS		
S_B	channel slope		.03
S_{RU}	slope of upstream riffle face		0.5 (2:1)
S_{RD}	slope of downstream riffle face		0.1 (10:1)
R_U	distance of heel to crest m	$R_U = R_H / (S_{RU} + S_B)$	1.47
R_D	distance of crest to toe m	$R_D = R_H / (S_{RD} - S_B)$	11.14
Y_D	height of bed at the crest above toe m	$Y_D = R_D (S_B)$	0.33
	total drop in chute m	$Y_D + R_H$	1.11
	SPACING		
L	pool length with no back-flooding m	$L = R_H / S_B$	26
B_F	height of back-flooding on upstream riffle m		0.20
I_{step}	interval between crests with back-flooding m	$I_{step} = L - (B_F / S_B) + R_D$	30.5
I_{run}	interval between crests with run and pool m	$I_{run} = L + R_D + run$	na

Table 5.5: Summary of Oulette Creek riffle and reach geometry calculations

c: construction: Cobble and boulder sizes for the riffle crest and downstream face were based on the conservative assumption that the critical flow would follow the upper segment of the riffle slope at the bankfull stage. The maximum depth (0.94 m) and velocity (3 m/s) occur in the narrowed riffle. The sloping face of the riffle was set at 1:10, producing a tractive force of 1000 x .94 x 0.1 = 94 kg/m^2 equivalent to a 0.94 m diameter riprap size. Consequently large boulders up to 1m in diameter were embedded in the upper parts of the riffle to create and stabilize the 0.78 m high crest (Figure 5.33).

Forces exerted on the boulders placed on the riffle crest to narrow the flow (Figures 5.29 and 5.33) were estimated using the momentum equation. The cross-sectional area A of the bankfull flow blocked by 1.0 m wide boulders placed on the riffle crest is (π x 0.5^2) = 0.79 m^2. The force exerted by the flow is 100 x A x ΔV^2 or 100 x 0.79 x $(1.05)^2$ = 87 kg. Since a 1 m diameter submerged boulder weighs approximately 875 kg, the coefficient of sliding friction would have to be exceedingly low before it would slide over the riffle. This is unlikely if the boulders are embedded and nested together on the crest. No movement has been observed in the first 15 years following construction.

Figure 5.33: Scoured pools caused by large boulders placed on the riffle crests to narrow the flow in the Coho spawning and rearing reach of Oulette Creek. The photo was taken 10 years after construction.

5. Monitoring: Annual biophysical and topographic surveys are undertaken in the re-constructed reach of Oulette Creek. The surveys have shown that approximately equal areas of pool and riffle habitats have been maintained by the narrowed riffles (Figure 5.34). The biomass of fish in the upper Coho and Cutthroat trout reaches increased dramatically following restoration (Figure 5.35). Spawning Pink and Chum salmon have been observed every year in the pools above the lower two riffles.

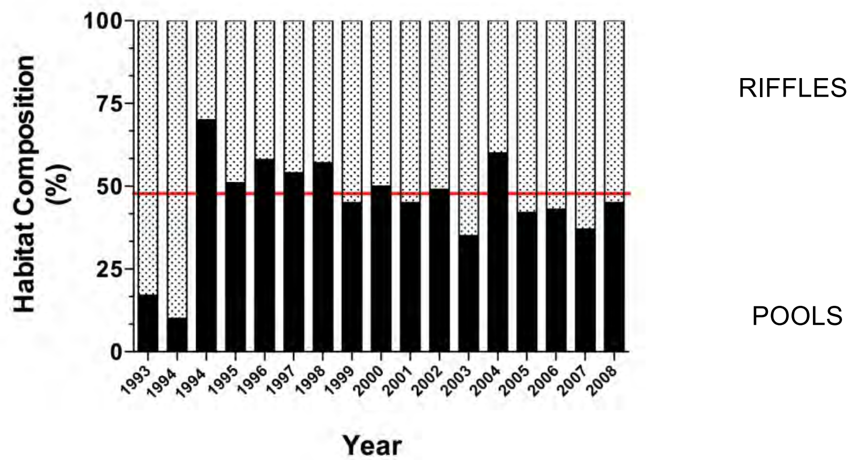


Figure 5.34: The distribution of riffles and pools in the Oulette Creek diversion channel before and after the addition of riffles in 1994 (Bates, FSCI Consulting, pers. com 2010).

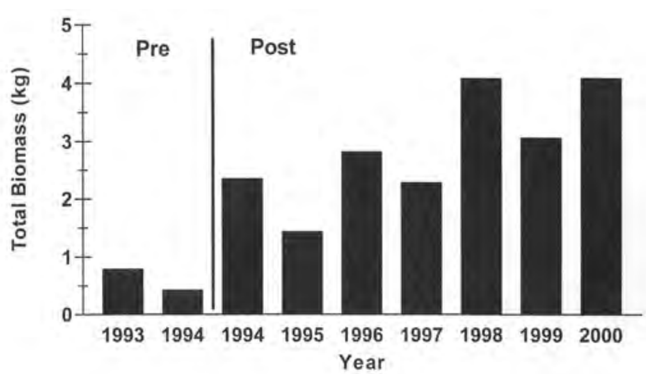


Figure 5.35: The response of fish biomass to the creation of a pool and riffle profile in Oulette Creek (Bates, FSCI Consulting, pers. com 2010).

Design Example 3: Pool and Riffle 1.1% Gradient Channel for Brook Trout and Atlantic Salmon (Dickson Brook, Fundy National Park NB 2004-2009).

1. Background: Dickson Brook, a tributary to the Bay of Fundy near Alma NB in Fundy National Park has been channelized for farming and recreation for over 100 years. The lower end of the watershed was first cleared for agriculture in the 1800's. It was then re-worked when the Park was established in a golf course designed by Stanley Thompson in 1950. The 1 km long lower channel had been sequentially lined with wooden planks (Figure 5.36), laid rock walls and finally gabion mats and baskets (Figure 5.37). By 2002 most of the stabilization works had failed (Figures 5.38 and 5.39). Fish habitat in the golf course reach was limited to shallow runs in the uniform ditch. Deposition of eroded bed and bank materials had blocked the estuary preventing sea run trout and salmon access to and from the Bay of Fundy.

Figure 5.36: Dickson Brook was re-aligned as a water hazard in plank-lined channels in the initial Fundy National Park golf course layout (photo mid 1950's).

Figure 5.37: Rock wall, gabion and wire mesh lined channels replaced the failing plank lined channels throughout the course.

The Dickson Brook project was constructed by the resident Parks Canada “stream team” led by Warden Jane Watts: Donald Porter, Philip Porter, Jeff Rossiter, Kevin Rossiter, David Bishop, Gary Ackerley and Darren Hoar.

Figure 5.38: Typical gabion basket and bed-lined channel failure 10 years after installation.

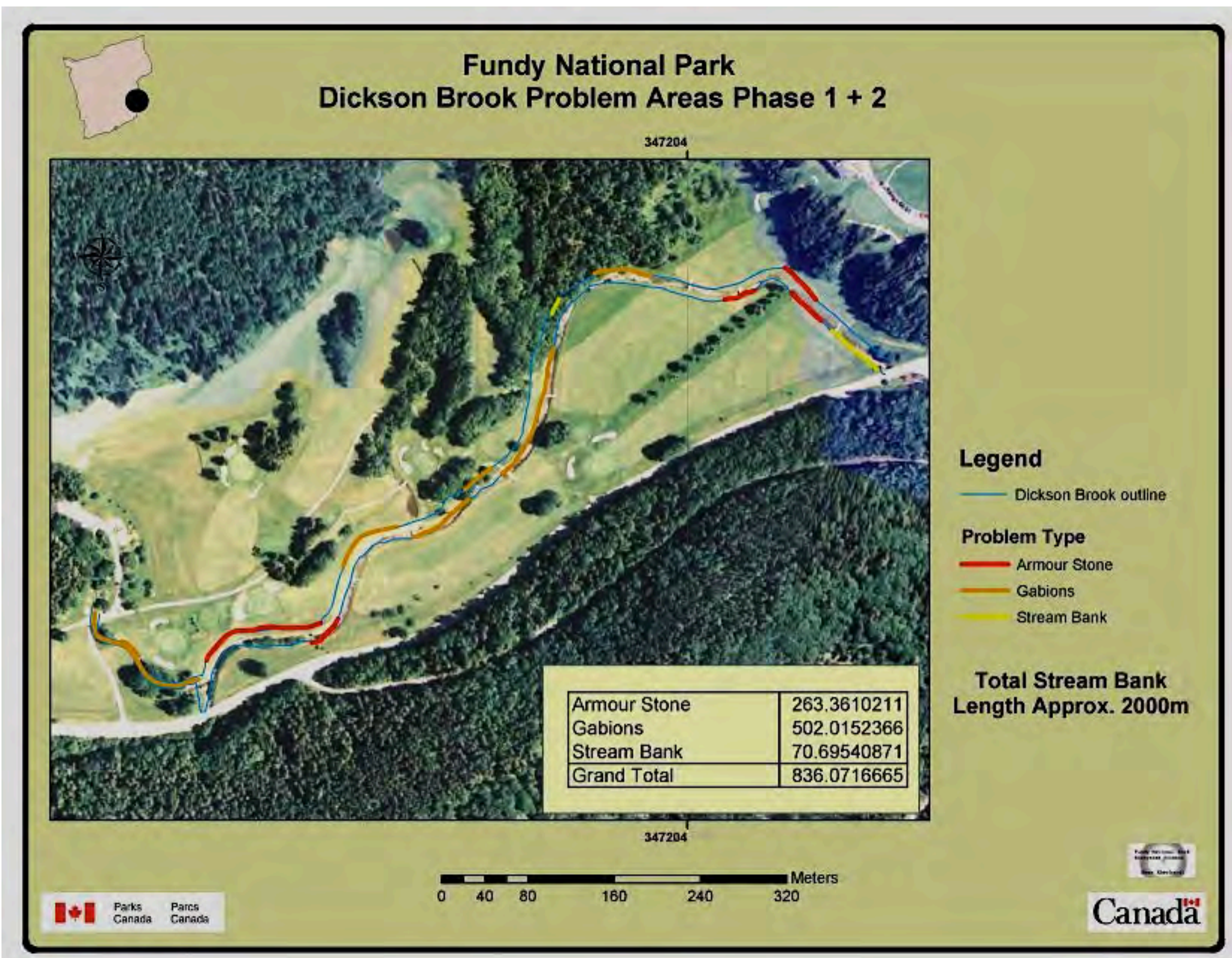


Figure 5.39: Areas with failing armour stone, gabions and banks (Parks Canada 2002).

There is a large population of resident brook trout in shallow pools, riffles and runs in the unaltered reaches of the brook above the golf course. Studies in 2002 and 2003 proposed natural channel dimensions and native riparian plants that would stabilize the channel and increase fish habitat (Newbury Hydraulics 2003). Work on the brook began in 2004.

2. Natural Channel Dimensions: The Dickson Brook watershed consists of 4 sub-basins (Figure 5.40). The hydraulic geometry (width, depth, velocity and flood capacity) was determined in reference reaches in three unaltered tributaries with similar channel slopes to the golf course reaches (Figures 5.41 and 5.42).

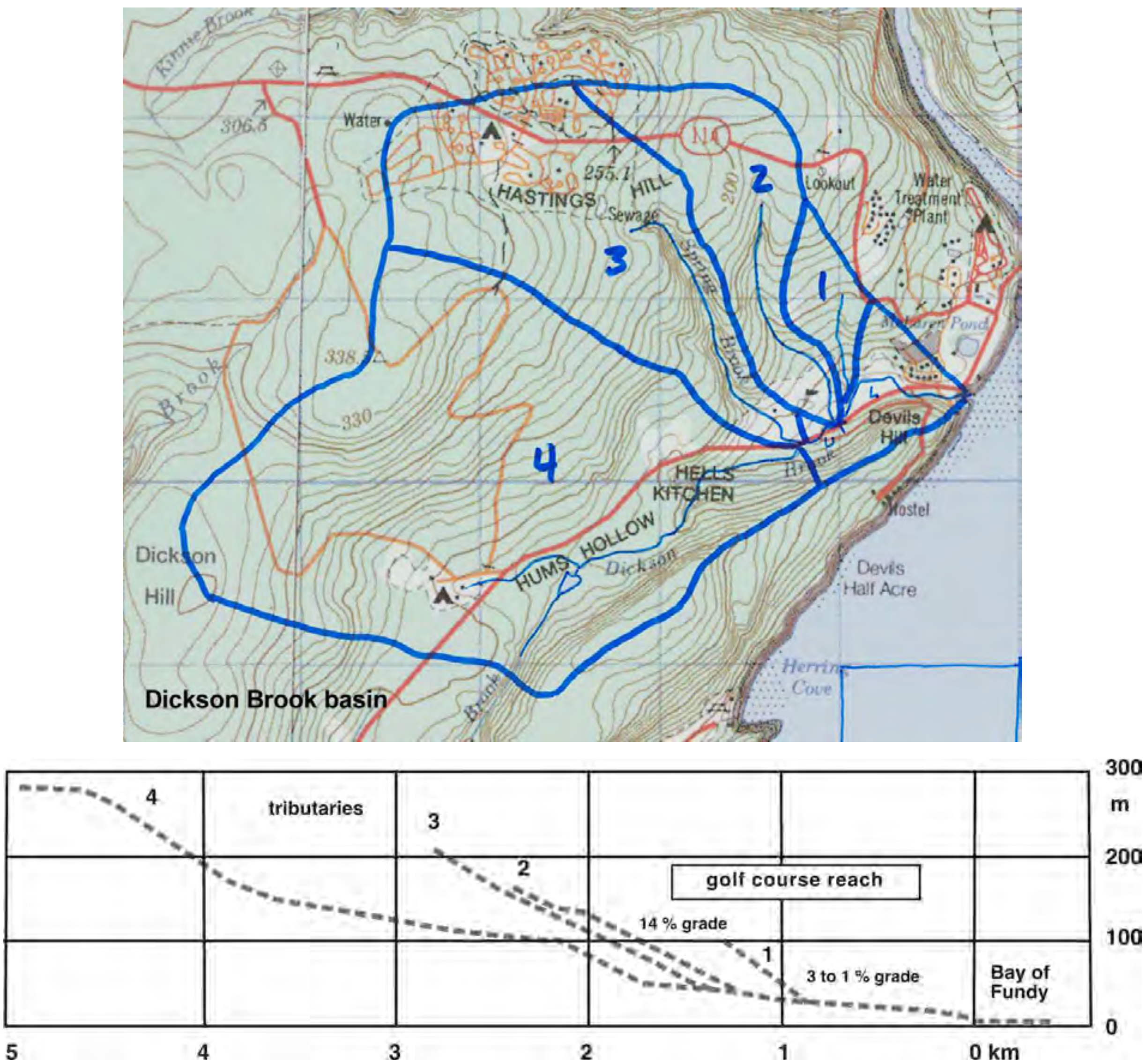


Figure 5.40: Dickson Brook watershed and tributary profiles from 1:50,000 map contours.

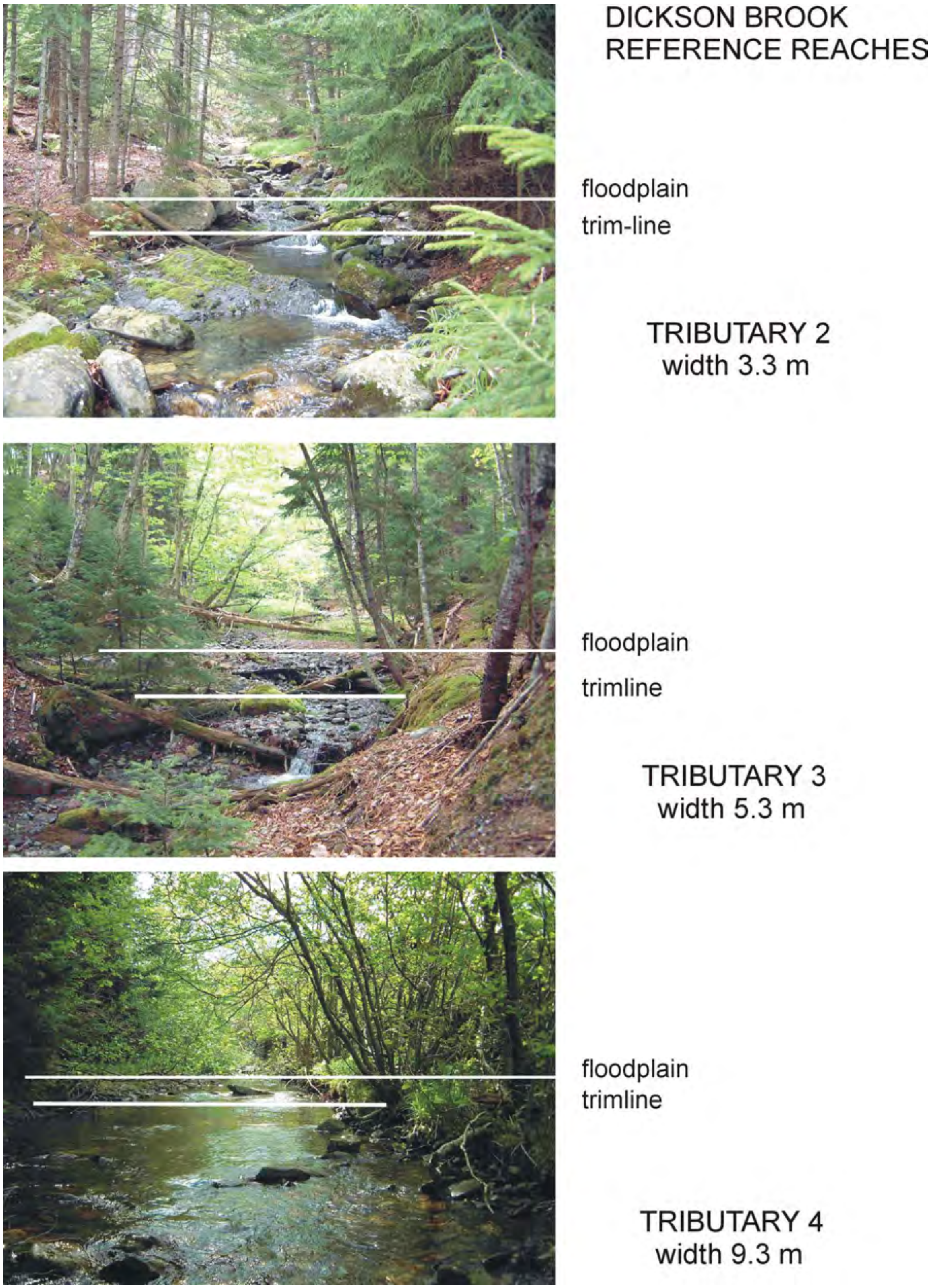


Figure 5.41: Dickson Brook reference reaches in the natural sections above the golf course.

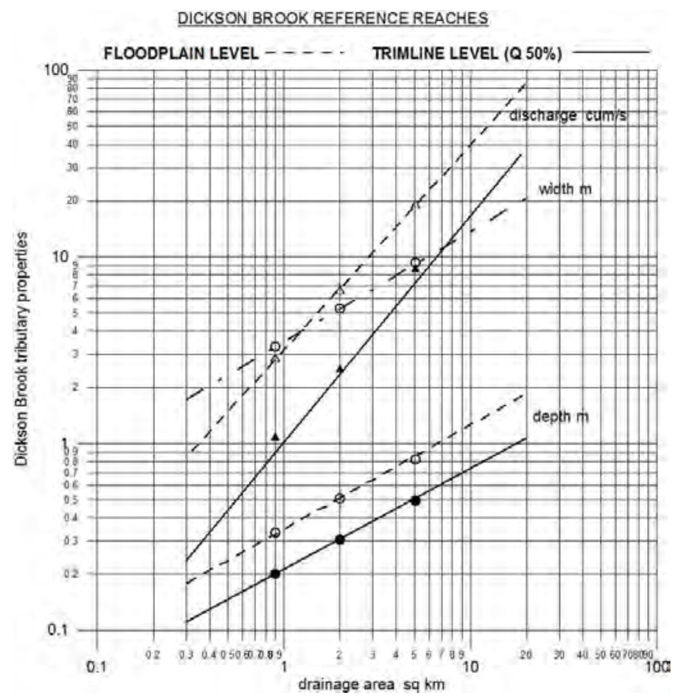


Figure 5.42: Hydraulic geometry relationships in the natural channels tributary to the Dickson Brook golf course reach. The trimline and bankfull widths are similar in the almost rectangular channel cross-sections.

The trim-line discharge estimated for the drainage area tributary to the lower golf course reach was 13.4 m^3/s. This is in the range of the median annual flood.

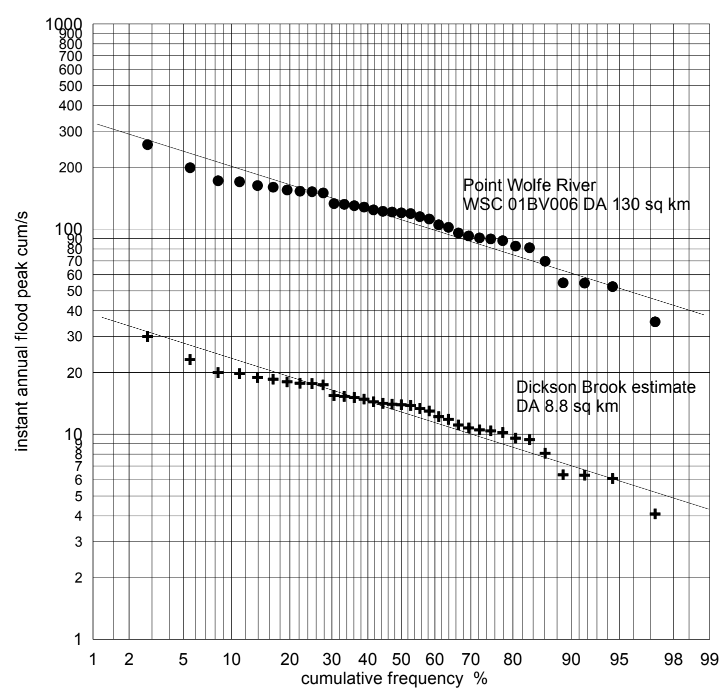


Figure 5.43: Frequency curve of the Point Wolfe River and a derived curve for Dickson Brook.

3. Design Goals and Constraints: Three alternative designs to restore the channel geometry and fish habitats to the golf course reach were considered: 1. continue the reference reach geometry at the floodplain level, 2. adopt the median flood trim-line level geometry or 3. construct a new geometry based on average alluvial channel dimensions (Figure 1.7). The Parks Canada restoration committee chose the reference reach median flood trim-line option. The pool, run and riffle profile was designed to create a variety of habitats for maintaining pools and creating gravel spawning bars. To protect the channel from further erosion riffle spacing was shortened to create a stepped pool pattern in the mainstem and a riffle and run pattern in the steeper tributaries. Low impact flood breakout areas were identified for flows greater than the median flood of 13.4 m^3/s.

4. Riffle Design

Flood Capacity and Height: Calculation of the riffle height was determined by the setting the median flood elevation in the pool immediately above the riffle equal to the floodplain elevation at selected sites on open fairways and out-of-play areas in the golf course. For a typical 1 m deep, 14 m average width section of the channel, the velocity of the flow in the pool approaching the riffle is 0.96 m/s. The specific energy is 1.05 m. As the flow accelerates over the riffle crest the critical specific energy is 0.69 m. Ignoring small contraction losses the height of the 14 m wide riffle is equal to the difference in specific energies or 1.05 – 0.69 = 0.36 m (Table 5.6). This forces the median flood to just reach the floodplain level at selected sites (Figure 5.44).

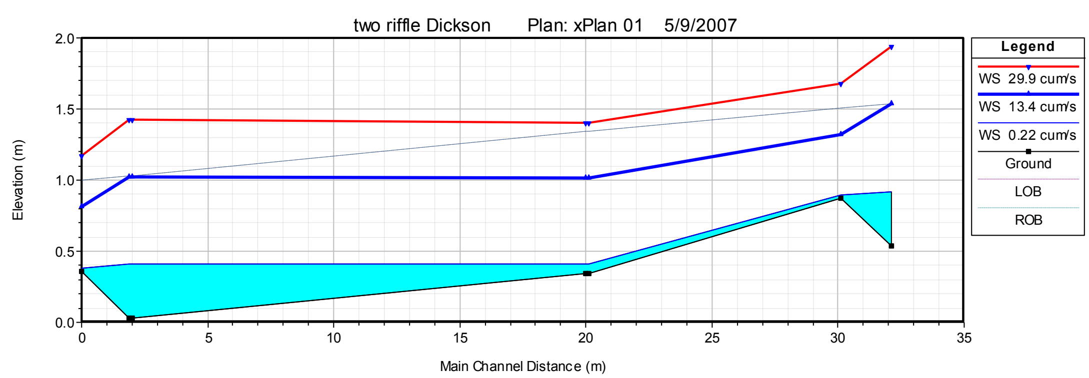


Figure 5.44: HEC-RAS outline view of a typical Dickson Brook mainstem riffle with floodplain breakout at 13.4 m^3/s. The estimated maximum flood based on Pointe Wolfe River records is 29.9 m^3/s.

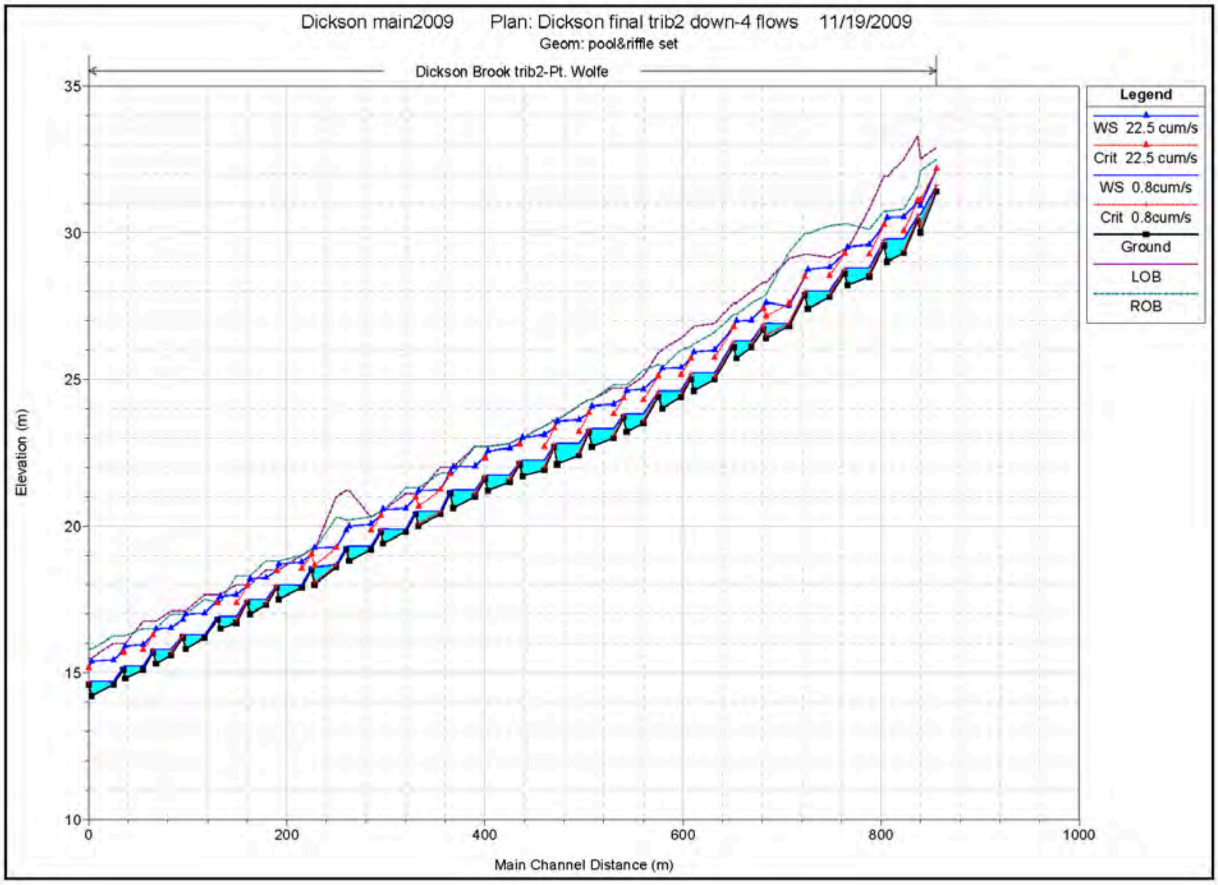


Figure 5.45: HEC-RAS profile of the Dickson Brook mainstem. Riffle elevations and spacing were adjusted to create continuous fish passage at low flows (0.8 m3/s) and flood breakout points in areas of least damage to the golf course (greens, tees, and bridges for example). The maximum post-project recorded flood is 22.5 m^3/s

Unique flood events that exceed the bankfull elevation but not enter the floodplain may also occur in mid-winter during rain on snow events (Figure 5.46).

Figure 5.46: Dickson Brook flowing above the floodplain level between 1 m high snow banks (Feb. 18, 2008). Direct runoff was observed from the snow surface.

Geometry and Spacing: The geometry calculations and dimensions of the Dickson Creek mainstem pools and riffles are summarized in Table 5.7 (see Appendix A for diagrams and dimensions).

	RIFFLE HEIGHT		Dickson Brook NB
Q	design discharge m^3/s		13.4
D	depth of flow approaching riffle m		1.0
W	average width of flow m		14
V	approaching velocity m/s	$Q / W D$	0.96
$V^2/2g$	velocity head of approaching flow m		0.05
H	specific energy of approaching flow m	$D + V^2/2g$	1.05
D_c	critical depth of flow on riffle crest m	$D_c = (Q^2 / gW^2)^{1/3}$	0.46
$v_c^2/2g$	critical velocity head m	$D_c / 2$	0.23
H_c	critical specific energy m	$H_c = D_c + v_c^2/2g$	0.69
R_H	riffle height above channel bed m	$H – H_c$	0.36
	DIMENSIONS		
S_B	channel slope	1.7%	0.017
S_{RU}	slope of upstream riffle face	2:1	0.5
S_{RD}	slope of downstream riffle face	20:1	0.05
R_U	distance of heel to crest m	$R_U = R_H / (S_{RU} + S_B)$	0.70
R_D	distance of crest to toe m	$R_D = R_H / (S_{RD} – S_B)$	10.91
Y_D	height of bed at the crest above toe m	$Y_D = R_D (S_B)$	0.19
	total drop in chute m	$Y_D + R_H$	0.55
	SPACING		
L	pool length with no back-flooding m	$L = R_H / S_B$	21.18
B_F	height of back-flooding on upstream riffle m		0
I_{step}	interval between crests with back-flooding m	$I_{step} = L – (B_F / S_B) + R_D$	32.09
I_{run}	interval between crests with run and pool m	$I_{run} = L + R_D + run$	na

Table 5.6: Dickson Brook riffle and reach geometry calculation summary.

Construction: Areas under construction were fenced off and cleared of fish (Figure 5.47). Open banks were covered with seeded mats or sod and replanted with riparian shrubs as the construction proceeded. Emergent boulders up to 50 cm diameter were added to the riffles to provide low flow channels (Figure 5.48). Boulder clusters and cabled logs were added to pools to increase habitat diversity (Figure 5.49).

Figure 5.47: Dickson Brook riffles on the lower mainstem under construction (2008). The banks are covered and grassed as construction proceeds. The end of the upper fish fence is shown in the left corner.

Figure 5.48: Emergent boulders were added to the riffle surfaces to create low flow fish passage channels.

Figure 5.49: Boulder clusters and root clumps were added to pools to create covered habitats .

Monitoring: Hourly water levels were monitored in 2009 in the upper mainstem between riffles 22 and 24 (Figure 5.50). Roughness values for the pools and riffles based on HEC-RAS modeling were determined from the profile observed during a 20 m^3/s storm event (Figures 5.51 and 5.52).

Figure 5.50: Hourly water level records were monitored with ONSET pressure transducer recorders installed on the riffle crests and pools.

Figure 5.51: The monitored reach at a near bankfull flow 20 m^3/s on October 24, 2009

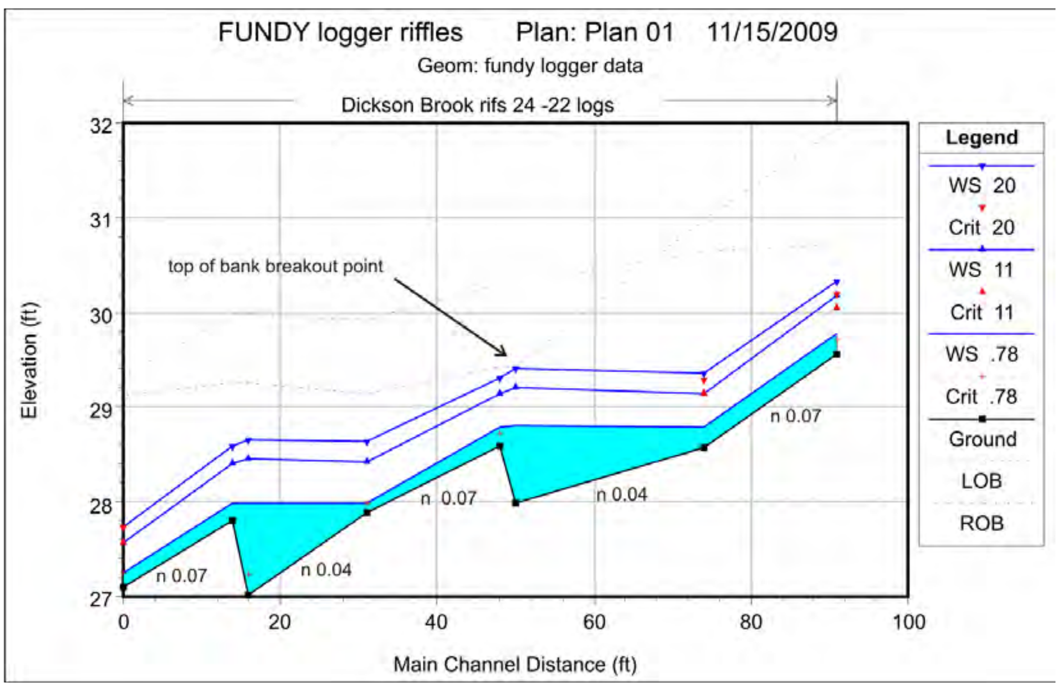


Figure 5.52: The HEC-RAS flow profile and consequent roughness values based on the observed water levels between riffles 22 and 24 at a floodplain breakout flow of 20 m^3/s in this reach.

Schools of brook trout and occasional eels and stocked Atlantic salmon are observed in the lower brook (Figure 5.53). Fish density is slightly lower than in natural reaches but age-class sizes are larger (pers. com. Jane Watts, Fundy National Park).

Figure 5.53: Aerial view of the Dickson Brook mainstem channel and restoration dates.

Other Step-Pool Project Summaries

Similar pool and riffle projects have been built across Canada to solve a specific concern or stream stabilization problem. Three typical examples summarized below deal with the stabilization of alluvial fans, protection of pipeline crossings and the construction of a put-and-take trout fishing reach.

1. Alluvial Fan Headcut Stabilization 1977: One of the first projects was built in 1977 on the alluvial fan of Wilson Creek MB to stop a deep headcut from progressing into Riding Mountain National Park. The original channel was cut across the alluvial fan with a horse and scoop in the early 1900's. A 100 m wide 10 m deep canyon eroded in the ensuing 50 years (Figure 5.54).

Figure 5.54: The pre-project Wilson Creek headcut channel 50 years after a horse and scoop drainage ditch was constructed across the alluvial fan surface in the 1920's.

The headcut progressed upstream as the formerly braided stream was concentrated in a steep single drain on the alluvial fan below the Manitoba escarpment (Figure 5.55) .

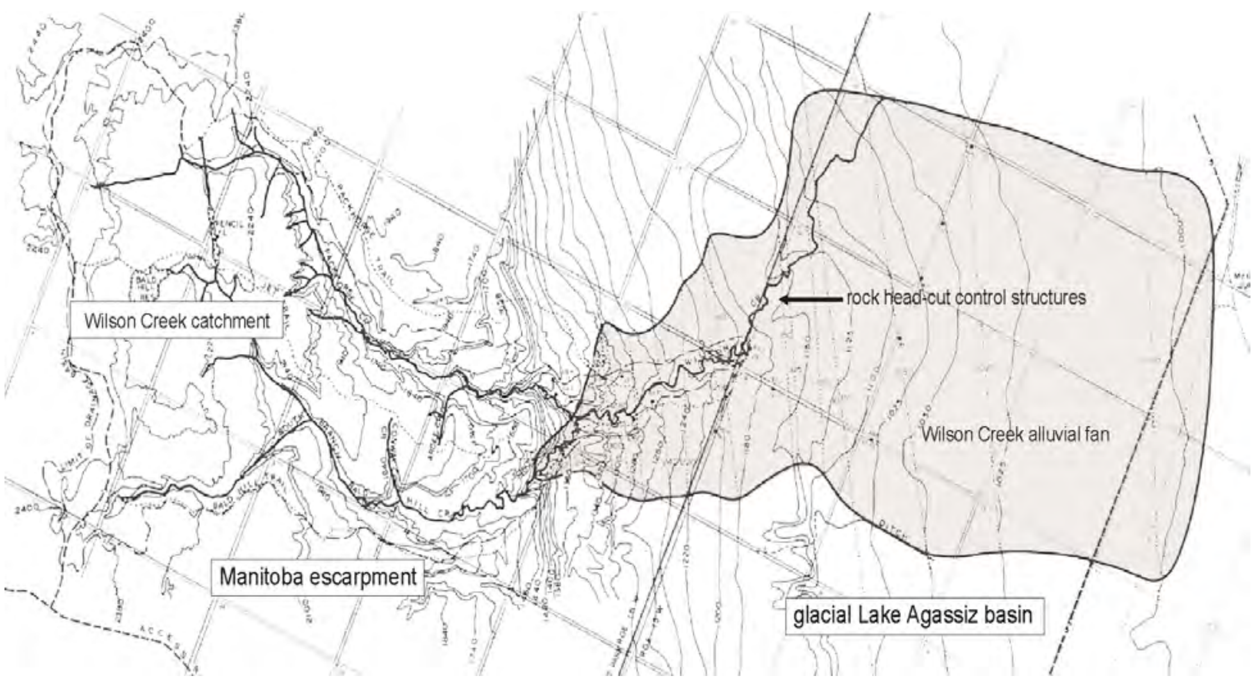


Figure 5.55: The Wilson Creek catchment on the Manitoba escarpment. A braided channel deposited an alluvial fan of weathered shale on the upper beaches of glacial Lake Agassiz as the lake drained 7500 BP (McKay 1969).

Three 2.5 m high rock riffles were designed as drop structures to create a stepped channel below the headcut. A vertical timber crest wall was built across the canyon to guide the construction for the first riffle (Figures 5.56 and 5.57). The riffle materials were graded in size and packed in layers to prevent seepage.

Figure 5.56: Crest wall of riffle drop structure.

Figure 5.57: A completed Wilson Creek riffle.

The stabilized channel and canyon 5 years after construction are shown in Figure 5.58. In the following 20 years headcut control riffles were built on most of the alluvial fan head-cuts below the Manitoba escarpment (J. Whitaker pers. com.).

Figure 5.58: A stable backflooded reach above a Wilson Creek rock riffle drop structure 5 years after construction.

The Wilson Creek project was built with the Manitoba Water Resources Branch (Hugh MacKay). Follow-up projects on other escarpment streams were constructed by Conservation Districts working with the Riding Mountain Biosphere Reserve Committee (John Whitaker).

2. Pipeline Stream Crossing 1990: Smaller projects were also undertaken to stabilize streambeds disturbed by construction. For example, walleye spawning riffles were hand-built on trenched and back-filled pipeline crossings on Hamilton Creek MB to stabilize the bed and prevent erosion of the infilled channel (Figures 5.59 and 5.60).

Figure 5.59: The gas pipeline right-of-way crossing Hamilton Creek near Falcon Lake MB.

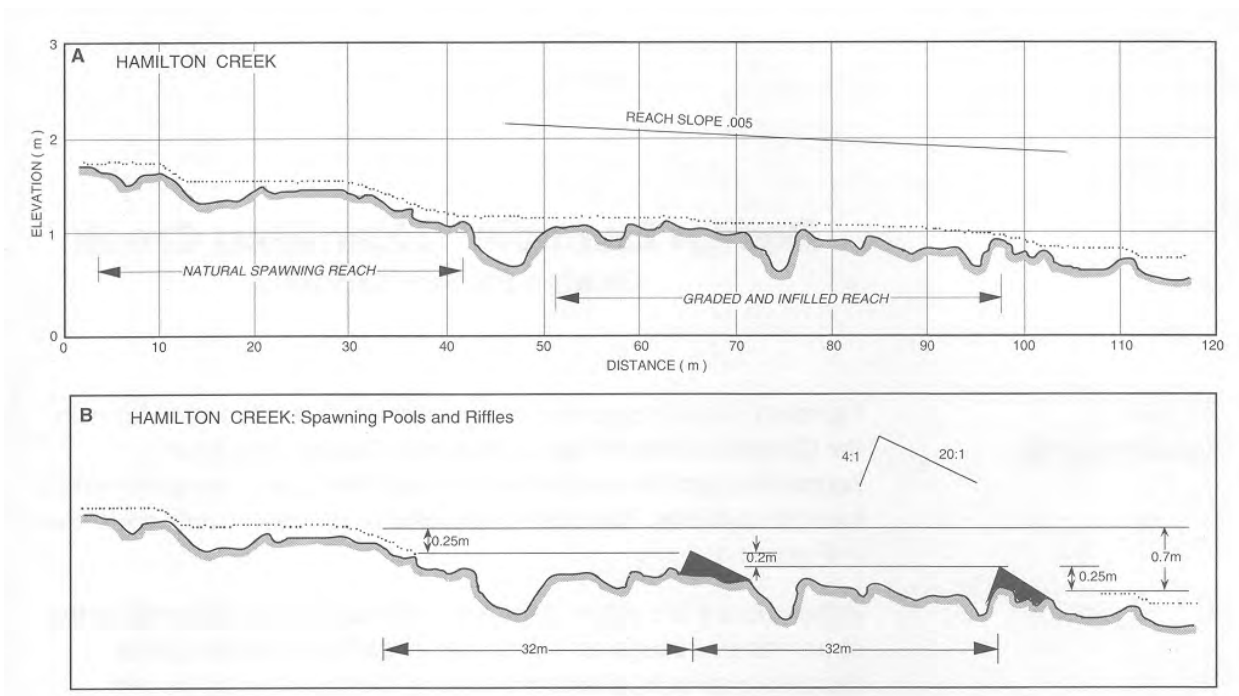


Figure 5.60: Before and after profiles of the right-of-way showing the location of small riffles built over two pipeline crossings.

The pipeline project was hand-built by Manitoba Fisheries and Water Resources Branch staff (Marc Gaboury, Martin Erickson, Rich Janusz, James Love).

The riffles were hand-built with rocks and gravel brought to the site on ATV trailers (Figures 5.61 and 5.62). A completed pool and riffle several years later is shown in Figure 5.63.

Figure 5.61: hand-building pipeline crossing riffles.

Figure 5.63: Completed riffle over pipeline.

Figure 5.63: Hamilton Creek pipeline crossing riffle 3 years after construction.

3. Trout Fishing Pools 1991: Adult trout are released from the Caddy Lake hatchery into the Whiteshell River in eastern Manitoba. The hatchery reach is used for sport fishing and as a classroom for budding anglers by the Manitoba Fly Fishers Association. Seven riffles were added to along the reach to create deeper pools and increase benthic habitats in the shallow bedrock channel in 1991 (Figure 5.64). The profile and pool depths are shown in Figure 5.65.

Figure 5.64: Riffle and trout holding pool constructed on the Whiteshell River MB in 1991.

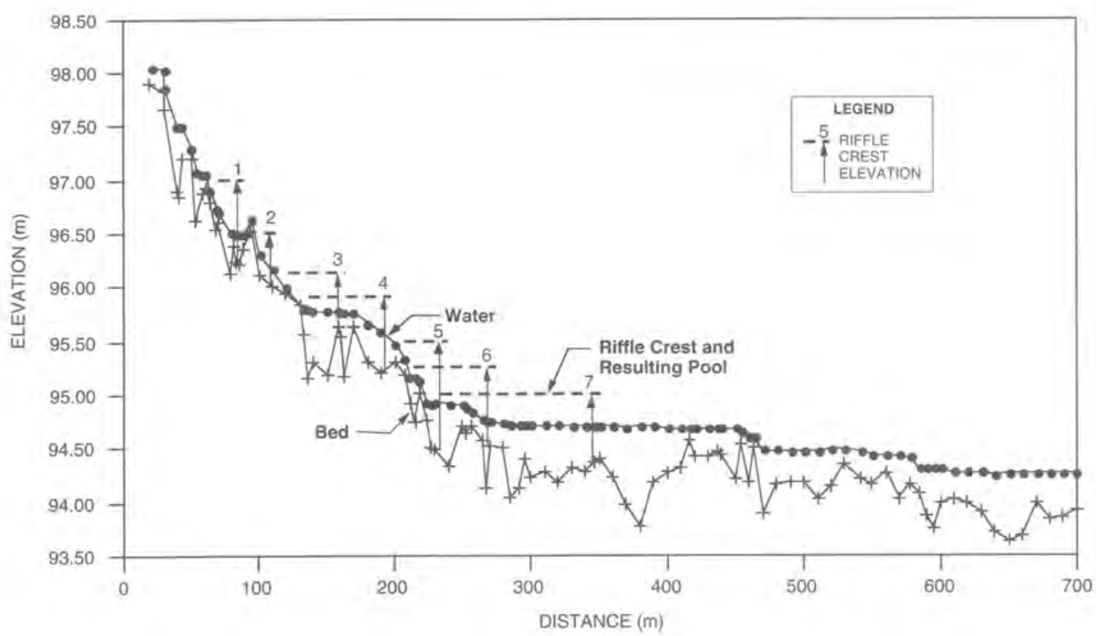


Figure 5.65: The profile of the Whiteshell River MB showing the bed, water surface and seven riffle crest elevations for creating deeper holding pools and habitats.

To provide covered habitats and reduce fish predation, boulders were added to the pools and clusters of overhanging black spruce trees were buried in the bank (Figure 5.66).

The Whiteshell River project was built with the Manitoba Fisheries Branch (Marc Gaboury) and Manitoba Fly Fishers Association volunteers (Don McMaster).

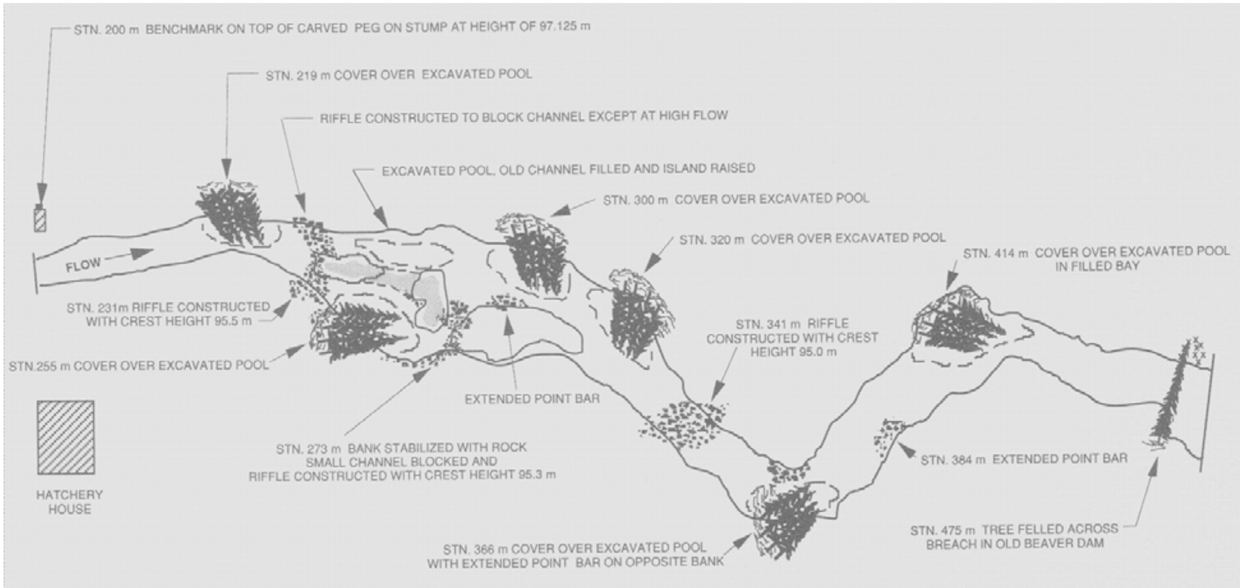


Figure 5.66: The central section of the Whiteshell River hatchery reach showing the location of tree clusters overhanging the newly created riffles and pools.

An environmental review of the project undertaken 17 years later in 2008 found “the riffles are still intact…the pools maintained their depth” (Figure 5.67) but the tree clusters provided inadequate cover after their leaves and needles dropped (AAE Technical Services 2008). The use of anchored root clumps was recommended as replacements.

Figure 5.67: Whiteshell River project assessment survey undertaken in 2008 in the reach shown in Figure 5.64 (1991) by AAE Tech Services Winnipeg, MB (photo: M. Lowdon).

4. Penticton Creek 2016: Urban Stream Semi-Restoration

After drastic urban flooding in the 1940's Penticton Creek was collected in a single channel running directly into Lake Okanagan on the northern flank of the city core (Figure 5.68). The lower reaches of the high gradient channel (1.8 %) were lined with concrete (Figure 5.69). Over 30 drop structures were added to steeper upstream reaches (3.8%) to control erosion.

Figure 5.68: The lower reach of Penticton Creek in the downtown city core. A short restoration reach was constructed in 2015 as a "showcase" for a larger master plan.

Figure 5.69: The channelized and concrete lined lower reach of Penticton Creek. Parking barriers are placed on the stream bed to provide resting refuge for spawning kokanee as they struggle to move through the shallow and fast flowing lower reach.

In 2015 the concrete lining in a 90m "showcase" reach was replaced with a rocky bed of shallow pools and short riffles. The channel banks were riprapped with coarse rock (Figure 5.70).

Figure 5.70: A rocky pool and riffle channel replaced the concrete-lined channel in the Penticton Creek showcase project.

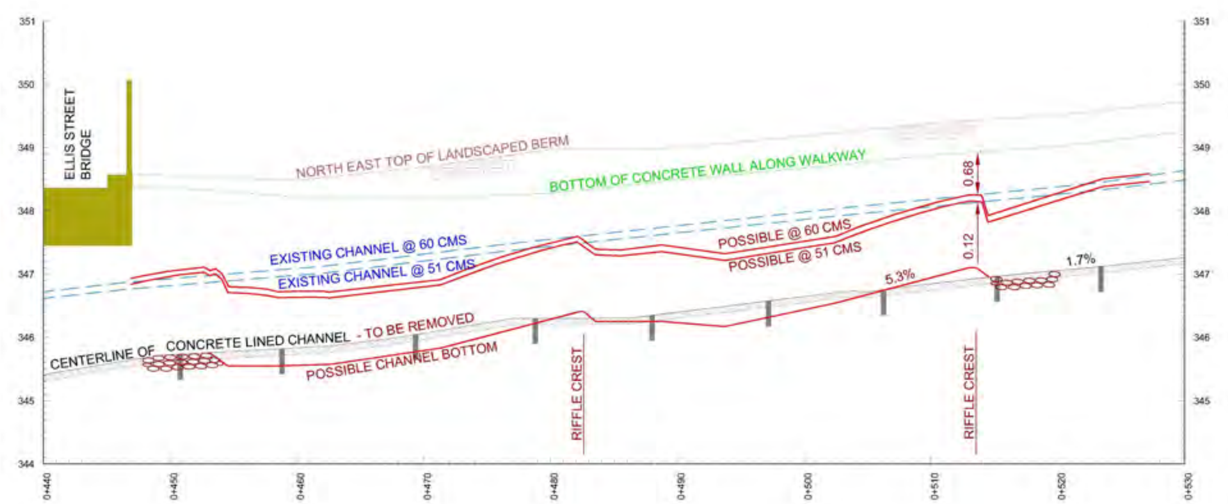
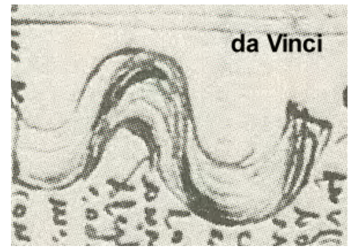


Figure 5.71: The showcase reach was widened by 2m to achieve similar flood stages in the rougher channel.

In 2015 spawning kokanee moved easily though the re-constructed reach. In 2016 juvenile rainbow trout, brook trout, long nose dace and kokanee were found under the large boulders in the pools. A masterplan for the whole creek is in preparation (Mould Engineering, Newbury Hydraulics 2016).

Chapter 6: Restoring and Aligning Meandering Channels



Opportunities to restore river meanders in channelized streams are often limited by dyking regulations and land use in the former floodplains (Kondolf 2006). Land was available to re-create or re-access meanders in the first two examples in this chapter. In the first example meanders and a highway bridge alignment were re-constructed on the North Pine River MB, a heavily fished trout stream. In the second example, a dyke was set back along a 1 km reach of the Okanagan River BC to re-access the original floodplain, create new sockeye spawning bars and connect meanders that were cut off 50 years ago by channelization. Other salmon habitat projects that simply shift the flow pattern in the existing channel with retarding bars are summarized for projects on the Miramichi and Clyburn Rivers in the Canadian Maritimes.

Design Example 1: Restoring Meanders, Pools, and Riffles for Resident Trout Habitat (1990 North Pine River MB)

1. Background: The North Pine River is a productive rainbow trout stream with a large resident population. Local highways cross several branches and the mainstem at six locations as it flows down the east face of the Manitoba Escarpment in Duck Mountain Provincial Park. The route follows a pre-European trail from the top of the escarpment to the lowland lakes in central Manitoba. When the road was built the crossing reaches were straightened, although not aligned at right angles to the roadway.

Trout habitats in the Pine River are reach specific and limited, occurring where there are well-developed meander pools that are often coincident with up-welling groundwater on the channel bed (Newbury and Gaboury 2003). The restoration project was undertaken in 1990 in a straightened groundwater-fed reach at one of the highway crossings (Figure 6.1).

The Pine River project was constructed by the Manitoba Habitat Heritage Corporation, Manitoba Fisheries Branch (M. Gaboury and M. Erickson) and the Swan River Fish and Game Assoc. (R. Wowchuk).

Figure 6.1: The straightened reach of the North Pine River approaching the PTH #20 bridge crossing.

To determine the habitat dimensions and configuration, reference reaches with proven trout populations were surveyed on the Pine River and similar escarpment rivers (Figure 6.2). It was found that the habitats shared a common trait of being in a meander bend with an average spacing of 6w and radius of curvature of 2.3w where w is the trimline width.

Figure 6.2: Channel surveys and habitat mapping in a typical adult trout habitat. The rate of translation down the valley bottom is slow enough to allow the riparian vegetation to correct its growth habit by curving upwards as the outer banks slump in the meander.

A helical flow pattern that occurs with these meander dimensions plays a role in maintaining the aquatic insect supply and delivery to the deepest parts of the pools (Figure 6.3). Other common characteristics were (1) the energy loss in the habitat reaches at moderate flows was divided equally between meanders and riffle sections. The specific energy rose above the mean energy gradient in the pools and fell below the gradient in the riffles as suggested in Leopold, Wolman and Miller 1964) and (2) in general the riffles were square in plan (one channel width long).

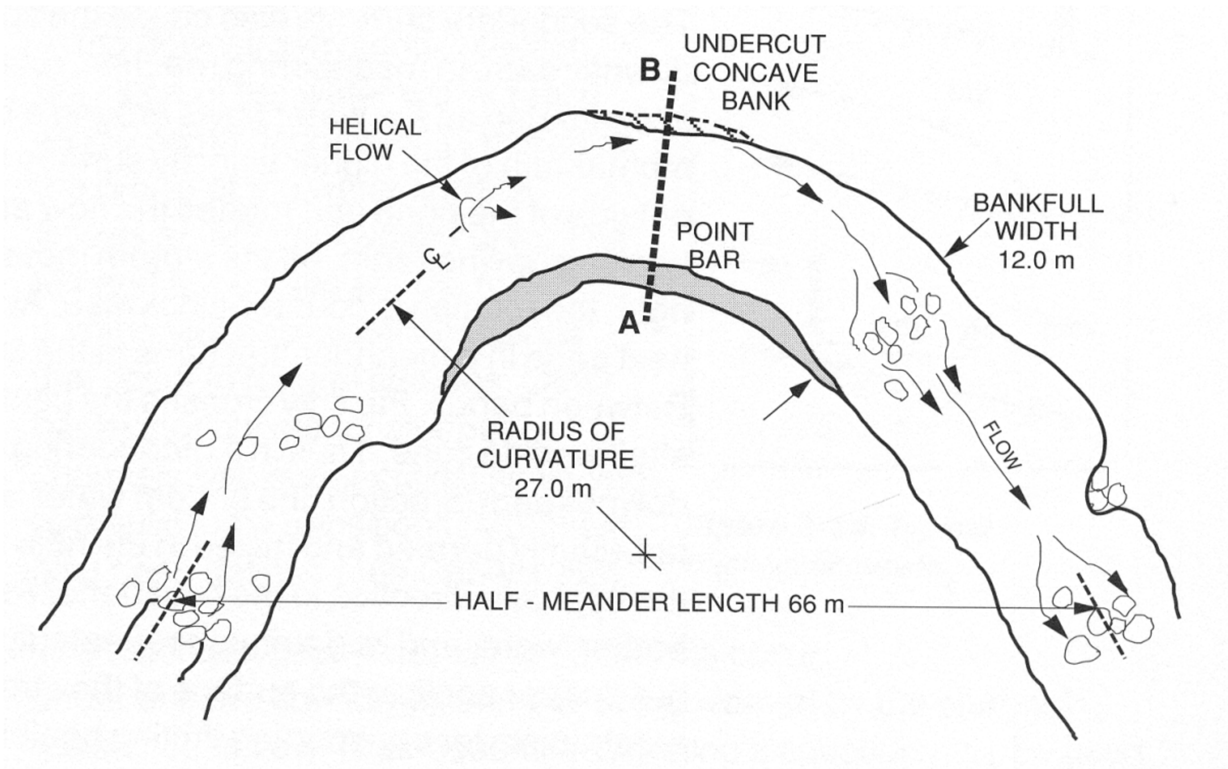


Figure 6.3: Plan view of the meander shown in Figure 6.2. Helical rotation causes up-welling at A and down-welling at B in the same cross-section.

2. Channel Conveyance Calculations: Channel dimensions for the reach were determined by surveying natural reaches above and below the highway crossing (Table 6.1). The observed dimensions were narrower and deeper than those predicted for alluvial rivers as the channel is incised into the Manitoba escarpment through layers of boulder tills. The median diameter of the boulder lag deposit in the channel bed was 45 cm.

bankfull width	9.7 m
bankfull depth	0.84 m
average slope	0.022
median bed paving material size.	0.45 m
assumed bankfull roughness	0.16
predicted bankfull velocity	0.83 m/s
bankfull tractive force.	18.5 kg/m^2
bankfull Froude number	0.3
bankfull discharge	6.7 m^3/s

Table 6.1: Average natural channel dimensions in the North Pine River trout habitat restoration reach.

The bankfull depth of flow of 0.84 is less than twice the median diameter of the bed materials, producing a very high Manning's resistance factor of 0.16. This is approximately equal to values observed in boulder-filled streams at similar discharges (see Hicks and Mason (1991) reference channel 93901). The bankfull velocity and discharge estimates are:

$$\mathbf{V} = (.84)^{.67}\ (.022)^{.5} / 0.16 = 0.83 \text{ m/s}$$
$$\mathbf{Q} = 0.83 \times 0.84 \times 9.7 = 6.76 \text{ m}^3\text{/s}$$

The bankfull discharge estimate is close to the median annual flood estimated for the natural reach based on a nearby gauging station record (WSC 05G001 Pine River) (Figure 6.4).

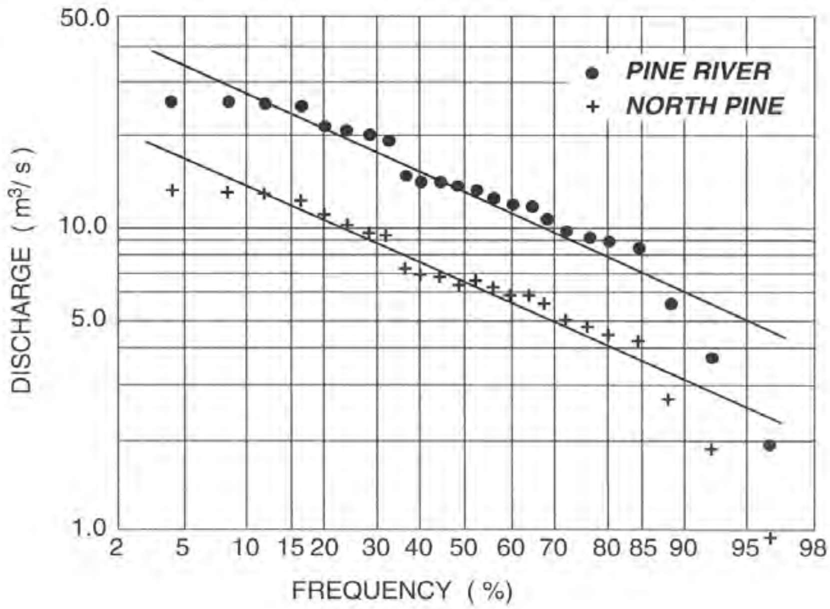


Figure 6.4: Annual flood frequency curve adjusted for the tributary area of the North Pine River restoration reach (based on WSC station 05G001, Pine River).

3. Channel Design and Construction: A meandering channel was designed to replace the straightened reach using the average meander characteristics observed in the trout habitat reference reaches. The cleared path on the floodplain, plan, profile and the new channel being excavated are shown in Figures 6.5, 6.6 and 6.7.

Figure 6.5: Clearing and staking the centreline of the new meandering channel on the adjacent floodplain.

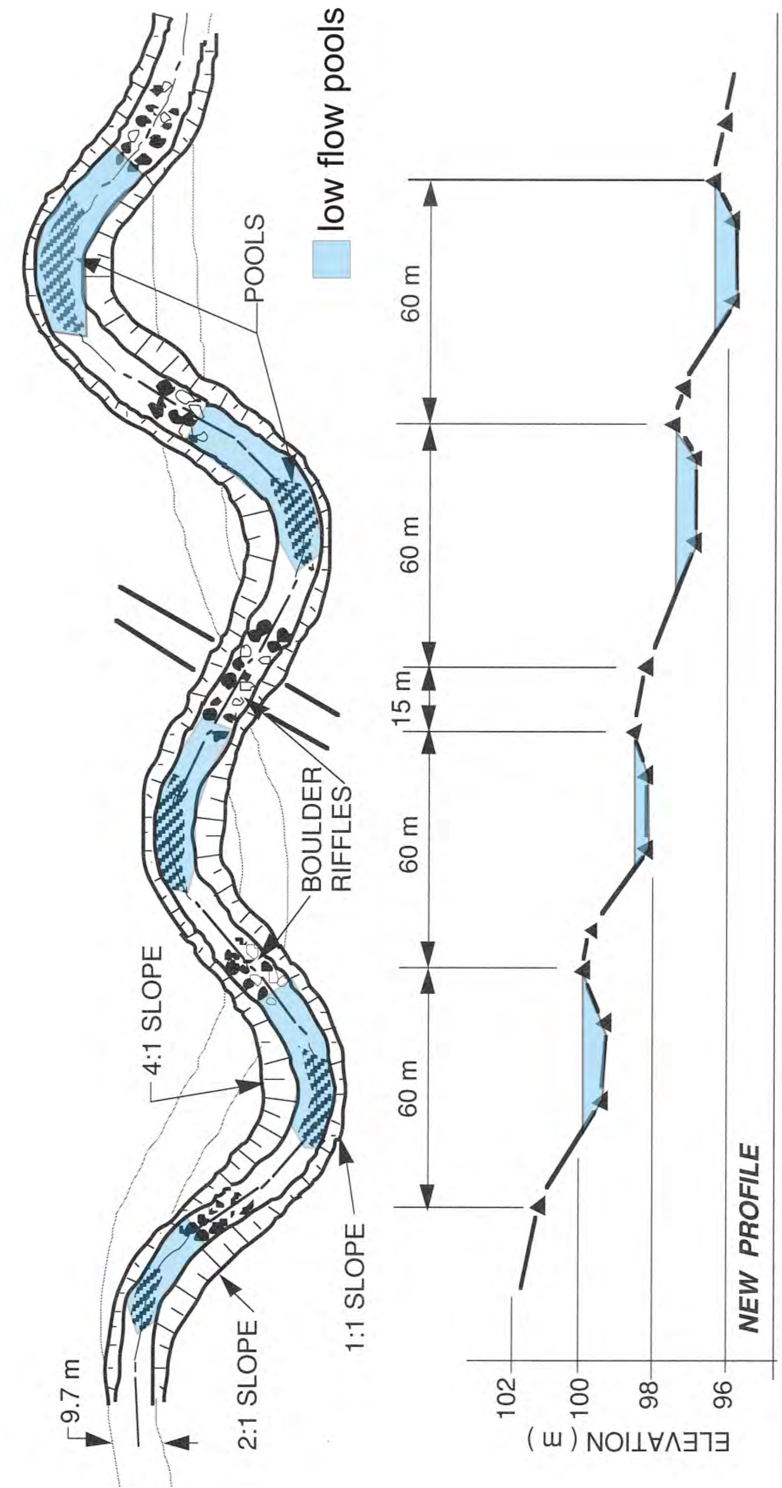


Figure 6.6: Plan and profile for the North Pine River restoration reach. Low flow pools extend to the midpoint of the meanders.

Figure 6.7: Initial excavation of a North Pine River meander. Boulders and cobbles found in the till were collected in riffles as the cross-sections were finished and graded.

In the restored reach, the meander length of 120 m was 12.4 times the bankfull width of 9.7 m. The meander amplitude was governed by cut-banks and terraces located on either side of the floodplain. The radius of curvature of the meanders was 2.3 times the bankfull width or 22 m. This was reduced to 18 m to align the channel squarely with the bridge abutments. The channel cross-sections were uniform in the riffles and skewed in the meanders to approximate point bars and steep outer banks (Figure 6.8). The completed project is shown in Figures 6.9 and 6.10 (20 years later).

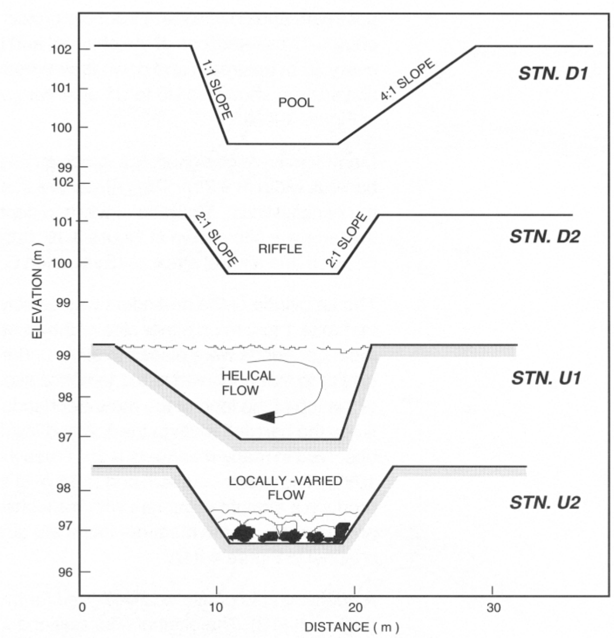


Figure 6.8: Cross-sections excavated in the meander restoration reach. D1 and U1 are in meanders. D2 and U2 are in riffles.

Figure 6.9: The restored North Pine River trout habitat restoration reach as constructed in 1990.

Figure 6.10: The North Pine River restoration reach 20 years later in 2010 (Google Maps™).

The riffle heights were calculated as the difference between the specific head of the bankfull pool stage and the specific head of the critical flow on a riffle crest (Table 6.2, Figure 6.11).

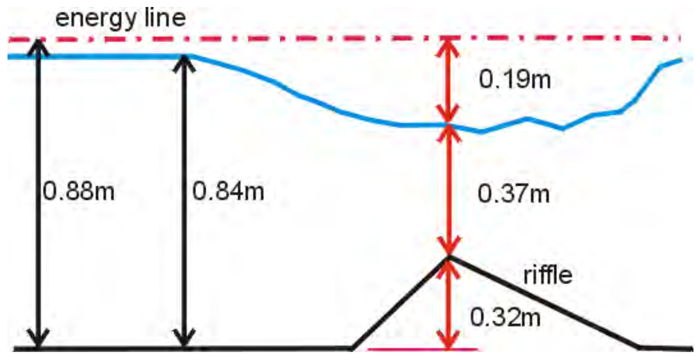


Figure 6.11: The bankfull flow enters the floodplain at a depth of 0.84 m in the pool approaching a 0.32 m high riffle.

The minimum boulder sizes selected for the riffle crest were based on a 15:1 riffle downslope. Assuming the bankfull flow would achieve this slope as it passes the crest, the tractive force is 24.7 kg/m^2, equivalent to a riprap size of 24.7 cm diameter. Many of the lag deposit boulders put aside for riffle construction were larger (Figure 6.12).

Figure 6.12: North Pine River completed meander midwinter 1990.

	RIFFLE HEIGHT		N Pine River MB
Q	design discharge m^3/s		6.7
D	depth of flow approaching riffle m		0.84
W	average width of flow m		9.7
V	approaching velocity m/s	$Q / W D$	0.82
$V^2/2g$	velocity head of approaching flow m		0.03
H	specific energy of approaching flow m	$D + V^2/2g$	0.87
D_c	critical depth of flow on riffle crest m	$D_c = (Q^2 / gW^2)^{1/3}$	0.37
$v_c^2/2g$	critical velocity head m	$D_c / 2$	0.18
H_c	critical specific energy m	$H_c = D_c + v_c^2/2g$	0.55
R_H	riffle height above channel bed m	$H – H_c$	0.32
	DIMENSIONS		
S_B	channel slope		0.03
S_{RU}	slope of upstream riffle face	2:1	0.5
S_{RD}	slope of downstream riffle face	15:1	0.067
R_U	distance of heel to crest m	$R_U = R_H / (S_{RU} + S_B)$	0.60
R_D	distance of crest to toe m	$R_D = R_H / (S_{RD} – S_B)$	8.69
Y_D	height of bed at the crest above toe m	$Y_D = R_D (S_B)$	0.26
	total drop in chute m	$Y_D + R_H$	0.58
	SPACING		
L	pool length with no back-flooding m	$L = R_H / S_B$	10.71
B_F	height of back-flooding on upstream riffle m	Input	0
Run	length of run between pools	Input	40.60
I_{run}	interval between crests with run and pool m	$I_{run} = L + R_D + run$	60.00

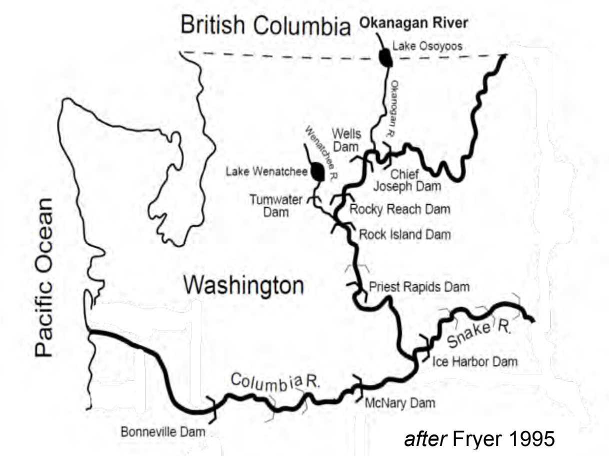
Table: 6.2: Summary of riffle and channel geometry calculations for North Pine River MB. Dimensions are based on the valley slope for a centreline survey layout.

4. Monitoring: Moderate floods in the first year following construction removed silts and fine sands from the riffles and an outside thalweg was formed in the meander bends. In 1994, a 1:40 year flood peak occurred that scoured the pools and riffles and began undercutting the outside of the meander bends (Figure 6.13). The peak flow accessed the floodplain without damage. The crest elevations of the riffles and channel alignment was not altered significantly although other non-aligned skewed bridge crossings on the highway were washed out or damaged by the flood event.

Figure 6.13: North Pine River restoration reach following a 1:40 year flood peak in 1994.

Adult trout are caught in all of the restored pools but a creel census has not been possible in this highly public, easily accessible (off the bridge) and now well-known fishing reach. It has appeared in popular fishing journals as a "sure producer" for the Duck Mountain region.

Design Example 2: Meander, Spawning Bar and Side Channel Restoration 2008-2013 Okanagan River Restoration Initiative (ORRI))



1. Background: The Okanagan River (Okanogan in the USA) is a northern tributary of the Columbia River. Over 90% of the river in Canada was straightened and dyked in the mid 1950's (Figure 6.14) to provide irrigation water and access to the rich floodplains in the bottom of the Okanagan valley. Approximately half of the remaining Columbia River sockeye salmon return to the river to spawn after migrating 1200 km and being transported over nine power dams (Long 2004). A 6 km long natural reach at the head of the channelized section near Oliver BC provides 95% of the spawning habitat. The reach is classified as "unimproved" in the 1950's plans.

Figure 6.14: The channelized project reach of the Okanagan River in 2006 before restoration. The reach runs from Vertical Drop Structure 13 (VDS 13) to the unaltered natural spawning reach 1 km upstream.

Phase I: To increase habitat diversity and extend the natural channel spawning area, the west dyke was set back in the first kilometre of the channelized reach in 2008. In 2009 the former floodplain was opened to the mainstem at three locations and two abandoned meanders were re-connected in the lower half of the reach above VDS 13.

2. Reference Channel Configuration: Two design options were evaluated; a single thread meandering channel and a dual channel with approximately a 50-50 split in discharge between the reconnected meanders and the existing channel. Both options are limited in gradient because of backflooding by VDS 13. The dual channel option was adopted because more pool and spawning areas similar to those observed in the natural reach could be constructed. A dual channel segment in anastomosing section of the natural reach was used as a template for the re-connections and spawning bar features (Figure 6.15, as constructed Figure 6.23).

Figure 6.15: A dual channel segment in the natural reach of the Okanagan River 1 km upstream from the project reach. The entrance riffle to the side channel and the long gravel bar in the mainstem are heavily used by spawning sockeye salmon (Wild Earth Photography 2006).

To mimic natural conditions spawning riffles were added to the meander entrances and exits, raised spawning bars were constructed in the mainstem and three access points were excavated between the original floodplain and the channel (Figure 6.16).

Construction of the Okanagan River project was undertaken by Mould Engineering, Kelowna BC (Jody Good, Stuart Mould). A committee of agencies provided oversight and guidance (Chris Bull, Steve Mathews). The project is part of the Okanagan First Nations river restoration plan (Karilyn Long Alex).

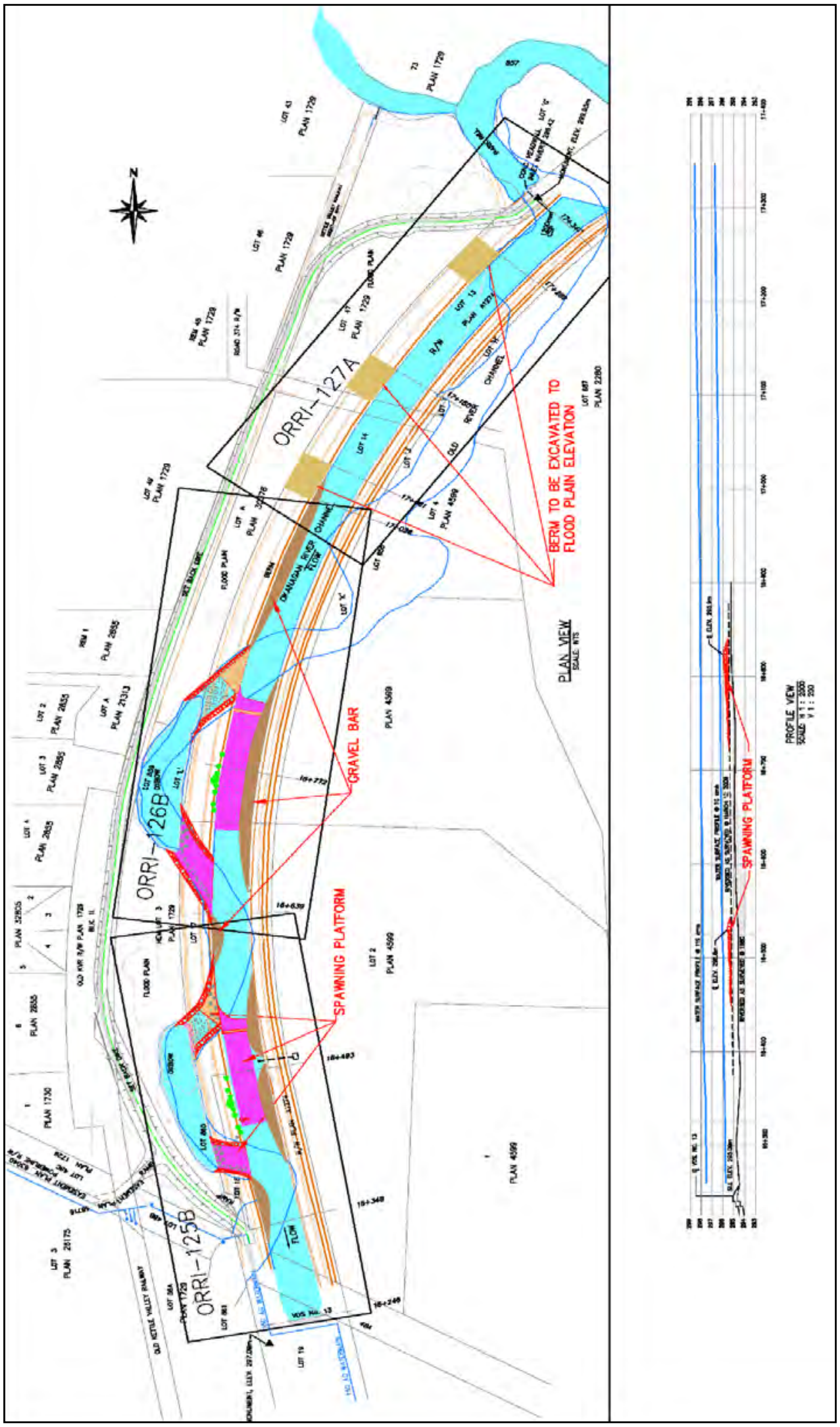


Figure 6.16: Okanagan River Phase 1 restoration plan (Mould Engineering 2009).

3. Hydraulic Design: Hydraulic conditions were modeled with HEC-RAS 4.0 to establish the flood capacity and the maximum extent of spawning features that could be added to the channels (Figure 6.17, Mould Engineering 2009).

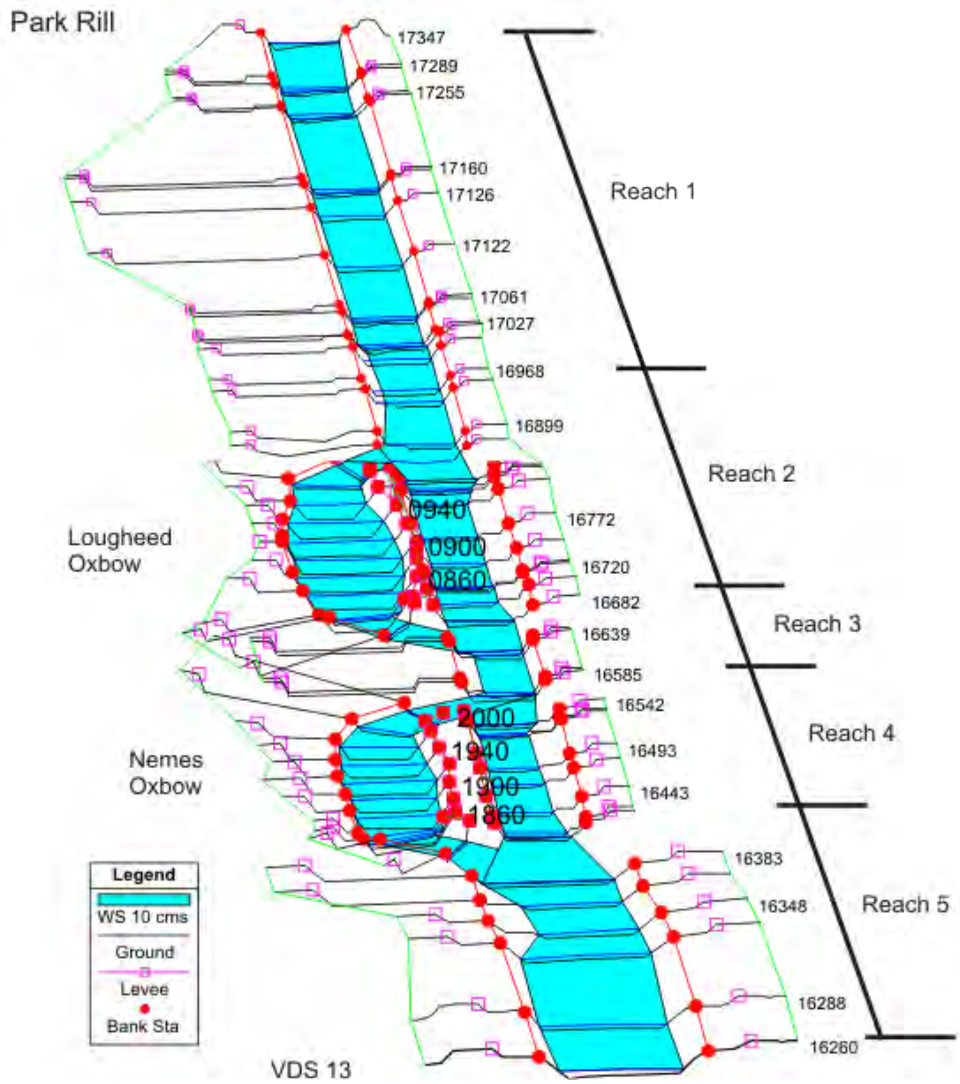


Figure 6.17: HEC-RAS schematic at a typical Fall spawning discharge of 10 m^3/s (Mould Engineering 2009).

A 200-year design flow of 119 m^3/s was approved for the setback dykes and channel capacity by Provincial water authorities. Spawning bars were designed for flows up to 10 m^3/s to reproduce the depth and velocity combinations (Froude numbers) observed in preferred natural spawning sites at typical Fall spawning period discharges (see Figure 3.15). The total drop in water level in the uniform channelized reach is less than 1 m (Figure 6.18).

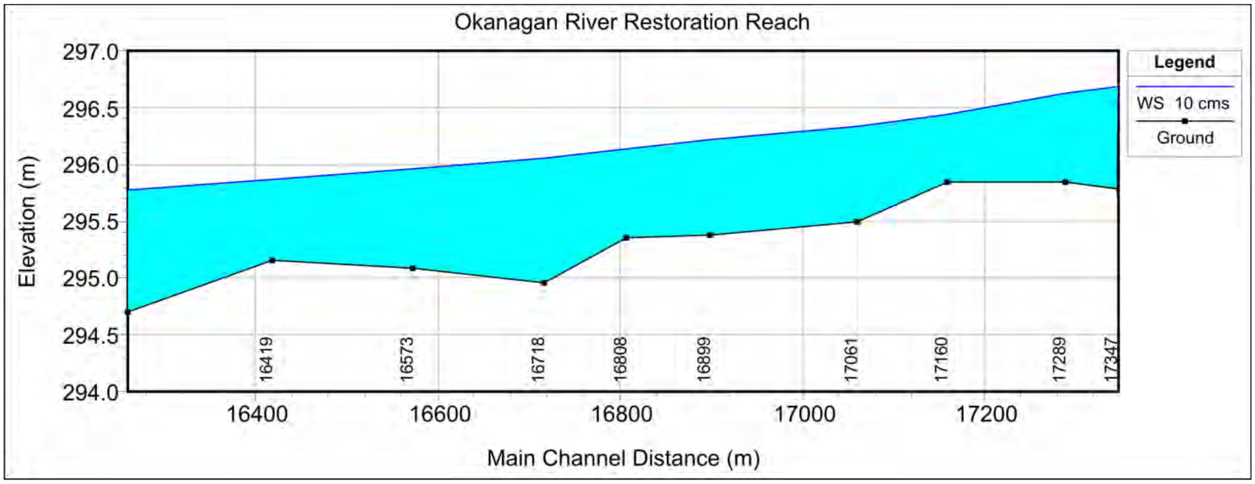


Figure 6.18: The uniform HEC-RAS profile of the pre-restoration channelized restoration reach.

The design challenge with such a small amount of energy to allocate was difficult. Many profile iterations were modeled before a combination of riffles and ramps were found that would divide the flow between the mainstem and re-connected meanders and not cause upstream flooding. The final HEC-RAS profile at a 10 m^3/s flow is shown in Figure 6.19.

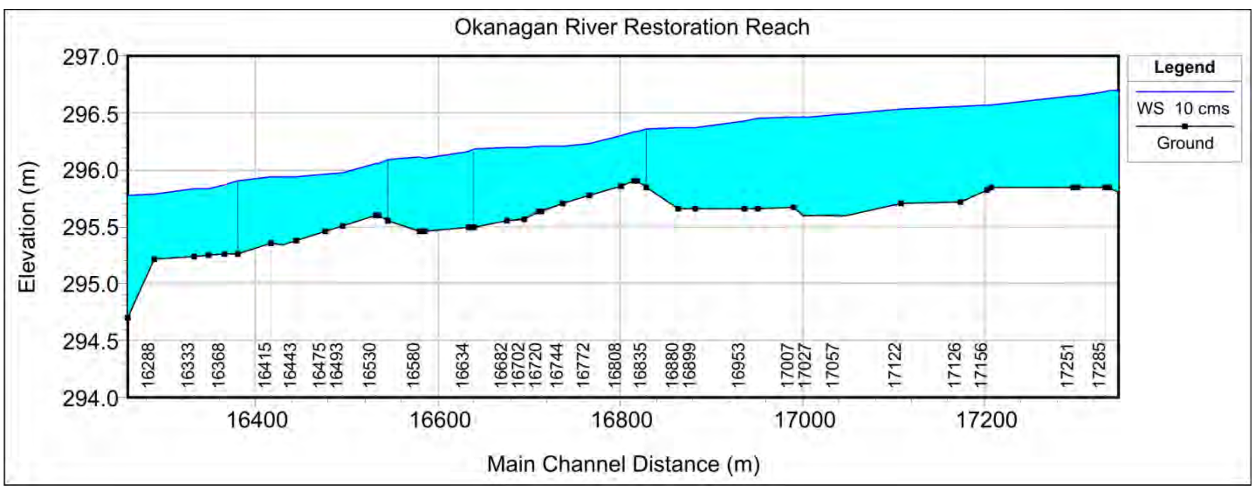


Figure 6.19: The restored HEC-RAS mainstem profile (Mould Engineering 2009).

4. Construction: Materials for the setback dykes were salvaged from the existing dykes and added to a pre-existing railway grade on the western side of the project area (Figure 6.20).

Figure 6.20. The setback dyke was constructed on the abandoned grade of the Kettle Valley Railway (V-Line Construction, Oliver BC).

The channels connecting the meanders were isolated with lined lock-block dams during construction to limit the mainstem turbidity (Figures 6.21). Spawning gravels and large cover rocks were added to the connecting channels before the barriers were removed (Figure 6.22). The completed entrance channel is shown in Figure 6.23.

Figure 6.21: Excavation of the Lougheed meander entrance channel isolated by lock-block dams.

Figure 6.22: Placing cover rocks in the Nemes meander entrance channel before the lock block barriers are removed.

Figure 6.23: The completed Lougheed meander entrance and mainstem spawning platform 2 years after construction (2012). Peak flows exceeded the bankfull design stage in both years.

An aerial view of the completed Phase I segment of the project is shown in Figure 6.24. Sockeye salmon have utilized the mainstem spawning bar annually (Long and Rivard-Sirois 2010) (Figure 6.25).

Figure 6.24: Phase I of the Okanagan River restoration project completed in 2009 (photo Kevin Dunn).

Figure 6.25: Spawning ramp in the mainstem and riffle elevation control entering the abandoned Lougheed meander on the right (October 2011).

5. Monitoring: Habitat preferences for the project are summarized in Table 6.3.

	Velocity Range (m/sec)	Depth Range (m)	Froude Number Range
Chinook[1] spawning	 0.50 - 1.25	 0.80 +	
Steelhead[1] spawning fry parr	 0.58 - 0.77 0.04 - 0.20 0.25 – 0.55	 0.30 - 1.00 0.05 - 0.25 0.30 – 1.50	
Rainbow Trout[2] spawning fry juvenile adult	 0.50 – 0.91 0 – 0.18 (50%) 0 – 0.30 (50%) 0.15 – 0.60	 0.18 – 2.5 0.25 – 0.50 0.50 – 3.04 0.50 – 3.04	
Sockeye[3] spawning (natural reach redds)	 0.20 – 0.80	 0.15 – 0.30	 0.18 – 0.50

1. Gaboury 2009 2. Raleigh et al. 1984 3. Long 2006

Table 6.3: Fish habitat hydraulic conditions for desired fish species in the project reach.

Velocity and depth measurements were taken at a discharge of 8 m^3/s during construction to ensure that the Froude number conditions were met as the spawning bars and platforms were completed. Hydraulic conditions before and after the project are summarized in Table 6.4.

	Velocity Range (m/sec)	Depth Range (m)	Froude Number Range
Existing Channel	0.45 - 0.67	0.60 – 0.85	0.23 – 0.40
Phase 1 Channel Lougheed Oxbow Nemes Oxbow Reach 1 Reach 2 Reach 3 Reach 4 Reach 5	 0.08 - 0.72 0.10 – 0.66 0.50 – 0.72 0.30 – 0.74 0.58 – 0.82 0.30 – 0.83 0.60 – 0.90	 0.38 – 1.87 0.37 – 1.55 0.50 – 0.75 0.30 – 0.60 0.60 – 0.65 0.34 – 0.70 0.55 – 0.68	 0.02 - 0.39 0.03 – 0.35 0.18 – 0.33 0.12 – 0.42 0.23 – 0.35 0.12 – 0.45 0.23 – 0.40

Table 6.4: Before and after hydraulic conditions in the Phase I reach (reach segments Figure 6.16).

The range of hydraulic conditions increased in the Phase 1 channels:

- velocity range from 0.45 – 0.67 to 0.08 - 0.90 m/sec, extending Chinook spawning areas and adding Rainbow and Steelhead habitats
- depth range from 0.60 – 0.85 to 0.30 - 1.87 m adding Rainbow and Steelhead habitats
- Froude numbers from 0.23 – 0.40 to 0.02 - 0.45 increasing the extent of Sockeye spawning redd conditions.

The lower end of the range occurs during the typical mid-winter low flow periods but the oxbow pools and spawning bars are not de-watered. During high flood events the mainstem channel velocities are reduced because access to the meanders and floodplain has been restored. In addition to the hydraulic changes, several habitat improvements were added:

- v-shaped spawning bars to provide a deeper central channel,
- boulder clusters for cover to the inside margins of the meanders,
- larger cover rocks on the shallow entrance and exit channels to the old oxbows, and
- low rock benches on the east and west banks to confine the lower flows and create target spawning Froude numbers with the decreased flow in the mainstem.

In 2013 portions of the downstream control structure crest (VDS 13) were removed to increase the gradient in the lower portion of the restored reach (Figure 6.26).

Figure 6.26: The v-shaped middle bays of drop structure 13 were widened to a rectangular shape to increase the hydraulic gradient in the lower end of the restoration reach (Mould Engineering 2013).

PHASE II: In 2013 a riffle weir and off-take channel were constructed in the mainstem at the upper end of the restoration reach (Figure 6.27). The backwater elevation allowed low discharges to flow eastwards into an abandoned portion of the original channel (Figures 6.28 and 6.29).

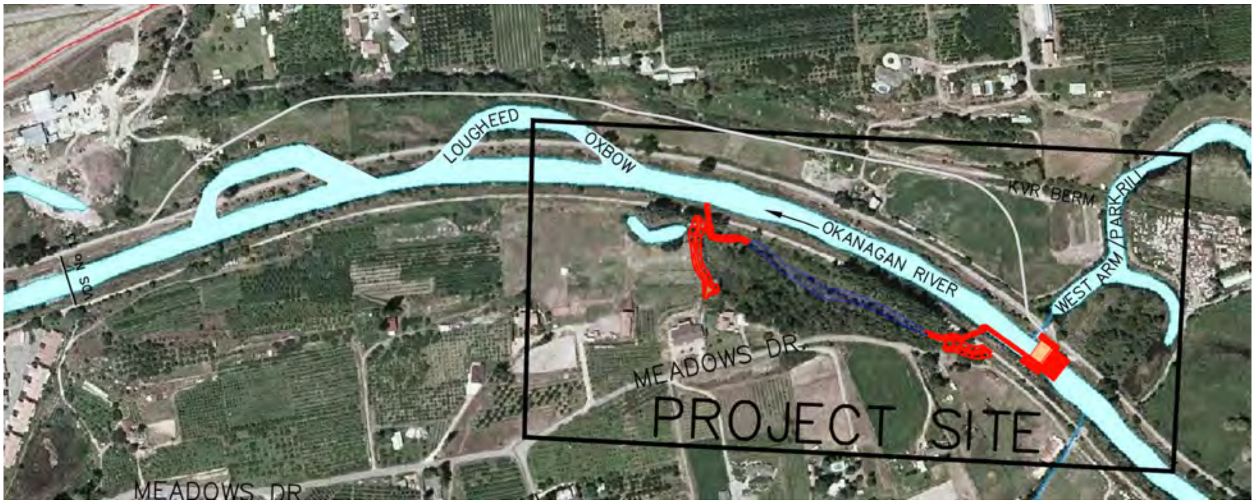


Figure 6.27: Plan showing the riffle weir, side channel entrance and return (red) to an abandoned section of the natural channel on the east side of the upper half of the Okanagan River restoration reach (Mould Engineering 2012).

Figure 6.28: Construction of a mainstem riffle weir and side channel offtake to an abandoned segment of the natural channel on the east side of the restoration reach.

Figure 6.29: To provide pools and shading existing trees and beaver dams were not disturbed between the entrance and exit segments of the side channel.

Okanagan River Spawning Platforms I Penticton BC (2014): Based on the successful use of the spawning ramps added to the mainstem in ORRI Phase I three additional ramps were added to the channelized river below the Okanagan Lake control dam in Penticton BC (Figure 6:30).

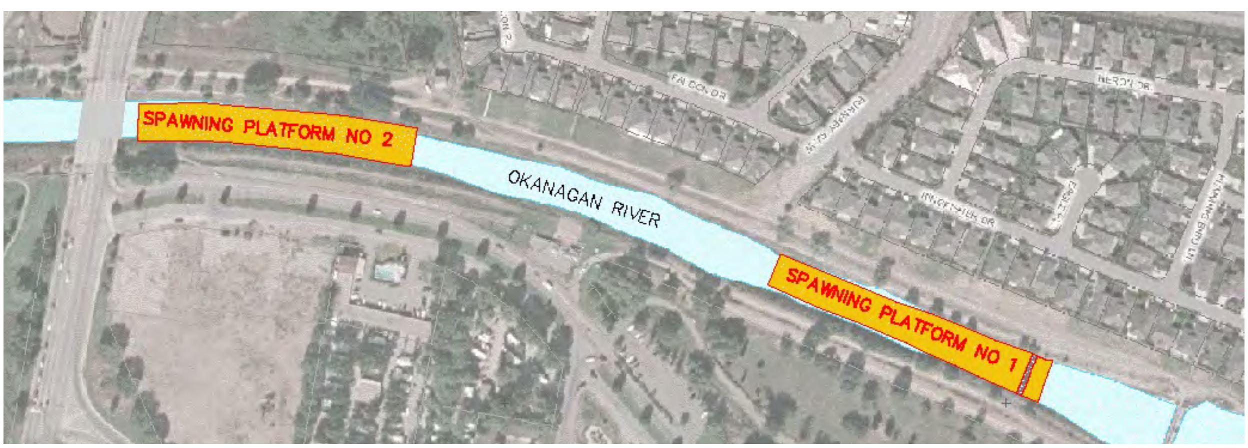


Figure 6.30: Spawning ramps (platforms) added to the channelized Okanagan River below the Okanagan Lake control dam in the city of Penticton BC. A third ramp below the highway bridge was added in 2015.

Washed gravel up to 75 mm in diameter was added to the existing channel bottom (Figure 6:31) The platform 1 profile is shown in Figure 6:32.

Figure 6.31: A central berm of spawning gravels was distributed to both sides of the channel to create the spawning platform.

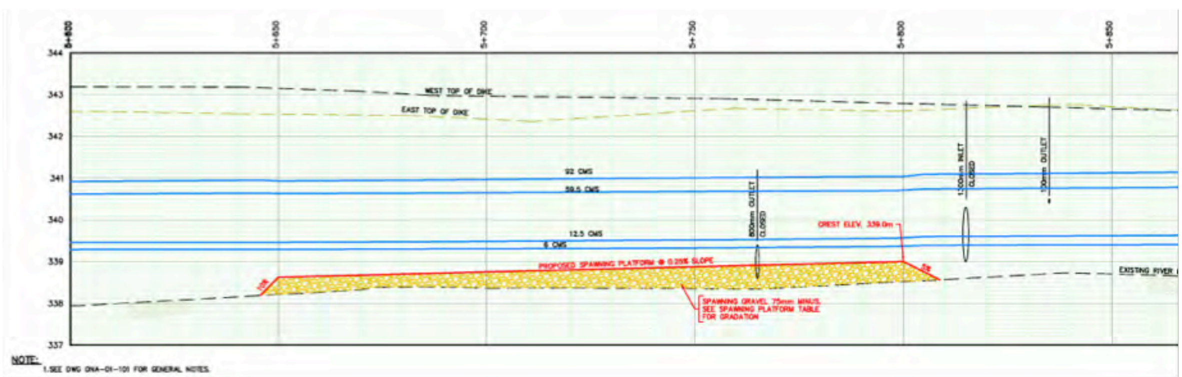


Figure 6.32: Spawning ramp 1 profile (Mould Engineering).

Froude numbers during the spawning period at river flows up to 12 cum/s ranged from 0.15 to 0.24. The spawning ramps were fully utilized in October 2014 and 2015 (Figure 6.33).

Figure 6.33: Spawning sockeye on platform 1, October 2014.

Other Channel Realignment Projects

Flow retarding bars similar to those proposed for navigation channels (Leliavsky 1955) have been adapted to stop bank erosion and re-align the thalweg of a river where meander progression has shifted the main flow away from fixed structures (Victoria Water 1991). Retarding bar projects on the Miramichi River NB: a bank cave-in caused by gravel extraction on the floodplain and a channel infill by sediments from an eroding riparian zone are detailed. Similar salmon pool restoration projects are summarized as well.

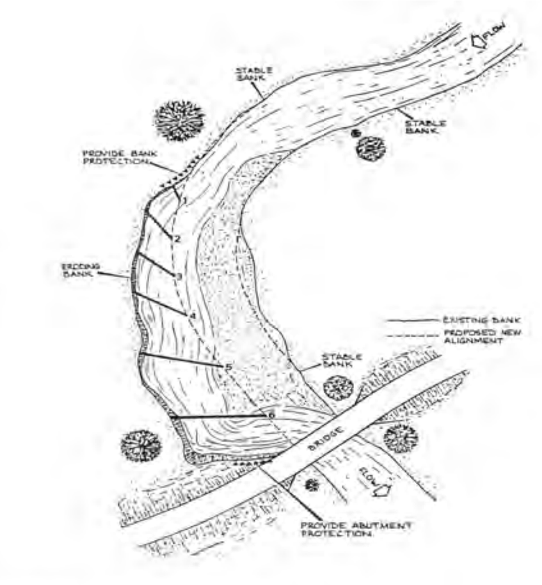


Figure 4.4[5] Example of Final Retard Layout

1. Bank Cave-In, Little SW Miramichi River NB (2000): Bank failure and a channel shift occurred on the Little SW Miramichi River near Lyttleton, NB, locally called the "cave-in" site. Gravel pits near the edge of the entrenched channel filled with runoff and saturated the steep silty-clay banks leading to their collapse. The channel rapidly eroded the collapsed banks forming an almost right angle pocket in the floodplain (Figure 6.34).

Figure 6.34: The "cave-in" reach of the Little SW Miramichi River prior to realignment.

Six flow retarding bars were built across the eroded segment in 2000. The bars project from the bank pointing 10 to 45 degrees downstream. The ends of the bars follow the edge of a new bank with a stable radius of curvature, in this case 2.5 times the river width (Figure 6.35). The height of the bars coincides with the median level floodplain elevation. The bars end with a "hockey stick" tip that is tangent to new curvature of the bank. This prevents back-eddies from swirling around the ends and eroding the tips.

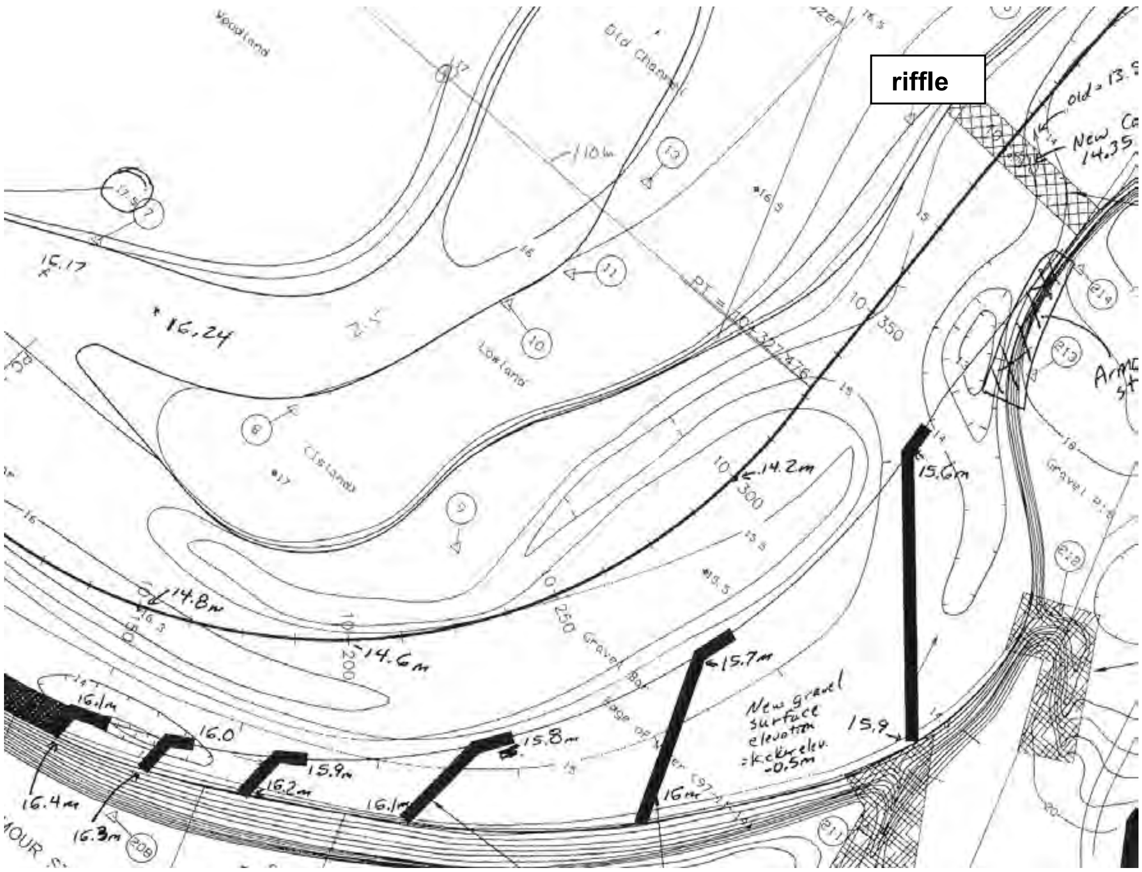


Figure 6.35: Flow retarding bars extend from the eroded bank to re-establish the original alignment of the channel, Little SW Miramichi River NB (R. Jenkins).

To limit the rate of erosion and prevent a headcut above the new alignment a low rock riffle was added below the reach.

The project was researched for NB Fisheries and built by Woods Lake River Enhancement NB (Ron Jenkins).

The re-aligned channel was constructed in stages. The original channel alignment was excavated by stockpiling the point bar materials in a mid-channel berm (Figure 6.36), isolating and seining the old channel segment to capture any stranded fish (Figure 6:37) and then infilling the channel to form the floodplain and install the rock retarding bars (Figure 6:38).

Figure 6.36: A mid-channel berm was formed with the materials excavated from the original channel alignment (photo R. Jenkins).

Figure 6.37: The old channel was sieved to remove trapped fish before it was infilled with the berm materials (photo R. Jenkins)

Figure 6.38: Rock retarding bars with end deflectors parallel to the flow were added to the in-filled floodplain (photo R. Jenkins).

Following construction annual floods and ice movement shaped the channel into a smoothly curving parabolic meander cross-section. (Figure 6:39)

Figure 6.39 (2014): Fourteen years later only the tips of retarding bars are exposed on the edge of the infilled and re-forested floodplain.

The heights of retarding bars is set below the median annual floodplain stage to avoid ice jams and excessive erosion from overtopping flows. For example, low reading bars were added to the Clyburn River NS to restore the channel alignment with the Cabot Trail highway bridge similar to the Australian plan (Figures 6.40 to 6:43).

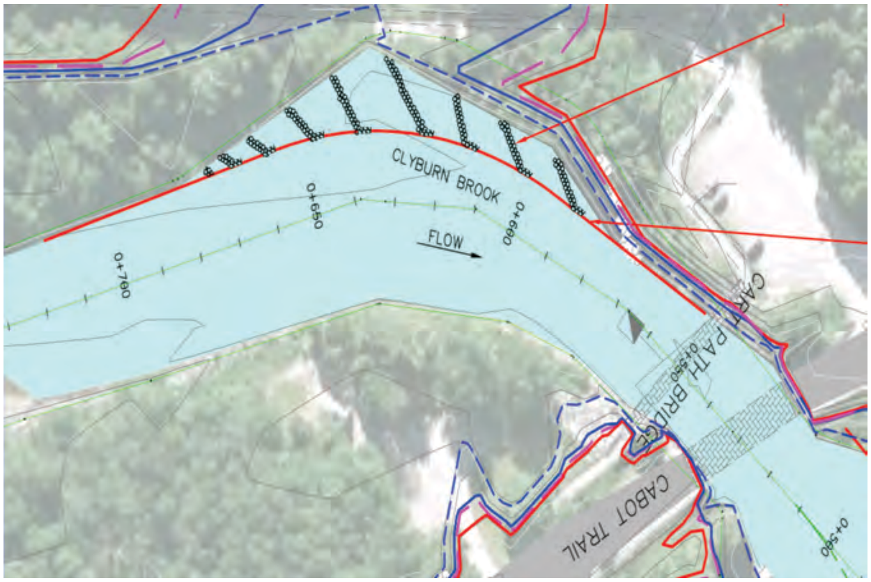


Figure 6.40: Retarding bars added to an advancing meander to re-align the channel with the Cabot Trail cart highway bridge (Mould Engineering 2013).

Figure 6.41: Clyburn River retarding bars under construction (2013). The elevation of the bars is set below the bankfull channel stage.

Figure 6.42: Ice jam and flood in the Clyburn River retarding bar reach, January 2014 (A. Buchanan).

Figure 6.43: Clyburn River retarding bar reach after initial floods and ice jams have re-aligned the channel.

Chapter 7: Restoring Fish Passage

Fish passage works may be designed as pool and riffle channels to create launching pools or swimmable paths through rapids for non-jumping species. Depending on the channel conveyance downstream, small dams and perched culverts up to a few metres in height may be overcome with a series of low riffles that will backflood pools below and through the exit spillway. Higher dams may require independent side channels that lead from the tailrace pond over the dam into the upstream reservoir. In the first example, a two-step pool and riffle profile was constructed to provide a salmon launching pool below the spillway of a dam with a 1.5 m stoplog gate in the outlet of Sakinaw Lake BC. In the second example, a small pool and riffle bypass channel was constructed to provide fish passage for a variety of freshwater fish over a 3 m earth-fill and concrete dam on the Little Saskatchewan River MB. Other fish passage summaries deal with a dam breaching channel, stilling basin backflooding and jump pool creation below overshot gates.

Design Example 1: In-Channel Fish Passage Works, Sakinaw Lake dam, BC.

1. Background: A 2.5 m concrete dam and fish counting basket were constructed in 1955 in the outlet channel of Sakinaw Lake BC, a tributary to the Strait of Georgia (Figure 7.1).

Figure 7.1: The Sakinaw Lake dam before backflooding. There is no launching pool below the spillway for returning coho and sockeye salmon.

The Sakinaw Lake project was built with the Sechelt Indian Band, Fisheries and Oceans Canada (Grant McBain) and FSCI Biological Consulting (Dave Bates).

A gamekeeper monitored sockeye salmon with a manually operated basket trap during the July and October migration periods. By 1990 the dam was no longer attended and the basket trap was abandoned. Initially fish jumped over the spillway when the stop logs were removed. In later years fish were blocked below the dam because 1.5 m high stop logs were kept in place to maintain the forebay lake levels. The launching pool below the spillway was too shallow to allow them to gain enough vertical speed to launch over the spillway (Figure 7.2).

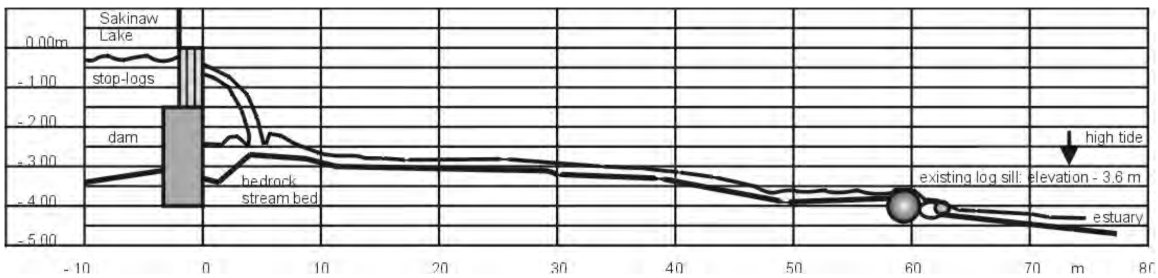


Figure 7.2: Sakinaw Lake BC outlet stream and dam pre-project profile. The launching depth at low and moderate flows is less than 20 cm deep below the dam.

The salmon escapement dwindled from a peak of 150,000 monitored in the late-1980's to 15,000 in 1996 (pers. com. Dave Bates). This estimate was based on returning smolt monitored by the Sechelt Indian Band. Removal of the dam would lower the level of Sakinaw Lake by over 1 m during low runoff periods and was not permitted as it had become a popular water-access recreational site with fixed wharves and beach facilities.

2. Channel Conveyance: The fish passage works were designed to act in concert with the existing spillway and elevated lake levels with the stop logs in place. To accomplish this a spillway rating curve of elevation vs. discharge was established using the critical flow formula. The width and elevation of the first riffle constructed below the dam to create a launching pool were then set so that its rating curve would always exceed the capacity of the spillway at the same elevation. For example, at the full capacity of the dam spillway of 33.5 m^3/s the riffle capacity is 39.4 m^3/s (Figure 7.3). The riffle rating curve is offset below the dam rating curve for all flows. With this configuration the dam did not require re-licensing because the spillway capacity was not affected by the downstream water level.

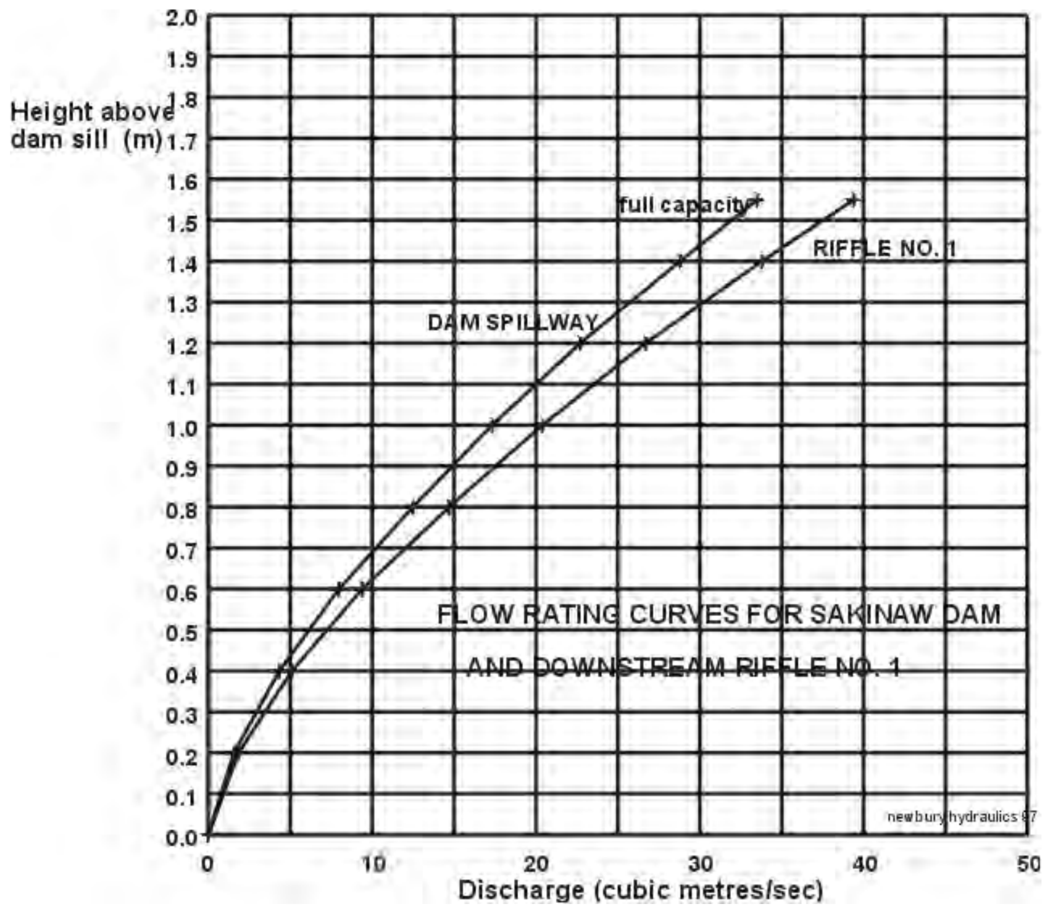


Figure 7.3: Rating curves for the Sakinaw Lake dam and the first riffle downstream.

3. Design and Construction: In 1997 two riffles were used to step the channel from high tide level to the launching pool (Figure 7.4). They were constructed with boulders, cobbles and gravel gathered from the channel and floodplains (Figures 7.5). The riffles were set to pass the maximum spillway capacity using the full width of the channel and floodplains. The minimum launching pool depth backflooded against the dam is 1.2 m under low flow conditions (Figure 7.6). Under flood conditions, there is no backwater effect on the dam spillway (Figure 7.7).

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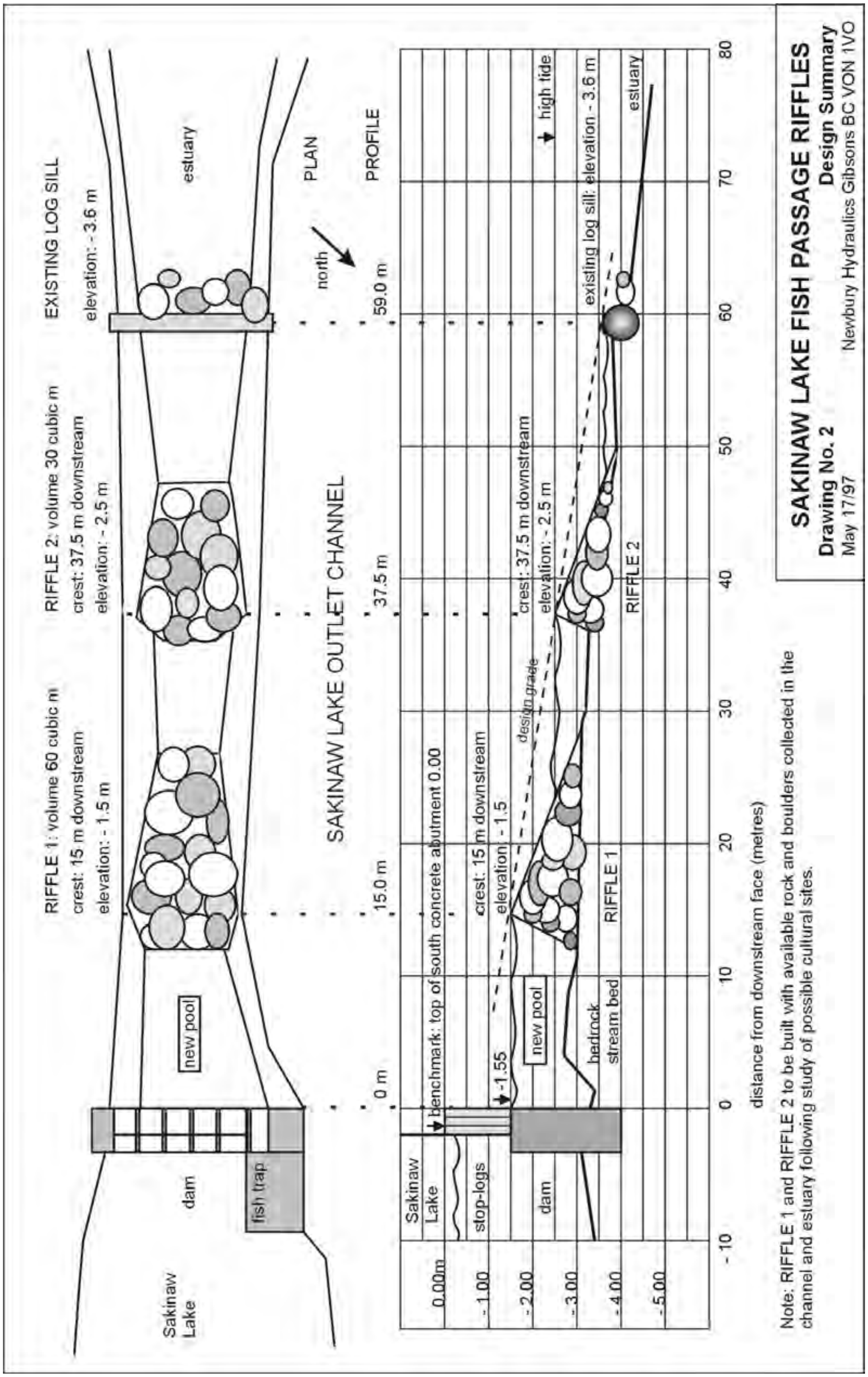

Figure 7.4: Plan and profile of the Sakinaw pool and riffle fish passage works.

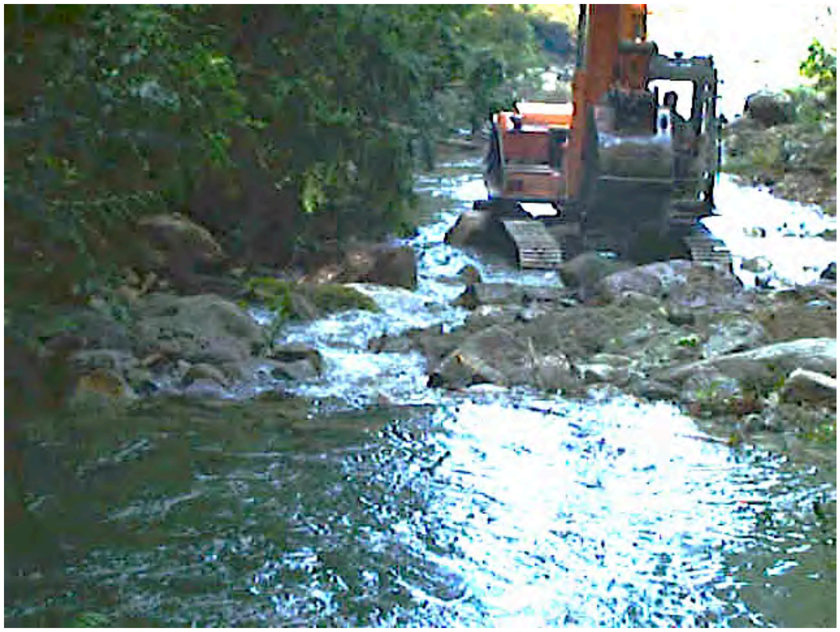

Figure 7.5: Riffle and pool construction below the Sakinaw Lake dam, 1997.

Figure 7.6: The pool formed below the dam spillway was 1.2 m deep under low flow conditions with the stop logs in place.

Figure 7.7: The pool below the dam is lower than the lake level controlled by the spillway at full capacity (stop logs removed).

4. Monitoring: Sockeye and Coho salmon have been observed spawning on both of the constructed riffles and in Sakinaw Lake after 1997. In 2001, the spillway stop logs were not removed to preserve the lake level as it was an extremely dry year. The salmon jumped the maximum height of the spillway from the downstream pool (video frames Figures 7.8 and 7.9).

Figure 7.8: A Coho salmon launching from pool backflooded against the Sakinaw dam spillway.

Figure 7.9: Almost vertical jumps are accomplished from the less turbulent margins of the launching pool below the Sakinaw dam.

Design Example 2: Dam Fish Passage Works, Little Saskatchewan River MB

1. Background: The Rapid City dam on the Little Saskatchewan River, a tributary of the Assiniboine River in southern Manitoba, was first built in 1883 for the town water supply. The present dam was constructed in 1962 (Figure 7.10).

Figure 7.10: The Rapid City water supply dam on the Little Saskatchewan River MB.

The upper tributaries of the Assiniboine had been used for spawning until the vertical spillway (Figure 7.11) blocked the river for all local fish species (walleye, pike, perch, rock bass and various coarse fish). To provide passage, a Denil fish ladder was installed in one bay of the spillway but no fish had managed to negotiate the ladder.

The reservoir is controlled to operate between elevations of 479.3 and 479.6 m. The upper level may be exceeded for short periods before the reservoir gates are adjusted.

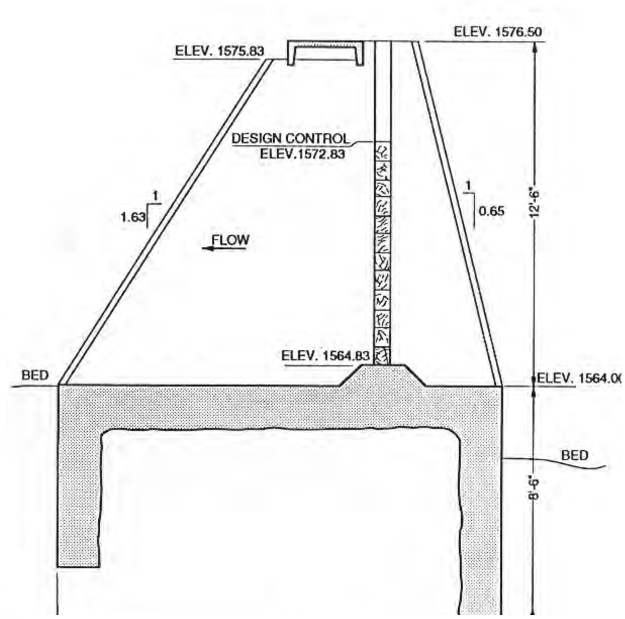

Figure 7.11: Spillway of the Rapid City dam (Manitoba Water Resources Branch 1962).

2. Side Channel Design and Construction: A pool and riffle side channel was constructed in 1992 from the crest of the dam down the lower face of the earth fill portion to the tailrace. The channel was designed to carry a maximum flow of 0.4 m^3/s (Figures 7.12 and 7.13).

Figure 7.12: Aerial view of the reservoir and pool and riffle fishway on the earth fill portion of the Rapid City dam (left bank).

Figure 7.13: The Rapid City pool and riffle fishway channel two years after construction (1994).

Inflow to the upper pond of the fishway channel is through a culvert in the crest of the dam with an adjustable entrance gate (Figure 7.14). During construction the reservoir was lowered to allow the culvert to be placed above the water level. A clay cut-off wall and tamped fill was placed around the culvert to prevent piping at high water levels. The construction plan is shown in Figure 7.15.

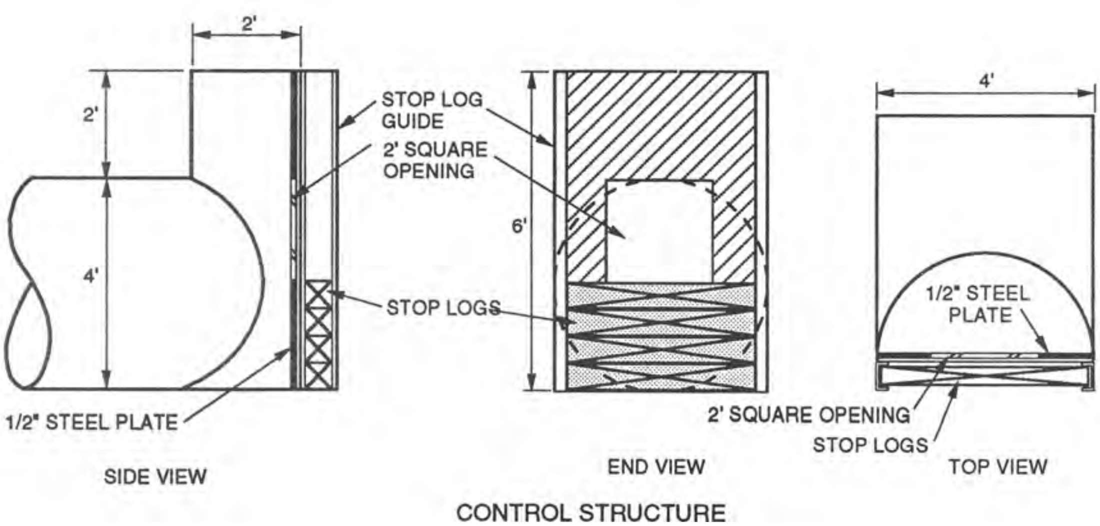

Figure 7.14: Culvert and controlled entrance to the Rapid City fish passage channel. The gate opening may be adjusted by adding or removing stop logs (drawing Ewashko Consulting).

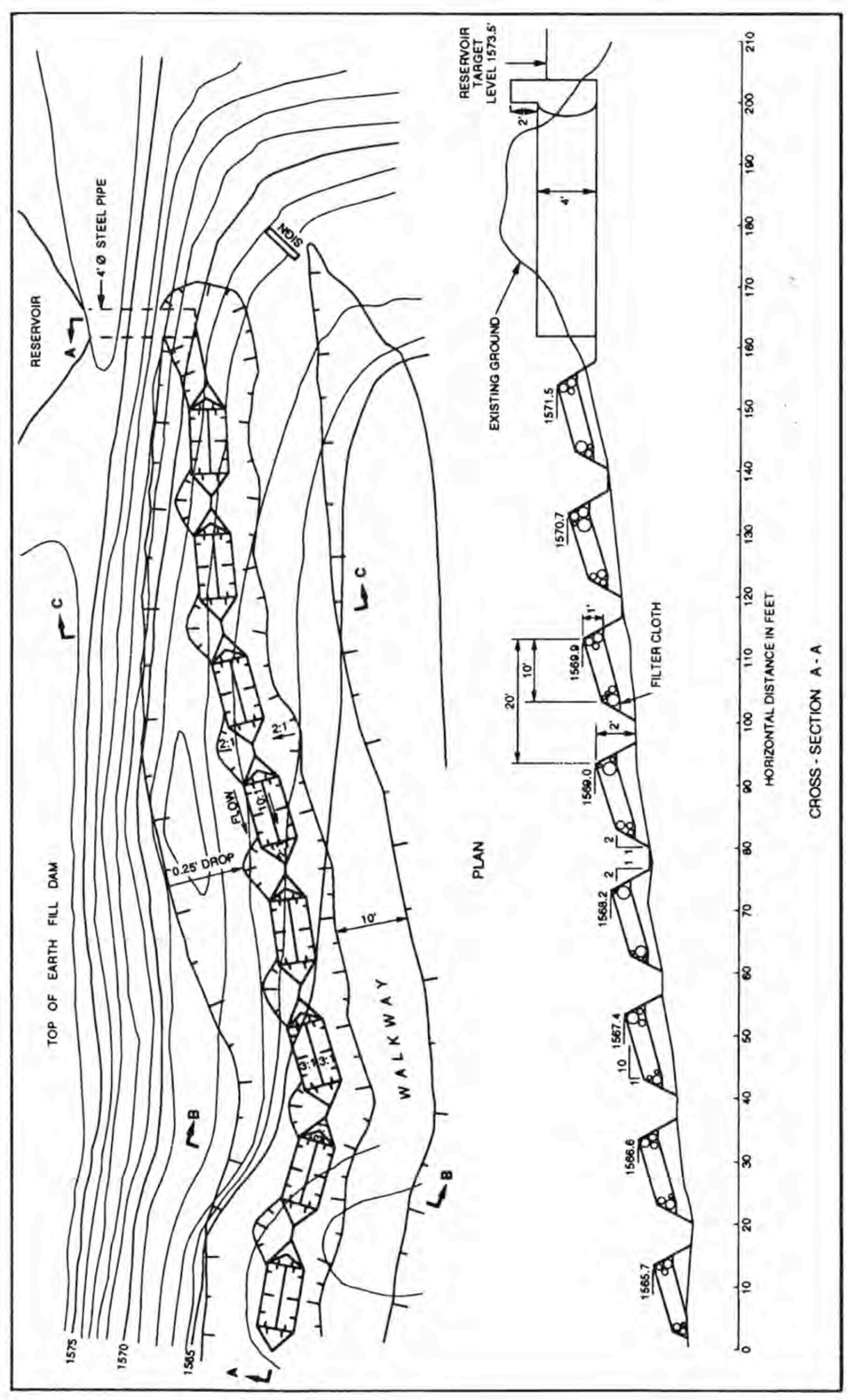

Figure 7.15: Plan and profile of the Rapid City fishway (drawing: Ewashko Consulting).

The size of the inlet opening was set to pass a design flow of 0.4 m^3/s at the maximum reservoir level (Figure 7.16). The top of the inlet is set to the maximum elevation of the reservoir.

Figure 7.16: Entrance control on the culvert leading from the reservoir to the top pool of the fishway.

The crest of the riffle controlling the water level in the culvert is low enough to allow free overflow at the entrance. The inlet crest can be lowered to maintain the design flow at lower reservoir levels. With the top of the 2 foot square gate set at the water level, the critical depth spilling into the culvert is 0.41 m with a critical velocity of 2 m/s. The discharge is 0.4 m^3/s. The effective width of the inlet was reduced by the factor 0.8 to allow for the contraction of the flow (Brater and King 1976).

The channel was built on the downstream face of the dam by adding compacted fill and a cobble toe drain without disturbing the original dam materials (Figure 7.17).

Figure 7.17: The pool and riffle fishway is built on impervious fill added to the earth fill segment of the dam. The structure toe drain has been extended beyond the new fill boundary (Figure 7.18).

The riffle cross-sections were v-shaped and built with boulders and cobbles to allow for passage at low flows (Figure 7.18).

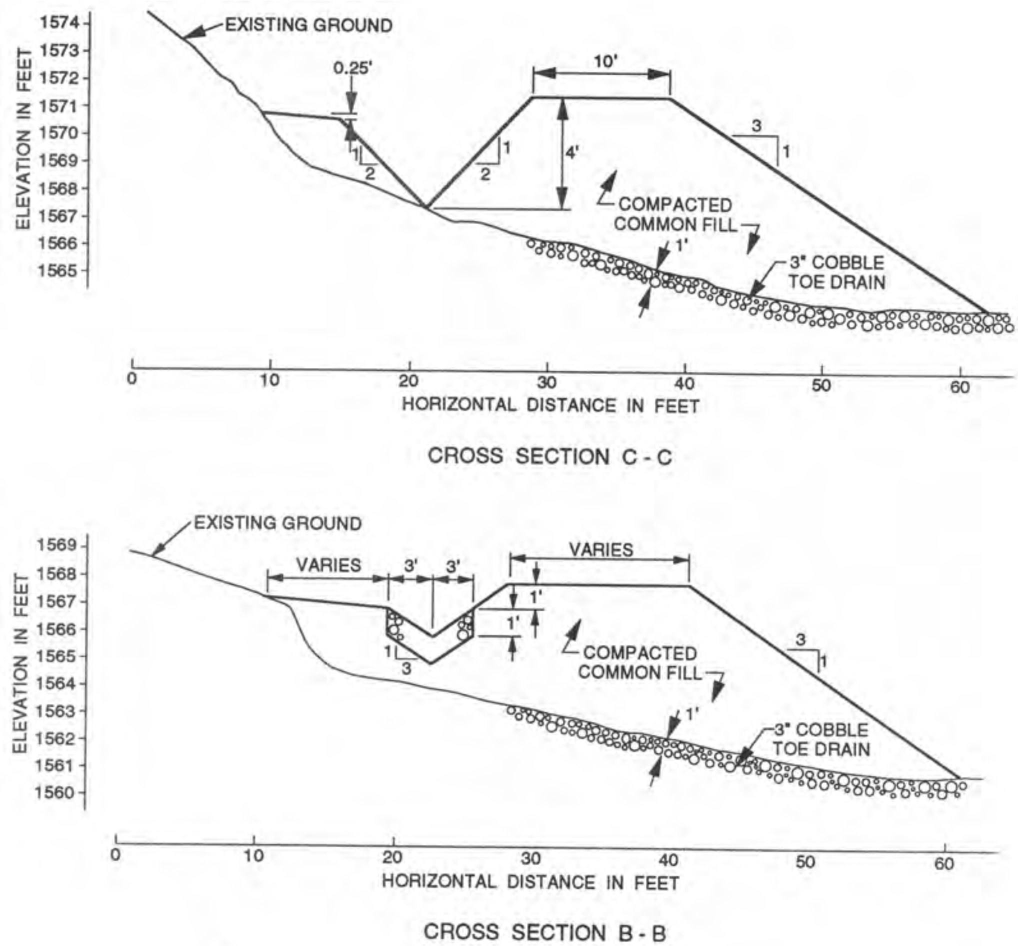

Figure 7.18: The fishway is built on new material added to the existing dam with a toe drain that joins with the original toe drain (drawing Ewashko Consulting).

The flow capacity of the v-shaped riffle crests is equal to the inlet capacity at the maximum reservoir level. Boulders on the riffle crests were adjusted by hand to obtain a central torrent that caused two side eddies to form in the downstream pools to create resting areas.

The Rapid City dam project was constructed by the Manitoba Habitat Heritage Corporation, Ewashko Consulting (Arvin Ewashko) and Manitoba Fisheries (M. Gaboury, M. Erickson).

3. Monitoring: Spring fish migration through the channel was monitored using nets set in the reservoir in front of the culvert entrance. All native species were found passing through the channel, much to the enthusiasm of upstream anglers and the citizens of Rapid City. Lighting was added along the channel to discourage fish poaching at night. No modifications have been required although the v-shaped crests appear to have flattened by one means or another (Figure 7.19, 8 years later). Similar fishway projects for higher dams were successfully undertaken at other water supply dams in the Assiniboine River basin by KGS Engineering Ltd. (Winnipeg MB).

Figure 7.19: Rapid City pool and riffle fishway, July 2000.

Other Fish Passage Project Summaries

1. Dam Breaching: Occasionally there are projects such as dam breaching or complete dam removal that require stepped channels to restore the connection to the river. The geometry is based on creating a stable fish-passable connection and may vary from the spacing and curvatures observed in natural channels. A typical breaching project was undertaken to re-connect Cranberry Creek by removing the old Revelstoke City dam in southern British Columbia. After the reservoir was de-watered, a wide stable notch was excavated through the dam to the level of the valley bottom (Figure 7.20). The project was reviewed several times over 10 years before it was undertaken in 2003 by BC Hydro (Seyers 2004). The original sketch design proposed in 1994 is shown in Figure 7.21. A stepped channel with 1 metre high riffles was built through the notch, climbing from the level of the first natural pool below the dam to the former shoreline of Coursier Lake impounded under the reservoir (Figure 7.22). The emergent rock spacing and low flow channels on the surface of the steep rock riffles were adjusted for fish passage prior to commissioning by pumping 0.5 m^3 from Coursier Lake into the head of the channel (2003, Figure 7.23). Fish passage has been observed in subsequent years.

Figure 7.20: A stable notch was excavated through the old Revelstoke City dam to re-connect Cranberry Creek in 2003 by BC Hydro (photo W. Seyers).

The Coursier Lake dam decommissioning project was undertaken by BC Hydro Construction (Carol Lamont, William Seyers).

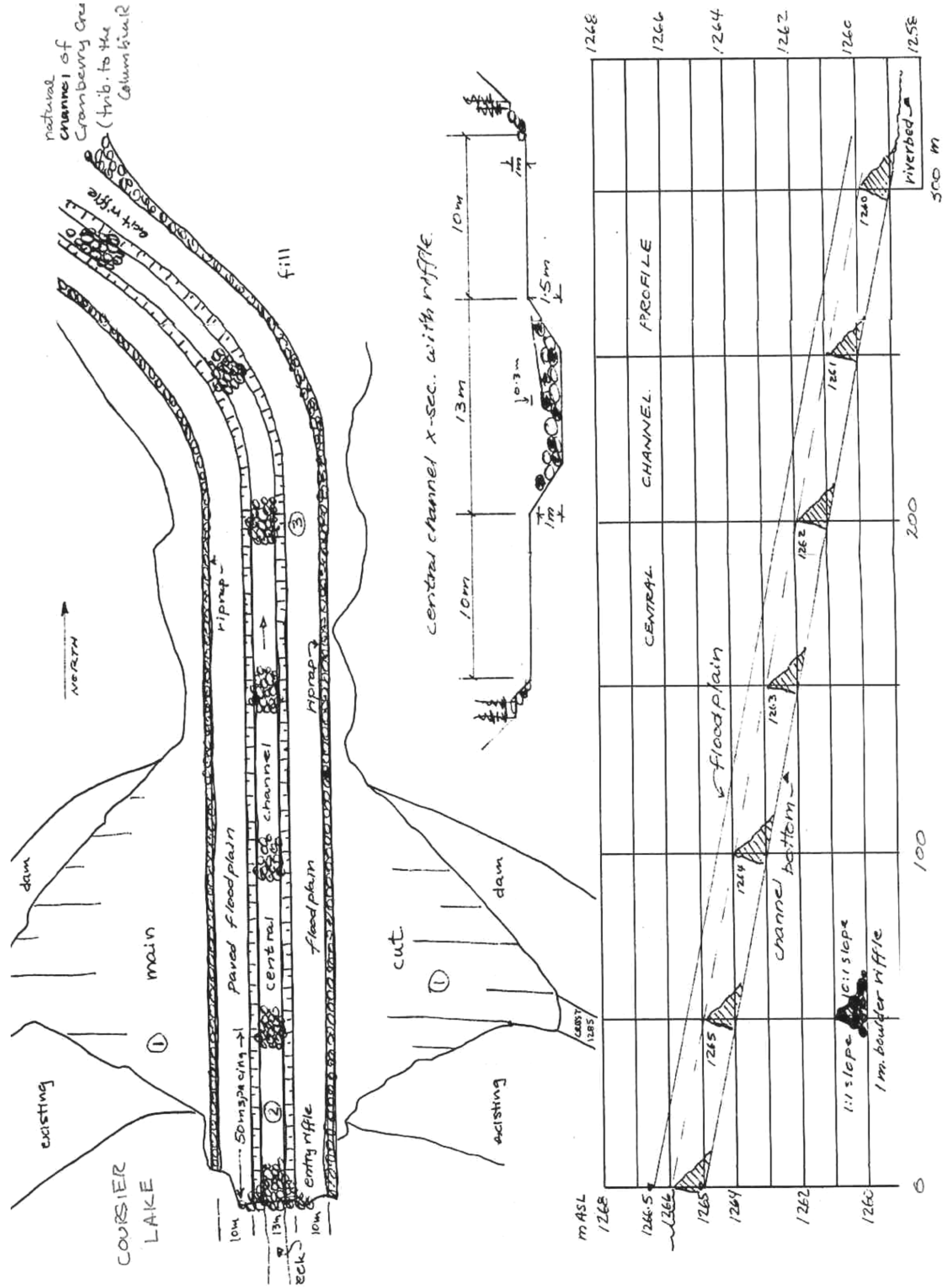

Figure 7.21: Sketch design for notch through dam and stepped channel re-connection of Cranberry Creek (Newbury Hydraulics design 1994).

Figure 7.22: The level range of Coursier Lake was re-established by setting the elevation and width of the upstream riffle entering the stepped channel (photo W. Seyers).

Figure 7.23: Low flow channels on the rock riffles were measured and adjusted for fish passage prior to the commissioning of the connecting channel with a pumped flow of 0.52 m^3/s (2003).

2. Stilling Basin Backflooding

Example 1 Okanagan River BC (salmonid species): Seventeen vertical drop structures reduce the gradient of the shortened channelized reaches of the Okanagan River, BC (Figure 7.24).

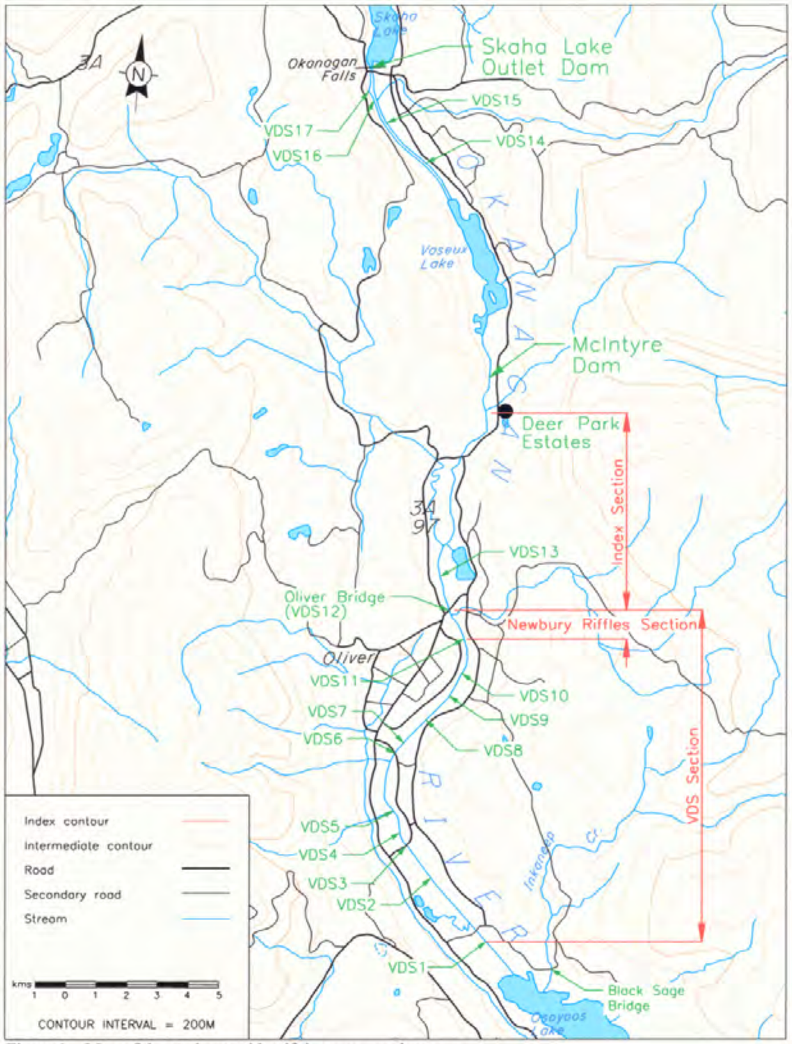

Figure 7.24: Seventeen vertical drop structures (VDS) are required to control erosion of the steeper channelized and dyked southern reach of the of the Okanagan River, a spawning tributary for Columbia River sockeye salmon (Long 2003A).

A common structure design was used with a shallow concrete platform below the spillway that drops into a stilling basin (Figure 7.25). During the fall migration period salmon pass through the structure by launching from the stilling basin, landing on the platform and bursting over the spillway crest.

The VDS 13 project was undertaken by Mould Engineering (Kelowna) (Jody Good, Stu Mould) as part of the Okanagan First Nations river restoration plan (Karilyn Long Alex).

Figure 7.25: Vertical drop structure #13 on the channelized section of the Okanagan River near Oliver BC.

To reduce the fish passage effort, a pilot project was undertaken in 2001 backflooding VDS 12 in Oliver BC. Four riffles were constructed downstream from the structure to gradually step up to the backflooding elevation. The crest of the highest riffle was set low enough to not affect critical flow over the structure crest. The design profile and completed upper riffle are shown in Figures 7.26 and 7.27. The velocity measurements in several chutes constructed on the riffle surface were taken at a discharge 8 m^3/s, typical of the flows during the Fall spawning migration period.

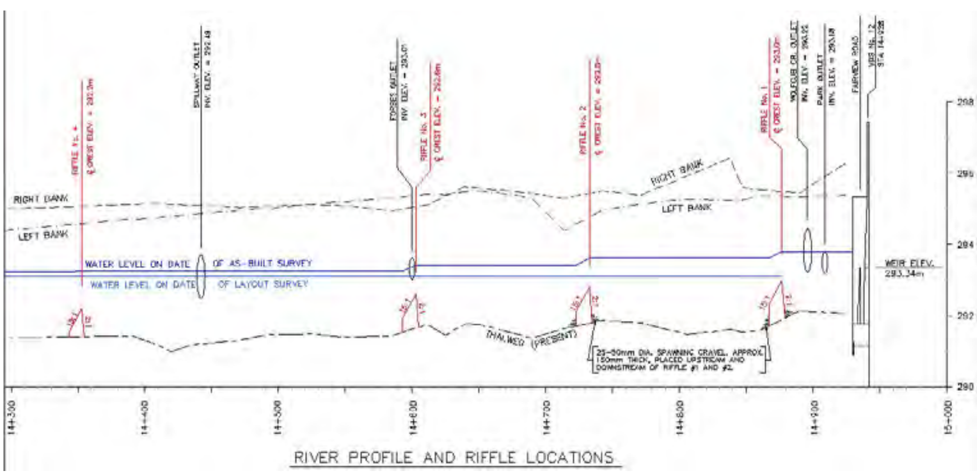

Figure 7.26: Design profile for backflooding VDS 13 on the Okanagan River in Oliver BC shown with a vertical exaggeration of 30:1 (Mould Engineering Ltd. 2001).

Okanagan River Constructed Riffle No. 1 at Oliver

Maximum Velocities in Chutes

	length m	width m	depth m	velocity m/s
A	3.0	0.4	0.3	1.6
B	4.0	1.0	0.2	1.4
C	7.0	6.0	0.2 - 0.4	1.2 – 2.0
D	4.0	1.0	0.25	1.5 est.

(discharge approx. 8 m^3/s, no backflooding, 08/22/01)

Figure 7.27: The upper riffle below VDS 13 as constructed in 2001.

Sockeye salmon spawned on the upper gravel slope of the riffles as soon as they were constructed. (Figure 7.28, Long 2003A).

Figure 7.28: Spawning sockeye on the upstream slope of the first riffle below VDS 13 (2001).

The upper riffle passing a flood discharge of 70 m^3/s in May 2006 is shown in Figure 7.29. The v-shaped surface of the riffle forms a central torrent with low-velocity back-eddies on the banks.

Figure 7.29: The upper riffle below VDS 13 at a flood discharge of 70 m^3/s (2006).

Example 2 Roseau River MB (freshwater species): The Roseau River is a tributary of the Red River rising in northern Minnesota. A wide range of freshwater species including northern pike, walleye, goldeye, rockbass, drum, catfish and lake sturgeon utilize the river. In 1957 a typical water supply dam was built on the river for Dominion City MB (Figure 7.30). Fish migration over the dam (no stop logs in place) was limited to Spring runoff periods in high flow years when there was sufficient depth in the stilling basin to allow fish to approach and swim over the crest. Two riffles below the dam and a rock ramp in the stilling basin (Figure 7.31) were added in 1992 to provide

Figure 7.30: The Dominion City water supply dam on the Roseau River MB.

passage over the crest under all flow conditions. The construction detail and an upstream view of the completed project are shown in Figures 7.32 and 7.33.

Figure 7.31: A rock ramp with low flow channels was added to the dam stilling basin leading up to the spillway crest. A few oversize rocks from nearby fields were enthusiastically added after the initial construction.

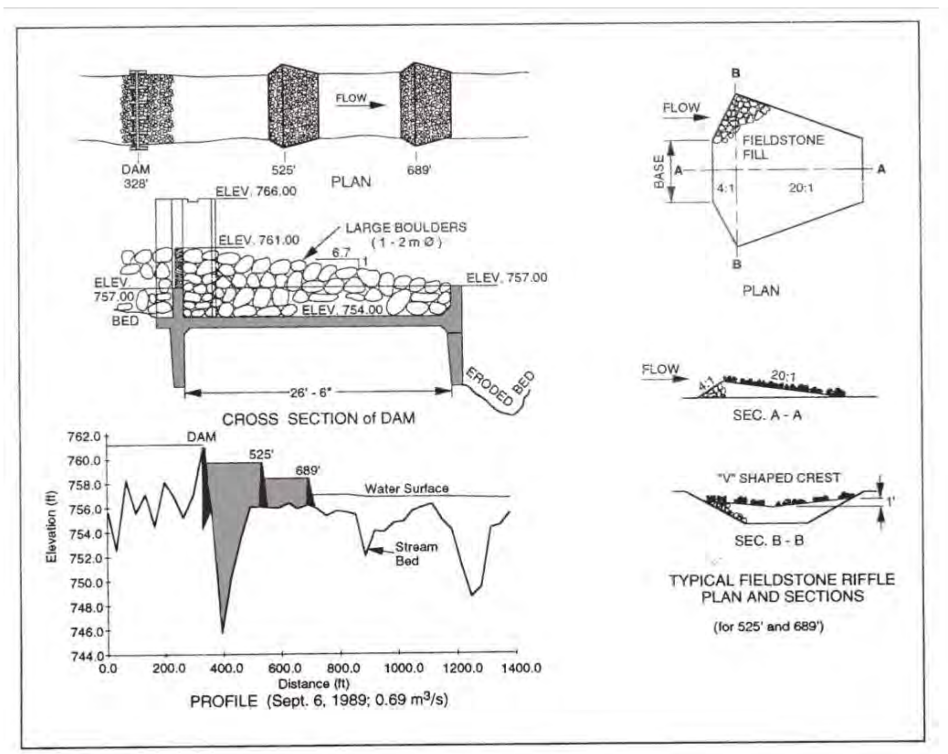

Figure 7.32: Roseau River dam back-flooding construction details (Gaboury et al. 1995).

Figure 7.33: Upstream view of the two riffles and ramp back-flooding the Roseau River dam.

No re-construction was required after the Red River maximum flood of record (144 year return period, Burn and Goel 2001) occurred in 1997. Debris from the flood was removed from the ramp and riffle sites after the flood (Figure 7.34).

Figure 7.34: The Roseau River fish passage works following the maximum Red River basin flood on record in 1997.

The Roseau River dam project was constructed by the Manitoba Natural Resources Branch (M. Gaboury, M. Erickson) and the South East Border Wildlife Association.

3. Overshot Gate Passage: When impounded water is released under vertical gates, the upstream head is almost entirely converted into kinetic energy. The shallow high velocity flow under the gates exceeds fish burst speeds. Passage may be restored by replacing the "undershot" gates with overflowing gates and a deep launching pool in the stilling basin below the dam. For example, the vertical gates on the McIntyre dam on the Okanagan River below Vaseux Lake BC blocked the upstream progress of Columbia River sockeye salmon for over 60 years (see location Figure 7.24). Shallow flows shooting under the gates during the low flow migration period reached velocities of 7 m/s (Figure 7.35). The aerated plunge pool in the shallow stilling basin was impassable. To replace the gates the dam piers in each bay were extended downstream to form a passage that could be blocked by a gate hinged to the lower lip. The gates are raised or lowered from above with a power driven spindle and cables.

Figure 7.35: Five undershot gates on the McIntyre dam spillway (Okanagan River BC) before replacement with overshot gates in 2009.

A 1.9 m high river-wide riffle was built below the dam to create a launching pool that is l.1 times the height of the maximum jump in depth (Figures 7.36 and 7.37). Salmon successfully swam up the riffle and launched over the gates as soon as they were opened (Figures 7.38 and 7.39). Ground and aerial surveys above the dam found over 4000 redd sites in gravel bars and riffles between VDS 14 and VDS 17 in the Vaseux Lake to Okanagan Falls reach (Figure 7.24) (pers. com. Camille Rivard-Sirois, ONA).

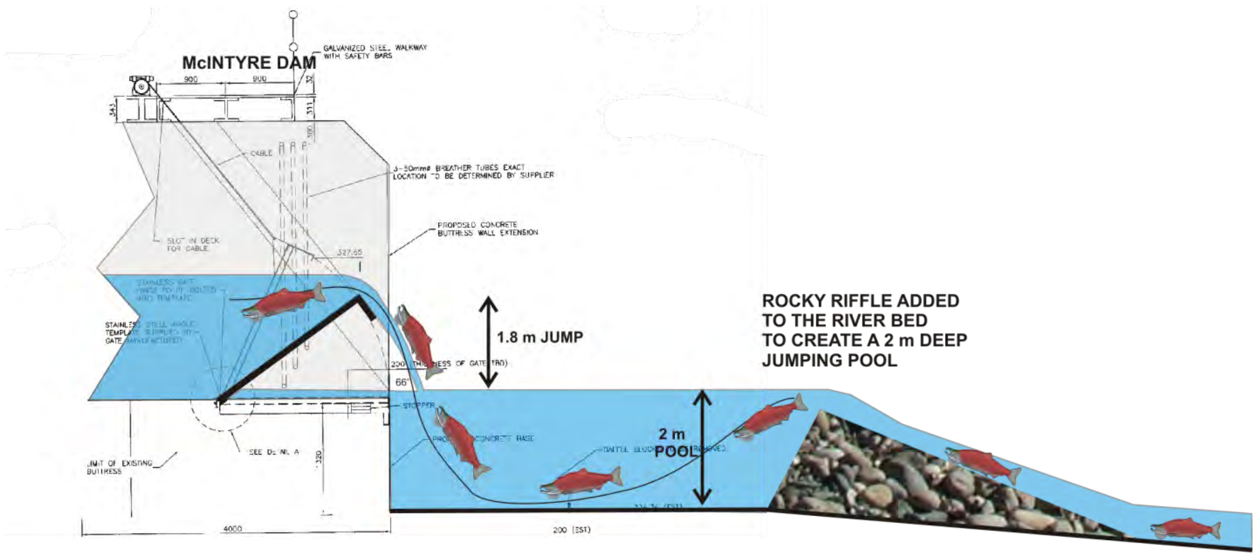

Figure 7.36: Fish passage over the McIntyre dam gates was achieved by creating a 2 m deep launching pool and setting gate discharges that would allow the fish to navigate under and through the aerated portion of the new plunge pool (background dam drawing Associated Engineering Ltd. BC).

Figure 7.37: A 1.9 m high riffle was constructed 50 m downstream from the dam to create a deep launching pool approaching the gates.

The McIntyre dam project was supervised by Associated Engineering Ltd. Kelowna (Rod McLean) for the Okanagan Nations Fisheries Department (Karylin Long Alex, Camille Rivard-Sirois). The overshot gates were manufactured by ARMTEC Ltd. (Calgary) and installed by Greyback Construction Ltd., Penticton.

Figure 7.38: Sockeye salmon swimming over the crest of the riffle into the backflooded jumping pool (photo R. McLean).

Figure 7:39: Sockeye salmon passing the overshot gates set at approximately 2 cum/s (photo: R. McLean).

Tests during the spawning run indicated that gate openings greater than 2 m^3/s created too large a pool of aerated flow in the flooded stilling basin that limited the zone of solid swimmable water necessary to achieve exit velocities below the gates (Figure 7.40 and 7.41).

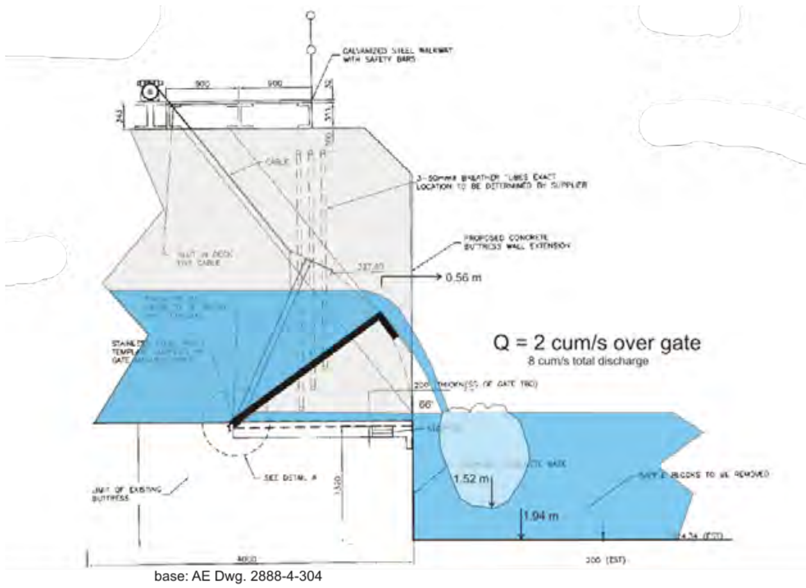

Figure 7.40: The extent of aerated water at a gate setting of 2 m^3/s based on jet penetration tests by Clanet and Lasheras (1997). The plunge pool does not reach the bottom of the launching pool.

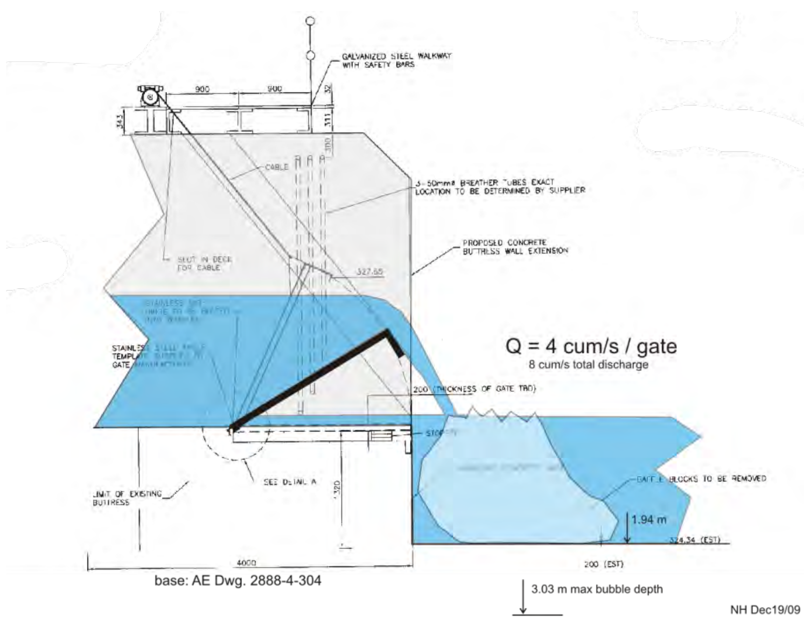

Figure 7.41: The aerated plunge pool fills the stilling basin a gate setting of 4 m^3/s.

An zone of solid water next to the dam underlies the bubble cloud at 2 m^3/s. At 4 m^3/s and greater the plunging flow strikes the bottom of the stilling basin and fills the zone below the gate with a return current of aerated water. Underwater images were obtained with a Didson Dual Frequency acoustic camera (G. Cronkite, DFO Canada).

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