

# Constructing Riffles and Pools in Channelized Streams

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## Abstract

Pool and riffle hydraulics may be created in some channelized and uniform streams by adding riffle structures that mimic natural materials and dimensions. The structures and hydraulic conditions observed in natural streams serve as template designs with appropriate adjustments to fit the catchment hydrology and hydraulic geometry of the restored reaches. Two examples of the analysis, design, and construction of riffle reaches are presented for streams with gradients of 0.3% and a 3.0% respectively.

## Introduction

Urban and agricultural developments on floodplains, alluvial fans and deltas are often facilitated by relocating and channelizing (uniformly excavating) streams (Apmann and Otis 1965, Bates et al. 1996 in prep., Corning 1975, Emerson 1971, Hogan 1986, Keller 1975). Two typical streams that have been channelized for agricultural and industrial developments



Figure 1: Mink Creek Walleye Spawning Restoration Project 1985, Central Manitoba. The channelized and unstable reach prior to the addition of rock riffles.

are shown in Figures 1 and 2 (Mink Creek, Manitoba and Oulette Creek, British Columbia). In these uniform channels, the natural sequence of pools and riffles or swift and flat water features are eliminated. Regular flood flows may re-build the features but in many cases, the lack of suitable bed materials, changes in the flow regime, and long periods of recovery can eliminate suitable invertebrate and fish habitats for decades.

Aquatic organisms have evolved to exploit the spatial and temporal variations found in pools, riffles and meanders (Allan 1995, Frissell et al. 1986, Higler and Mol 1984, Sullivan et al. 1987). The replacement of this complexity with uniformly graded channels reduces or eliminates the sorting of substrates, vegetation and woody debris in pools, overhanging riparian vegetation, and a variety of flow structures and functions (Apmann and Otis 1965, Corning 1975, Emerson 1971, Keller 1975).



Figure 2: Oulette Creek Diversion Channel 1978, Howe Sound, BC.

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## Meander, Pool and Riffle Habitats

The repeated wave-form of naturally flowing waters that creates meanders, pools and riffles has been observed and measured by stream researchers and anglers. One of the earliest observers was Tokkichi Kani, a student of stream habitats in Japan (1981). Kani found that the preferred habitats of benthic insects and fish could be related to the pattern of pools and riffles on the stream bed. In the 1930's, he proposed a classification system for a range of streams based on their pool and riffle patterns (Figure 3).

The significance of pools and riffles to trout stream habitats was observed by Stuart in Scotland as well (1953). He was one of the first stream restorers to have naturally-spaced pools and riffles built on a channelized stream bed as described in Leopold, Wolman and Miller (1964):

*Being concerned with the effect of diversion and re-alignment of certain gravel streams in Scotland on their ability to maintain trout, Stuart noted that new stream beds dredged by a dragline were, when just constructed, of uniform depth without pools and riffles. With the aim of producing the usual pool and riffle sequence, he directed the operator of the dragline to leave piles of gravel on the stream bed at intervals appropriate to riffles .. that is, 5 to 7 [stream] widths apart. After a few flood seasons, these piles had been smoothed out and presented to the eye a picture that in all respects appeared natural for a pool and riffle sequence. Moreover, the riffles so formed have been stable over a number of years of subsequent observation.*

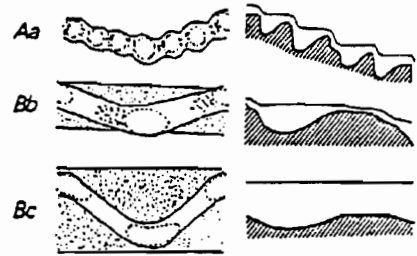


Figure 3: The classification of pools, riffles and meanders for several Japanese streams (Kani [1944] 1981).

The dimensions of pools and riffles and their relationship to river size was summarized by Leopold, Wolman, and Miller in 1964 and Gregory and Walling in 1973. The natural width and corresponding flood discharge for channels that range in size from those of small streams to the Amazon River follow a surprisingly unified relationship (Figure 4, Kellerhals and Church 1989).

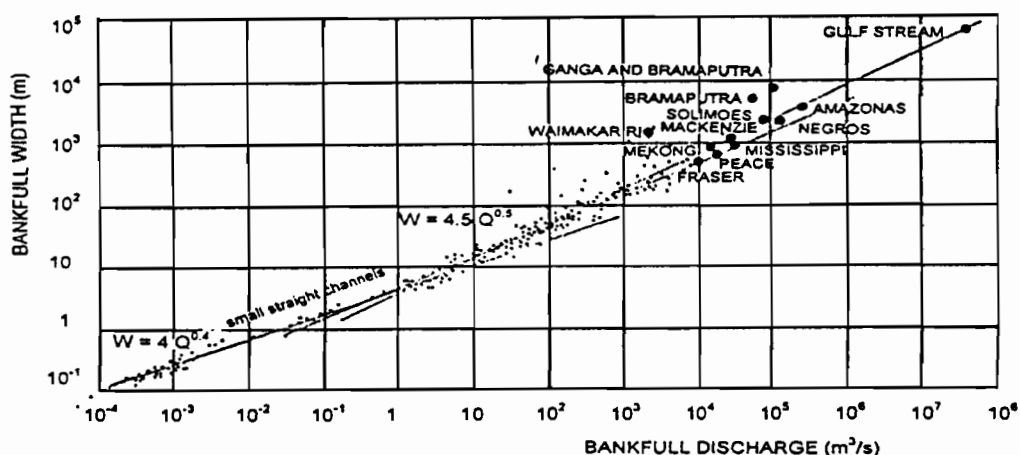


Figure 4: The relationship between bankfull width and discharge has been compiled for all ranges of river size by Kellerhals and Church (1989). For streams with bankfull discharges between 1 and 1000 m<sup>3</sup>/sec, the relationship was estimated to be width = 4.5 x bankfull discharge<sup>0.5</sup>.

The average length of a pool and riffle reach was found to be 6 times the bankfull width of the river. For some combinations of discharge and slope, rivers were found to meander horizontally with the same wave form as well. The average meander wave length was found to be 12 times the bankfull width as it consists of two pool and riffle reaches. The average radius of curvature of the meander bends was 2.3 times the bankfull width.

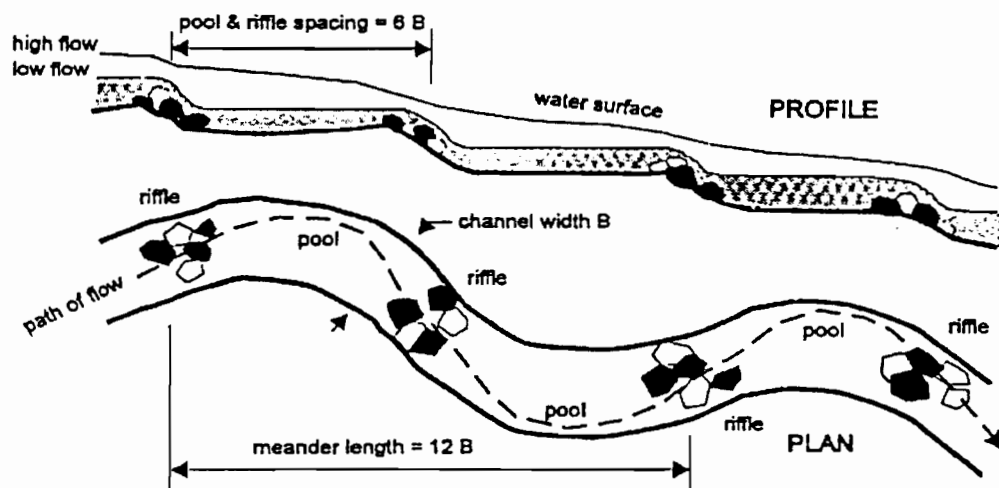


Figure 5: Pool and riffle profiles are formed in erodible channels with an average spacing of 6 times the bankfull width. In steeper streams, and where logs and tree roots are abundant, the spacing decreases.

These dimensions are important in understanding the structure and function of the habitats created in the water mass. For example, the outside bends of meanders in rivers with erodible banks are scoured and trimmed by regular bankfull flood flows (Figure 5 plan), often forming deeper pools with overhead cover that are preferred by trout. A fly cast into the centre of the riffle above the meander pool is carried to the outside of the bend under the overhanging bank and back across the lower edge of the pool by the curving helical flow that occurs as the stream changes direction. Surveys of trout habitat in mid-Canada have shown that the most preferred reaches occur in meanders with an average curvature of 2.3 river widths, suggesting that the fish may have adapted to the flow patterns and habitats created by the most frequently encountered meander curves in natural rivers.

At intermediate and lower discharges, water is stored in the pools impounded above the riffles or rapids (Figure 5, low flow profile). This maintains deeper fish habitats required for all life stages of the fish and provides water for passage up and down the river. In the riffles, the shallow flows are broken into chutes and waterfalls by cobble bars and boulders (Figure 6). Where the flow drops over an obstruction or is drawn through a narrow gap between boulders, it often reaches the critical state, a condition where the velocity is maximized for the total static and kinematic head of water that exists above the obstruction. If the water continues to accelerate over and past the obstruction, it attains super-critical velocities. Achieving this state of flow is important to maintaining the dissolved oxygen level in the river water. The super-critical flow sweeps air bubbles into the water and forms a hydraulic jump as it enters a deeper pocket or pool of sub-critical water downstream. The collapsing air bubbles rapidly re-aerate the flow. This is also the source of noise in the river as the breaking bubbles on the surface make the sounds of babbling brooks or roaring rapids. It may be an important acoustic signal for detecting spawning areas and passage opportunities (Stuart 1953).

The shallow flows in riffles are efficient habitats for caddisflies, blackflies, and other benthic insects (Statzner et al 1988). By locating on the tops and sides of boulders, they are able to expand their capture nets and cephalic fans to gather detritus from the flow as it converges to narrow passages over and around cobbles and boulders. The varied structure of the flow also creates chutes and local backeddies that allow fish to follow a deeper and staged path through the rapids.

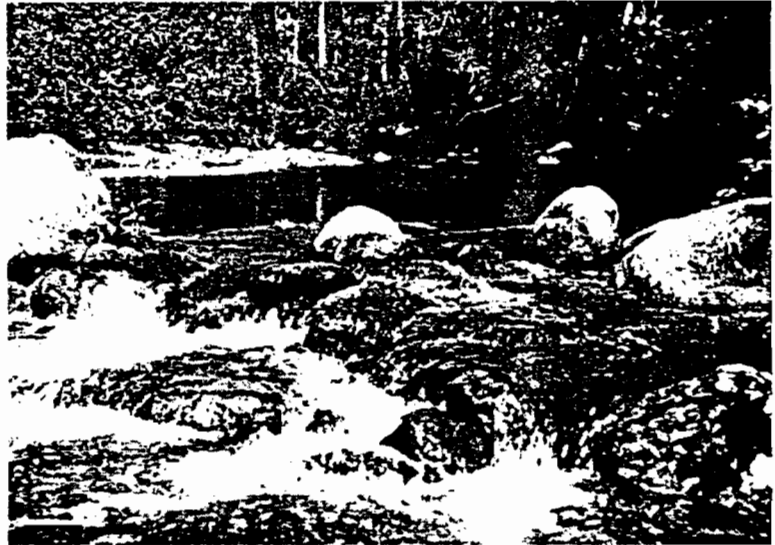


Figure 6: Varied natural flow states in a small rapids and upstream pool on the Pine River in central Manitoba.

### Designing and Constructing Pools and Riffles

Properly designed rock riffles or rapids may be constructed in naturally uniform and channelized streams to re-establish some aspects of their lost habitats. A successfully constructed riffle and pool in a channelized reach of Chapman Creek (Sechelt Peninsula, BC) is shown in Figure 7. Other examples of pool and riffle restoration projects and techniques are described in Brookes (1987), Gregory et al. (1994), Jungwirth et al. (1995), Madsen (1995), Muhar et al. (1995), Newbury and Gaboury (1993, 1994) and Shields et al. (1995). The projects have enhanced walleye (*Stizostedion vitreum*) spawning habitat and fry passage in uniformly excavated drainage channels, created year-round adult rainbow and brook trout (*S. fontinalis*) habitats in naturally uniform bedrock and boulder-dominated streams, and increased salmon spawning and over-wintering habitats in coastal streams.

Pool and riffle restoration projects are based on the pattern of channels and their natural dimensions in the catchment. The design process is summarized in Table I. Constructed riffles should mimic natural rapids in form, materials, and function as closely as possible. Stability of the riffles is not absolute, but can be adjusted to the bankfull flow stage assuming that higher floods will utilize floodplains. In channels where floodplains are removed or constricted, higher than bankfull flows must be evaluated as well.



Figure 7: Chapman Creek Restoration Project 1995, Strait of Georgia, BC. Coarse gravel bars have in-filled in the upstream pool that are utilised by spawning salmon. The downstream slope and crest elevation were not changed by greater than bankfull flood flows.

- 1) **Basins:** trace watershed lines on topographical and geological maps to identify the rehabilitation drainage basin and, if possible, nearby natural basins. Map the stream orders and measure a typical set of tributary drainage areas.
- 2) **Profiles:** sketch mainstem and tributary long profiles to identify discontinuities which may cause abrupt changes in stream characteristics (falls, former base levels, bedrock outcrops, etc.).
- 3) **Flow:** prepare a flow summary for the rehabilitation reaches using existing or nearby records if available (flood frequency, minimum flows, historical mass curve).
- 4) **Regional Channel Geometry Surveys:** select and survey sample reaches to establish the relationship between the channel geometry, drainage area, and bankfull discharge in the rehabilitation and nearby basins.
- 5) **Rehabilitation Reaches:** survey a plan and profile of the rehabilitation reaches in sufficient detail to prepare construction drawings and establish survey reference markers.
- 6) **Template Habitats:** prepare a summary of habitat factors for biologically preferred reaches using regional references and surveys. Where possible, undertake reach surveys in reference streams with proven populations to identify local flow forms, substrate, pool and riffle geometry, refugia, etc.
- 7) **Size Rehabilitation Works:** select potential schemes and structures that will be reinforced by the post-project stream discharges and geometry.
- 8) **Stability and Instream Flow Requirements:** test designs for minimum and maximum flows, set target flows for critical periods derived from historical mass curves in successful habitats and instream flow preferences.
- 9) **Supervise Construction:** arrange for on-site location and elevation surveys for enhancement works and provide ongoing advice for finishing details in the stream.
- 10) **Monitor and Adjust Design:** arrange for periodic surveys of the rehabilitated reach and reference reaches to improve the design as planting matures and the reconstructed channel ages.

Table I: Summary of Steps in Stream Analysis and Restoration Projects (Newbury and Gaboury 1994).

If the riffle structures are eroded by extreme flows, the riffle will become a run. In these cases, riffle materials should be stockpiled nearby for post-flood repairs.

The design steps described below are presented as an iterative process, where the effects of an assumption made in one step must be re-checked for all steps. Additional background references and discussions related to natural channel designs are included in Heede (1985), Tripp (1986), Jungwirth et al. (1995), Lisle (1986), Muhar et al. (1995), Newbury (1995), Nunnally (1985) and OMNR (1993).

1) Location. At low flow, the pools and riffles distribute the fall in the reach in a series of steps. To establish a first approximation for the location of riffles, a template marked off in units of six bankfull widths can be placed on a large scale plot of the reach profile as shown in Figure 8. The locations can be adjusted so that they take advantage of existing pools, cross-over points in the flow between meander bends or other habitat features. In steeper slopes (5% or more) or where large woody debris is present, the riffle spacing may be decreased to as low as 4 times the bankfull width (Hogan 1986). The locations can also be checked on aerial photographs of the reach but they must be confirmed in the field. In the Twin Creek design summary shown in Figure 9, the riffle spacing was decreased to 4 times the bankfull width of the channel in the steeper 6.5% slope upstream reach. A typical riffle constructed in the 2.5% slope reach downstream is shown in Figure 10.

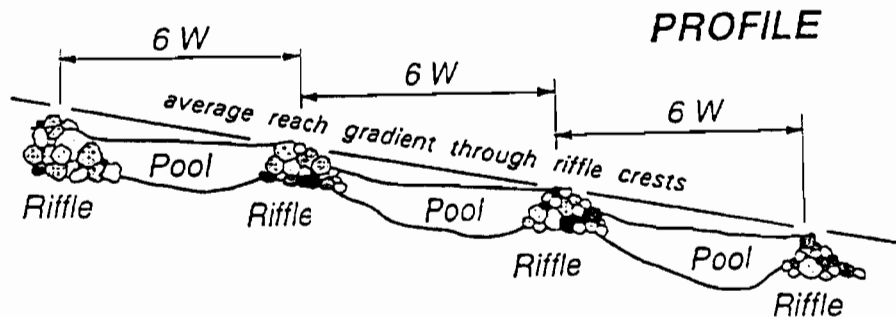


Figure 8: A design template based on average and observed pool and riffle spacing may be placed on the project reach profile to determine potential locations for constructing riffles. The riffle crest elevations are adjusted to follow the average reach gradient. The maximum height of the riffles above the stream bed is set to allow the bankfull discharge to be conducted over the riffle crest within the channel.

2) Elevation and Flood Capacity. The height of riffle crests will depend on the local profile elevation, the slope of the stream and the desired depth of the low-flow pools. As a first approximation, the riffle location template (Figure 8) with a gradient equal to the average reach slope may be placed on the profile and adjusted to obtain the desired pool depths. The trial gradient may be adjusted to coincide with upstream and downstream conditions in the reach, or it may be varied at each end for a smooth transition to the adjacent reaches.

The elevation and specific energy at the riffle crests are evaluated relative to the floodplain elevations to determine if there is sufficient local channel capacity to maintain the bankfull flows within the floodplains (Chow 1959). The bankfull flow may be estimated from the reference channel surveys, regional flood frequency curves, or precipitation/catchment area relationships for the basin. The discharge capacity at the riffle site can be estimated by assuming that the flow is critical at the riffle crest for in-channel, non-backwater conditions. Typical bankfull flow conditions with critical flows occurring on the riffle crests in a

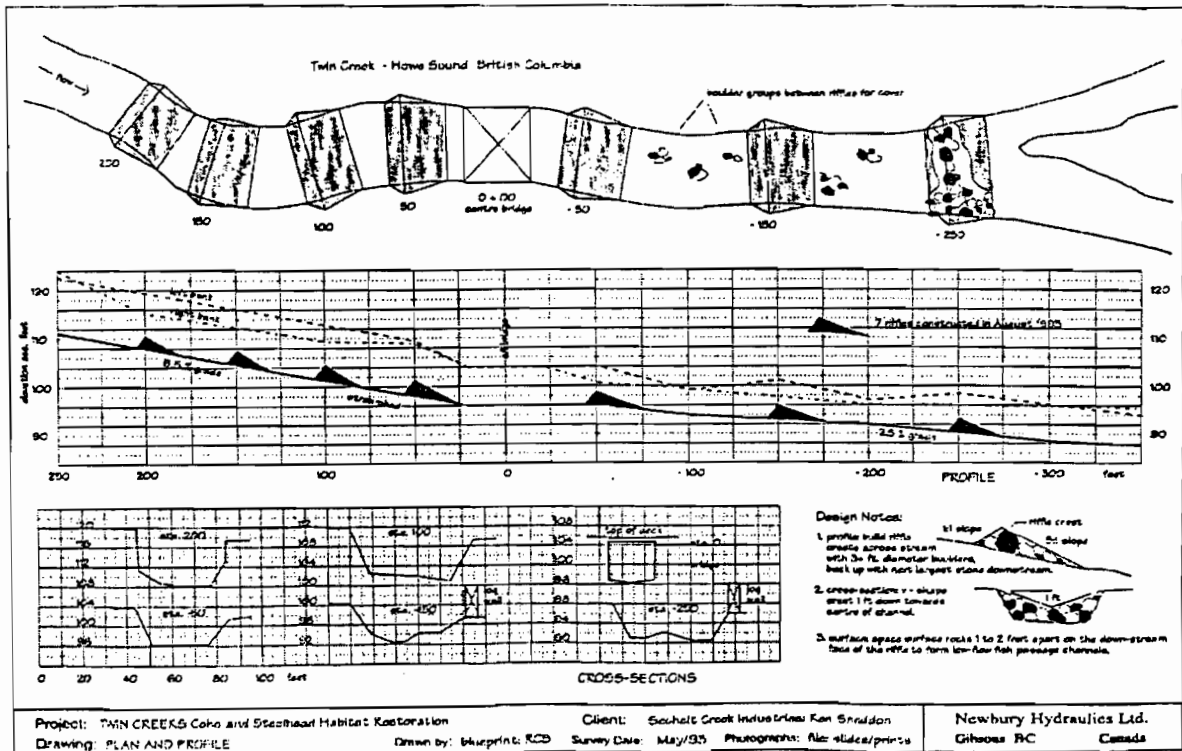


Figure 9: Twin Creek Restoration Project 1993, Howe Sound BC. Seven rock riffles were constructed on the lower channelized reach adjacent to a log sort yard. The upper riffles in the 6.5% gradient reach were spaced at 4 times the bankfull width. In the lower 2.5% gradient reach, the riffle spacing was increased to 6 times the bankfull width. In the first year, gravel and cobble bars were deposited in the upstream pools as the stream bed stabilized.

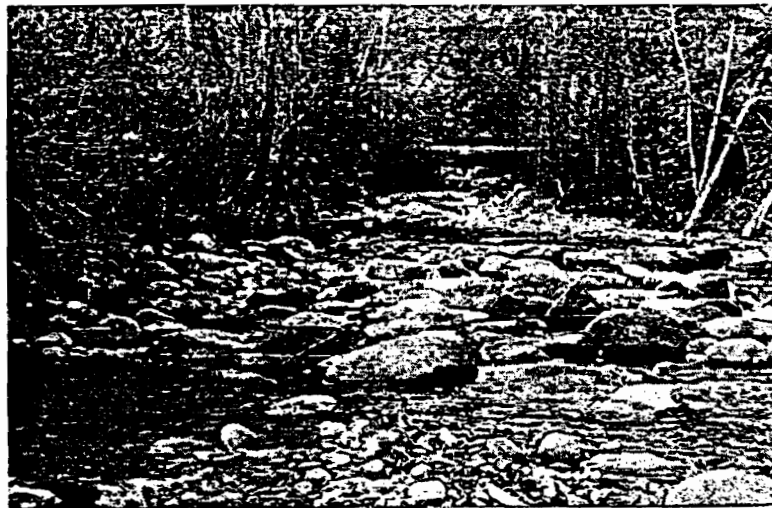


Figure 10: Twin Creek Restoration Project 1995, Howe Sound, BC. Upstream view from the toe of constructed riffle number 2 in the lower reach.

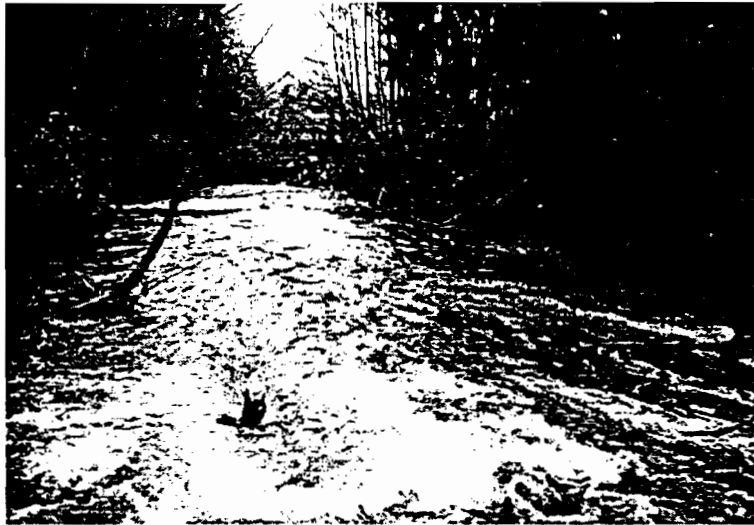


Figure 11: Oulette Creek Restoration Project 1994, Howe Sound, BC. Downstream view overlooking constructed riffles at the bankfull flood discharge. The low flow pool and riffle steps are submerged as the average gradient of the water surface and stream bed become parallel. Critical flow occurs on the riffle crest.

Oulette Creek are shown in Figure 11. If more channel capacity is required, the proposed riffle crest gradient may be lowered relative to the floodplain, the floodplain elevation may be adjusted with fill, or the riffles may be re-located to sites with higher banks. After several iterations of the spacing and elevation template, sites are usually found that will allow the regular bankfull flows to be maintained at the natural level in the main channel. The channel banks at the riffle sites must be rip-rapped to conduct the locally accelerated flows over the riffle crests without scouring.

When flood flows are larger than the bankfull discharge, the channel and floodplain capacity must be assessed using open channel flow resistance formulas. Resistance values for the central channel should be chosen that are similar to those observed in pool and riffle rivers of similar dimensions. Visual and graphic references for small channels of all types are presented in "Roughness Characteristics of New Zealand Rivers" (Hicks and Mason 1991). Complex channels with backwater conditions may require flood routing studies for higher than bankfull conditions.

3) Configuration. Surveys of natural rapids and riffles, including the collection of photographs, should be undertaken and used to develop riffle designs. The rapids shown in Figure 12 illustrate the diverse surface and flow conditions that occur in a rough and steep natural channel. A riffle constructed on Langdale Creek (Howe Sound, BC) that mimics these natural conditions is shown in Figure 13.

Most natural riffles have a downstream slope of less than 6 degrees (10:1 slope). This allows the water to enter the downstream pool at a shallow angle between the riffle face and the channel bed. Surveys of spawning rapids used by walleye were found to have downstream slopes of 20:1 (Newbury and Gaboury 1993). Riffles surveyed in several BC coastal streams generally had downstream slopes of 10:1 with some as steep as 6:1 in boulder bed streams.



Figure 12: In a natural rapids, hydraulics jumps, pools, and chutes in various combinations dissipate energy and provide opportunities for fish to find navigable passages up the steep face. This diversity can be reproduced in man-made riffles with careful placement of large rocks on the downstream face.



Figure 13: Langdale Creek Restoration Project 1995, Howe Sound, BC. Diverse hydraulic conditions have been created by strategically placing large boulders on the downstream face of this constructed riffle. Note the well rip-rapped banks in the riffle zone adjacent to the re-constructed Sunshine Coast highway.

The riffle crest and downstream surface should be v-shaped in cross-section to direct the flow towards the centre of the downstream channel. This reduces bank scour at the riffle site and assists in maintaining a central pool depth downstream. At higher flows, the v-shape will form important back-eddies above and below the riffle that provide refuge for both adult and juvenile fish and promote coarse gravel accumulation on the sides of the channel.

4) Materials. The riffles are built with a range of rock sizes. The largest rocks are selected to be stable at the bankfull flood stage. They may tumble as smaller boulders are initially adjusted around them. The larger rocks placed on the surface of the riffle create chutes and small drops that assist fish passage at low flows. These rocks are the most vulnerable to movement and represent the upper range of rock size required for the riffle. An approximation of the maximum size required may be obtained by analyzing the tractive force (the average bed shear stress) on the face of the riffle. The tractive force  $T$  ( $\text{kg/m}^2$ ) may be estimated as  $T = 1000 \times \text{flow depth (D in metres)} \times \text{slope of the downstream face of the riffle (S)}$  or:

$$T = 1000 D S \quad (\text{Chow 1959})$$

For bankfull design conditions, the tractive force may be based on depth of flow established by the height of the floodplains above the riffle crest and the slope of the downstream face of the riffle. Studies of stable channels summarized by Lane (1955) indicate that the relationship between the tractive force and bed material diameter at incipient motion for pebble-size and larger materials is  $T$  ( $\text{kg/m}^2$ ) = diameter  $\varnothing$  (cm). A safety factor of 1.5 is recommended (US Federal Highway Administration 1988). With this safety factor, the estimated diameter of the stable rock size  $\varnothing$  (cm) may be summarized in one relationship:

$$\varnothing_{(\text{centimetres})} = 1500 D_{(\text{metres})} S$$

The volume of rock required at each riffle site is approximately equal to the riffle height  $\times$  the riffle length  $\times$  the bankfull channel width. This volume allows for extra rock to riprap the banks adjacent to the riffle site and to roughen the downstream slope of the riffle face. The rock sizes should cover the entire range observed in natural template riffles, with an adequate number of the larger rocks to build the riffle crest and armor the downstream slope. Any remaining rock may be stockpiled nearby for adjustments to the riffle and banks following the first few flood events.

5) Construction. The construction process is summarized in the notes accompanying Figure 14. This figure may be reproduced and supplemented with photographs of riffles and rapids as a guide for machine operators. To build a riffle with natural characteristics, large rock must be sorted and used with skill to create a stable crest and to form a properly roughened surface on the downstream face. A riffle under construction in the summer low-flow period on Twin Creek, Howe Sound, BC is shown in Figure 15.

Construction surveys at the riffle sites must be referenced to a benchmark established during the project reach profile survey. Construction stakes should be placed on either side of the channel at the upstream toe, crest, and downstream toe of the riffle. The crest elevation at the banks and in the centre of the channel can be marked on the location stakes. These elevations will have to be checked as the construction proceeds. This can be done with a hand or surveyor's level and a reference elevation. Measurements may be made by the machine operator from a horizontal string line between points established on adjacent floodplains.

Natural riffle and pool habitat projects are designed to be adjusted by flood flows that will scour pools and deposit gravel bars. The adjustments often take place in the first 4 or 5 bankfull or greater flood events. After these events, the riffle configuration should be re-surveyed and assessed to see if additional rock is required to infill gaps or to improve the configuration of the flow on the riffle face.

## RIFFLE CONSTRUCTION

1. **PLAN:** build riffle crest across the stream with large diameter boulders, back up with next largest stone downstream.
2. **PROFILE:** construct downstream face of riffle at 20:1 slope and upstream face at 4:1 slope.
3. **CROSS-SECTION:** V-shape crest down towards the centre of channel.
4. **SURFACE:** space large surface rocks 20 to 30 cm apart on the downstream face of the riffle to form low flow fish passage channels.
5. **BANKS:** rip-rap banks with embedded rock to the floodplain level on both sides of the riffle.

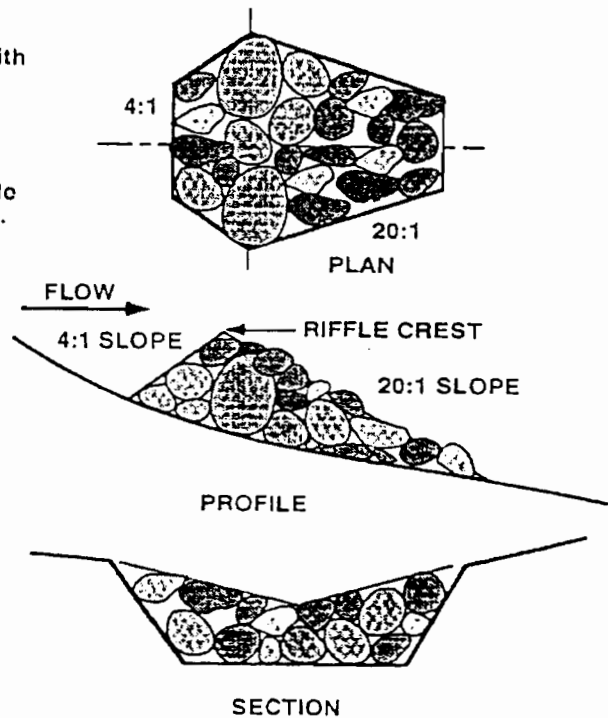


Figure 14: This schematic pool and riffle construction drawing may be augmented for machine operators with notes on the placement of construction survey stakes and photographs on natural and well-constructed riffles.



Figure 15: Twin Creek Restoration Project 1993, Howe Sound, BC. Following the steps in the schematic construction drawing (Figure 14), the backhoe operator is sorting and placing the larger boulders along and below the riffle crest. The hydraulic thumb attached to the bucket allows boulders to be moved and placed individually.

## Conclusion: Two Monitored Pool and Riffle Projects

### 1) The Mink Creek Walleye Stream Restoration Project in Central Manitoba

**Background:** An extensive program of channelization to improve agricultural drainage and reduce Spring flooding occurred throughout the Dauphin Lake lowlands beginning in the early 1900's. The lower meandering reaches of Mink Creek were channelized in 1950 to improve the capacity of the channel to carry flood flows (Figure 1). The new channel streambed was steeper and had a more uniform grade than the natural channel. From 1950 to 1984, a repeated cycle of downcutting, bank slumping and channel widening occurred. The channel, constructed with a width to depth ratio of 7:1 had by 1984 re-established a more natural width to depth ratio of 12.5:1 (Newbury and Gaboury 1993). The extensive erosion lowered the bed elevation by 1 m and created a 1 km<sup>2</sup> delta of eroded channel materials at the river's mouth. Channelizing and re-grading eliminated many of the pools and riffles used by walleye as spawning and incubation habitats.

**Restoration:** In 1985, seven experimental riffle structures were constructed in Mink Creek with designs based on surveys of successful walleye spawning areas in the unchannelized Valley River nearby (Figure 16A). The size, spacing and distribution of boulders and cobbles on the downstream face of the natural riffles served as templates for the man-made riffles shown schematically in Figure 16B.

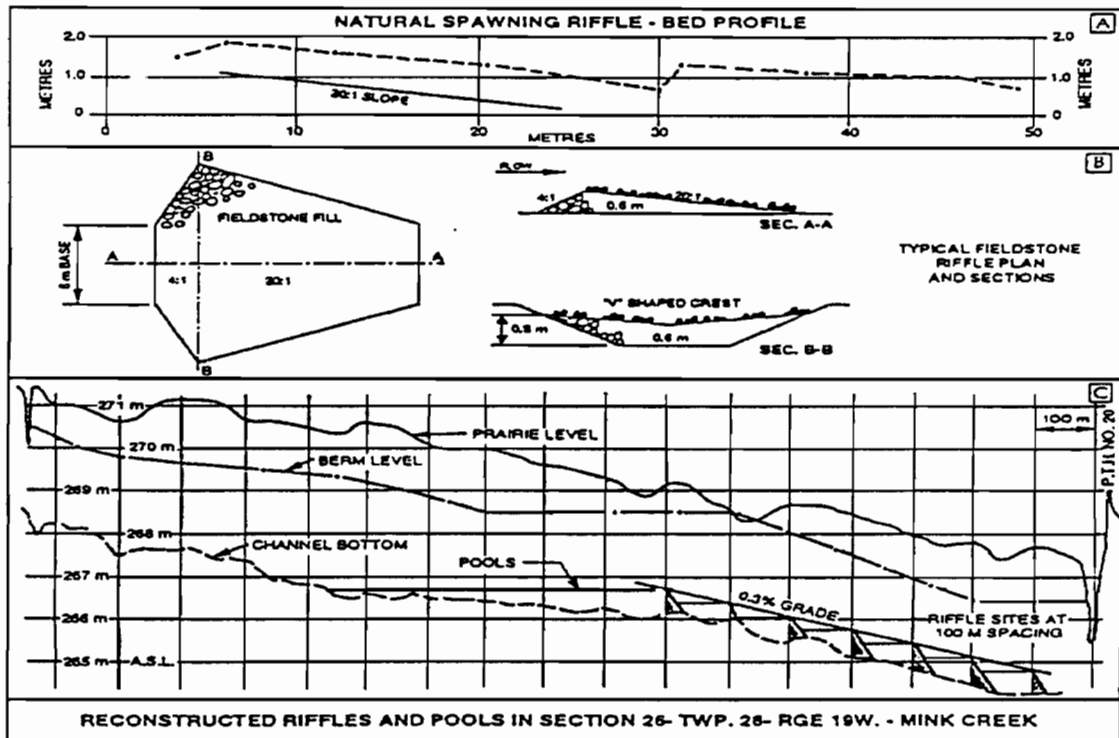


Figure 16: Mink Creek Walleye Spawning Restoration Project, Central Manitoba. A natural spawning riffle was surveyed to provide the design template (16A). Seven 1m high riffles (16B) were added to the easily eroded bed of the channelized stream (16C).

The Mink Creek riffles were spaced 100 m apart along the channelized reach (Figure 16C). The spacing of riffles was 6.5 times the natural bankfull width of the creek (Figure 17). Each riffle required 100 m<sup>3</sup> of fieldstone (donated) and cost approximately \$1000. (CAN1985) to construct.



Figure 17: Mink Creek Walleye Spawning Restoration Project 1988, Central Manitoba. The channelized reach 3 years after rock riffles were added. After several bankfull and greater flood events formed downstream pools, the channel has stabilized. The riffles and upstream pools are utilised by spawning walleye.

Assessment: Walleye reproductive success was monitored by sampling the rehabilitated and unimproved riffle and pool sections during the spawning, incubation and larval drift periods. The assessment procedure was undertaken for six successive Spring spawning periods between 1986 and 1992. It consisted of five components:

- 1) pump/surber sampling to determine egg density and survival;
- 2) local hydraulic conditions at incubation sites (depth, velocity, slope, substrate);
- 3) drift net sampling of dislodged eggs;
- 4) drift net sampling of walleye larvae;
- 5) mean daily discharge and water temperature.

The assessment techniques for each component are described in Newbury and Gaboury (1994).

Results: From the comparison between the rehabilitated section and isolated, shallow riffle-pool reaches in the channelized section, it was evident that the walleye utilized both reach types for spawning and incubation (Table II). Viability of the eggs was similar with live eggs comprising 73% and 68 % respectively, of the samples from all years. The number of larvae produced appeared to be similar from both sites as well. Egg scour and drift were positively correlated with discharge during the incubation period. The egg drift was greater from the channelized compared to the rehabilitated section, suggesting that although the built habitat was used with the same intensity, the added riffles provided more protection from scour and hence higher net survival rates.

Large floods, up to a 1 in 40 year event, were recorded in Mink Creek during the first five years after the riffles were constructed. A comparison of the 1986 and 1991 profile surveys indicates that the constructed riffles at the natural spacing of 6 times the bankfull width remained stable (Figure 18) with a minimal change in crest elevations (as Stuart found in 1953). Pool depths

Measurement	Reach Type	Year					
		1986	1987	1988	1989	1990	1991
Mean egg density (catch/m <sup>2</sup> )	Single riffle rehab	0.73	1.27	19.73	0	29.22	0
	Double riffle rehab	-	4.18	7.01	0	40.52	0
	Existing channelized	3.22	8.41	4.65	0	65.53	0
Mean egg drift (catch/24h)	Single riffle rehab	19.38	0.33	163.00	0	567.00	0
	Double riffle rehab	-	0	233.00	0	1251.00	0
	Existing channelized	166.17	1.89	41.00	0	3701.00	0
Mean larval drift density (catch/h/100m <sup>2</sup> water filtered)	Single riffle rehab	0.27	5.47	1.02	0	11.18	0
	Double riffle rehab	-	41.73	1.58	0	no data	0
	Existing channelized	0.78	16.13	0.26	0	no data	0
	Mean spawning flow (m <sup>3</sup> /s)	2.82	7.96	1.09	0.48	9.04	0.34
	Mean incubation flow (m <sup>3</sup> /s)	5.61	1.36	7.92	0.19	3.09	0.36
	Mean larval drift flow (m <sup>3</sup> /s)	2.43	0.27	1.00	0.10	6.07	0.92

Table II: Summary of walleye spawning success information, Mink Creek restoration project (Newbury and Gaboury 1994).

immediately upstream of the riffle structures have decreased since construction as a result of infilling but were maintained at a residual depth of 0.3-0.4 m immediately downstream. By 1991, the bankfull widths and depths of the pools had returned to an average ratio of 19:1, re-establishing the historic channel geometry. Increasing the cross-section of the flow in the pools decreased eroding velocities and allowed the streambanks to re-vegetate and stabilize. In contrast, erosion of the streambanks upstream from the rehabilitated reach has continued unabated. Consequently, restoring pool and riffle reaches has been adopted as a pre-requisite to riparian restoration activities that are now being undertaken on all similarly channelized Dauphin Lake tributaries (Dauphin Lake Advisory Board 1989).

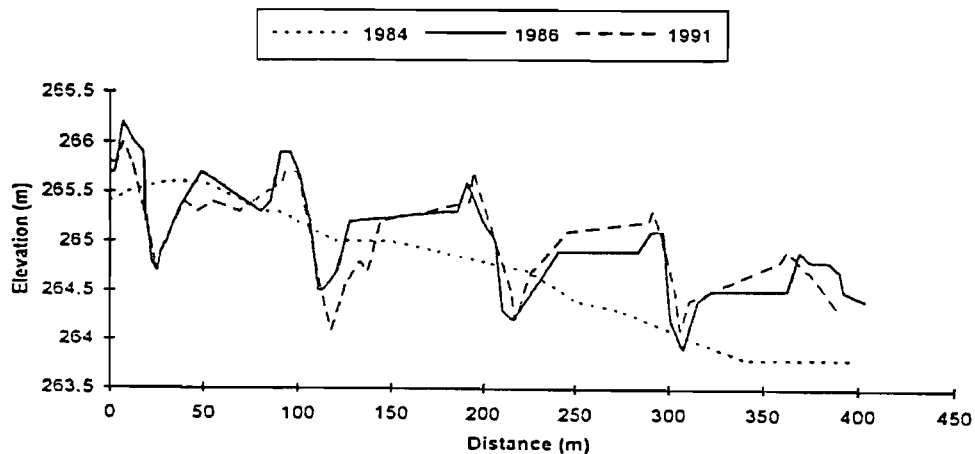


Figure 18: Mink Creek Walleye Spawning Restoration Project, Central Manitoba. Detailed profiles of the pool and riffle reach one year and six years after construction show that the pools that were scoured initially below the man-made riffles have maintained their depth and stability through several years of high-runoff events. The approximate profile of the pre-project channelized streambed is shown as a dotted line.

2) The Oulette Creek Salmonid Habitat Restoration Project, Howe Sound, Southern British Columbia

Background: In 1978, the steep (3% grade) lower 0.5 km reach of Oulette Creek was diverted to run on the western and northern edge of its alluvial fan in west Howe Sound (Figure 2). The fan surface was uniformly filled and graded for a sawmill and dry-land log sort with an offshore booming ground. Initially, restoration works were installed by dividing the diversion channel into 100 ft (30.5 m) steps with two alternating types of drop structure; a single log 0.75 m in diameter and a single row of 1 m diameter boulders. The logs were embedded in the stream banks to anchor them. Two years later, the drop structures were undercut or breached by flood flows as the new channel bed eroded (Figure 19). The downcutting was rapid in the unprotected bed below the logs and boulder drop structures where the energy of the flow was not dissipated on a sloping riffle face. Ten years later, the entire channel profile was approximately 0.7 m lower than the constructed elevation and a small delta of bed materials had accumulated in the mouth of the stream.



Figure 19: Oulette Creek 1982, Howe Sound, BC. In the first three years following channelization, the single log drop structures added to the uniform channel were undercut. Alternating single boulder drop structures were buried in deep scour holes formed immediately below the structure crests as there was no downstream riffle to convey the flows away from the structure.

Restoration: In 1994, the Oulette Creek diversion was re-constructed by adding 12 boulder riffles to the channel, one at each of the old drop structure sites (Figure 20 before, Figure 21 after). Initially, the re-constructed steps in the channel profile formed 1 m deep pools above the riffles. The energy in the drop was dissipated on the 10:1 downstream sloping riffle face. The spacing of the pools and riffles is 30.5 m, approximately 4.3 times the natural stream width of 7 m measured above the diversion (Figure 22). Donated rock was hauled to the stream bank beside each riffle site from a nearby quarry prior to construction in the channel. The boulder sizes ranged from 0.5 m to 1 m in diameter. The total volume of rock used for 12 riffles was approximately 250 m<sup>3</sup> at a unit cost for hauling and placing of \$35.00/m<sup>3</sup> (\$730 CAN1994 per riffle).



Figure 20: Oulette Creek 1994 (before), Howe Sound, BC. Prior to the addition of riffles (Figure 21) the channelized reach was a uniform run of cobbles and boulders.

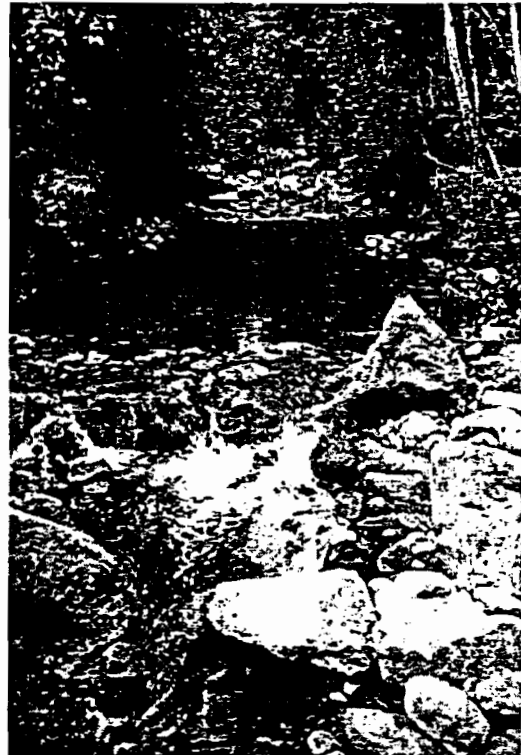


Figure 21: Oulette Creek 1994 (after), Howe Sound, BC. Rock riffles were added to the uniform reach at the former drop structure sites, creating a series of metre deep pools.

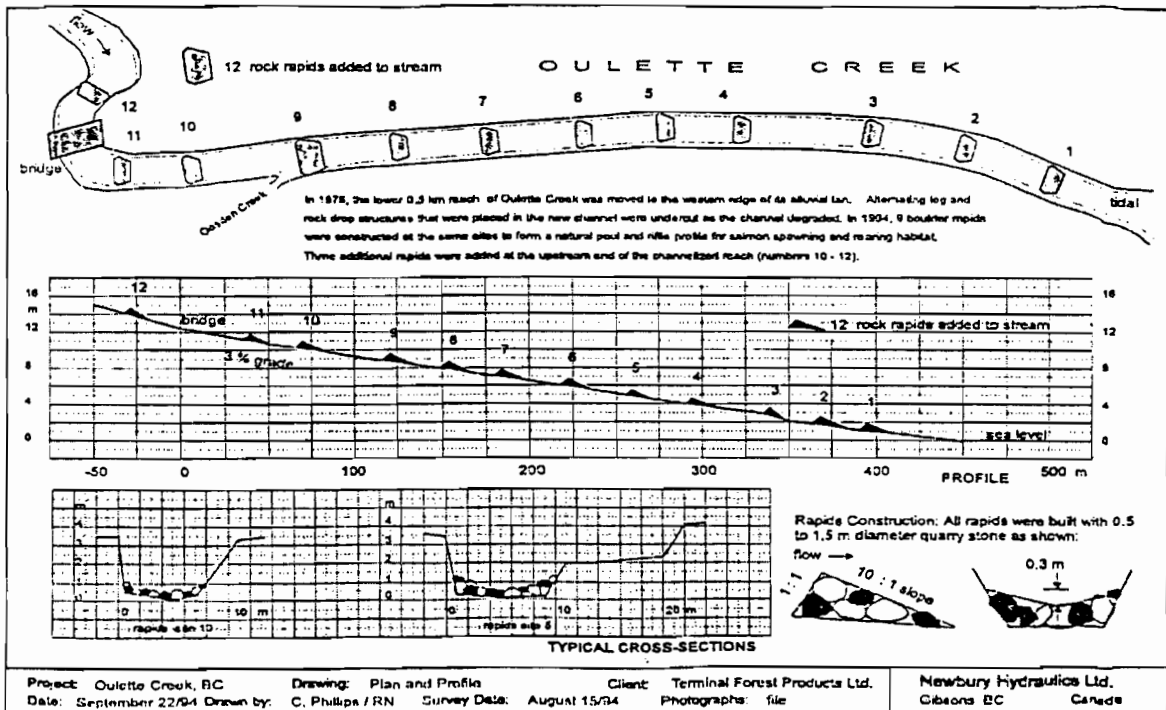


Figure 22: Oulette Creek 1994, Howe Sound BC. Plan and profile drawings for the restoration project undertaken in 1994.

Pools up to 1.5 m deep were formed by mid-winter bankfull flood flows in 1994/95 below the constructed riffles. After the flood peaks, gravel infilling occurred on the margins of the pools. In the summer of 1995, minor adjustments were made to the surface rocks in several riffles, boulder clusters were added to pools, and two floodplain ponds were excavated to augment winter rearing habitat.

Assessment: Fish population data were collected from representative sample sites for each habitat unit before and after restoration by electrofishing enclosed sample areas using a multiple pass and total removal method (Bates et al. 1996 in prep.). The channelized reach was dominated by riffles and shallow glides which accounted for 83% and 90% of the available habitat in 1993 and 1994 (pre-restoration). Restoration shifted the pool-riffle ratio immediately with pools increasing to 70% of the existing habitat. In the ensuing year after several bankfull flood events, the habitat consisted of 51% pools and 49% riffles (Figure 23).

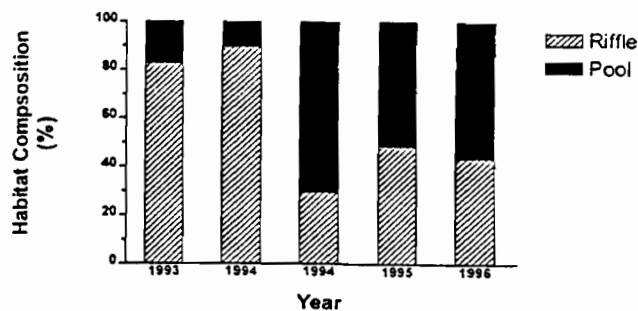


Figure 23: Available pool and riffle habitat before and after restoration of the channelized reach of Oulette Creek, Howe Sound, BC.

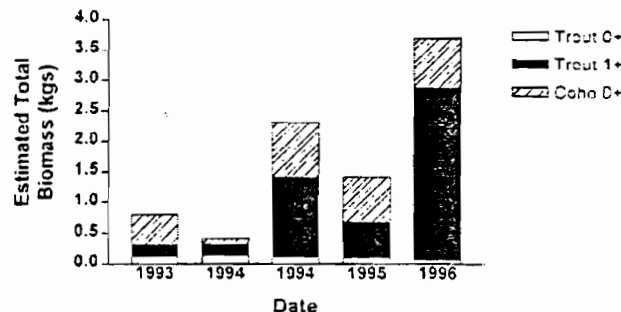


Figure 24: Total biomass before and after restoration of the channelized reach of Oulette Creek, Howe Sound, BC.

Calculated biomass per unit area ( $\text{g}/\text{m}^2$ ) for all species increased after restoration suggesting immediate recruitment by fish to the new habitat from upstream reaches and a shift in species and/or age class structure. This increase resulted in a larger total biomass in the restored section (Figure 24). The most notable increase (540%) occurred in age 1+ steelhead and cutthroat trout. Density results show a decrease in the post-restoration stream for all species followed by an increase one year later. Although densities of fry decreased, actual fish numbers increased as the species and age class composition shifted.

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