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Exploration and rehabilitation of hydraulic habitats in streams using principles of fluvial behaviour

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SUMMARY

1. The combination of elements from geomorphology, open-channel hydraulics, and hydraulic habitat requirements of stream fish forms the basis for an ecologically sound 'soft engineering' of river channels.
2. Interpreting and mapping the hydraulic geometry of streams and locally varied flow conditions can be accomplished with plane table surveys and customized field-data sheets. This information can serve to manage hydraulic habitats preferred by fish.
3. The use of fluvial characteristics to design preferred hydraulic habitats is illustrated in two examples: (i) a walleye (*Stizostedion vitreum vitreum* Mitchill) spawning rehabilitation project undertaken in a stream channelized as a lowland drainage canal, and (ii) a trout (*Salvelinus fontinalis* Mitchill and *Oncorhynchus mykiss* Walbaum) habitat-enhancement project to create additional holding and resting areas for adult fish in a stream paved with glacially deposited boulders modified by a road crossing.
4. In both examples the 'soft engineering' of the river channels enhanced the hydraulic fish habitat.

Introduction

Rivers and streams are integrated flowing systems that create and maintain aquatic habitats within the structure of their flow as well as on and below their wetted boundaries. In a drainage basin, the flow habitats are nested within one another at smaller and smaller scales (Fig. 1). In porous-bed streams, a 'hidden' habitat also exists in the interstitial flow through the substrate (Fig. 1).

At Level I (Fig. 1), the size and geometry (width, depth, slope) of stream segments in a branching channel network are determined by the bankfull flows from their tributary drainage areas. At Level II, reaches may be distinguished within the segment with characteristic pools, riffles, substrates, and channel patterns. At Level III, within a section of the reach, the state and structure of the streamflow can be delineated. At Level IV, the boundary habitat of an individual benthic organism location within the local flow structure may be characterized by direct and analogous measurements. The characteristics of habitats in the fifth level, the hyporheic zone, cannot be observed directly but may be implied from measurements of the local piezometric gradient (Pinay, Roques & Fabre, in press) and the conductance of the stream-bed deposits. Tracer techniques may also be applied to interpret the hidden flow patterns (Triska, 1993).

Successful stream rehabilitation or enhancement designs must often re-create hydraulic conditions in all levels of habitat definition. The design parameters for fluvial processes, site-specific hydraulics, and aquatic organisms have defied complete analysis, particularly at the lower levels. Fortunately, geographical, engineering, and biological studies undertaken in the last 30 years can be used to design the simple components. The more complex habitat characteristics can be produced by mimicking the natural materials and geometry of the stream. This is the design principle that we wish to emphasize. In some countries, it is referred to as 'soft engineering'

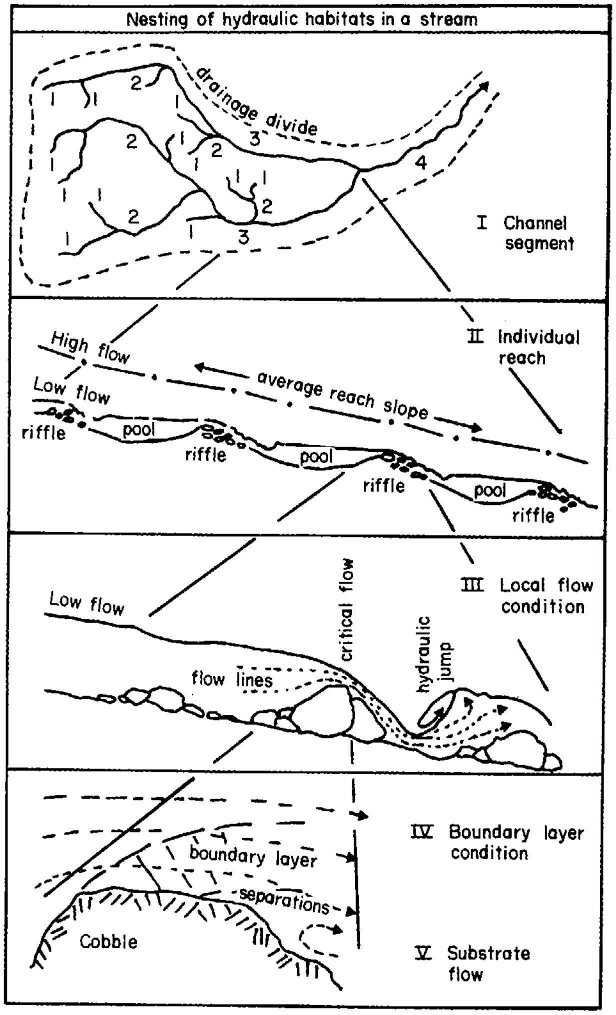

Fig. 1 The nesting of hydraulic habitats in a drainage basin and stream channel.

river channels, in the sense that natural materials and forms are used, some level of instability is anticipated, and knowledge of the desired ecosystem is applied in the design. In contrast, 'hard engineered' channels are designed to be stable with fixed geometries, usually built in concrete or lined with protective materials, and for the single purpose of efficient water conductance.

A major contribution to the soft engineering approach has been made in geography. Regional studies of fluvial processes and the geometry of river channels in North America were first summarized by Leopold, Wolman & Miller (1964). In Great Britain, a similar summary was compiled for drainage basins by Gregory & Walling (1973). In the more established field of river engineering, Chow (1959) prepared a broad treatment of open-channel hydraulics. Later, Chow (1964) compiled a massive handbook of river and drainage-basin hydrology. Both books still serve as basic references in many engineering design offices. More recently Chang (1988) combined information and techniques from both fields. In biology, attempts to match the considerable bulk of river morphology and engineering hydraulic theory with biological data were undertaken by Hynes (1970), and further articulated by Vannote *et al.* (1980) in the river continuum paradigm and by Bovee & Milhous (1978) for instream flow requirements. There are many contemporary studies that match physical and hydraulic characteristics with fish and benthic populations (e.g. Schlosser, 1986; Statzner, Gore & Resh 1988), but there is not yet a summary volume for stream biology and habitats that matches the geomorphology and engineering hydrology handbooks.

This brief history ignores many recent articles and conference proceedings prepared by stream researchers in all three fields and is intended only as an historical overview. We have not yet found even these historical references being used together in a design office. In consequence, the objective of this paper is to demonstrate the potential of combining elements from geomorphology, open-channel hydraulics, and hydraulic habitat requirements of lotic fish for an ecologically sound 'soft engineering' of river channels.

Designing stream works to create hydraulic habitats

A design process for stream rehabilitation that has been used successfully in central Canada based on natural habitats is summarized in Fig. 2. The surveys, sample sheets, and evaluation methods used in the design process are extracted from a field manual for stream habitat exploration and rehabilitation (Newbury & Gaboury, in press).

For steps 1 and 2, topographical maps and satellite images are available for most drainage basins. However, streamflow data for steps 3 and 8 are generally available only for larger rivers. For most stream projects, local flow data may be derived by partitioning regional flow records or by rainfall–runoff models from small basins similar to those proposed by Howard (1989). In steps 4 and 5, sample reach surveys are undertaken to establish the local channel

Fig. 2 A design process for stream rehabilitation works used for fisheries projects in southern Manitoba.

1. Basins: trace catchment boundaries from topographical and geological maps to identify sample and rehabilitation basins.
2. Profiles: sketch mainstem and tributary long profiles to identify discontinuities which may cause abrupt changes in stream characteristics (falls, former base levels, etc.).
3. Flow: prepare flow summary for rehabilitation reach using existing or nearby records if available (flood frequency, minimum flows, historical mass curve).
4. Channel geometry surveys: select and survey sample reaches to establish channel geometry relationships with drainage area and bankfull discharge.
5. Rehabilitation reaches: survey rehabilitation reaches in sufficient detail to prepare construction drawings and establish survey reference markers.
6. Preferred habitats: prepare a summary of habitat factors for biologically preferred reaches using regional references and surveys. If possible, detailed reach surveys to identify local flow conditions, substrate, refugia, etc. should be undertaken in reference streams with proven populations.
7. Size rehabilitation works: select potential schemes and structures that will be reinforced by the existing stream dynamics and geometry.
8. Instream flow requirements: test designs for minimum and maximum flows, set target flows for critical periods derived from the historical mass curve.
9. Supervise construction: arrange for on-site location and elevation surveys and provide advice for finishing details in the streams.
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.

configuration and flow conditions (Level II, Fig. 1). Standard data sheets adopted to promote uniformity in measuring techniques for reach surveys are included in Appendix 1.

Following the survey, the distribution of slope, hydraulic resistance, substrate size, and channel stability may be characterized for stream segments in the whole drainage basin (Level I, Fig. 1). The flood capacity and hydraulic geometry of the bankfull stage may be compared to similar trends in other basins. For example, the measurements summarized in Table 1 and plotted in Figs 3 and 4 were gathered using the standard data sheets and analysed with conventional open-channel hydraulic formulae (see Chow, 1959 or Chang, 1988).

Examination of the bankfull relationship plots at this stage in the design process, often reveals anomalous characteristics in the reach in which rehabilitation is required. Some of the commoner anomalies that cause the altered reach to plot differently from the trend of the general bankfull relationships are: (i) the channel gradient is increased due to straightening, producing a high discharge estimate; (ii) the channel has been excavated to a narrower and deeper trapezoidal cross-section than the natural cross-section, often reflected by local channel degradation and bank failures; (iii) the reach has been channelized and uniformly graded with no pools, riffles, vegetation, or bed material diversity, producing a low resistance to flow and a high bankfull discharge estimate.

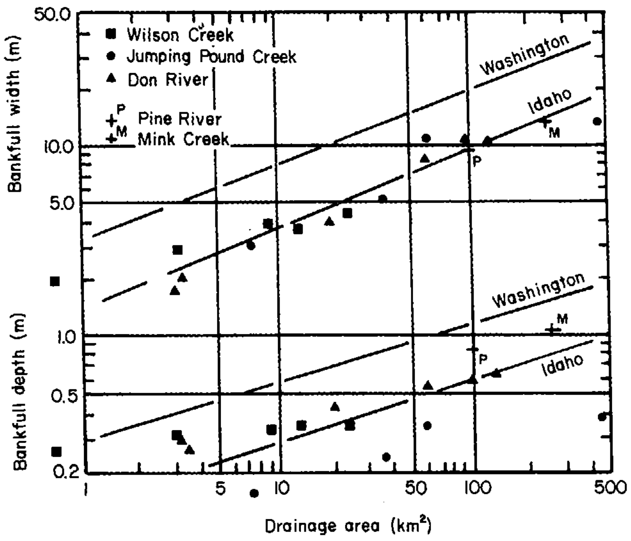

Fig. 3 Bankfull channel geometry relationships for several Canadian streams (Table 1). Dashed lines bracket relationships for U.S. streams.

Table 1 Bankfull stream dimensions surveyed in several Canadian watersheds with different land uses

				Bankfull	
Stream and reach	Order number	Drainage area (km^2)	Slope	Width (m)	Depth (m)
Wilson Creek, Manitoba: natural forested escarpmental catchment					
Conway Creek	1	0.7	0.06	2.0	0.29
South Branch	2	3.0	0.06	3.0	0.30
Bald Hill	3	8.6	0.04	3.8	0.32
Junction	3	12.7	0.015	3.6	0.33
Weir Site	4	22.1	0.008	4.3	0.35
Jumping Pound Creek, Alberta: extensive pasturelands					
Moose Mountain	1	7.3	0.02	3.1	0.17
Coxhill Creek	2	36.0	0.02	5.1	0.24
Pinetop Hill	3	59.0	0.019	10.9	0.35
Gauging Station	5	455.0	0.007	13.4	0.38
Don River, Ontario: agricultural and urban lowlands					
Dufferin Road	1	3.1		1.8	0.30
Elgin Mills	1	3.4		2.2	0.27
Longstaff Road	2	19.0		4.2	0.46
Bayview Road	4	57.9		8.3	0.55
Finch Ave.*		98.3		10.7	0.60
Overlea Blvd.*		125.5		10.1	0.65
Pine River, Manitoba: logged forested escarpmental catchment					
	4	100.0	0.022	9.7	0.84
Mink Creek, Manitoba: agricultural lowlands					
Natural reach	4	230.est.	0.0019	16.0	1.10
Channelized	5	250.0	0.0022	20.0	1.60

* Order unknown because the urban tributaries are conducted underground.

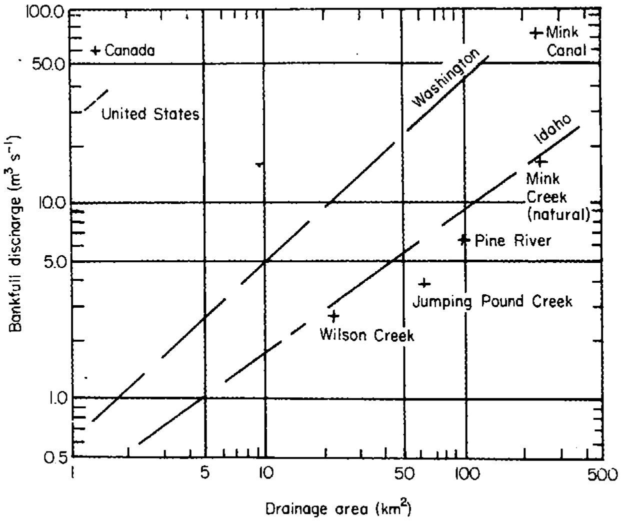

Fig. 4 Bankfull flow relationships for several Canadian streams estimated from stream survey data (Table 1). Dashed lines bracket relationships for U.S. streams.

The methods used to complete the design process (steps 6 to 8) are discussed in two examples of fish habitat restoration and enhancement.

Example 1: rehabilitation of a channelized lowland stream

In 1950, the lower meandering reaches of Mink Creek (catchment drainage area = 250 km^2) were channelized and straightened to increase the flood capacity of the stream. A new centre line for the channel was surveyed that ran approximately down the points of inflection of the natural meander belt (Fig. 5a and b). The initial channel was designed to be narrower and deeper than the natural channel to optimize the hydraulic radius of the flow, minimize excavation, and use the minimum width of right-of-way through agricultural lands. The stream bed and banks were uniformly graded to achieve the minimum resistance to flow and the maximum gradient.

Immediately after channelization, the stream began a repeated cycle of downcutting, bank slumping, and

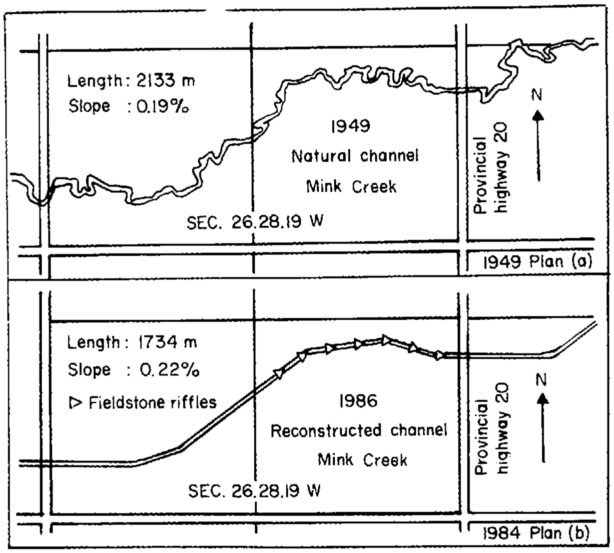

Fig. 5 A typical meandering reach of the lower Mink Creek channel before and after channelization (a and b, respectively) to improve its flood capacity. Pools and riffles were eliminated.

widening as the original bankfull width and depth were restored in the rapidly entrenching channel. The ratios of bankfull channel width to depth reflect this shift. The natural channel width/depth ratio was 14.5:1. The initial design ratio was only 6.9:1. At the time of survey in 1984, 34 years after construction, the ratio had been eroded to 12.5:1. The channel bed was also 1 m lower. The eroding channel materials are carried downstream by the steeper gradients and depths of flow. By 1986, a 1-km^2 delta had been deposited on the north-western shore of Lake Dauphin at the river's mouth.

The 1950 channelization project also eliminated the local hydraulic conditions in pools and riffles used by walleye (*Stizostedion vitreum vitreum* Mitchill) as spawning and rearing habitat. High exploitation pressure and extensive fish habitat destruction has caused annual commercial fishing yields for the past three decades to average about 10% of pre-1950 levels (Gaboury, 1985).

In 1985, spawning habitats were successfully restored to the channelized reaches of Mink Creek by creating pools and riffles in the existing channel (Newbury & Gaboury, 1988). Initially, engineering surveys were undertaken in the channelized reach to determine the plan, profile, and cross-sections of the channel. Similar surveys for the natural pre-channelized reach were available in historic files. Segments of the abandoned meander loops were surveyed to confirm the bankfull width dimensions of the natural stream. The bed paving materials in the natural channel were not surveyed originally as they were obscured in the abandoned channel by drifted topsoil deposits and forest litter. Standard open-channel hydraulic relationships for velocity, tractive force, Froude number, and discharge were applied to determine the estimates of the channel characteristics before and after channelization (Table 2). Fisheres surveys undertaken during the spring spawning period identified several natural spawning reaches in the Valley River that runs parallel to Mink Creek into the south-western shore of Lake Dauphin. Plan, profile (Fig. 6a) and cross-section surveys were undertaken in these traditional spawning areas to determine the depth of pools and characteristics of the spawning riffles (Fig. 6).

Table 2 Channel characteristics for Mink Creek before (natural) and after channelization and for the Pine River

	Mink Creek		Pine River
	Natural	Channelized	
Bankfull width (m)	15.5	22.0	9.7
Bankfull depth (m)	1.1	1.6	0.84
Average slope	0.0019	0.0022	0.022
Median bed paving (cm)	—*	2.0	45.0
Bankfull roughness est.	0.045	0.03	0.16
Bankfull velocity (m s^{-1})	1.0	2.1	0.83
Bankfull tractive force (kg m^{-2})	2.1	3.4	18.5
Bankfull Froude number	0.31	0.54	0.3
Bankfull discharge (m^3 s^{-1})	17.6	76	6.7

*Abandoned stream bed obscured by drifted topsoil.

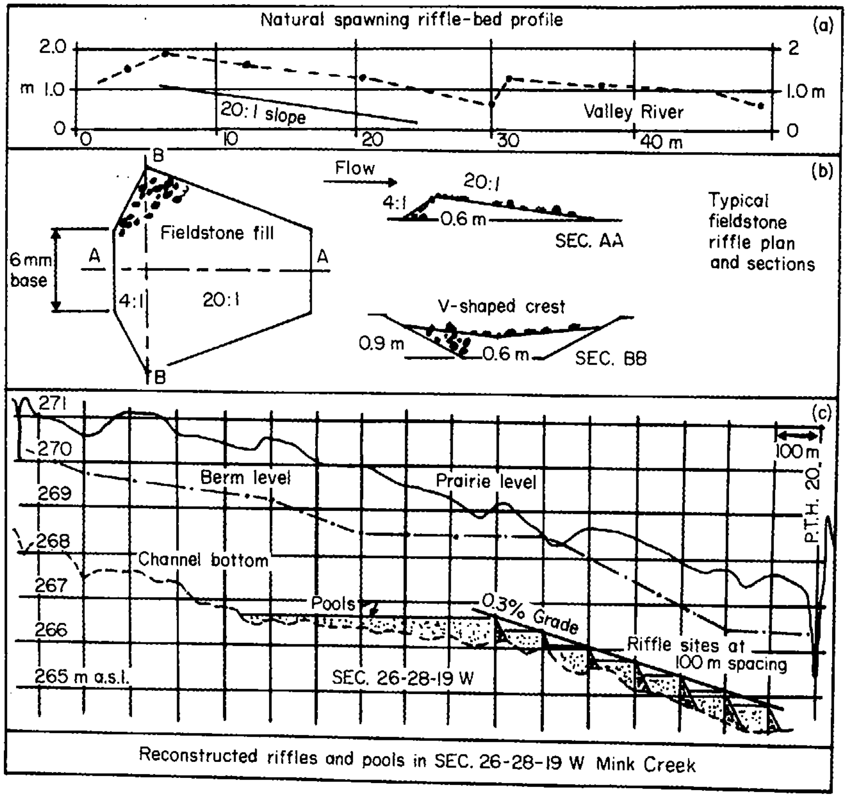

Fig. 6 Profile of (a) a natural walleye spawning riffle, (b) designed fieldstone riffles, and (c) riffle spacing along the profile of a channelized reach of Mink Creek, Manitoba.

In addition to measuring the channel geometry, the natural spawning areas were surveyed to map the size, location, and spacing of boulders and cobbles on the downstream face of the spawning riffles (Level III, Fig. 1). The distribution and characteristics served as a template for the man-made riffles shown schematically in Fig. 6b for a representative section of the rehabilitated reach. The riffles were spaced at 100-m intervals along the straightened reach (Fig. 6c). The spacing is 6.5 times the natural bankfull width of the stream, similar to that observed for many natural pools and riffles (Chang, 1988). Riffles with two crests spaced 20 m apart (double riffles) were also constructed in an adjacent reach (Fig. 7).

A total of twenty-seven riffles were constructed in November 1985 and December 1986 using local 'fieldstone', a glacial deposit of flat limestone and rounded granitic cobbles and boulders. The fieldstone was readily available in piles on adjacent fields that had been gathered when the land was cleared for agricultural use. Larger boulders were placed on the surface of the riffles to create aeration in local hydraulic jumps and narrow low-flow chutes similar to those observed in the natural spawning riffles. The boulders were selected from the local fieldstone to exceed the mean diameter that the bankfull flows could transport on the 20:1 downstream slope of the riffles using a traditional engineering tractive-force analysis (Lane, 1955).

Fig. 7 A constructed riffle with two crests on the lower Mink Creek channel under moderate flows. Spawning walleye were observed in the central pool.

The cost components for the twenty-seven riffle project were: surveys and design, 34 person days;

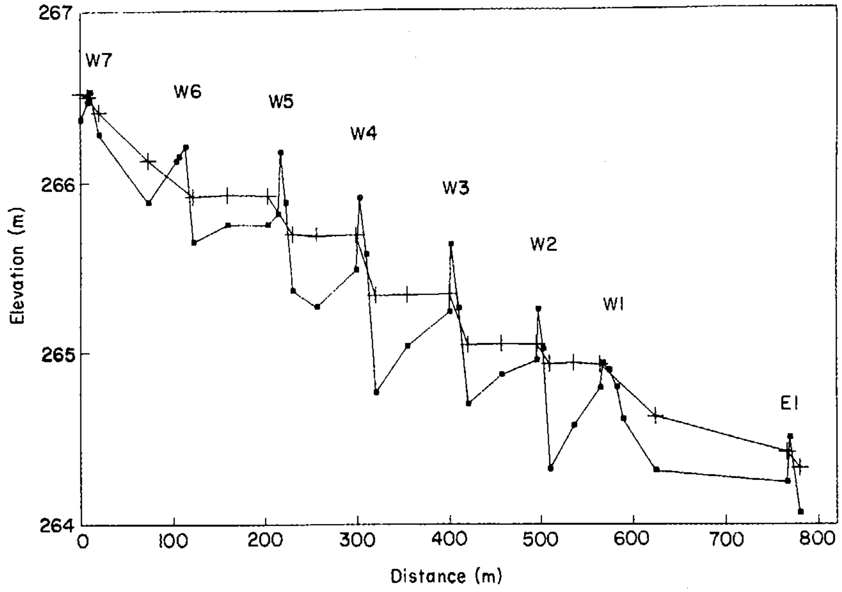

Fig. 8 Profile of the Mink Creek channel 3 years after fieldstone riffles were added at 100-m intervals. The scour pools were formed in the initial year with a 3× bankfull flow peak. The riffle crests were not eroded. □, Bed level; + water level.

construction supervision, 20 person days; monitoring, 700 person days; machine rentals, $US20 500.

A large flood peak (3× bankfull) passed through the reach in the first year following construction. Pools were scoured in the channel bottom below the riffles as shown in Figs 8 and 9 but the constructed riffles and banks of the channel were stable. In contrast, extensive erosion occurred in the channelized untreated river above and below the man-made riffle segment during the same flood. In subsequent floods (2× bankfull), the scour pools have not been further eroded.

Fig. 9 Fieldstone riffles added to the lower Mink Creek channel. The riffles continue to impound shallow pools under low-flow conditions after the spawning season, facilitating the return of drifting fry to the lake downstream.

Walleye reproduction in Mink Creek was monitored for 6 years (1986–91) (Janusz & Janusz, 1993). Deposited eggs were sampled by 'vacuuming' the riffle surface with a flexible hose connected to a diaphragm pump that discharged into a 1.1-mm sieve. At each riffle, three egg samples were collected from each of five zones; backwater pool, mid-riffle, crest, upstream riffle face and upstream pool. At each sampling site eggs were collected from a substrate area of 0.4 m^2 over a pumping period of 60 s. Within each of the channelized and rehabilitated reaches, between fifteen and 255 samples were collected each year.

Total daily estimates of egg scour and drift from the pool and riffle zones were extrapolated from catches in conical drift nets set for short periods (0.5–1 h) during the day. Larval fish were captured with conical drift nets set continuously (24 h) throughout the hatching period. The nets were serviced daily, and twice daily during peak walleye larvae drift.

To evaluate the rehabilitation design, comparisons were made between spawning success in the rehabilitated riffle–pool reaches and in isolated shallow riffles and pools in the channelized reaches above the rehabilitation sites. Few riffle–pool sequences occurred in the channelized reaches. However, those that did were similar to the man-made structures in terms of pool depth, riffle slopes, and median substrate sizes.

Comparison of the two reaches could not be made in all years because spring discharges also control the occurrence and location of walleye spawning. In 1989 and 1991, discharges were insufficient to allow fish to ascend the stream to spawn (Table 3). In 1988, low flows limited the extent of walleye migration beyond the rehabilitated reaches. As a result, a lower egg density was recorded for the channelized section in comparison to the rehabilitation sites located in the lower reaches of the stream. In high discharge years, such as 1986, 1987 and 1990 when the fish could reach and accumulate in the upper reaches, egg densities were greater in the shallow pools in the upper channelized section. However, viability of the eggs from the channelized and rehabilitated sections was similar, with live eggs comprising, on average, 68 and 73%, respectively, of the samples from all years.

Large numbers of walleye eggs were scoured from their incubation sites when discharges exceeded $2\,m^3\,s^{-1}$. Egg scour and drift was considered a serious problem as viable eggs could settle and die in high siltation areas near Lake Dauphin. Relative to egg densities, mean egg drift was 1.5 times greater from the channelized versus the rehabilitated section (Table 3). In addition, the rehabilitated section appeared to trap and retain eggs that entered from the upstream channelized reach.

The rehabilitated section appeared to produce more larvae, relative to mean egg densities, than the channelized reach (Table 3). However, comparison of larval drift estimates from the two reaches was confounded by: (i) the rehabilitated section being situated downstream of the channelized section, and (ii) the rehabilitated section tending to trap and retain drifting eggs and larvae. Overall, larvae were produced by both rehabilitated and existing channelized areas with roughly equal frequency and magnitude. Of the two types of riffle design, double riffles tended to produce the most walleye larvae.

Experimental rehabilitation of the channelized creek has shown that greater stability to the channel bed and banks can be achieved using artificial riffle–pool sequences, and that suitable spawning and incubation habitats for walleye can be created using this riffle–pool design. Based on the Mink Creek experiment, fieldstone riffles are now being added to the other channelized streams that enter Lake Dauphin.

Example 2: the rehabilitation and enhancement of uniform reaches

The Pine River in western Manitoba is one of a limited number of escarpment streams with resident populations of rainbow trout (*Oncorhynchus mykiss* Walbaum) and brook trout (*Salvelinus fontinalis* Mitchill). The streams flow from the Manitoba escarpment, a raised platform of Cretaceous shales and glacial tills, on to the flat lowlands of the Red River valley. The middle reaches of the streams provide the

Table 3 Summary of walleye spawning success information for Mink Creek

		Year					
Measurement	Reach type	1986	1987	1988	1989	1990	1991
Mean egg density (catch m^{-2})	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 $24\,h^{-1}$)	Single riffle rehab.	19.38	0.33	163.0	0	567.00	0
	Double riffle rehab.	—	0	233.0	0	1251.00	0
	Existing channelized	166.1	1.89	41.00	0	3701.00	0
Mean larval drift density (catch h^{-1} $100\,m^{-3}$ 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 ($m^3\,s^{-1}$)	2.82	7.96	1.09	0.48	9.04	0.34
	Mean incubation flow ($m^3\,s^{-1}$)	5.61	1.36	7.92	0.19	3.09	0.36
	Mean larval drift flow ($m^3\,s^{-1}$)	2.43	0.27	1.00	0.10	6.07	0.92

only trout habitat for several hundred kilometres and are consequently heavily fished.

There are natural and man-made factors that have limited the availability of trout habitat within the escarpment streams as well. Because the escarpment impounded the western shore of glacial Lake Agassiz, several sections of the streams flow in uniformly shallow boulder-filled channels that cross abandoned shorelines from which the finer cobbles and gravels have been scoured by wave action. Flood flows are unable to transport the large residual deposits that pave the stream bed in these sections. Consequently, there are no meanders, pools, or riffles formed. There has also been extensive man-induced loss of habitat (as much as 50% on some streams) in reaches with erodible bed materials due to logging, clearing for pasture land, sedimentation from intensive farming adjacent to the channel, and meander straightening.

As the demand for recreational trout fishing is greater than the existing habitat can support, potential reaches that could maintain a resident population with rehabilitation or enhancement works have been identified as additional resources. The location of potential reaches was based on fisheries surveys, the geomorphological history and characteristics of the escarpment and Lake Agassiz, and by hydrological studies of the catchments.

To test rehabilitation and enhancement designs, an experimental reach was selected on the Pine River that flowed across a bouldery shoreline of Lake Agassiz. The floodplain on the east side of the reach had been cleared as a forestry staging area several decades ago and the middle section of the reach had been re-aligned to flow under an open bridge on a secondary road to former logging sites in the headwaters. The tributary drainage area to the

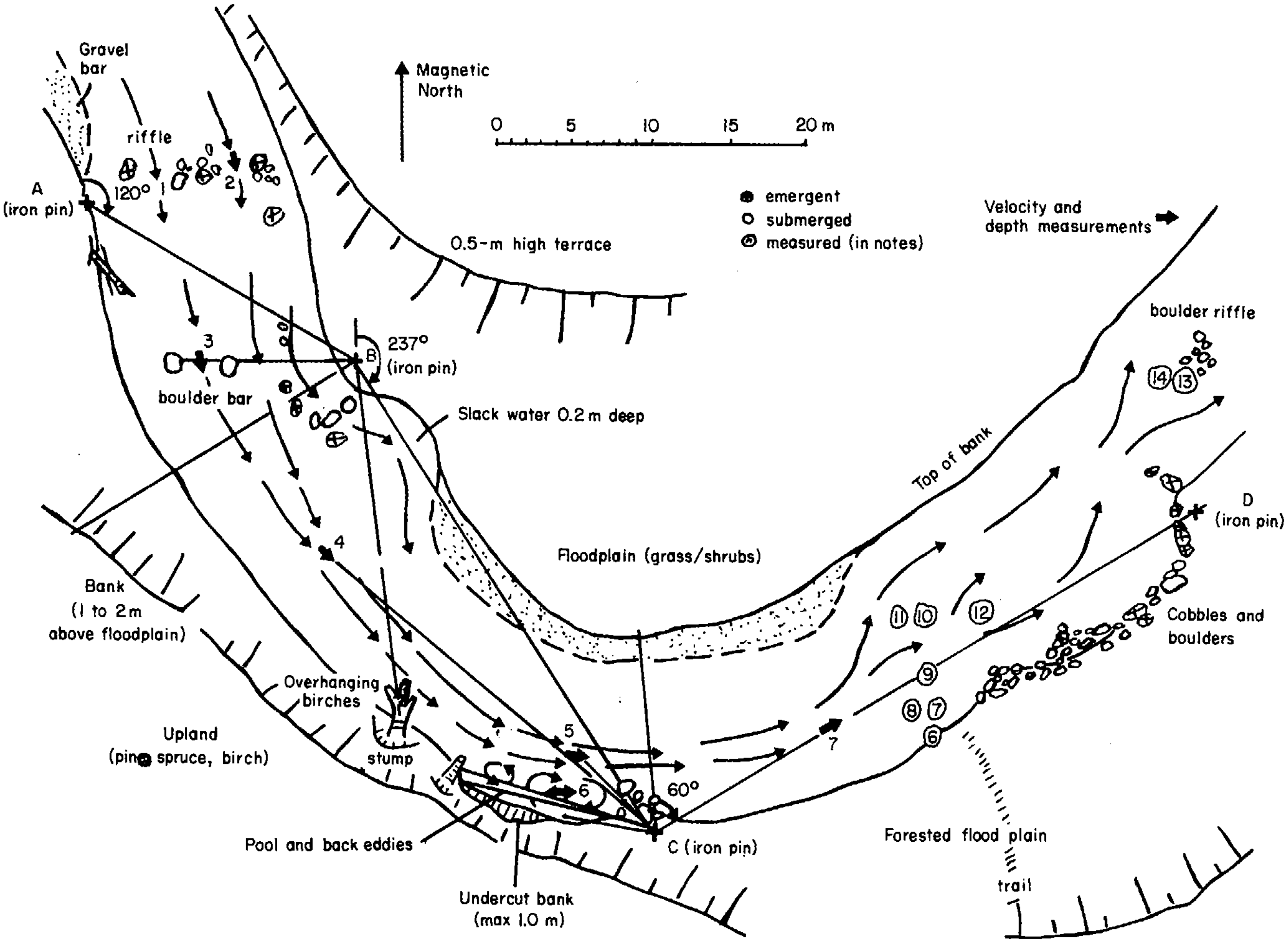

Fig. 10 Plane table survey of a typical reach of preferred trout habitat in a meander on the Pine River on the Manitoba escarpment.

reach is 100 km². A detailed plan, profile, and topographical survey was undertaken in the reach using a plane table and telescopic alidade (Brinker & Wolf, 1977). This traditional engineering survey method allowed contours of the stream bed and banks to be drawn directly on site. Notes were added to the reach plan concerning the nature and location of flow patterns and bed materials. Plane table surveys were used to prepare the reach plans (Figs 10 and 11) and the data was summarized (Table 2).

To gather information for designing the enhancement works, members of a local fishing club, the Swan Valley Sport Fishing Enhancement Inc., were asked to locate successful trout fishing reaches on the Pine River and adjacent streams. The locations were coded and sites that were identified by several anglers were chosen for sample fishing. A 'Trout Distribution and Catch' form (Appendix 2) was completed each time a sample reach was fished, recording the time, locations, catch, water conditions, and configuration of the catch site.

Based on the fishing surveys, the most frequently productive sites occurred in meanders with deep pools and smooth helical flows. These sites were utilized as holding and resting areas for adult rainbow and brook trout throughout the open water season. The deeper water, undercut banks, and submerged trees also provided the only escape cover for the trout which is limited in these shallow bouldery streams. During the winter, surveys found that trout were absent from meander pools, overwintering instead in deep beaver-dammed ponds downstream.

Plane table surveys of the productive sites were undertaken for a length of reach extending from the top of the upstream riffle, through the meander pool, to the bottom of the downstream riffle. The plane table drawing then became the template for the enhancement design. A typical survey of one of the sites is shown in Fig. 10. All of the reaches surveyed exhibited similar meander geometries (Fig. 12) despite a wide range of catchment and stream size (70–300 km²). Relative to the bankfull

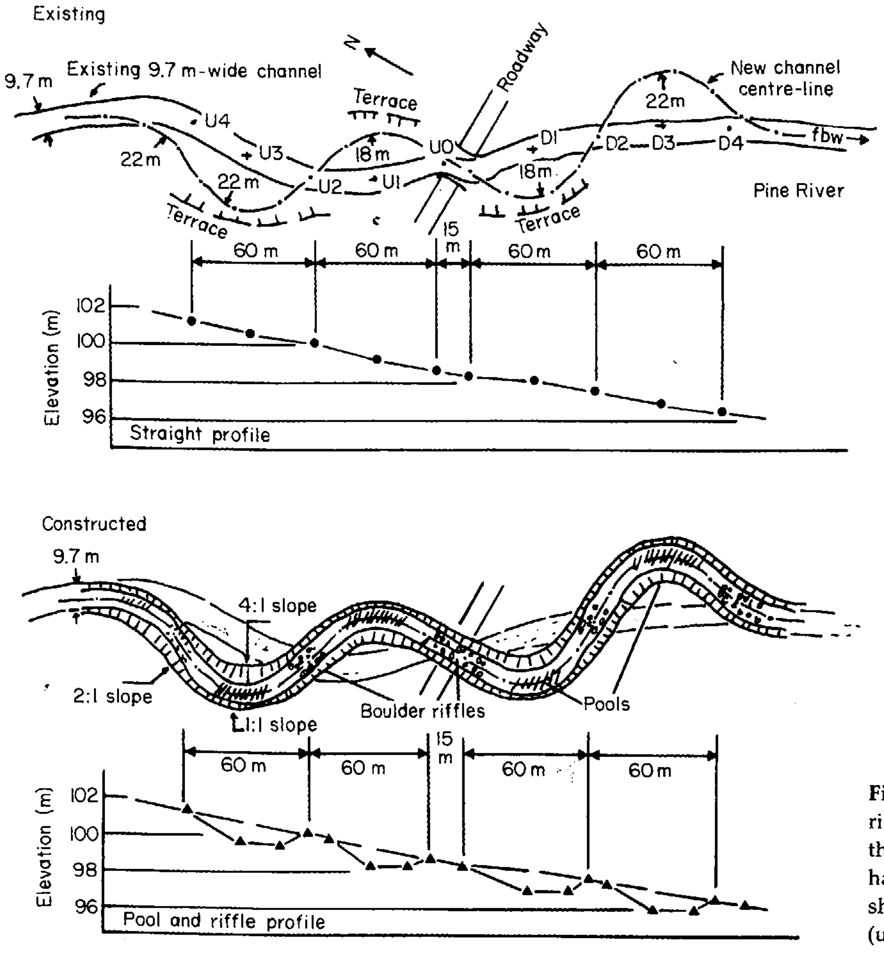

Fig. 11 Meanders with pool and riffle profiles (lower plan), similar to those observed in preferred trout habitats, were constructed in the straight shallow reach of Pine River, Manitoba (upper plan).

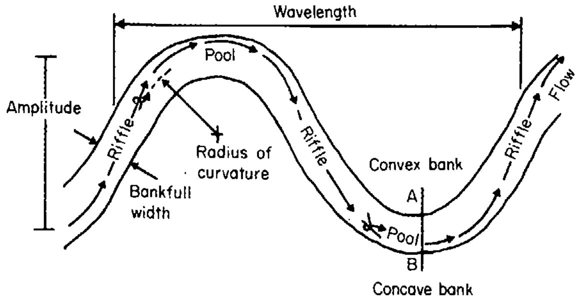

Fig. 12 Definition sketch for meander dimensions.

width of the stream, the average wave length was eleven times the bankfull width. The average radius of curvature of the meander loop was 2.3 times the bankfull width. The amplitude of the meanders varied between four and six times the bankfull width.

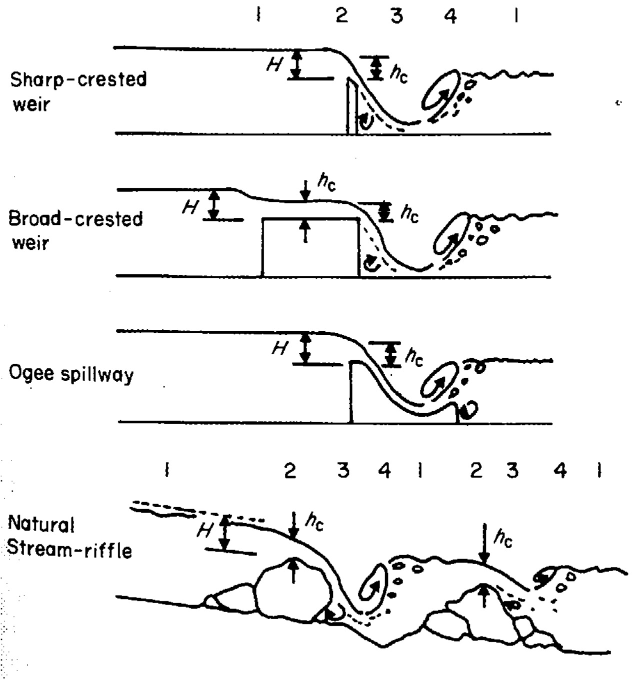

Fig. 13 Transitions and states of rapidly varied local flow over weirs and spillways applied to natural local flow conditions in a stream riffle. 1, Subcritical; 2, critical (depth h_c); 3, supercritical; 4, hydraulic jump. 1 → 3, Acceleration; 3 → 4 deceleration. H, head above obstruction; $h_c = \frac{2}{3}H$.

Local velocities and depths were identified and measured at selected sites throughout the habitat reaches. Local-flow phenomena (Level III, Fig. 1) were identified using simplified hydraulic classifications derived from hydraulic engineering definitions normally applied in designing weirs and spillways shown in Fig. 13. The pattern of flow in meanders was sketched on the plane table map as well. It was observed that the flow smoothly rotated in a helical pattern through the pools in meanders with a radius of curvature close to the average value of 2.3 times the bankfull width. In meanders that were terminated abruptly with a sharp turn due to large boulders, treefalls, or resistant bank materials (radius of curvature > 3), the rotating pattern was interrupted as the flow entered a turbulent mixing zone that often scoured a deep hole in the channel bottom. The rotational flow did not occur in gently curving reaches (radius of curvature < 2). The mean radius of curvature for meanders observed in many streams is 2.4 times the bankfull width and it has been argued that this is the 'most probable state' for the minimum energy to be expended by the flow (Chang, 1988).

Local stream-bed profiles were surveyed in the riffle zones to establish the depths and elevations of overflow conditions. Similar measurements made in other escarpment streams with the local profiling device shown in Fig. 14 demonstrated that some benthic organisms, important to trout as food, prefer habitats on the tops of cobbles and boulders in converging near-critical local-flow zones (Wetmore, Mackay & Newbury, 1990). These zones are important for gathering detritus efficiently. Similar studies by Cobb (1990) have shown that riffles may be constructed in uniform reaches to create overflow habitats that will augment benthic production. The characteristics of productive benthic riffles were used as guidelines for placing cobbles and boulders on the surface of the constructed riffles in the experimental reach of the Pine River.

The meanders were designed at a spacing of 120 m, or 12.4 times the bankfull width of 9.7 m (Fig. 11). The riffles were spaced at 60 m, or 6.2 times the bankfull width. The amplitude of the meanders was selected to fit between terraces that rose 1–2 m on either side of the existing floodplain. The meander bends were placed to allow undercutting of the terraces similar to that observed at the template site. The radius of curvature of the top of the loop of the meander bends was set at 22 m, or 2.3 times the bankfull width in the first and last bend. This was reduced to 18 m in the central bends to produce a straight alignment with the bridge on the secondary road. The centreline and geometry of the meander loops were superimposed on the existing channel (Fig. 11).

A pool and riffle profile was designed for the

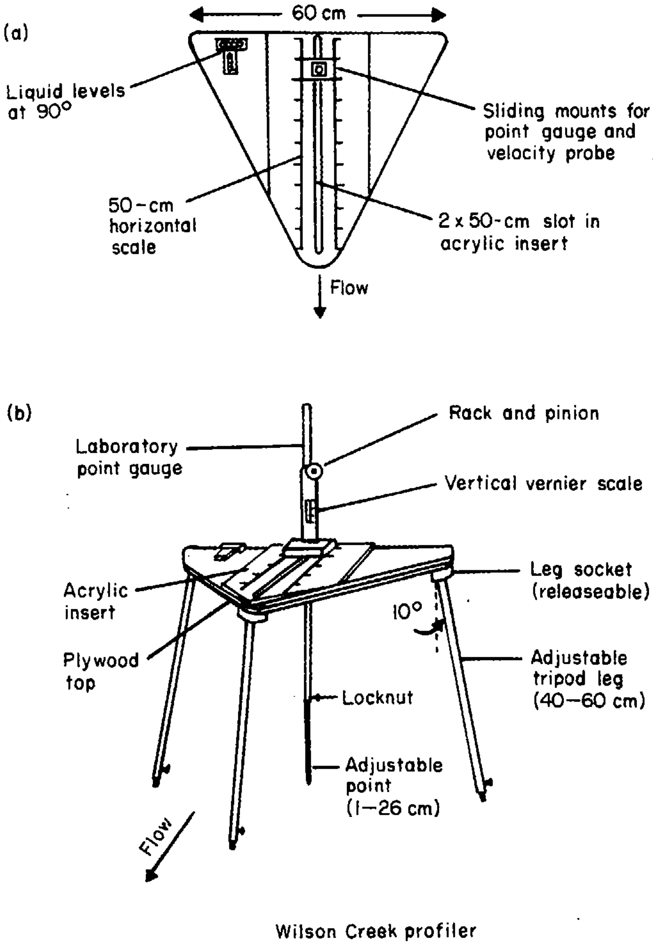

Fig. 14 A portable stream surface and bed profile measuring device used for characterizing local flow conditions and benthic habitat preferences.

meandering channel. Large rocks at varied elevations were added to the riffle sections at 0.2–0.5 m spacing to produce overflow conditions and chutes over a range of stream discharges. Pools were excavated between the riffles to depths varying from 0.5 to 0.7 m below the riffle crests. In the meander pools, the cross-section was designed with 1:1 slopes on the outside of the bend and 4:1 slopes on the inside of the bend to mimic the skewed channel cross-sections that occur in natural meander pools.

The experimental meandering reach was constructed in November 1990. The cost components for the project were: surveys and design, 20 person days; site preparation (clearing), 15 person days; construction supervision, 11 person days; excavation machine rental, $US9400.

An aerial view of the reach is shown in Fig. 15

Fig. 15 Aerial view of trout habitat meanders constructed in a straight reach of Pine River, Manitoba that is crossed by a local road. The near-bank vegetation is not yet restored.

during 1991, the first period of high spring runoff. A small volume of fine sediment from the former floodplain has been flushed from the reach and the water now flows clearly. Riparian vegetation was restored to the channel banks and floodplains from the nearby forest later in 1991. Trout have been observed and caught by anglers in the reach throughout the open water seasons of 1991 and 1992. Monitoring of the catch has not been possible as the reach is heavily fished by passing anglers because of its easy road access. Similar trout habitat meanders are now planned for naturally poor and channelized reaches on the other escarpmental streams of this size.

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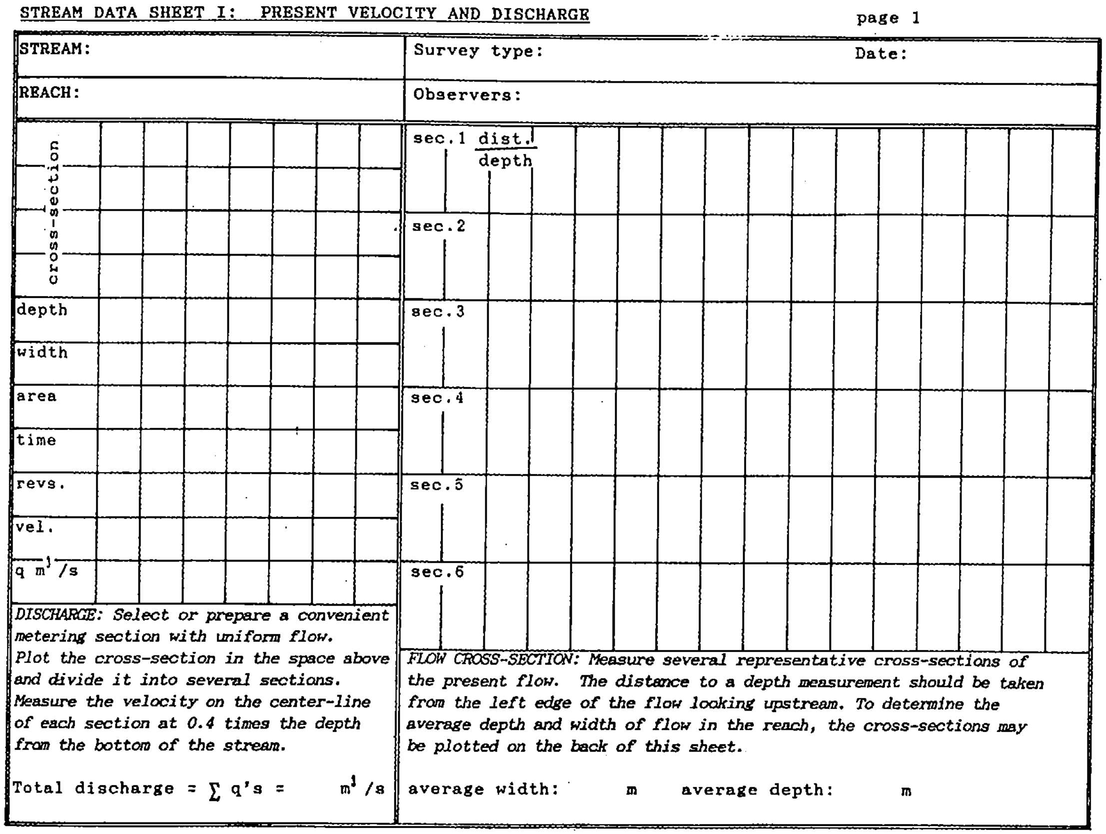
Appendix 1 Field data sheets



STREAM DATA SHEET I: PRESENT VELOCITY AND DISCHARGE page 1

STREAM:	Survey type:	Date:
REACH:	Observers:	

cross-section							
depth							
width							
area							
time							
revs.							
vel.							
q m^3/s							

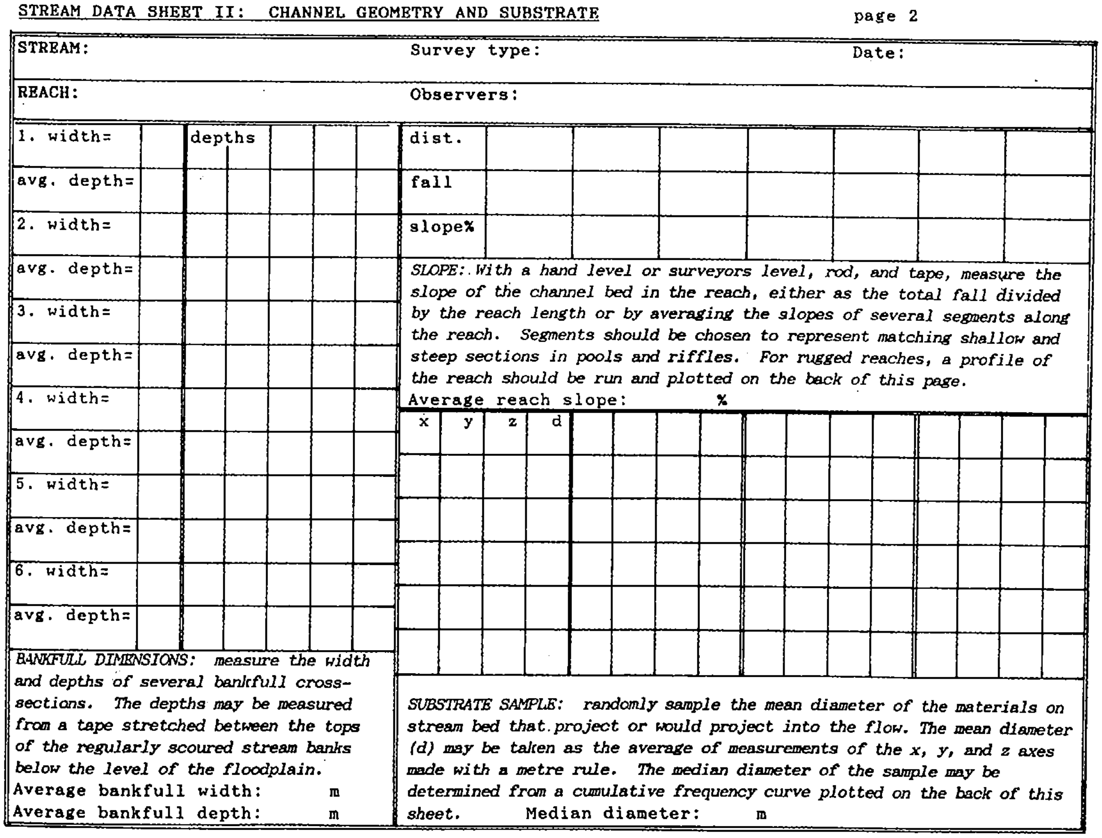
sec.1	dist./depth													
sec.2														
sec.3														
sec.4														
sec.5														
sec.6														

DISCHARGE: Select or prepare a convenient metering section with uniform flow. Plot the cross-section in the space above and divide it into several sections. Measure the velocity on the center-line of each section at 0.4 times the depth from the bottom of the stream.

Total discharge = $\sum$ q's = m^3/s

FLOW CROSS-SECTION: Measure several representative cross-sections of the present flow. The distance to a depth measurement should be taken from the left edge of the flow looking upstream. To determine the average depth and width of flow in the reach, the cross-sections may be plotted on the back of this sheet.

average width: m average depth: m



STREAM DATA SHEET II: CHANNEL GEOMETRY AND SUBSTRATE page 2

STREAM:	Survey type:	Date:
REACH:	Observers:	

1. width=		depths				
avg. depth=						
2. width=						
avg. depth=						
3. width=						
avg. depth=						
4. width=						
avg. depth=						
5. width=						
avg. depth=						
6. width=						
avg. depth=						

BANKFULL DIMENSIONS: measure the width and depths of several bankfull cross-sections. The depths may be measured from a tape stretched between the tops of the regularly scoured stream banks below the level of the floodplain.

Average bankfull width: m

Average bankfull depth: m

dist.							
fall							
slope%							

SLOPE: With a hand level or surveyors level, rod, and tape, measure the slope of the channel bed in the reach, either as the total fall divided by the reach length or by averaging the slopes of several segments along the reach. Segments should be chosen to represent matching shallow and steep sections in pools and riffles. For rugged reaches, a profile of the reach should be run and plotted on the back of this page.

Average reach slope: %

x	y	z	d												

SUBSTRATE SAMPLE: randomly sample the mean diameter of the materials on stream bed that project or would project into the flow. The mean diameter (d) may be taken as the average of measurements of the x, y, and z axes made with a metre rule. The median diameter of the sample may be determined from a cumulative frequency curve plotted on the back of this sheet. Median diameter: m

STREAM DATA SHEET III: REACH PLAN

page 3

STREAM: Survey type: Date:

REACH: Observers:

SKETCH: freehand ☐ supplemental mapping ☐ photographs:

APPROXIMATE SCALE:

Common Features: EW:edge of water TB:top of bank FP:floodplain BFS:bankfull stage UCB(m):undercut bank (amt)
P:pool R:riffle CC: central channel SC:side channel CH(m):chute(width) OF:overflow HJ:hydraulic jump/aeration
OD:organic debris L(m):log(diameter) EV:emergent vegetation OH(m):overhanging vegetation(width) LB:large boulder
clay/silt: <.06 mm sand: .06-2 mm gravel: 0.2-6.4 cm cobbles: 6.4-26 cm boulders: 26-410 cm

Appendix 2 Trout distribution and catch forms

TROUT DISTRIBUTION AND CATCH
FORMS FOR
ANGLING SURVEYS IN ESCARPMENT STREAMS
MANITOBA FISHERIES BRANCH

General Information

This form has been designed to improve our understanding of brook and rainbow trout habitat in Porcupine and Duck Mountain streams. It will also provide information on trout distribution and abundance.

To complete the form, anglers should indicate the date, time period and number of anglers fishing a particular stream site or section. Using a 1:50,000 topographical map, anglers should identify their fishing locations by topographical elevation. Long sections of stream that are fished should be limited to an elevation change of no more than 25 ft. For example, a typical stream section on the Pine River would be identified with an elevation between 1600 and 1625 ft. For each trout caught, measure its total length and describe the habitat in which it was found. It is important that a form be completed describing the habitat for each section of stream fished, eventhough in some cases no fish were caught.

On the opposite page of the form provide your comments on the trout habitat, flow conditions and fishing success. If possible sketch a plan view drawing of the site identifying the characteristics which you feel are key trout habitat components.

Good Luck and Good Fishing!

TROUT DISTRIBUTION AND CATCH FORM

Stream ______________________________

No. of Anglers reporting on this form ____________

Fished at this site from________AM/PM to________AM\PM

Date ____________

HABITAT AND CATCH DESCRIPTION

Topographical elevation of fishing site:

at________ ft or between________ and ________ft

SPECIES	LENGTH (cm)	HABITAT			
		Meander Pool (✓)	Beaver Pond (✓)	Rapids (✓)	Depth (cm)

Submitted by ______________________________

Comments: Have you caught fish here before?
Is the water lower or higher than average?
Is the catch rate at this site today better, worse or the same as usual?
Is the habitat alternating pools and riffles?
Other comments?

Sketch of the site-showing pool, rapids, large boulders, undercut banks