STREAM ANALYSIS AND FISH HABITAT DESIGN

A Field Manual

ROBERT W. NEWBURY • MARC N. GABOURY

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Preface to the 2nd Printing

Since the first printing in 1993, we have heard many encouraging reports of successful stream restoration projects in central North America from users of the 10-step analysis and design procedure presented in Chapter 4. There were also helpful suggestions and corrections, some of which have been incorporated in this edition.

We have had several enquiries about the feasibility of constructing pools and riffles in higher gradient streams that have degraded salmon and trout habitats. Since the first printing, four sample pool and riffle habitat projects have been completed on small streams (5 to 70 square kilometre basins) that had been diverted or straightened on the Sunshine Coast in southern British Columbia. The stream gradients range from 1% to 9% in the project reaches. Initial monitoring results show increasing use of the enhanced salmonid habitats, particularly where logs and boulder clusters have been added to the pools and stream margins. A summary of three of the sample projects with their design drawings has been added to Appendix F.

Although there have been minor shifts in constructed riffles and some filling of pools in coarse sediment transport streams, all of the constructed projects have remained in place in spite of flood flows with annual return periods of up to 40 years. In many cases, the complexity of the restored channel habitats was improved by channel scouring in pools below the riffles and re-sorting of the riffle rocks during high flow periods.

We wish to thank all of those who have reviewed the manual and made suggestions for corrections and additions.

R. Newbury
M. Gaboury

October, 1994

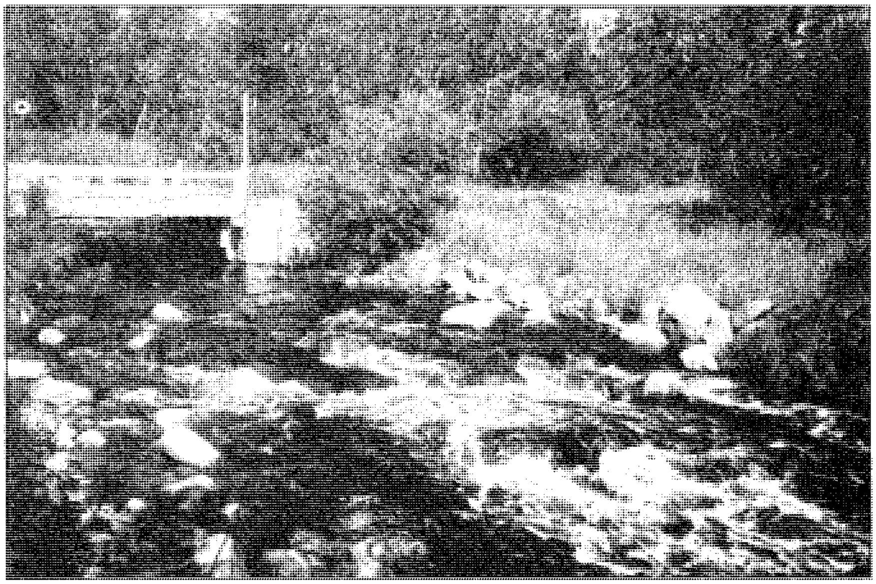


Figure P-1: *Naturally re-sorted rapids and scoured pool on the North Pine River in 1993 following a 40 year annual return period flood (see Figures 4-40 to 4-45 taken in 1990).*

Introduction

Workshops and short courses on stream behaviour have been held on Wilson Creek in Riding Mountain National Park since 1968. In the courses, we observed that the sample reaches within the national park were vastly different from those beyond the park boundaries. Outside the park, the stream had been channelized and straightened to reduce flooding on adjacent agricultural lands. The steeper man-made channel had downcut over 10 m through its own alluvial fan deposits in just 30 years. The energy of the mean annual flood was two times greater in the channelized reaches. In 1978, rock-fill rapids 2 m high were designed for the eroding reaches that would dissipate half the flood energy. When the rapids were added, the channel stabilized. Pools were formed in the valley bottom and natural riparian vegetation returned to the banks of the stream. The natural biota, once confined to the park reaches, moved into the stabilized zone. This was our first lesson in stream restoration.

Stream habitat restoration through the adjustment of a stream's long profile to concentrate or dissipate flood flow energies became the theme for future workshops. The addition or removal of pools and riffles and the adjustment of gradient control points along the profile was a technique that could be applied to a wide variety of stream stability and habitat restoration problems. Flow depth, velocity, continuity, hydraulic habitats, aeration, fish passage, and bed stability could be manipulated by analyzing and adjusting the channel profile and geometry without the loss of flood capacity. For fish habitat, the relationship between all of these factors, and probably more, was too complex for us to characterize precisely. Instead, we carried out surveys and made analyses in reaches of natural streams that sustained successful benthic and fish habitats and used them as natural templates for altering the deficient streams. To carry out these broader surveys, we condensed and shortened the original research-based stream analysis methods, eventually producing the "10 step" analysis and design procedure used in this manual.

Beginning in 1984, the methods were tested and refined by analyzing and constructing 15 new projects in different geological and hydrological settings for a variety of fish habitat rehabilitation problems in Manitoba. Five typical projects are used as examples in Chapter 4.

Understanding stream habitats

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. A schematic diagram locating the nested habitats to the level of the streambed is shown in Figure I-1. In porous bed streams, a "hidden" habitat also exists in the interstitial flow through the substrate.

At Level I, 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 a 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 layer habitat of an individual benthic organism located 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 and the conductance of the streambed deposits.

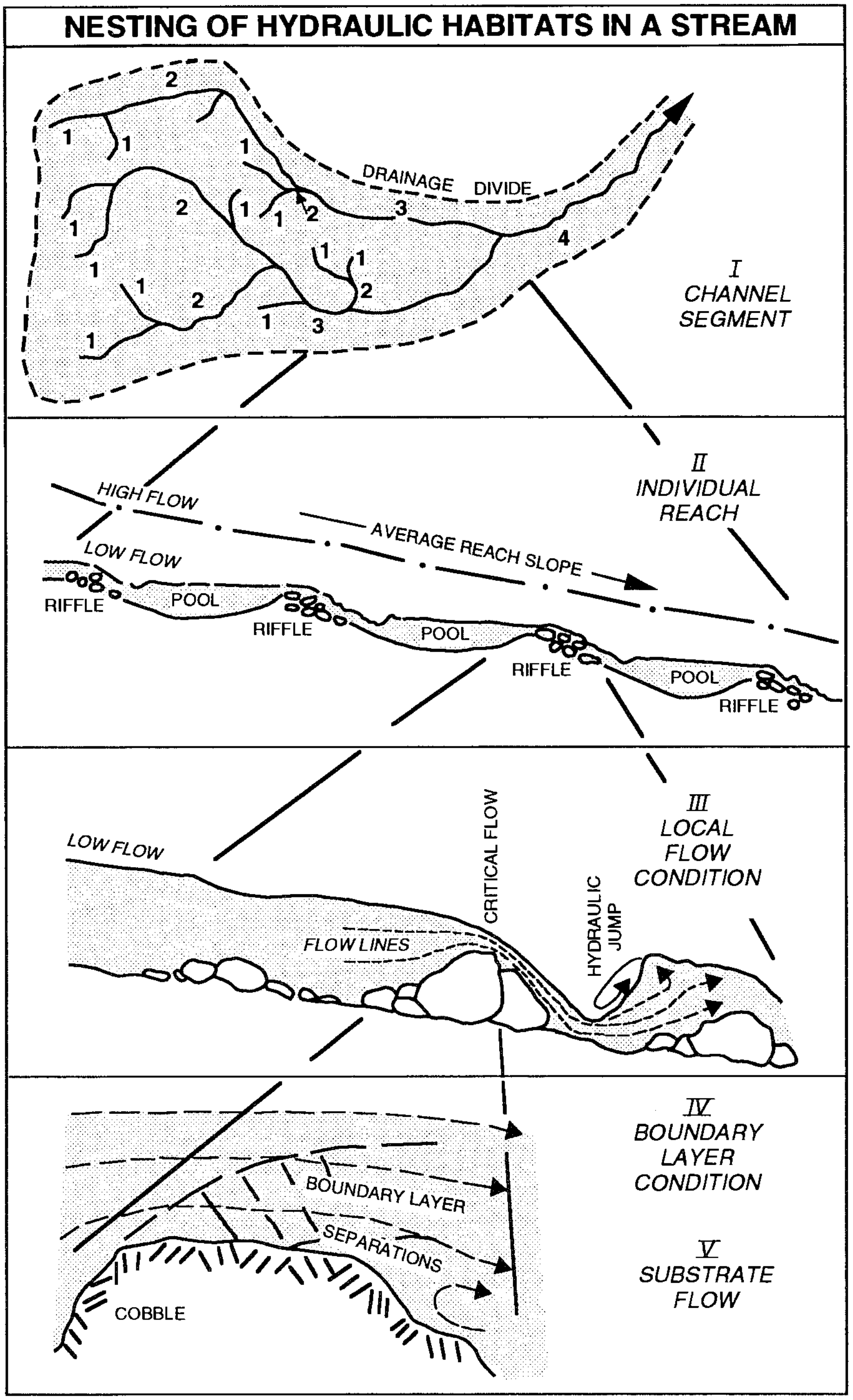


Figure I-1: *The nesting of smaller and smaller levels of stream habitats in a drainage basin.*

Successful stream rehabilitation or enhancement designs must often recreate hydraulic conditions in all levels of habitat but the design parameters for fluvial processes, site-specific hydraulics, and aquatic organisms have defied complete analysis, particularly at the lower levels. However, geographical, engineering, and biological studies undertaken in the last 30 years can be used to design the simple components, and the more complex habitat characteristics can be produced by mimicking the natural materials and geometry of the stream. In some countries, this is referred to as "soft engineering" 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 for the single purpose of efficient water conductance.

Background reading

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, and Miller in 1964. In Great Britain, a similar summary was compiled for drainage basins by Gregory and Walling (1973). In the more established field of river engineering, Chow prepared a broad treatment of open channel hydraulics in 1959. A few years later in 1964, he compiled a comprehensive handbook of river and drainage basin hydrology. Both books still serve as basic references in many engineering design offices. A recent book by Chang (1988) combines 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 in 1970, and later further articulated by Vannote et al. (1980) in the river continuum proposal and by Bovee (1978) for instream flow requirements.

There are many contemporary studies that match physical and hydraulic characteristics with fish and benthic populations, for example Schlosser (1986) and Statzner et al. (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 to promote integrated designs.

Using this manual

Stream analysis and design procedures in this manual are based on the design and construction of fish habitat projects undertaken in the last 10 years in natural and man-made streams (Figure I-2 and Appendix F). Of the 15 projects completed in southern Manitoba, five typical projects of increasing complexity in lowland, escarpmental, and bedrock-controlled channels have been chosen as design examples in Chapter 4 (Table I-1).

The organization of the manual corresponds to a ten step design and construction process presented in Chapter 4 (Figure 4-1) as follows:

Chapter 1: Planning Stream Habitat Projects .... *steps 1, 2, 3*

Chapter 2: Field Exploration .... *steps 4, 5*

Chapter 3: Evaluation of Stream Behaviour .... *step 6*

Chapter 4: Design and Construction of Stream Habitats . *steps 7 -10.*

The first three chapters present the theory and methods applied in the design examples presented in Chapter 4. Readers with experience in stream hydrology or fish habitat projects can follow an example in Chapter 4 directly and use the first three chapters for background references.

Appendix A contains a summary of fish behaviour and habitat preferences for selected Manitoba species.

Spawning Riffles

1 North Duck River
2 Mink Creek
3 Wilson River
4 Edwards Creek
5 Crawford Creek
6 Basket Creek
7 Icelandic River
8 Wavey Creek
9 Coca Cola Falls
10 Rainbow Falls - Inlet to White Lake
11 Rennie River - nr. Hwy 44
12 Falcon Creek
13 Hamilton Creek

Trout Habitat Development

14 Pine River
15 Whiteshell River

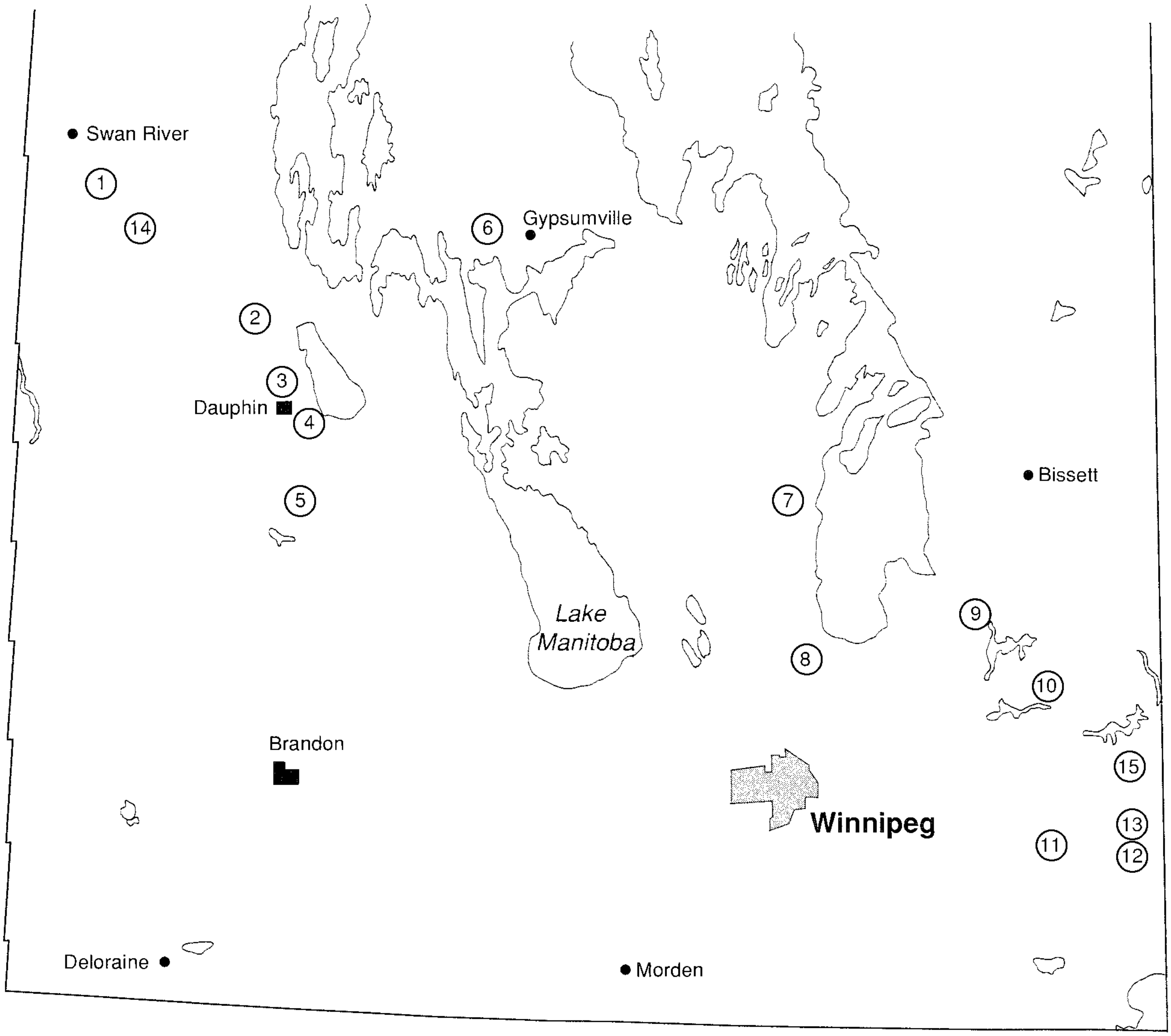


Figure I-2: *The location of fish habitat projects undertaken in southern Manitoba. Five typical projects (locations 2, 3, 13, 14, and 15) are discussed as design examples in Chapter 4.*

Table I-1 Summary of problem analysis and restoration measures applied for the five design examples described in Chapter 4.

Design Example	Location	Analysis	Restoration
1. Gas pipelines buried across stream	Hamilton Creek, Manitoba (bedrock)	lower half of the walleye spawning area was excavated and graded for crossing; channel widened and silted after earlier cobble placement	two pool and riffle reaches have improved walleye spawning habitat and reduced sedimentation
2. Natural creek altered to drainage canal	Mink Creek, Manitoba (lowland)	ongoing channelization since 1951 has eliminated meanders, pools and riffles, causing bed and bank erosion	27 riffle structures, 0.5–0.8 m high spaced 60–100 m apart, stabilized channel erosion and improved walleye spawning habitat
3. Stream channelization	Wilson River, Manitoba (lowland)	removal of meander loops has shortened the river by one–third, causing up to 2 m of down–cutting, bank slumping and sedimentation	9 rock–fill spawning riffles created pools 0.5–1.5 m deep, re–stabilized the reach, and improved walleye reproductive success
4. Uniform and straight natural reach	North Pine River, Manitoba (escarpment)	reach paved with large stable boulders preventing the formation of meanders, pools and riffles	using a natural meander as a design template, two meanders with a pool and riffle profile have diversified hydraulic habitats for trout
5. Bedrock–controlled channel	Whiteshell River, Manitoba (bedrock)	broad shallow channel with no undercut banks, large organic debris or overhanging vegetation, limiting spawning, and holding habitats	meander pattern was reinforced, channel narrowed, pools excavated, and seven riffles and 12 cover structures constructed

***Note:** Design summaries for steeper gradient salmonid streams are included in Appendix F.*

Chapter 1

Planning Stream Habitat Projects

Before going to the field, a few days of office study are useful for compiling maps, gathering historical information, and analyzing the drainage network of the project stream and, if available, preferred habitat reference streams. Usually a preliminary list of sample reaches and a logistical plan can be prepared from the map and planning information. In this chapter, the planning studies have been divided into four sections:

1.1 Topography of the basin
1.2 Regional geology and hydrology
1.3 Stream reach analysis
1.4 Survey design for sample reaches.

1.1 Topography of the basin

Topographic maps and aerial photographs of the stream region should be obtained to determine the watershed boundaries, drainage area, stream pattern, and major geological features of the basin. National Topographic Series (NTS) maps are available at several scales. For stream basins greater than 20 km^2 in extent, 1:250,000 maps usually provide sufficient detail for selecting sample reaches. For smaller basins and surveys within a reach, the 1:50,000 and 1:10,000 scales are more useful. In developed areas, provincial drainage maps should be used to supplement the topographic maps by adding man-made drains and other works. Aerial photographs are available as township mosaics for most regions and larger scale individual aerial photos are usually available at regular intervals from 1930 onwards. Geological maps, often as part of regional geology reports, are not available for all basins at larger scales, but the general geological setting can be determined from regional maps.

Mapping of geological and hydrological subdivisions on a regional basis can provide a broad planning framework for conservation programs similar to Endangered Spaces, Ecological Reserves or Heritage Rivers (Appendix B). By overlapping geological and hydrological subdivisions with other landscape features, representative streams can be selected from specific biomes.

The stream plan or drainage basin

On the topographic maps, the drainage basin boundary should be traced along the watershed line. The watershed line follows all of the drainage divides at the outer limits of the basin. Using the contours as a guide, the watershed line can be sketched on the map by estimating the location at which surface waters will flow either into or away from the stream basin. If the basin is surrounded by flat areas, the watershed line is assumed to divide the area equally between the basin and the adjacent area. At the lower end of the basin, the watershed line converges upon the stream channel. If only part of the basin is being considered, for example, the tributary area to a sample reach, the watershed line may turn abruptly at the upper drainage divide and descend directly to reach, crossing the valley contours at right angles. The drainage basin area may be determined with manual or computer-linked planimeters. An approximate area can be determined by overlaying transparent grid paper on the basin and counting the number of unit areas contained within the watershed lines. Sample topographic map and watershed lines for Hamilton Creek, Mink Creek, and the Pine River are shown in Figures 1-1, 1-2, and 1-3.

The stream profile and basin cross-section

The general profile of the main stem and several branches may be determined from the topographic map of the basin by measuring and plotting the distance along the stream valley between successive contour line crossings. In low gradient streams, the profiles may have to be surveyed directly. Using the same method, a cross-section of the basin that follows the upland surface of the basin should be prepared.

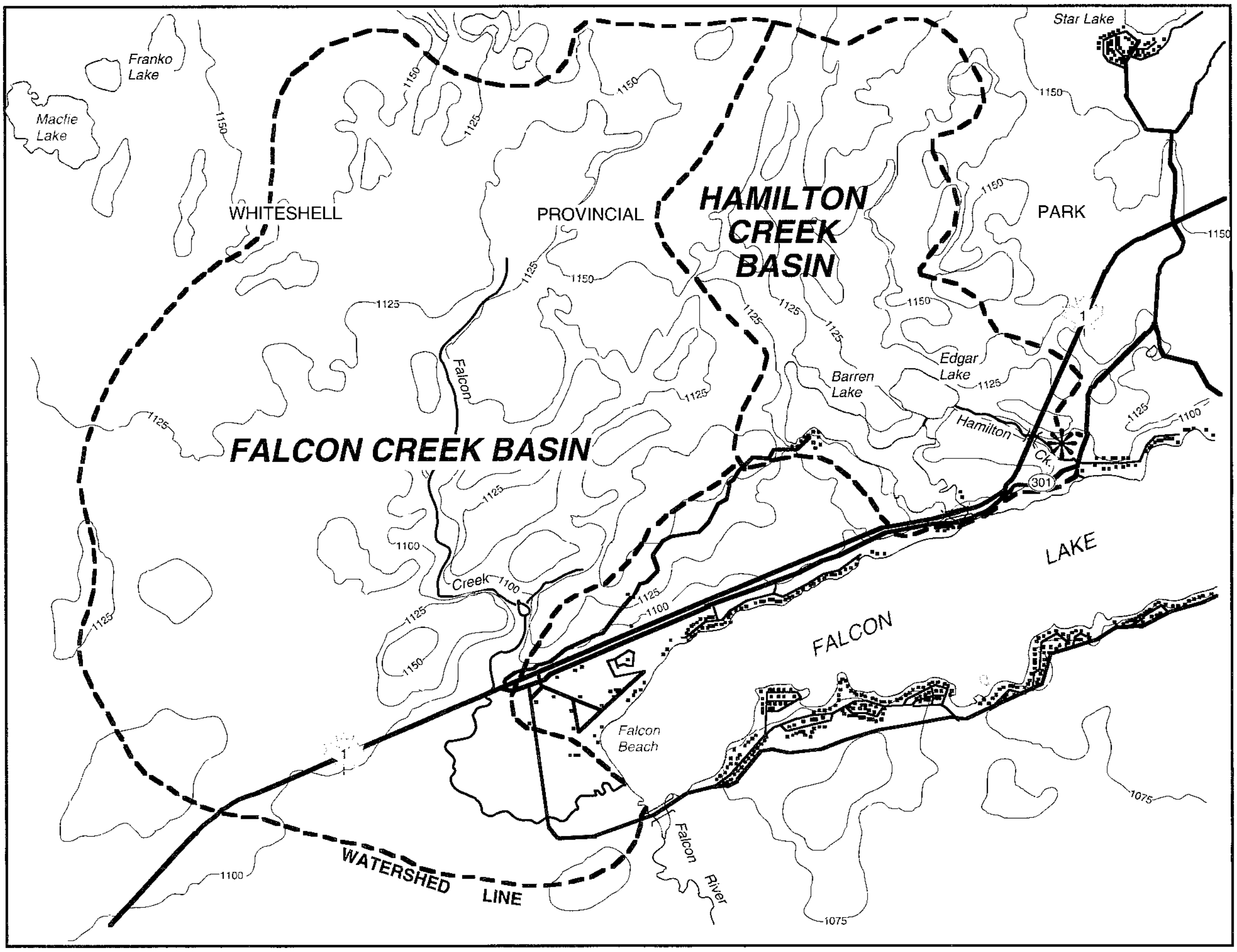
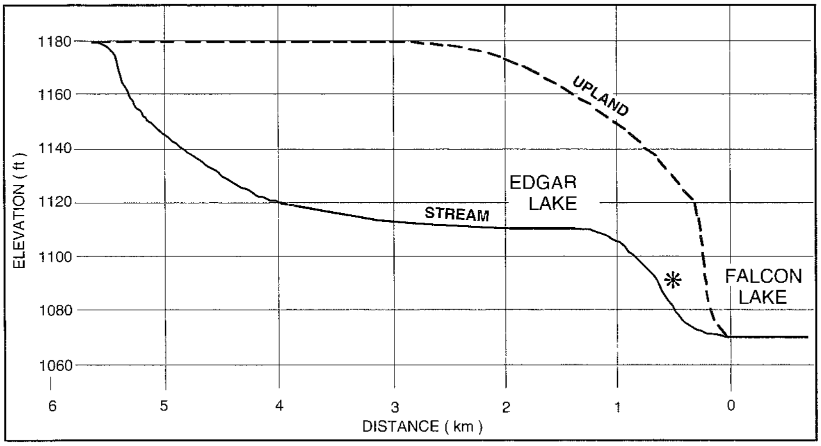


Figure 1-1: *Hamilton Creek watershed lines, profiles, and drainage basin (NTS map sheet 52E11, scale 1:50,000, contour interval 25 feet). The stream crossing walleye spawning rehabilitation site is marked* ✳.



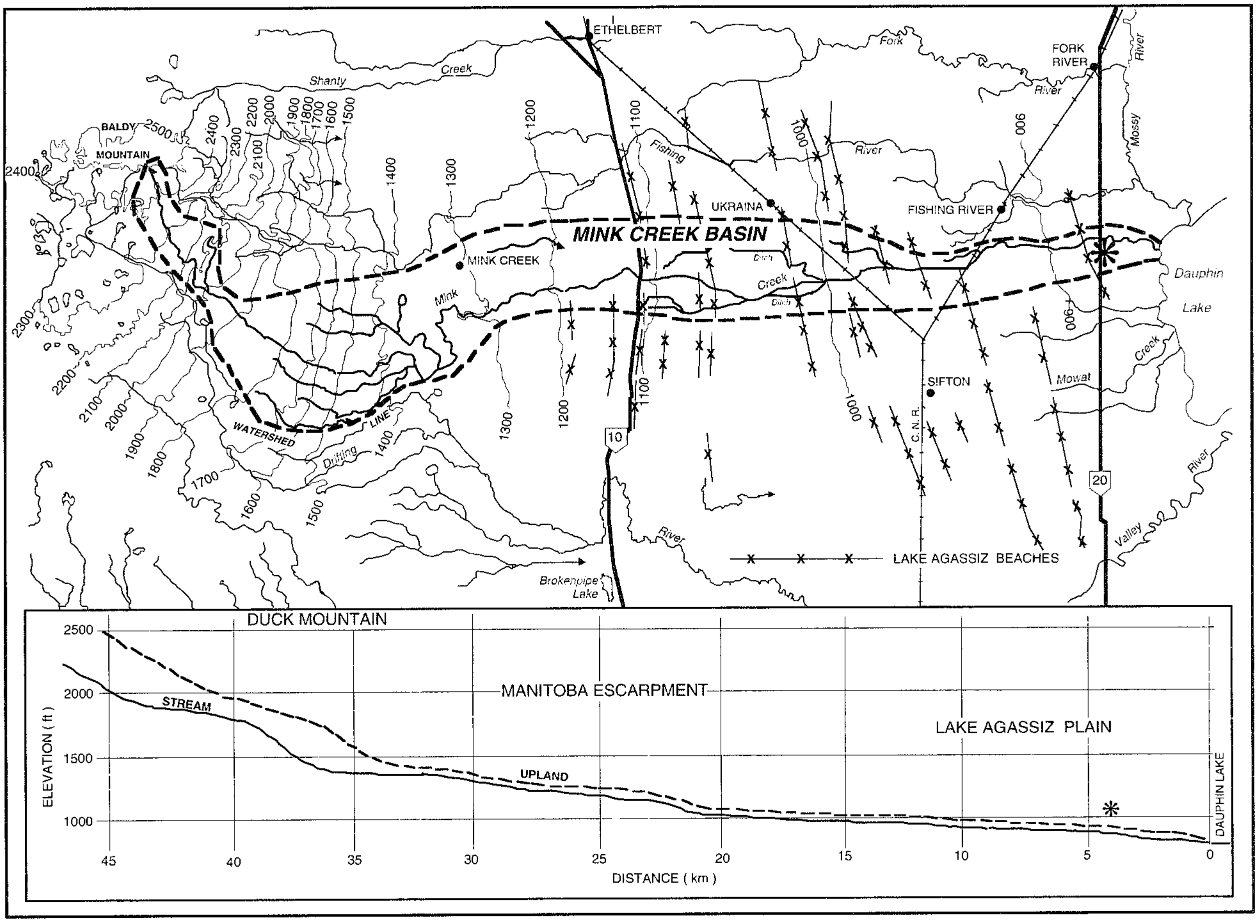
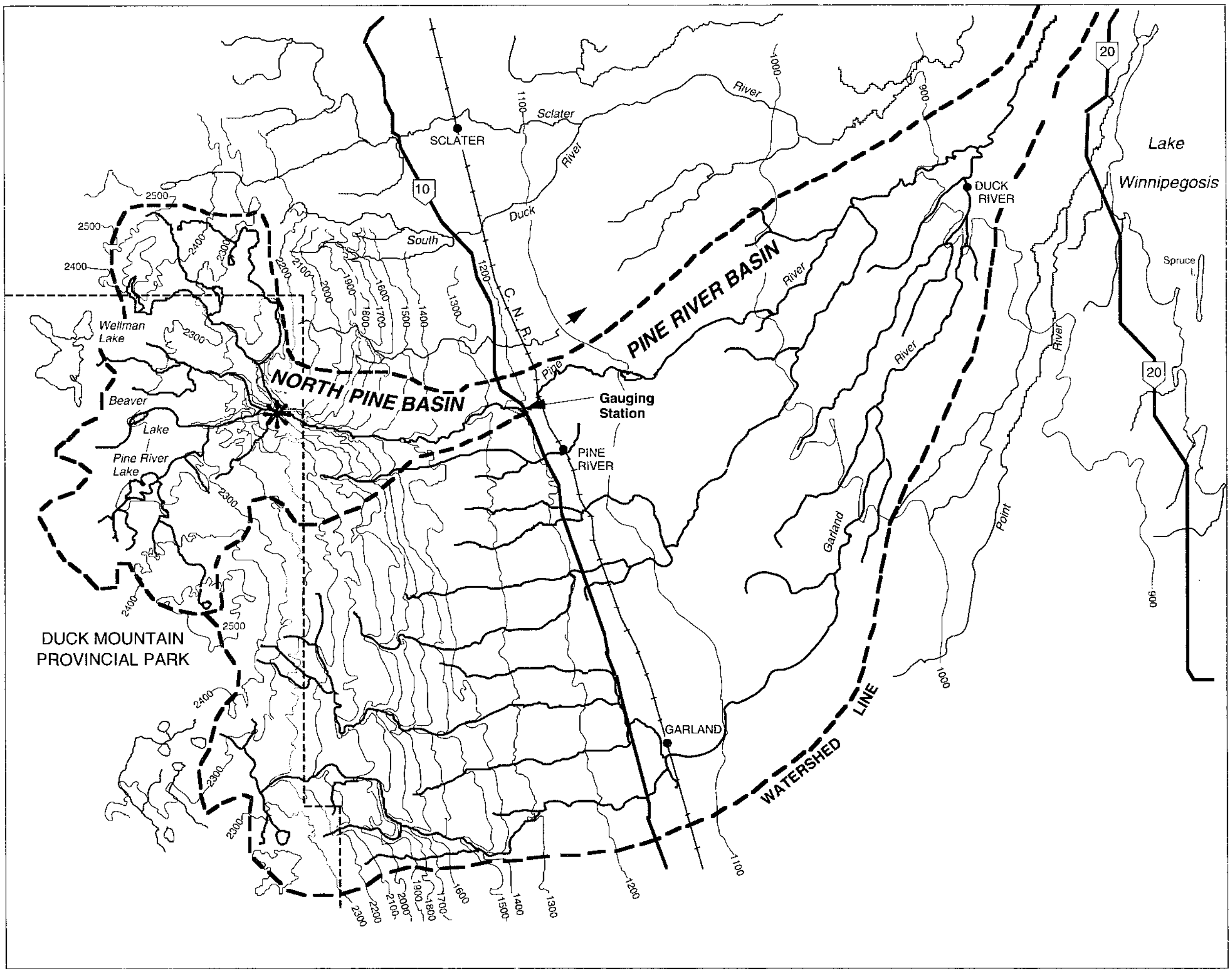


***Figure 1-2:** Mink Creek watershed lines, profiles, and drainage basin (NTS map sheet 62N, scale 1:250,000, contour interval 100 feet). The walleye spawning rehabilitation reaches in the channelized stream are marked ✻.*



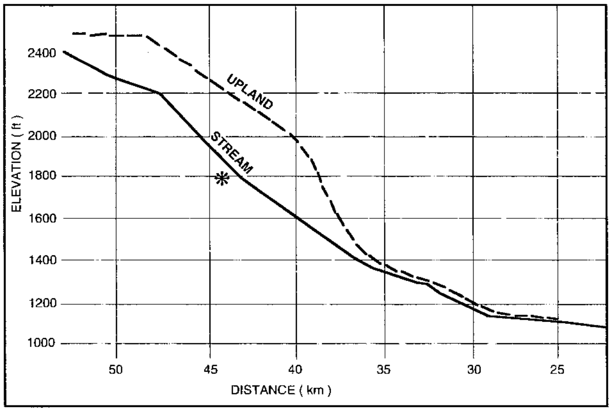


Figure 1-3: *Pine River watershed lines, profiles, and drainage basin (NTS map sheet 62N, scale 1:250,000, contour interval 100 feet). The meandering trout habitat enhancement reach is marked* ✳.

At the NTS map scales, the profiles will be generalized but indicative of average reach gradients from the headwaters to the lower reaches. By plotting all the profiles to the same scale, the usual deepening and smoothing effects of stream erosion in the valleys will be apparent.

The Hamilton Creek, Mink Creek, and Pine River profiles are shown on the basin plans in Figures 1-1, 1-2, and 1-3 based on the valley bottom and watershed contour lines. As in many streams in erodible materials, the mainstem profile is concave upwards. One explanation for this behaviour is the observation that for many rivers, the power of bankfull flood flows in individual reaches along the profile tends to be equal. The power of flowing water exerted in a reach is the product of the discharge and the total fall in the reach. Thus, upper reaches in the basin with small tributary drainage areas and subsequently low flood flows have high gradients. In lower reaches, with greater drainage areas and high flood flows, there are correspondingly lower gradients.

1.2 Regional geology and hydrology

The drainage basin map should be located and if possible, traced onto a geological map, noting where changes in rock types and structural boundaries occur in the basin. In some basins, both bedrock geology and surficial geology maps may be available, allowing both the rock type and materials through which the stream is running to be mapped.

The pattern of drainage in the basin may coincide with different bedrock and surficial deposits with changes in the stream profile at the geological boundaries. For example, the Hamilton Creek basin lies in a belt of volcanic and sedimentary rocks within the generally massive granitic rocks of the Precambrian Shield (Figures 1-4 and 1-5). Glacial advances from the northeast may have excavated the fractured rocks of the belt and assisted in the formation of Falcon Lake. The lake is now impounded by the granitic rocks on the southern boundary of the belt. The lake level controls the base level of the Hamilton Creek profile.

The Mink Creek and Pine River basins originate on the Duck Mountain portion of the Manitoba escarpment shown in Figures 1-5

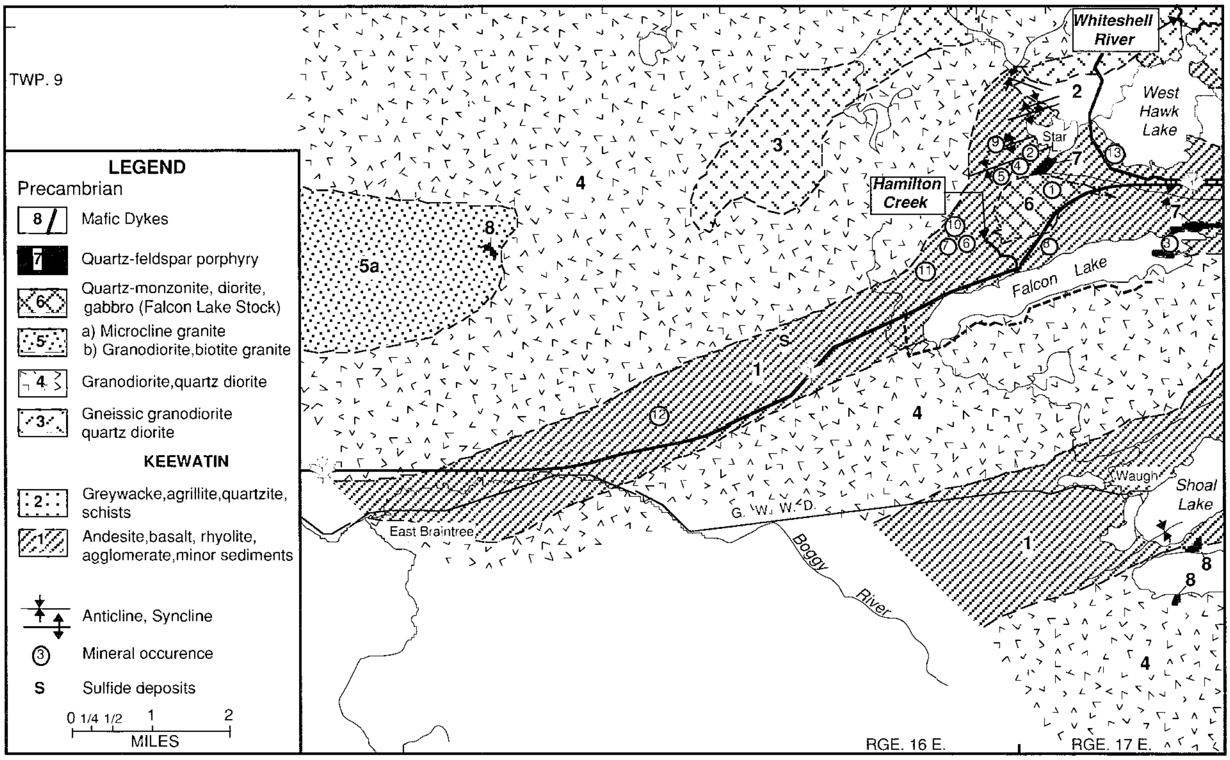


***Figure 1-4:** Geological setting of the Hamilton Creek and Whiteshell River basins (Davies et al. 1962).*

and 1-6. The escarpment is formed of easily weathered shales that are overlain with a thick deposit of glacial till, a mixture of boulders, sands, silts, and clays. The steep slope of the escarpment has been maintained by weathering and repeated glaciations. In the lower reaches, both streams flow over the more resistant flat limestone rocks that contain the Dauphin Lake and Lake Winnipegosis basins.

As a further aid in understanding the basin topography and geological setting, a simple contour model using layers of cardboard or foamboard to represent selected contour intervals may be constructed from the topographic map. Examples of basin models are shown for the Pine River at 1:250,000 scale and Wilson Creek at 1:50,000 scale in Figures 1-7 and 1-8. If an appropriate scale is available, the contour map may be combined with the geologic map to indicate the elevation and extent of geological features.

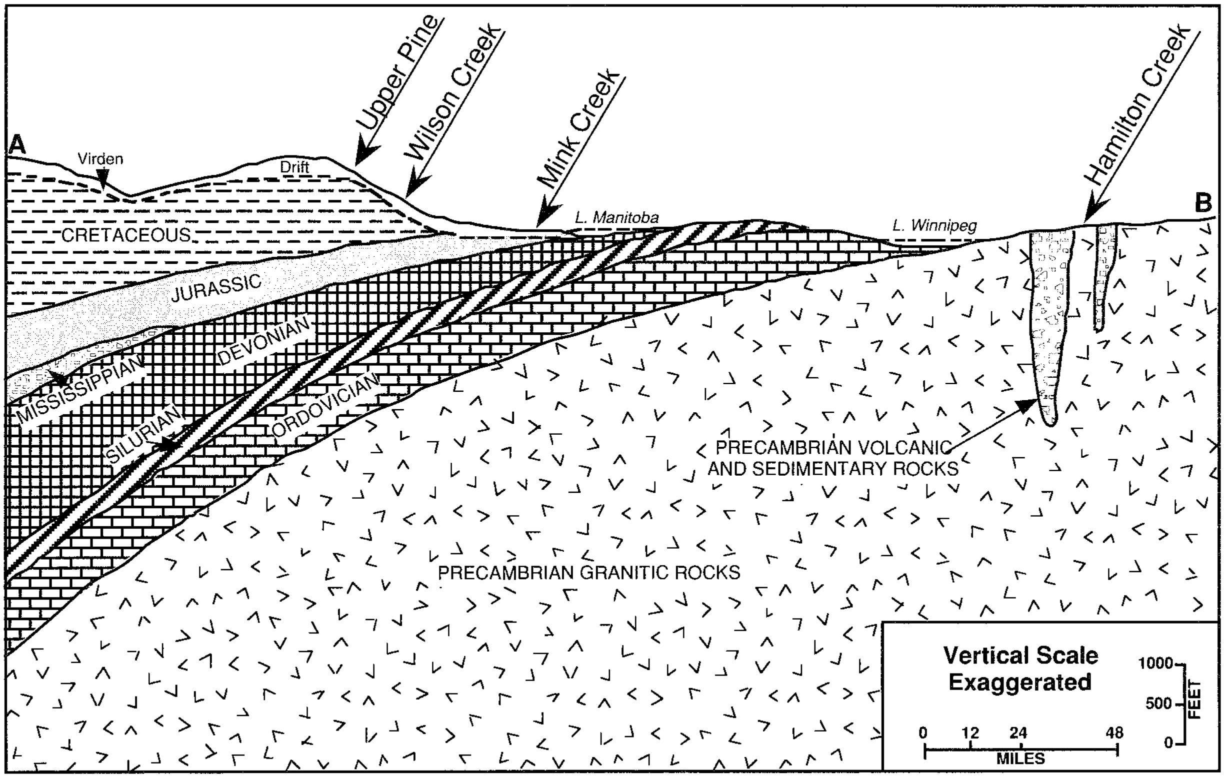


***Figure 1-5:** Geological cross-section of Manitoba showing the location of the sample drainage basins (Davies et al. 1962).*

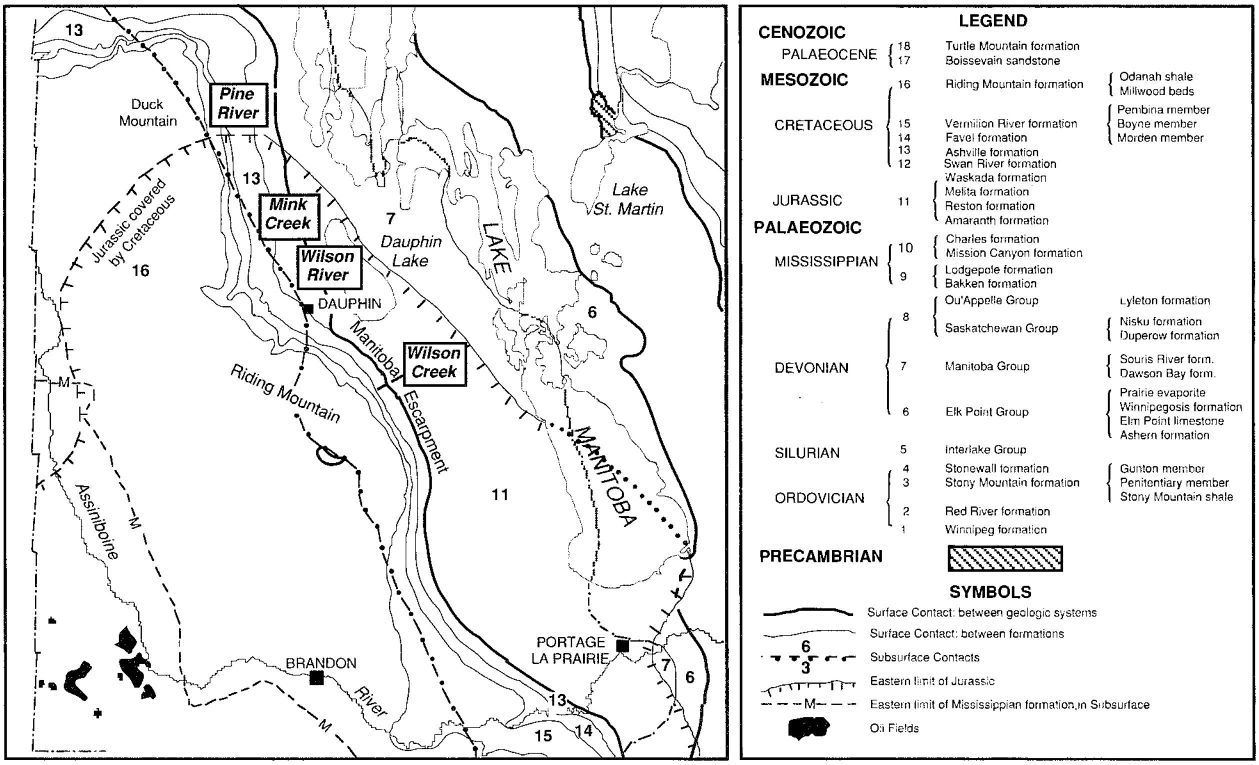


Figure 1-6: *Geological setting on the Manitoba escarpment for the Wilson Creek and North Pine River Basins. The Mink Creek and Wilson River rehabilitation reaches are located on the Lake Agassiz plain below the escarpment.*

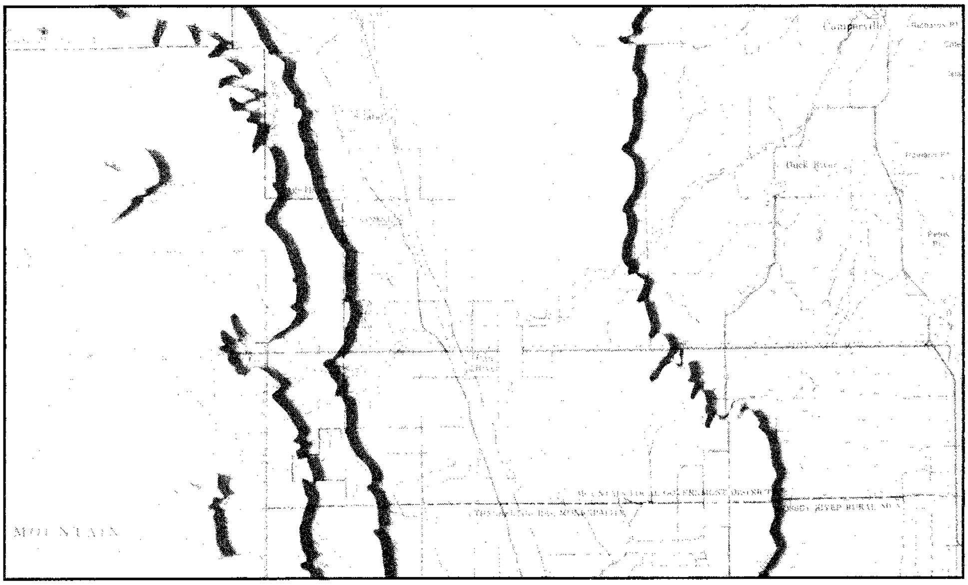


Figure 1-7: *Topographic model of the segment of the Manitoba escarpment that contains the Pine River basin (scale 1:250,000, Duck Mountain).*

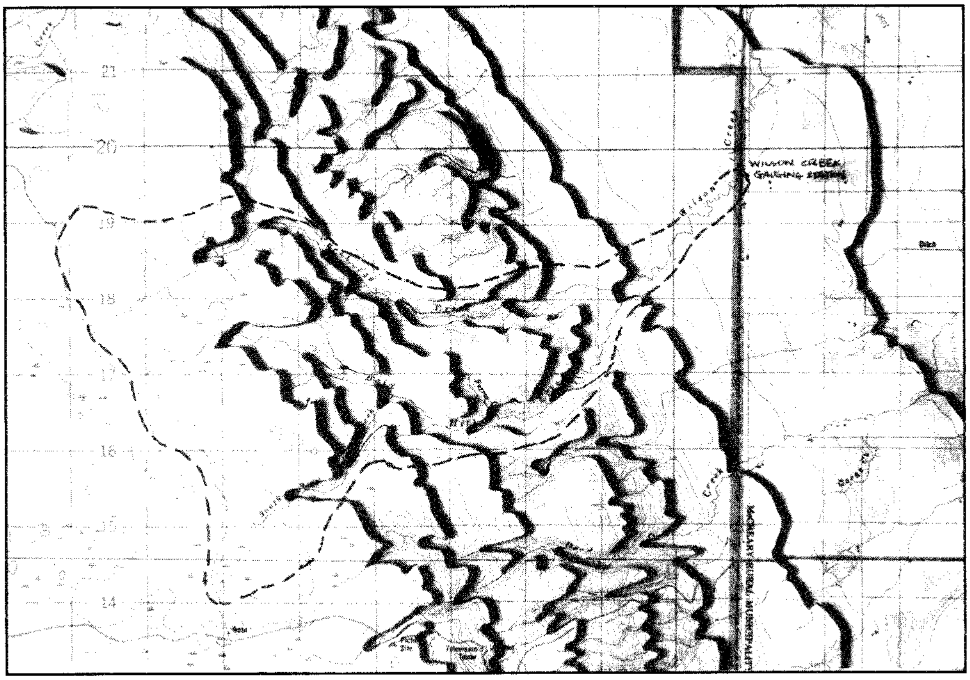


Figure 1-8: *Topographic model of the segment of the Manitoba escarpment that contains the Wilson Creek basin (scale 1:50,000, Riding Mountain).*

The topographic maps and models will be used extensively in the field to locate access roads and sample reaches. At least one copy should be protected with a waterproof spray or convenient cover.

Regional hydrology

Discharge records are available for large rivers and a few small streams in all physiographic and climatic regions of Manitoba. For example, discharge summary records for the Rennie River (adjacent to Hamilton Creek), Mink Creek, and the Pine River observed and compiled by the Water Survey of Canada (1990) are shown in Tables 1-1, 1-2, & 1-3.

For many small streams, there are no regular discharge observations. In these cases, approximate records must be constructed by assuming that runoff per unit area will be the same as that of a similar gauged stream in the region. For Hamilton Creek for example, flow records are available in the adjacent Rennie River basin (Table 1-1). The area of the Rennie River above the gauging station is 159 km^2 and of Hamilton Creek 12.5 km^2, implying that the Hamilton Creek flows would be about 8 percent (12.5/159) of the Rennie River flows. This estimate may only be reasonably accurate when lake storage and soil moisture conditions are similar in both basins, for example, during the spring snowmelt period. If possible, direct metering of the flow in the stream should be undertaken for a range of discharges to confirm or modify the relationship between the monitored basin and the ungauged stream. These records will be used in Chapters 3 and 4 to evaluate and design stream characteristics.

Table 1-1: Rennie River discharge records (Water Survey of Canada 1990).

RENNIE RIVER NEAR RENNIE - STATION NO. 05PG002

MONTHLY AND ANNUAL MEAN DISCHARGES IN CUBIC METRES PER SECOND FOR THE PERIOD OF RECORD

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	MEAN	YEAR
1960	---	---	0.044	3.17	2.95	0.459	0.046	0.055	0.045	0.056	---	---	---	1960
1961	---	---	0.092	0.205	0.904	0.301	0.077	0.058	0.037	0.122	---	---	---	1961
1962	---	---	0	0.255	7.54	3.95	0.836	5.21	2.09	0.043	---	---	---	1962
1963	---	---	0.082	2.01	2.61	3.76	0.547	1.57	0.366	0.247	---	---	---	1963
1964	---	---	0.221	1.99	4.11	0.362	0.412	0.531	0.842	1.82	---	---	---	1964
1965	---	---	0.105	4.01	4.02	0.548	1.08	0.379	0.377	---	---	---	---	1965
1966	---	---	0.300	4.88	5.99	1.03	2.28	0.062	0.122	0.167	0.248	0.323	---	1966
1967	0.311	0.251	0.184	3.55	3.04	0.017	0.093	2.04	0.428	0.021	0.019	0.047	0.837	1967
1968	0.112	0.101	0.084	1.90	1.87	1.48	1.45	0.224	0.491	1.86	0.827	0.403	0.903	1968
1969	0.280	0.259	0.160	1.37	1.86	0.161	0.200	0.151	0.141	0.107	0.105	0.080	0.407	1969
1970	0.147	0.132	0.149	0.680	5.05	2.26	0.051	0.018	0.018	0.018	1.23	0.680	0.874	1970
1971	0.295	0.164	0.164	2.43	1.77	0.352	0.647	0.038	0.041	0.027	0.202	0.713	0.571	1971
1972	0.370	0.186	0.142	0.694	1.44	0.180	0.008	0.006	0.004	0.003	0.001	0.001	0.254	1972
1973	0.003	0.022	0.121	0.014	0.024	3.51	0.883	0.479	0.580	4.10	1.97	0.763	1.04	1973
1974	0.362	0.244	0.164	3.36	6.11	1.61	0.107	0.028	0.392	0.531	0.318	0.237	1.13	1974
1975	0.201	0.153	0.147	0.899	1.89	0.459	1.65	0.055	0.280	0.231	0.446	0.220	0.556	1975
1976	0.194	0.129	0.137	1.66	1.22	0.129	0.518	0.032	0.014	0.008	0.003	0.005	0.338	1976
1977	0.003	0.002	0.004	0.005	0.007	1.81	1.05	0.093	0.143	0.873	0.766	0.750	0.461	1977
1978	0.448	0.244	0.141	1.66	3.41	0.746	0.160	0.045	0.026	0.195	0.227	0.144	0.623	1978
1979	0.138	0.135	0.177	0.890	3.57	0.843	0.067	0.064	0.034	0.013	0.043	0.127	0.512	1979
1980	0.156	0.177	0.171	0.244	0.328	0.065	0.104	0.062	0.528	0.356	0.350	0.360	0.241	1980
1981	0.185	0.160	0.022	0.005	0.012	0.009	0.010	0.022	0.203	1.85	0.677	0.540	0.310	1981
1982	0.247	0.174	0.096	0.410	1.92	0.724	0.635	0.244	0.032	0.439	0.389	0.250	0.466	1982
1983	0.204	0.140	0.173	0.156	1.12	1.11	0.428	0.044	0.018	0.016	0.005	0.003	0.285	1983
1984	0.002	0.001	0.066	0.010	0.003	1.69	0.762	0.043	0.005	0.378	1.26	0.649	0.404	1984
1985	0.320	0.171	0.083	---	---	0.573	0.794	0.413	0.624	0.798	0.841	0.494	---	1985
1986	0.255	0.149	0.126	2.24	4.61	0.120	0.029	0.019	0.009	0.007	0.009	0.011	0.637	1986
1987	0.003	0.002	0.005	1.16	0.275	0.137	0.057	0.037	0.013	0.006	0.004	0.003	0.141	1987
1988	0.006	0.005	0.006	0.014	0.005	0.014	0.021	0.025	0.011	0.008	0.054	0.122	0.024	1988
1989	0.230	0.118	0.058	1.30	2.85	2.61	1.30	1.08	0.926	0.341	0.343	0.264	0.955	1989
1990	0.234	0.206	0.184	0.089	1.42	4.86	1.15	0.011	0.004	0.001	0	0.001	0.677	1990
MEAN	0.196	0.139	0.116	1.38	2.40	1.16	0.563	0.424	0.285	0.488	0.413	0.288	0.550	MEAN

LOCATION - LAT 49 55 42 N   DRAINAGE AREA, 159 km²
LONG 095 32 40 W   REGULATED

RENNIE RIVER NEAR RENNIE - STATION NO. 05PG002

ANNUAL EXTREMES OF DISCHARGE AND ANNUAL TOTAL DISCHARGE FOR THE PERIOD OF RECORD

YEAR	MAXIMUM INSTANTANEOUS DISCHARGE (m^3/s)	MAXIMUM DAILY DISCHARGE (m^3/s)	MINIMUM DAILY DISCHARGE (m^3/s)	TOTAL DISCHARGE (dam^3)	YEAR
1960	---	7.31 ON APR 25	0 B ON MAR 25 *	---	1960
1961	---	1.14 ON MAY 16	0.014 ON AUG 24	---	1961
1962	---	14.0 ON MAY 26 *	0 B ON MAR 01	---	1962
1963	---	5.44 ON JUN 13	0.082B ON MAR 01	---	1963
1964	---	5.97 ON MAY 08	0.011B ON MAR 01	---	1964
1965	---	6.03 ON MAY 07	---	---	1965
1966	---	8.44 E ON APR 17	0.028 ON JUN 21	---	1966
1967	---	7.16 E ON APR 24	0.003E ON OCT 24	26 400	1967
1968	---	3.31 E ON APR 24	0.042E ON AUG 29	28 500	1968
1969	---	3.60 ON MAY 01	0.042 ON NOV 27	12 800	1969
1970	6.43 AT 14:17 CST ON MAY 06	6.40 ON MAY 06	0 ON APR 02	27 600	1970
1971	7.70 AT 13:21 CST ON APR 22	7.39 ON APR 24	0.012 ON MAY 29	18 000	1971
1972	---	2.80 ON MAY 09	0 ON DEC 23	8 030	1972
1973	---	14.0 E ON JUN 20	0 ON JAN 01	32 900	1973
1974	12.7 AT 14:20 CST ON APR 26 *	12.5 ON APR 26	0.012 ON AUG 10	35 500	1974
1975	3.68 ON JUL	3.68 ON JUL 04	0 ON MAY 30	17 500	1975
1976	---	3.91 E ON APR 29	0 ON MAY 19	10 700	1976
1977	7.76 AT 15:09 CST ON JUN 25	7.14 ON JUN 26	0.002E ON FEB 06	14 500	1977
1978	9.60 AT 15:56 CST ON MAY 02	8.61 ON MAY 03	0.004 ON SEP 30	19 700	1978
1979	---	4.45 E ON MAY 06	0.005A ON JUN 14	16 200	1979
1980	1.28 AT 09:23 CST ON SEP 22	1.12 ON SEP 23	0.020 ON JUN 27	7 640	1980
1981	5.89 AT 09:38 CST ON OCT 06	4.97 ON OCT 07	0 B ON APR 07	9 780	1981
1982	3.66 AT 07:49 CST ON MAY 19	3.36 ON MAY 20	0.011 ON SEP 21	14 700	1982
1983	2.56 AT 14:27 CST ON MAY 18	2.35 ON MAY 19	0.003 ON DEC 07	9 000	1983
1984	4.30 AT 14:46 CST ON JUN 18	4.18 ON JUN 19	0 ON OCT 18	12 800	1984
1985	---	---	---	---	1985
1986	---	11.7 A ON MAY 10	0.005 ON OCT 11	20 100	1986
1987	3.81 AT 13:39 CST ON APR 18	3.54 ON APR 19	0.002 ON JAN 10	4 450	1987
1988	0.305 AT 09:29 CST ON OCT 25	0.190 ON DEC 27	0.002 ON MAY 01	769	1988
1989	4.80 AT 17:13 CST ON MAY 02	4.69 ON MAY 03	0.037 ON MAR 26	30 100	1989
1990	8.90 AT 18:57 CST ON JUN 09	8.70 ON JUN 09	0 ON NOV 06	21 400	1990
				17 400	MEAN

A - MANUAL GAUGE   B - ICE CONDITIONS   * - EXTREME RECORDED FOR THE PERIOD OF RECORD
(SEE REFERENCE INDEX)   E - ESTIMATED

Table 1-2: Mink Creek discharge records (Water Survey of Canada 1990).

MINK CREEK NEAR ETHELBERT - STATION NO. 05LJ019

MONTHLY AND ANNUAL MEAN DISCHARGES FOR MAR TO OCT IN CUBIC METRES PER SECOND FOR THE PERIOD OF RECORD

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	MEAN	YEAR
1954	---	---	---	---	1.96	3.10	0.895	0.101	1.19	0.552	0.474	---	---	1954
1955	---	---	---	3.80	1.27	0.721	0.048	0	0.020	0.040	---	---	---	1955
1956	---	---	0.044	1.50	1.98	0.416	0.278	0.041	0.130	0.119	---	---	0.563	1956
1957	---	---	0.076	2.02	0.532	0.184	0.049	0.060	0.061	0.071	---	---	0.377	1957
1958	---	---	0.079	0.585	0.167	0.095	0.081	0.038	0.095	0.072	---	---	0.150	1958
1959	---	---	0.206	0.649	0.376	0.561	0.185	0.042	0.068	0.156	---	---	0.279	1959
1960	---	---	0	2.62	1.07	0.438	0.057	0.029	0.028	0.079	---	---	0.533	1960
1961	---	---	0.005	0.073	0.147	0.051	0.014	0	0.100	0.099	---	---	0.061	1961
1962	---	---	0.011	0.267	0.092	0.072	0.042	0.032	0.038	0.043	---	---	0.074	1962
1963	---	---	0.132	0.539	0.345	0.317	0.153	0.021	0.029	0.044	---	---	0.196	1963
1964	---	---	0.025	0.583	0.363	0.038	0.011	0.021	0.024	0.056	---	---	0.139	1964
1965	---	---	0	0.669	0.520	0.238	0.239	0.301	0.367	0.207	---	---	0.316	1965
1966	---	---	0.367	2.09	0.759	0.454	0.205	0.062	0.030	0.043	---	---	0.497	1966
1967	---	---	0	0.591	1.22	0.120	0.022	0.019	0.004	0.033	---	---	0.251	1967
1968	---	---	0.145	0.356	0.118	0.050	0.027	0.037	0.031	0.042	---	---	0.100	1968
1969	---	---	0.009	0.631	0.235	0.186	0.465	0.105	0.029	0.147	---	---	0.225	1969
1970	---	---	0.028	1.32	1.77	0.618	0.468	0.087	0.045	0.124	---	---	0.557	1970
1971	---	---	0.065	1.51	0.250	0.500	0.090	0.025	0.028	0.093	---	---	0.315	1971
1972	---	---	0.041	1.39	0.625	0.058	0.027	0.018	0.011	0.035	---	---	0.273	1972
1973	---	---	0.093	0.153	0.139	0.251	0.052	0.014	0.096	0.118	---	---	0.114	1973
1974	---	---	0	2.45	2.81	0.451	0.017	0.015	0.057	0.079	---	---	0.733	1974
1975	---	---	0	1.58	1.04	1.06	0.034	0.062	0.429	0.258	---	---	0.552	1975
1976	---	---	0.004	2.38	0.306	4.37	0.109	0.016	0.011	0.025	---	---	0.885	1976
1977	---	---	0.017	0.179	0.239	0.074	0.112	0.046	0.302	0.192	---	---	0.145	1977
1978	---	---	0.032	0.677	0.253	0.129	0.016	0.018	0.048	0.067	---	---	0.153	1978
1979	---	---	0.029	2.29	1.84	0.356	0.006	0.001	0.024	0.052	---	---	0.570	1979
1980	---	---	0.024	0.545	0.051	0.023	0.016	0.046	0.048	0.056	---	---	0.100	1980
1981	---	---	0.075	0.174	0.123	0.142	0.134	0.019	0.033	0.069	---	---	0.096	1981
1982	---	---	0.029	0.517	0.135	0.055	0.107	0.035	0.018	0.108	---	---	0.125	1982
1983	---	---	0	1.49	0.976	0.805	0.294	0.010	0.006	0.062	---	---	0.451	1983
1984	---	---	0.141	0.281	0.700	1.32	0.026	0	0.015	0.161	---	---	0.328	1984
1985	---	---	0.093	2.00	0.143	0.371	0.074	0.479	0.176	0.136	---	---	0.428	1985
1986	---	---	0.924	2.00	2.85	0.121	0.207	0.113	0.099	0.132	---	---	0.806	1986
1987	---	---	0.073	2.36	0.120	0.034	0.080	0.023	0.196	0.099	---	---	0.367	1987
1988	---	---	0.053	2.14	2.79	0.106	0.032	0.048	0.011	0.043	---	---	0.651	1988
1989	---	---	0.005	0.243	0.105	0.480	0.046	0.156	0.061	0.085	---	---	0.146	1989
1990	---	---	0.027	2.78	1.91	0.221	0.101	0.016	0.001	0.028	---	---	0.630	1990
MEAN	---	---	0.081	1.26	0.820	0.502	0.130	0.058	0.107	0.103	0.474	---	0.348	MEAN

LOCATION - LAT 51 25 00 N DRAINAGE AREA, 131 km^2
LONG 100 21 10 W NATURAL FLOW

REMARKS - PUBLISHED AS "MINK RIVER" PRIOR TO 1979

MINK CREEK NEAR ETHELBERT - STATION NO. 05LJ019

EXTREMES OF DISCHARGE AND TOTAL DISCHARGE FOR MAR TO OCT FOR THE PERIOD OF RECORD

YEAR	MAXIMUM INSTANTANEOUS DISCHARGE (m^3/s)	MAXIMUM DAILY DISCHARGE (m^3/s)	MINIMUM DAILY DISCHARGE (m^3/s)	TOTAL DISCHARGE (dam^3)	YEAR
1954	---	---	---	---	1954
1955	---	17.8 ON APR 05	0 ON JUN 29 *	---	1955
1956	---	7.62 B ON APR 30	0 B ON MAR 01	11 900	1956
1957	---	8.61 ON APR 25	0 ON JUL 29	7 980	1957
1958	---	1.10 ON APR 14	0 B ON MAR 01	3 180	1958
1959	2.01 AT 17:00 CST ON JUN 29	1.95 ON JUN 29	0 B ON MAR 01	5 900	1959
1960	13.5 B AT 00:00 CST ON APR 13	11.8 B ON APR 12	0 B ON MAR 01	11 300	1960
1961	---	0.249A ON SEP 05	0 B ON MAR 01	1 290	1961
1962	---	1.33 B ON APR 19	0 B ON MAR 01	1 570	1962
1963	---	1.42 ON APR 10	0 B ON MAR 01	4 150	1963
1964	---	1.45 B ON APR 24	0 A ON JUL 19	2 950	1964
1965	---	1.78 B ON APR 13	0 B ON MAR 01	6 700	1965
1966	---	12.5 B ON APR 02	0.023 ON SEP 08	10 500	1966
1967	---	3.77 B ON APR 28	0 B ON MAR 01	5 300	1967
1968	---	0.850B ON MAR 29	0.011 ON AUG 14	2 120	1968
1969	---	3.31 B ON APR 15	0.008B ON MAR 01	4 770	1969
1970	5.72 B AT 00:00 CST ON APR 26	4.45 B ON APR 26	0.012 ON AUG 26	11 800	1970
1971	8.67 B AT 01:24 CST ON APR 11	6.60 B ON APR 11	0 ON SEP 01	6 680	1971
1972	---	5.13 B ON APR 18	0 ON AUG 28	5 780	1972
1973	2.51 AT 14:12 CST ON AUG 10	0.796 ON JUN 21	0 ON AUG 26	2 410	1973
1974	---	15.7 B ON APR 19	0 B ON MAR 01	15 500	1974
1975	---	5.95 B ON APR 20	0 B ON MAR 01	11 700	1975
1976	44.2 AT 23:19 CST ON JUN 13 *	32.3 ON JUN 14 *	0.003B ON MAR 01	18 700	1976
1977	0.968 AT 18:56 CST ON SEP 27	0.932 ON SEP 27	0.013 ON AUG 20	3 060	1977
1978	---	1.41 ON APR 21	0 ON JUL 10	3 250	1978
1979	17.3 AT 00:00 CST ON APR 24	13.9 B ON APR 23	0 ON JUL 09	12 100	1979
1980	3.30 AT 11:13 CST ON OCT 28	1.57 B ON APR 08	0 ON JUN 17	2 110	1980
1981	0.991 AT 09:25 CST ON JUL 02	0.768 ON JUL 03	0 ON AUG 16	2 030	1981
1982	---	1.73 B ON APR 16	0 B ON MAR 01	2 640	1982
1983	---	8.31 B ON APR 24	0 B ON MAR 01	9 550	1983
1984	7.86 AT 20:12 CST ON JUN 24	7.27 ON JUN 24	0 B ON MAR 01	6 940	1984
1985	---	5.83 B ON APR 02	0 B ON MAR 01	9 070	1985
1986	10.6 AT 16:23 CST ON MAY 07	9.95 ON MAY 07	0 B ON MAR 01	17 100	1986
1987	11.5 AT 20:18 CST ON APR 06	9.55 B ON APR 06	0 ON JUN 18	7 760	1987
1988	16.6 AT 07:33 CST ON MAY 03	15.2 ON MAY 03	0 ON JUL 23	13 800	1988
1989	3.13 AT 18:28 CST ON JUN 13	2.73 ON JUN 13	0 B ON MAR 01	3 090	1989
1990	10.8 AT 21:43 CST ON MAY 16	9.44 A ON MAY 17	0 ON AUG 09	13 300	1990
				7 370	MEAN

A - MANUAL GAUGE (SEE REFERENCE INDEX) B - ICE CONDITIONS * - EXTREME RECORDED FOR THE PERIOD OF RECORD

Table 1-3: North Pine River discharge records (Water Survey of Canada 1990).

NORTH PINE RIVER NEAR PINE RIVER - STATION NO. 05LG001

MONTHLY AND ANNUAL MEAN DISCHARGES FOR MAR TO OCT IN CUBIC METRES PER SECOND FOR THE PERIOD OF RECORD

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	MEAN	YEAR
1954	---	---	---	0.582	6.18	9.13	2.32	0.969	2.08	1.65	---	---	---	1954
1955	---	---	---	1.54	3.56	1.43	0.315	0.020	0.074	0.143	---	---	---	1955
1956	---	---	---	0.062	3.32	2.94	1.86	0.204	0.326	0.311	---	---	---	1956
1957	---	---	0	1.36	3.54	0.457	0.177	0.062	0.127	0.123	---	---	0.732	1957
1958	---	---	0.100	0.603	0.390	0.228	1.76	0.269	1.14	0.728	---	---	0.652	1958
1959	---	---	0.206	0.614	1.67	3.80	1.33	0.145	2.63	1.68	---	---	1.50	1959
1960	---	---	0.026	1.38	5.29	3.02	0.782	0.268	0.185	0.260	---	---	1.40	1960
1961	---	---	0.029	0.127	0.315	0.072	0.013	0.004	0.014	0.109	---	---	0.085	1961
1962	---	---	0.029	0.461	0.622	0.446	0.154	0.126	0.379	0.237	---	---	0.305	1962
1963	---	---	0.024	1.11	2.35	2.03	0.441	0.051	0.095	0.104	---	---	0.772	1963
1964	---	---	0.177	0.578	1.45	0.131	0.061	0.053	0.062	0.109	---	---	0.328	1964
1965	---	---	0.087	0.541	4.29	1.73	1.16	1.72	1.86	0.587	---	---	1.50	1965
1966	---	---	0.157	0.614	4.83	3.81	1.61	0.781	0.078	0.167	---	---	1.51	1966
1967	---	---	0.234	0.975	5.22	2.08	0.621	1.01	0.197	0.496	---	---	1.36	1967
1968	---	---	0.145	0.584	1.58	1.38	1.49	2.50	0.604	0.438	---	---	1.09	1968
1969	---	---	0.181	2.10	1.65	1.30	1.85	0.805	1.09	2.80	---	---	1.47	1969
1970	---	---	0.317	1.21	7.07	2.69	4.31	1.28	0.984	2.18	---	---	2.52	1970
1971	---	---	0.198	3.22	1.96	2.91	2.15	0.745	0.213	1.60	---	---	1.62	1971
1972	---	---	0.152	2.03	4.86	1.23	0.870	0.215	0.154	0.195	---	---	1.21	1972
1973	---	---	0.067	0.433	1.75	5.37	2.46	0.639	1.88	0.725	---	---	1.65	1973
1974	---	---	0.226	3.10	7.52	2.74	0.813	0.660	1.75	0.970	---	---	2.22	1974
1975	---	---	0.122	1.40	5.72	3.76	0.861	0.411	1.81	1.66	---	---	1.96	1975
1976	---	---	0.176	3.49	2.04	6.70	1.51	0.673	0.201	0.174	---	---	1.85	1976
1977	---	---	0.100	1.09	1.29	0.295	1.67	1.02	3.58	2.13	---	---	1.39	1977
1978	---	---	0.114	0.922	1.41	1.43	0.455	0.110	0.546	0.662	---	---	0.702	1978
1979	---	---	0.149	0.581	8.64	3.23	0.575	0.458	0.479	0.475	---	---	1.83	1979
1980	---	---	0.252	1.94	0.569	0.319	0.264	2.45	0.480	0.545	---	---	0.851	1980
1981	---	---	0.353	0.511	0.785	2.54	0.518	0.238	0.150	0.503	---	---	0.696	1981
1982	---	---	0.033	0.761	0.955	0.402	2.62	0.741	0.389	1.25	---	---	0.898	1982
1983	---	---	0.101	1.12	5.64	2.30	2.21	0.632	0.465	0.608	---	---	1.64	1983
1984	---	---	0.120	1.23	3.03	5.28	1.35	0.856	0.754	1.59	---	---	1.77	1984
1985	---	---	0.048	2.93	2.17	2.37	1.40	3.79	1.47	1.41	---	---	1.94	1985
1986	---	---	0.269	2.21	4.01	1.15	1.17	0.565	1.31	1.97	---	---	1.58	1986
1987	---	---	0.556	2.76	1.12	1.10	2.22	0.399	0.415	0.960	---	---	1.19	1987
1988	---	---	0.420	2.65	9.87	1.60	0.755	0.307	0.205	0.219	---	---	2.01	1988
1989	---	---	0.050	0.409	0.465	3.01	0.997	0.564	0.548	0.595	---	---	0.823	1989
1990	---	---	0.185	2.65	6.13	2.16	1.34	0.362	0.104	0.165	---	---	1.64	1990
MEAN	---	---	0.159	1.35	3.33	2.34	1.26	0.705	0.779	0.825	---	---	1.31	MEAN

LOCATION - LAT 51 49 00 N DRAINAGE AREA, 210 km^2
LONG 100 32 00 W NATURAL FLOW

REMARKS - PUBLISHED AS PINE RIVER NEAR PINE RIVER PRIOR TO 1987

NORTH PINE RIVER NEAR PINE RIVER - STATION NO. 05LG001

EXTREMES OF DISCHARGE AND TOTAL DISCHARGE FOR MAR TO OCT FOR THE PERIOD OF RECORD

YEAR	MAXIMUM INSTANTANEOUS DISCHARGE (m^3/s)	MAXIMUM DAILY DISCHARGE (m^3/s)	MINIMUM DAILY DISCHARGE (m^3/s)	TOTAL DISCHARGE (dam^3)	YEAR
1954	---	24.1 ON MAY 28	0 B ON APR 01 *	---	1954
1955	---	13.6 ON MAY 04	0 ON AUG 12	---	1955
1956	---	9.03 ON JUN 26	0 B ON APR 01	---	1956
1957	---	12.6 ON MAY 01	0 B ON MAR 01	15 500	1957
1958	13.6 AT 09:00 CST ON JUL 06	10.7 ON JUL 07	0 B ON MAR 01	13 800	1958
1959	19.8 AT 19:00 CST ON JUN 27	16.8 ON JUN 28	0 B ON MAR 22	31 800	1959
1960	13.1 AT 21:00 CST ON MAY 13	12.4 ON MAY 13	0 B ON MAR 01	29 600	1960
1961	---	0.450 ON MAY 07	0 B ON MAR 01	1 810	1961
1962	1.89 AT 00:25 CST ON MAY 31	1.66 ON MAY 31	0 B ON MAR 01	6 460	1962
1963	9.12 AT 20:30 CST ON MAY 13	7.99 ON MAY 14	0 B ON MAR 01	16 300	1963
1964	5.38 AT 18:40 CST ON MAY 08	4.84 ON MAY 09	0.020 ON JUL 27	6 940	1964
1965	19.3 AT 12:15 CST ON MAY 07	18.0 ON MAY 07	0.071B ON MAR 01	31 700	1965
1966	13.5 AT 11:30 CST ON MAY 19	12.7 ON MAY 19	0.031 ON SEP 23	31 900	1966
1967	11.6 B AT 02:00 CST ON MAY 07	9.46 B ON MAY 07	0.099 ON SEP 07	28 700	1967
1968	8.30 AT 08:05 CST ON AUG 20	7.79 ON AUG 20	0.110B ON MAR 01	23 100	1968
1969	14.5 AT 02:01 CST ON OCT 04	12.2 ON OCT 04	0.181B ON MAR 01	31 200	1969
1970	25.7 AT 19:10 CST ON JUL 24	19.8 ON JUL 25	0.317B ON MAR 01	53 300	1970
1971	12.5 AT 02:30 CST ON JUN 06	11.4 ON JUN 06	0.164 ON SEP 12	34 300	1971
1972	11.8 AT 01:30 CST ON APR 30	10.6 ON APR 30	0.122 ON AUG 27	25 700	1972
1973	26.4 AT 20:56 CST ON JUN 19	24.9 ON JUN 20	0.025B ON MAR 01	35 000	1973
1974	20.5 AT 00:06 CST ON MAY 22	18.0 ON MAY 22	0.198B ON MAR 30	47 000	1974
1975	13.1 AT 04:23 CST ON MAY 09	12.3 ON MAY 08	0.122B ON MAR 01	41 600	1975
1976	26.2 AT 04:49 CST ON JUN 14	24.9 ON JUN 14	0.133 ON SEP 23	39 200	1976
1977	10.8 AT 05:11 CST ON SEP 26	10.1 ON SEP 26	0.079B ON MAR 01	29 500	1977
1978	3.65 AT 22:00 CST ON APR 27	3.23 ON APR 28	0.048 ON AUG 12	14 900	1978
1979	25.3 AT 01:39 CST ON MAY 26	23.8 ON MAY 26	0.133B ON MAR 01	38 700	1979
1980	9.37 AT 11:45 CST ON AUG 08	8.58 ON AUG 08	0.113 ON JUL 31	18 000	1980
1981	8.64 AT 11:36 CST ON JUN 18	7.50 ON JUN 18	0.075 ON SEP 11	14 700	1981
1982	21.6 AT 14:29 CST ON JUL 17	16.0 ON JUL 18	0.020B ON MAR 01	19 000	1982
1983	14.3 AT 03:19 CST ON MAY 19	12.9 ON MAY 19	0.088B ON APR 03	34 700	1983
1984	27.6 AT 09:11 CST ON JUN 23	24.3 ON JUN 23	0.052B ON MAR 31	37 400	1984
1985	21.7 AT 05:48 CST ON AUG 14	19.0 ON AUG 14	0 B ON MAR 01	41 200	1985
1986	10.2 AT 04:19 CST ON SEP 27	9.47 ON SEP 27	0.010E ON SEP 04	33 500	1986
1987	6.49 AT 03:27 CST ON APR 09	5.61 ON APR 09	0.140B ON MAR 01	25 200	1987
1988	36.3 AT 21:40 CST ON MAY 02 *	32.2 ON MAY 02 *	0.131 ON SEP 17	42 500	1988
1989	14.7 AT 09:44 CST ON JUN 27	13.9 ON JUN 27	0.039B ON MAR 12	17 400	1989
1990	21.6 AT 02:59 CST ON MAY 17	18.9 ON MAY 17	0.067 ON SEP 24	34 600	1990
				27 800	MEAN

B - ICE CONDITIONS
E - ESTIMATED

* - EXTREME RECORDED FOR THE PERIOD OF RECORD

1.3 Stream reach analysis

Channel segments in the theoretical drainage basin shown in Figure 1-9 have been assigned an order number based on a system of numbering first proposed by Strahler (1964). In this system, channels with no tributaries are numbered order one. Further downstream, segments of channels are assigned higher order numbers as the drainage system unites into a final single channel at the bottom of the basin. An order two segment occurs below the first junction of two order one channels, an order three segment occurs below the first junction of two order two streams, etc.

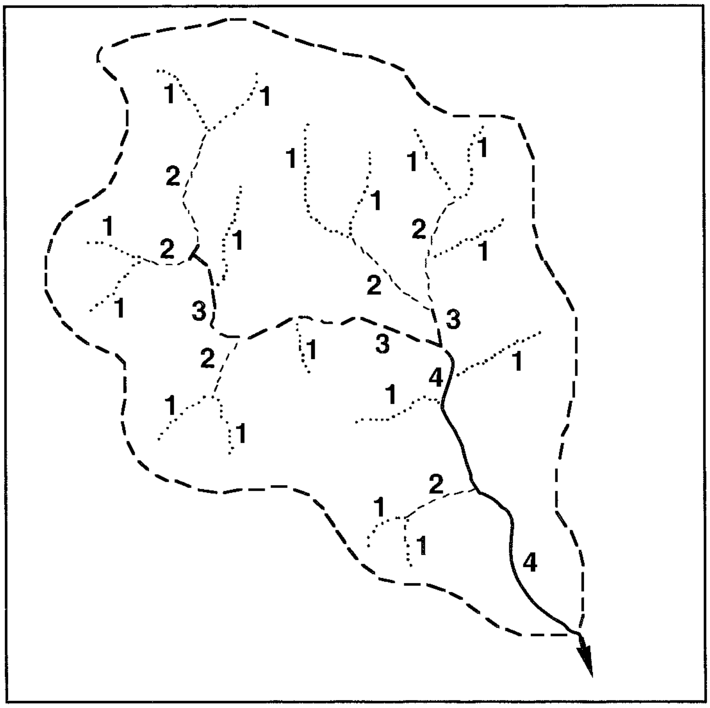
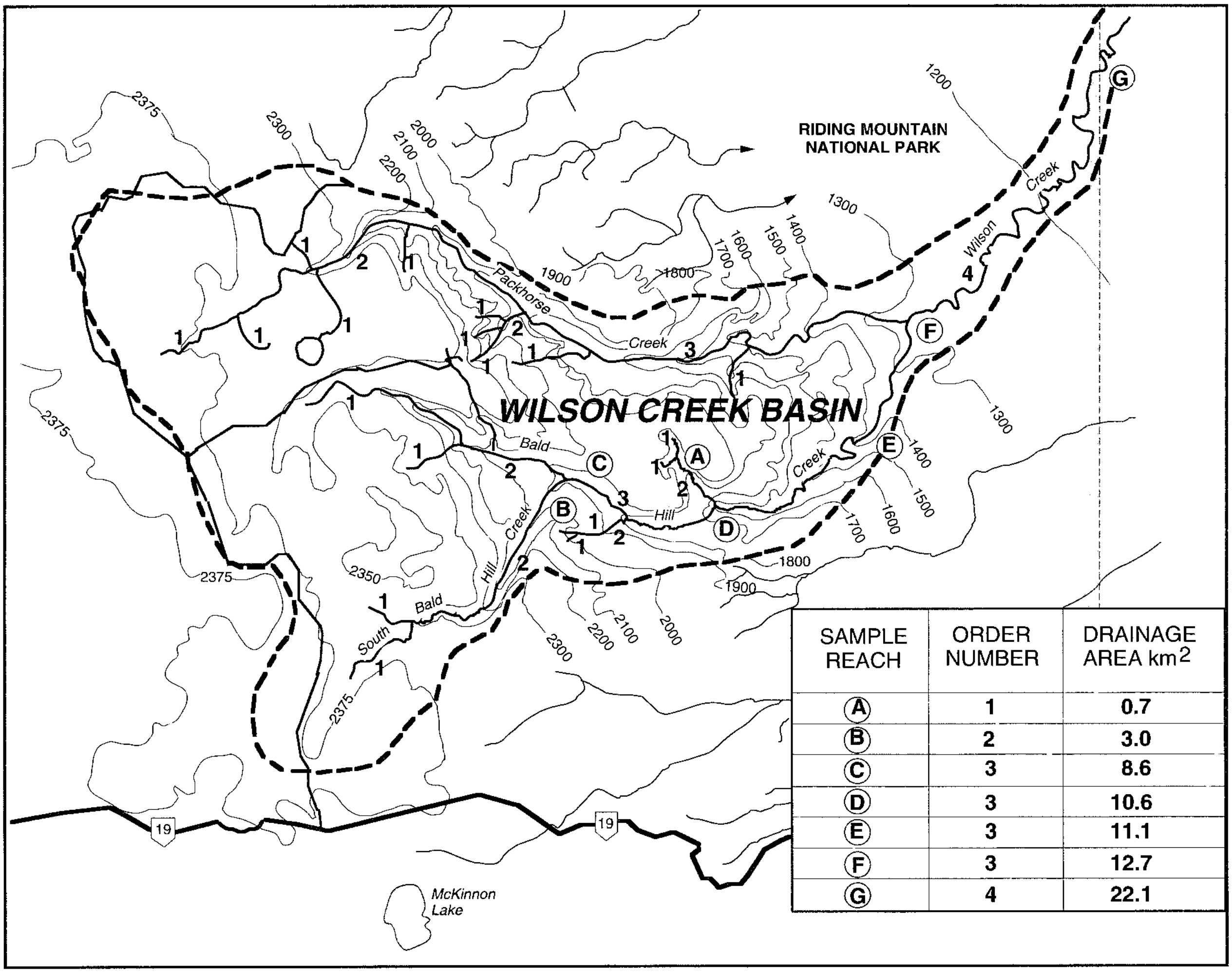


Figure 1-9: The ordering of stream channel segments (Strahler 1964).

The Strahler numbering system produces a consistent designation of order numbers for a particular scale of map or air photograph. At a different scale or using a different mapping technique, the order number of the same channel segment will be different. In most studies of streams with drainage areas of 50 to 1000 km^2 topographic maps at a scale of 1: 250,000 are used to designate stream segment order numbers. For smaller streams, map scales of 1: 50,000 or in some cases 1:10,000 may be more convenient but there will be many more low order number streams identified.



SAMPLE REACH	ORDER NUMBER	DRAINAGE AREA km^2
Ⓐ	1	0.7
Ⓑ	2	3.0
Ⓒ	3	8.6
Ⓓ	3	10.6
Ⓔ	3	11.1
Ⓕ	3	12.7
Ⓖ	4	22.1

Figure 1-10: *The Wilson Creek experimental watershed in the Riding Mountain segment of the Manitoba escarpment (NTS map 62J12, scale 1:50,000, contours 25 feet). Stream segment order numbers follow the Strahler system. Letters indicate stream geometry survey reaches.*

Using this numbering system to describe the stream channel network allows relationships to be derived between the order number and the number of stream segments in the basin, the order number and the length of a segment, and the order number and the tributary drainage area to the end of a segment. Anomalies in these relationships may indicate abnormalities in the stream system due to geological conditions or to the influence of man-made works. For example, there may be a profusion of first order channels in easily eroded soils or where extensive local land drainage canals have been excavated. Alternatively, higher order segments may be foreshortened by channelization, particularly where meanders have been eliminated.

To determine the order number of the stream segments in a basin, the segments should be highlighted on the basin topographic maps. It is helpful in counting and measuring segments to use different transparent colours for each order number. Stream segment orders for Wilson Creek are shown in Figure 1-10.

1.4 Survey design for sample reaches

The number and distribution of channels selected as sample reaches will depend on the purpose of the stream survey. Stream geometry surveys should sample a range of channel sizes and associated drainage areas. For example, to analyze the stream geometry of Wilson Creek, seven reaches were selected representing channels with drainage areas ranging from 0.7 km^2 to 22.1 km^2 (lettered sites, Figure 1-10). This type of survey may be used to develop regional relationships for natural stream channels that can serve as baselines for environmental assessments or as templates for stream rehabilitation projects (Chapter 3). In stream habitat surveys, only reaches that support a particular benthic or fisheries habitat may be sampled. Frissell et al. (1986, Figure 1-11) suggest that habitats follow the same organization as the branching network of the stream reaches, implying that sample reaches for habitat surveys may be selected on the basis of stream segment order numbers or position in the drainage network. In this case, the sample reaches would have similar tributary drainage areas rather than covering a range of channel sizes as in the geometry survey. This method assumes that the preferred habitat for a target species is known.

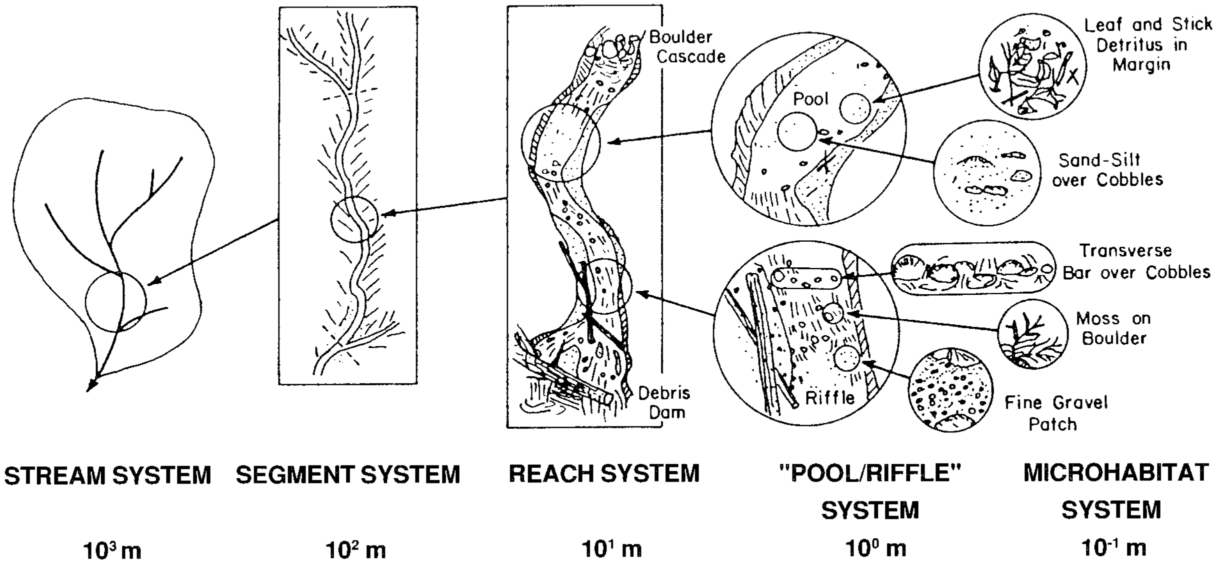


Figure 1-11: *Organization of stream habitats based on stream orders in a drainage basin (after Frissell et al. 1986).*

Several habitat assessment research groups have suggested what the preferred characteristics might be. As examples for further reading, the Illinois Index of Biotic Integrity combines substrate type, percent pools, and channel width (Osborne et al. 1988), the Instream Flow Service Group identifies velocity, depth, substrate type, and temperature as major parameters for life cycle stages and fish species (Bovee 1978), and a Rocky Mountain research group has found that elevation, relief, slope, and the width and depth of the channel are significant factors (Lanka et al. 1987).

However, it was found in Manitoba studies and elsewhere that the hydraulic habitats of streams are more complex than the groups of parameters that have been identified so far can describe (Annear and Conder 1983, Davis and Barmuta 1989, Wetmore et al. 1990). Consequently, to define preferred habitats, reach surveys in streams with known populations were undertaken to develop a “template” of flow patterns, bed materials, and channel geometries.

For example, for the Pine River project, reliable trout producing reaches were first surveyed on several escarpment rivers that were identified by the Swan Valley Sport Fishing Enhancement group. Similar meander, pool, and riffle geometry, observed in all of the successful habitats, was then used to design enhancement works in less productive reaches.

A similar approach was used for walleye spawning habitat rehabilitation projects. Successful spawning reaches were surveyed in natural stream channels to determine the geometry of pools, riffles, and large circulating eddies. Potential spawning rehabilitation reaches in channelized streams were identified by their similar position in the drainage network and by the size of their tributary drainage area. The characteristics of the natural spawning reaches were then used to reconstruct the channels with spawning riffles and pools. Methods for transferring habitat characteristics are discussed in the design process presented in Chapter 4.

Chapter 2

Field Exploration

Stream surveys

Within each of the sample reaches identified in the planning studies of the drainage basin, a field survey should be undertaken to measure the stream channel geometry, flood capacity, and characteristics. The observations may also be used to determine the hydraulic characteristics of preferred habitats. Biological sampling may be carried out at the same time.

Four standard field data sheets on the following pages (see also Appendices C and E) have been prepared to ensure that the same parameters are measured at all sites, particularly when the surveys are conducted by more than one party over several field seasons. The survey has been sub-divided into six observations:

Data Sheet I: 1) present discharge
2) flow cross-section and velocity
Data Sheet II: 3) bankfull channel dimensions
4) substrate sample
Data Sheet III: 5) reach plan and notes
Data Sheet IV: 6) local flow and channel features

The observations are summarized in a shortened form on the data sheets and discussed with examples in the following six sections.

STREAM DATA SHEET I: PRESENT VELOCITY AND DISCHARGE

page 1/4

STREAM:	Survey type:	Date:
REACH:	Observers:	

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

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 = Σ q's = m^3 /s

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

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 2/4

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 3/4

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

STREAM DATA SHEET IV: HYDRAULIC HABITAT OBSERVATIONS page 4/4

STREAM: Survey type: Date:

REACH: Observers:

BASELINES (AB to EF)

point	length	angle	notes
A			
AB			
B			
BC			
C			
CD			
D			
DE			
E			
EF			

LOCAL VELOCITIES

base	angle	dist	vel	depth	F_r	notes
						...over

CHANNEL FEATURES

base	angle	dist	feature

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

Observation 1: present discharge (Data Sheet I)

Present discharge is determined by multiplying the average velocity by the cross-sectional area of the flow. The cross-sectional area can be measured directly using a metre stick or survey rod and tape. To obtain the average velocity, several measurements may be required because the flow is unevenly distributed in the channel as shown in Figure 2-1.

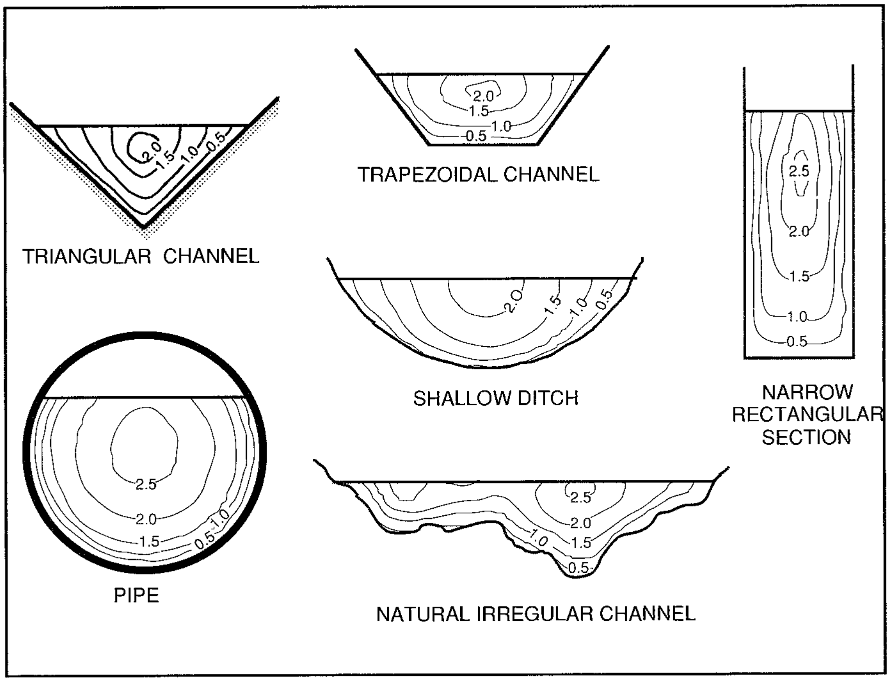


***Figure 2-1:** Velocity distributions under uniform flow conditions in various channel cross-sections (after Chow 1959).*

A velocity profile where the flow is uniform is shown in Figure 2-2. The mean velocity in the profile can be estimated by measuring the velocity with a current meter held at 0.4 times the depth.

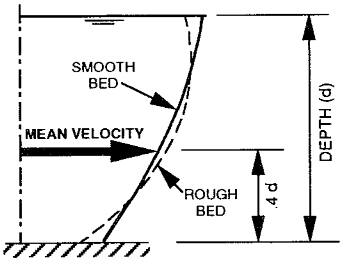


***Figure 2-2:** Vertical velocity distribution.*

If the flow is very irregular, for example, in a meander or when the water is forced over a bed obstruction, the whole velocity profile must be measured and plotted to determine the mean velocity.

To obtain the average velocity for the whole stream, a series of mean velocities must be measured across the stream channel cross-section as shown in Figure 2-3. The individual segments are referred to as "panels".

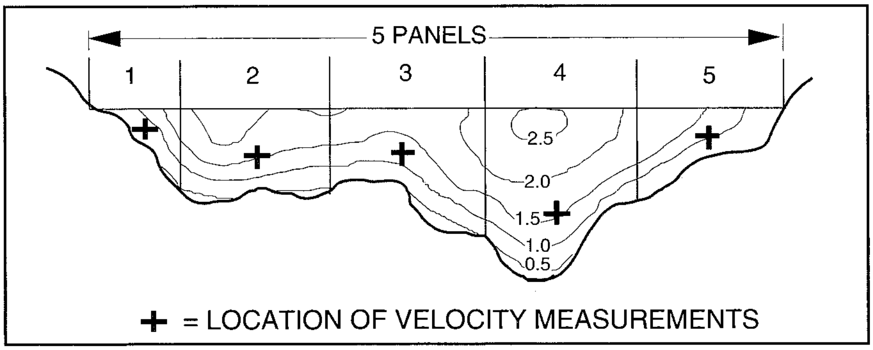


Figure 2-3: *Natural channel cross section divided into segments (panels) for metering.*

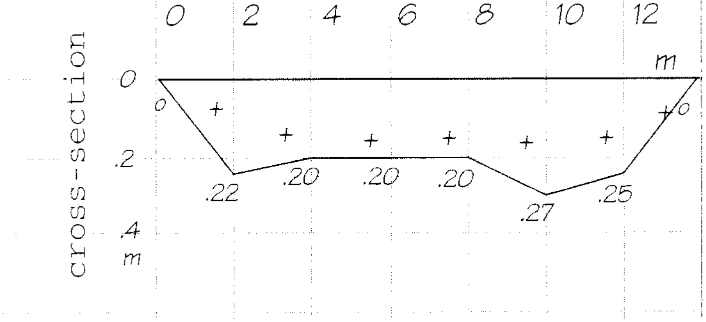
The metering section should be selected where the flow is uniform and parallel to the banks. By stretching a tape across the stream, the cross-section of the flow can be divided into convenient panels, varying from 0.3 m to 3 m in width, depending on the width of the stream. If the flow is uniform, the mean velocity can be measured in the middle of each segment at a height above the streambed surface of 0.4 times the total depth at that location. In cases where the flow is more irregular, the mean velocity may be better determined by averaging velocity measurements taken at 0.2 and 0.8 times the depth. For very irregular flows, the mean velocity must be estimated from a plotted velocity profile measured at every 0.1 increment of depth.

In smaller streams where the flow is only 2 or 3 m wide or in larger streams at very low discharges, it may be possible to simplify the velocity and depth measurements by building a straight narrow section of channel for metering using boulders and cobbles on the streambed. It is important to remember that this built metering section is not typical of the reach and should not be used as a sample of the natural cross-section of the flow.

Although there are a variety of velocity meters available, the simplest and most rugged are recommended for stream surveys. The pygmy and regular horizontal bucket impeller types seem to withstand a lot of backpacking and require only a small battery to operate an auditory counter. Other propeller and electro-magnetic meters are more convenient if servicing is available.

Before leaving a metering section, particularly in a remote area, it is advisable to calculate the total discharge in the stream by adding up the discharge in each of the measurement panels. The discharge in each panel (q) is obtained by multiplying the mean velocity times the cross-sectional area of the panel (the width times the average depth of the panel). A sample discharge measurement is shown in Table 2-1.

Table 2-1: Sample metering notes for the North Pine River



depth m	.11	.21	.20	.20	.25	.26	.13
width m	2	2	2	2	2	2	2
area m^2	.22	.42	.40	.40	.50	.52	.26
time s	30	30	30	30	30	30	30
revs.	29	40	37	33	28	32	19
vel. m/s	.3	.41	.38	.34	.28	.33	.19
q m^3/s	.07	.17	.15	.14	.14	.17	.05

Total discharge = Σ q's = .89 m^3/s

Observation 2: flow cross-section and average velocity (Data Sheet I)

In small streams, cross-sections of the present flow can be determined by stretching a flexible tape across the stream and measuring the depth of flow at regular intervals with a metre stick. In larger streams, the tape may be attached to an observer wading across the stream while taking depth measurements with a survey rod. A second observer at the side of the stream can record the distance from the edge of the flow to each depth measurement. Remember the general "rule of thumb" that wading can only be safely done if the product of the velocity in metres per second times the flow depth in metres is less than 1. For deeper and faster streams, boats attached to cables anchored across the streams may be necessary.

The number of cross-section measurements required to estimate the average cross-section in the reach, depends on the configuration of the reach. If the flow is uniform, only 3 or 4 sections may be required. However, if the flow is chaotic with frequent breaks in the water surface, additional measurements will be required. In meandering channels, the measured sections should be chosen to represent the variety of pools, riffles, chutes, and small ponds that may occur along a length of reach that is at least 12 times the bankfull width of the channel.

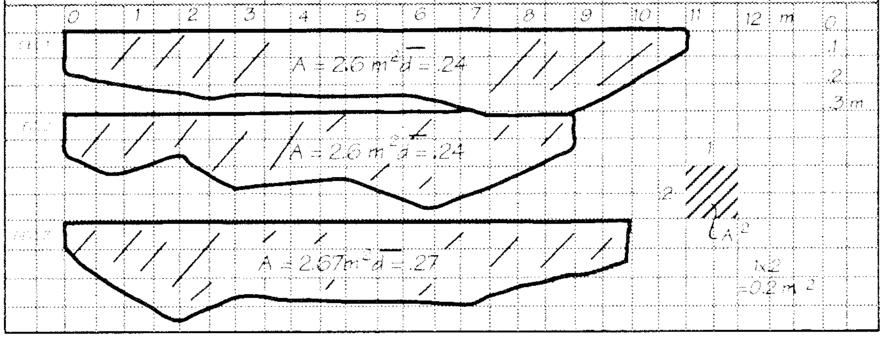
The average cross-section of the flow can be determined by averaging the mean depths and widths of the sample sections. In rugged channels, the mean depth of a section may be determined by plotting the observations on graph paper to determine the cross-sectional area of the flow and dividing the area by the water surface width as shown in Table 2-2.

The average velocity of the stream as it flows through the sample reach can be determined by dividing the total discharge (measured in Observation 1) by the average cross-sectional area of the flow. To see if this is a reasonable value, a piece of floating debris (woodchip, leaves, an orange, etc.) can be timed as it passes along a measured portion of the reach. If it is in the centre of the flow, the velocity will be slightly greater than the calculated average velocity.

If the average of several trials of this observation differs widely from the value obtained in Observations 1 and 2, the techniques for measuring should be checked, particularly where units must be

Table 2-2: Notes for three cross-sections of flow. The sections may be plotted on the back of the data sheet to determine the average depth of flow, when streambeds are irregular.

sec. 1 m/m	dist./depth	0/0	0/.17	2.5/.24	4.5/.23	6.0/.23	7.5/.31	9.0/.32	11.0/.10	11.0/0	RIGHT BANK	
sec. 2	0/0	0/.13	0.8/.22	2.2/.15	3.0/.29	5.0/.24	6.5/.34	9.0/.13	9.0/0			
sec. 3	0/0	0/.08	1.0/.24	2.0/.38	3.0/.28	5.0/.29	7.0/.30	8.0/.24	10.0/.17	10.0/0		



converted or averaged. Alternatively, the calibration of the flow meter may have been altered in transportation or handling. This can be roughly checked by building a small segment of channel a metre or so long to create uniform flow conditions. The velocity near the surface can be determined by timing the passage of floating debris through the centre of the channel. The meter estimate can then be compared to the debris value at the same position in the artificial channel.

Observation 3: bankfull channel dimensions (Data Sheet II)

Stream surveys are rarely conducted at the bankfull and higher stages of flow. Usually, the depths of flow are lower and the bankfull stage shown in Figure 2-4 must be estimated. In many cases, the tops of the banks are obscured by bank slumping, bedrock outcrops, and vegetation. In these cases, the bankfull flow may be translated as

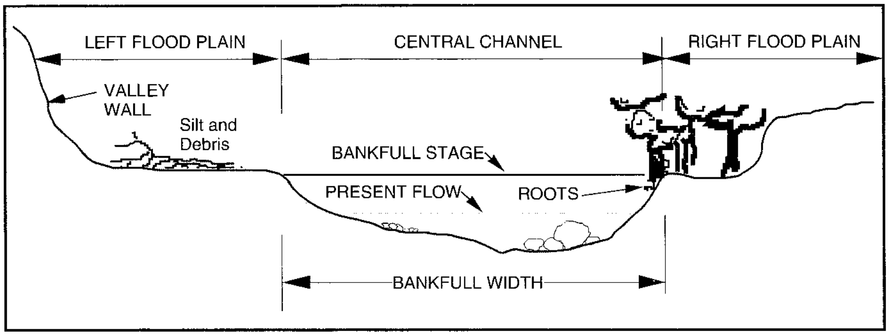


***Figure 2-4:** Cross section of stream valley with floodplains and a well-defined central channel and bankfull stage.*

a "channel maintenance flow". The channel maintenance stage is often coincident with the level of roots of perennial vegetation on the banks and slightly lower than a "bankfull" stage. A consistent method of making the estimate should be used for all of the sample reaches and noted on the observation sheet.

In small streams, cross-sections of the channel up to the bankfull stage may be measured using the same techniques that were used for measuring the cross-section of the present flow (Observation 2) but the depths to the channel bottom must be measured from a level line that extends across the channel between the tops of the stream banks. A sample of bankfull depths is given in Table 2-3. In larger streams, cross-sections of the channel that extend above the bankfull stage onto the floodplain may be measured using a standard surveyors level, rod, and tape.

Considerable judgement is required to obtain a representative channel cross-section and slope for the sample reach. The whole reach should be walked through and examined before sample sections are chosen to determine the extent of the floodplains that may exist on one or both sides of the channel and the possible presence of obstructions such as beaver dams or log jams that would cause artificially high local water stages. Sample cross-sections can then be chosen where the best evidence exists for the channel boundaries that would be just filled with water at the bankfull stage or alternately, scoured by regularly-occurring flood flows. In deeply incised channels where there are no floodplains, the maximum stage that is regularly scoured by flood flows may provide the best estimate of an equivalent bankfull stage.

Table 2-3: A sample of bankfull depth estimates made at four representative cross-sections on the North Pine River.

1. width =	depths				
8.0	1.0	1.0	0.9		
avg. depth =					
.96					
2. width =					
10.0	0.5	1.0	0.9	0.9	
avg. depth =					
.83					
3. width =					
10.8	0.8	0.7	0.8	0.7	
avg. depth =					
.75					
4. width =					
10.0	0.9	0.9	0.7		
avg. depth =					
.83					
Average bankfull width:			9.7		m
Average bankfull depth:			.84		m

Slope

The average slope of the streambed may be measured with a surveyors level by dividing the total fall in the reach by the reach length as shown in Figure 2-5. Shorter slope measurements may be made with a hand level and tape and averaged to obtain a total reach value. In both cases, the reach lengths should be chosen to equally represent all of the pool, riffle, and chute conditions in the reach. Sample reach slope measurements are given in Table 2-4.

Some of the difficulties of estimating bankfull stages and channel slopes can be overcome if a profile is surveyed that runs along the lowest points of the streambed cross-sections throughout the reach (the thalweg of the stream). Measurements should be taken at each major break in the streambed slope. At the same time, profiles should be surveyed along the tops of the streambanks as shown in Figure 2-6. When the three profiles are plotted together, a more accurate estimate of the reach slope can be obtained. By plotting the mean depths at the sites of cross-sections on the profile, a better estimate of the bankfull depth may be obtained as well.

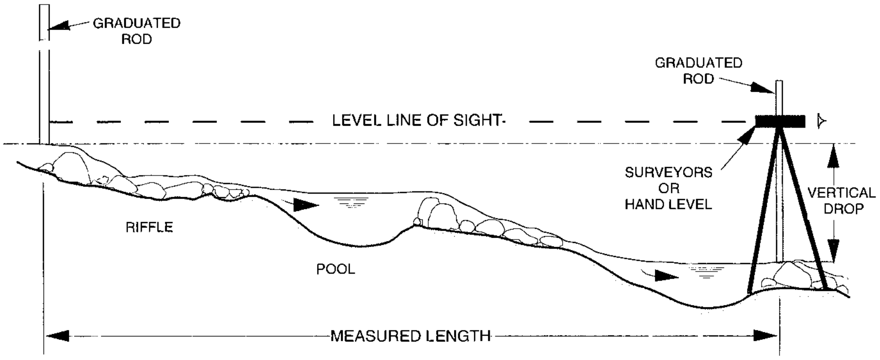


Figure 2-5: *A hand or surveyors level and graduated rod may be used to measure local slopes.*

Table 2-4: A representative sample of slope measurements in a pool and riffle reach of North Pine River.

dist. m	11	24	22
fall m	.24	.5	.5
slope	.022	.021	.023
Average reach slope: 0.022			

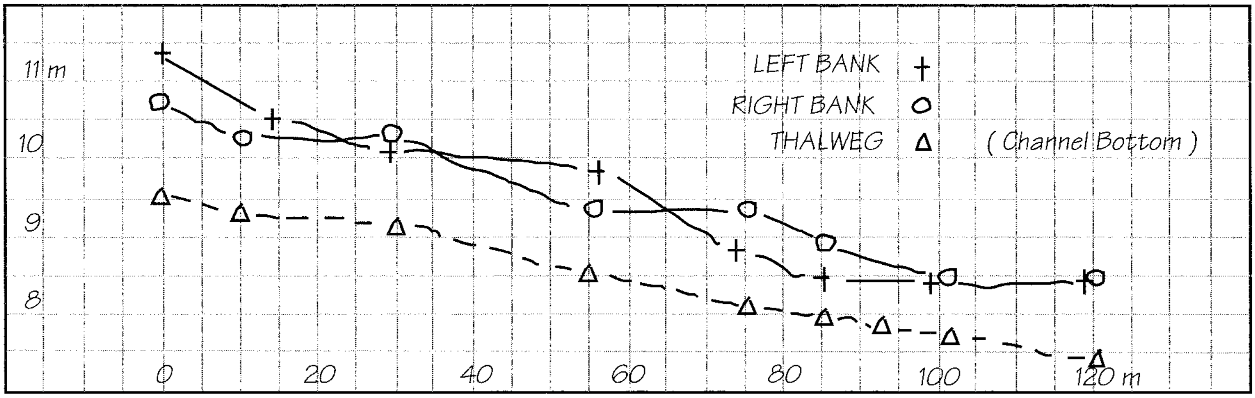


Figure 2-6: *A profile of the streambed and tops of the banks showing the mean bankfull depth at cross-section sites.*

Observation 4: substrate paving sample (Data Sheet II)

The gravels, cobbles, boulders, logs, and other debris that pave the streambed offer resistance to the flow, particularly when the mean depth is less than three times their average height. The amount of resistance depends upon their projection into the flow relative to the flow depth. This is the "relative roughness" of the bed, the height of an obstruction above the bed divided by the depth of flow. The relative roughness must be determined by measuring the size of the streambed surface materials.

The streambed surface materials may be randomly sampled for size throughout the reach using several techniques. Locations of surface materials may be determined using random distances and arcs or randomly selected grid points within the reach. However, since the purpose of the sample is to determine the elements that obviously project up into the flow, a less rigorous technique is to simply walk through the reach, stopping every few steps to feel the bottom of the stream and to measure the mean diameter of materials projecting into the flow. Large boulders and logs that project above the flow offer resistance as well, and should be included in the sample.

The mean diameter of paving materials may be determined by measuring the x, y, and z axes and averaging the values as shown in Table 2-5. Larger samples may be recorded on the back of the data sheet as well.

Table 2-5: A random sample of the size of surface materials on the streambed that project into flow, North Pine River.

x	y	z	d												
1.0	.7	.4	.7	.8	.5	.3	.5	.7	.6	.5	.6	.3	.2	.2	.2
.5	.4	.2	.4	.8	.4	.6	.6	1.0	1.0	.9	1.0	1.6	1.5	.8	1.3
.5	.3	.3	.4	1.2	.7	.3	.7	.9	.5	.4	.6	.6	.4	.4	.5
.8	.5	.2	.5	.9	.6	.5	.7	.4	.4	.2	.3	2.2	1.2	.9	1.4
.7	.7	.2	.5	.6	.6	.4	.5	.7	.6	.2	.5	.8	.6	.4	.6
.5	.4	.3	.4	1.0	.8	.6	.8	.5	.3	.2	.3	.7	.6	.3	.5

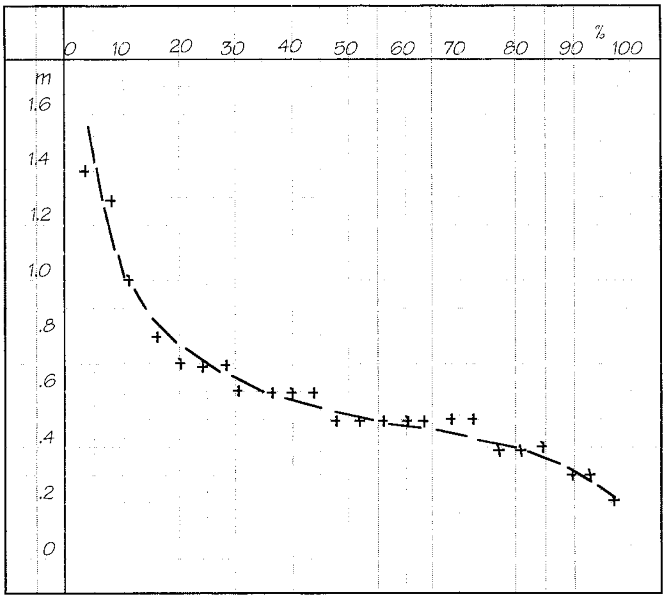


Figure 2-7: *Cumulative frequency curve of bed paving material from Table 2-5, North Pine River.*

The median diameter of the bed materials may be determined by plotting a cumulative frequency curve of the average diameters on the back of the data sheet as shown in Figure 2-7. The median diameter estimate is usually similar regardless of the bed sampling methods.

Observation 5: reach plan and features (Data Sheet III)

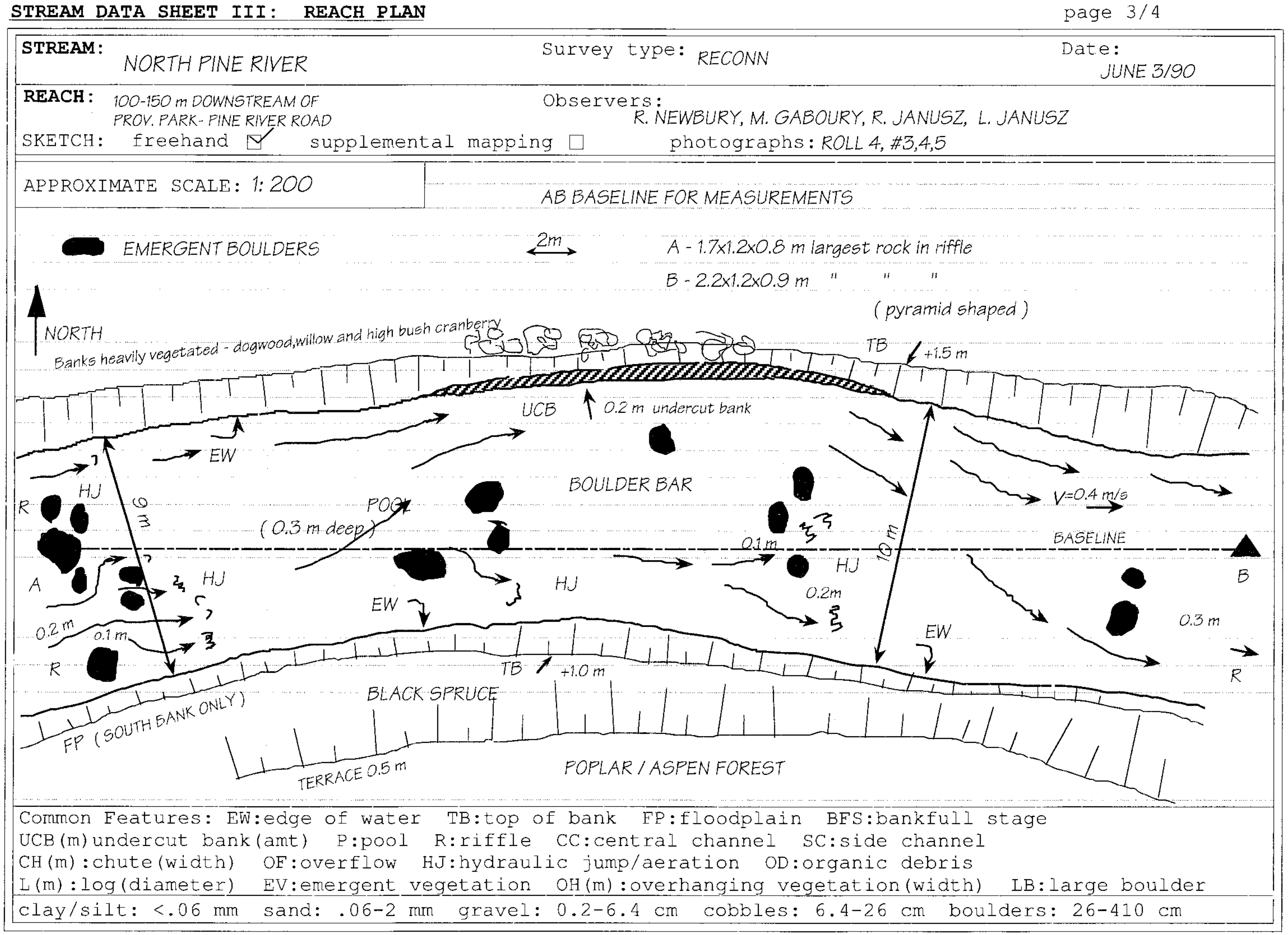
A sketch plan (as opposed to a surveyed plan) of the reach provides a useful addition to the channel measurements and sampling. A simple method for sketching the plan is to measure and mark a baseline of one or more straight segments that runs along the reach to use as a longitudinal reference line. The segments may be marked with temporary stakes that will allow a measuring tape to be stretched between them. The baseline should be plotted on the grid section of Data Sheet III and the scale noted. The channel boundaries should then be established by measuring their perpendicular distance from the baseline at regular intervals. When plotted, this will provide an approximate plan of the reach. For most streams, a plan at a scale of approximately 1:100 (1 cm = 1 m) will allow sufficient space to note other observations.

The locations of sample flow cross-sections, slope measurements, and bankfull sections used in the survey should be marked on the plan, particularly if the reach is to be re-surveyed as a monitoring site in the future. Some useful notes that may be added to the sketch are:

- the location of fish and invertebrate sampling sites,
- whether the flow in the reach is uniform or chaotic,
- the size and distribution of substrate materials,
- the presence and type of instream, emergent, or overhanging vegetation,
- the occurrence of organic debris in the channel (logs, snags, beaverdams etc.),
- what the bank materials are and whether they are stable,
- the nature of the evidence for the bankfull stage,
- the width of the floodplains (if any),
- the vegetation growing beside the streambanks,
- the presence of springs or seepages on the streambank,
- the water temperature in the substrate and in the flow,
- the sites of additional detailed habitat mapping that may be recorded on Data Sheet IV.

Depending upon the reach, man-made influences such as water intakes, outfalls, fences, livestock access sites, ford crossings, channelization, bank protection works, etc. may be located on the sketch as well. These features may also be noted on a fisheries inventory habitat condition sheet for the reach. Sample sheets used by the Manitoba Fisheries Branch are included in Appendix C.

A photograph looking upstream into the reach is a useful addition to the sketch. The date, identification number, and location of the photograph should be noted on the plan. Sample sketches of the North Pine River and Bald Hill Creek are shown in Figures 2-8 and 2-9.



STREAM DATA SHEET III: REACH PLAN page 3/4

STREAM: NORTH PINE RIVER
Survey type: RECONN
Date: JUNE 3/90

REACH: 100-150 m DOWNSTREAM OF PROV. PARK- PINE RIVER ROAD
Observers: R. NEWBURY, M. GABOURY, R. JANUSZ, L. JANUSZ
SKETCH: freehand ☑ supplemental mapping ☐ photographs: ROLL 4, #3,4,5

APPROXIMATE SCALE: 1: 200

AB BASELINE FOR MEASUREMENTS

● EMERGENT BOULDERS

A - 1.7x1.2x0.8 m largest rock in riffle
B - 2.2x1.2x0.9 m " " "
(pyramid shaped)

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

***Figure 2-8:** Sample sketch of a straight reach of the North Pine River.*

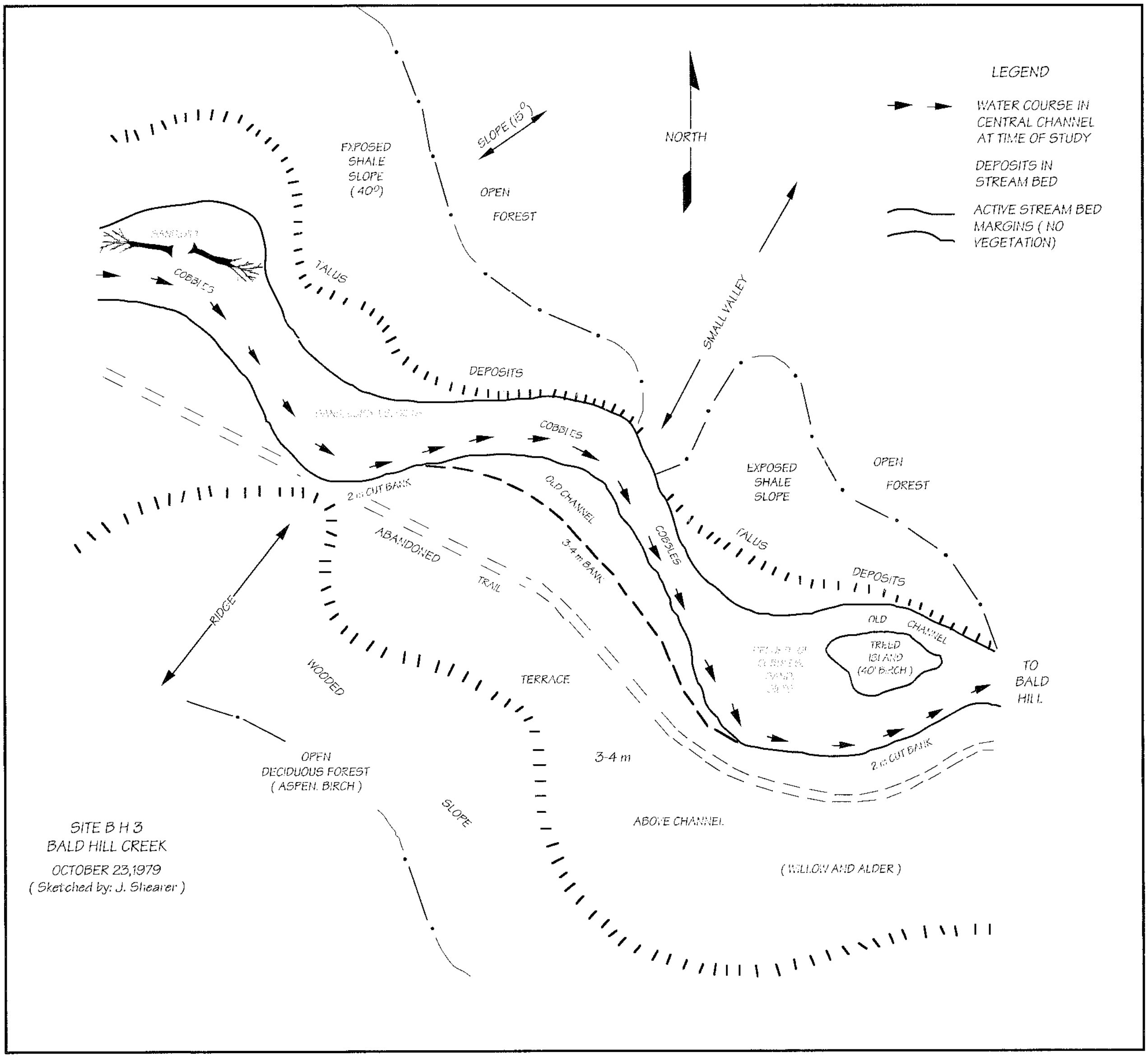


***Figure 2-9:** A free-hand sketch of Bald Hill Creek, a meandering tributary of Wilson Creek on the Manitoba escarpment.*

Observation 6: local flow and channel features (Data Sheet IV)

The physical characteristics of stream reaches may be evaluated with the planning studies and data gathered in the first five field observations. With a few additional observations, the hydraulic conditions that create stream habitats may be characterized as well.

To locate the habitat observations and sampling sites, a surveyed map of the reach plan and features is required. The survey may be accomplished by establishing two or more reference points and baselines in the reach from which to measure the distance and bearing of the observations as shown in Table 2-6. In traditional land surveys, this is done using a plane table and alidade to produce a map directly in the field. However, the same results may be obtained using a tape or electronic distance meter and any survey instrument with a horizontal scale for measuring angles. The measurements are plotted with a scale and protractor.

After the baselines have been surveyed and marked, the locations of observations are measured as a distance from one end of a baseline and an angle or bearing from the point on the other end of the baseline. Alternately, the bearing of locations and baselines may be measured from magnetic north with a compass. This method may not be reliable if the streams contain iron-bearing strata or heavily mineralized boulders because the local magnetic north may vary.

Table 2-6: Baseline survey notes for the reach plan shown in Figure 2-10.

BASELINES (AB to EF)
1/2" iron pins at stn., angle=bearings from magnetic north

point	length	angle	notes
A			*top of left bank*
AB	*20 m*	*120°*	
B			*boulder bar, right bank*
BC	*35 m*	*147°*	
C			*cut bank, left bank*
CD	*40 m*	*60°*	
D			*boulder bar, left bank*
DE			
E			
EF			

Supplementary hydraulic habitat observations include:

- the texture of fine sediments on the streambed,
- the effective shading of streambank vegetation,
- the size of logs and other organic debris,
- the pattern of the flow as it moves through the reach, particularly the formation of horizontal eddies,
- the distribution of aeration zones where shooting flows decelerate into slower flows,
- the depths and velocities of local chutes and pools.

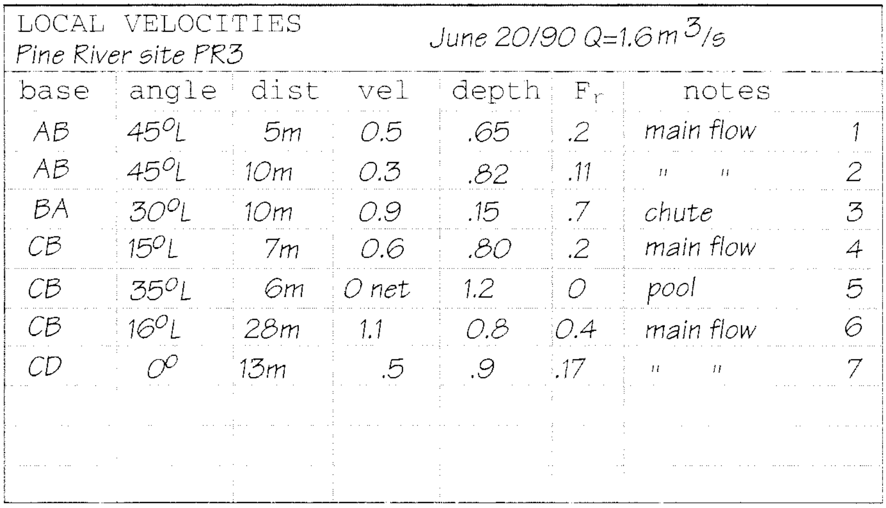
Abbreviations for mapping common features found in a sample reach are summarized on Data Sheet IV. Sample observations of channel features are summarized in Table 2-7.

Table 2-7: Observations of channel features in the upper half of the sample trout habitat reach on the Pine River shown in Figure 2-10.

CHANNEL FEATURES Pine River - site PR3
June 20/90 (trout habitat)

base	angle	dist	feature
AB	45° L	13	right bank
	73° L	4.5	emergent boulder
	43° L	6.5	" "
	43° L	8	" "
	28° L	12	" "
	40° R	5	snagged log (0.3mØ)
BA	30° L	12.5	boulder ④ 0.8 x 0.8 x 0.6
	30° L	8	boulder ⑤ 0.8 x 0.8 x 0.7
	60° L	1,13.5	right, left banks
	60° L	21	upland terrace
BC	25° R	22.5	overhanging birch (dead)
	0°	9.5,20	edges of point bar
CB	39° L	13	overhanging birch (alive)
	43° L	12.5	undercut upstream
	51° L	6.5	undercut downstream
	30° R	10.5,12	bar, top of bank

Table 2-8: A sample of local velocities and depths in the reach shown in Figure 2-10.



LOCAL VELOCITIES
Pine River site PR3

June 20/90 Q=1.6 m^3/s

base	angle	dist	vel	depth	F_r	notes	
AB	45°L	5m	0.5	.65	.2	main flow	1
AB	45°L	10m	0.3	.82	.11	" "	2
BA	30°L	10m	0.9	.15	.7	chute	3
CB	15°L	7m	0.6	.80	.2	main flow	4
CB	35°L	6m	0 net	1.2	0	pool	5
CB	16°L	28m	1.1	0.8	0.4	main flow	6
CD	0°	13m	.5	.9	.17	" "	7

The extent of overhanging vegetation, the size of logs and organic debris, and the depths and widths of chutes and pools may be measured with the tapes, metre rules, and survey rods used for the earlier observations. Small direct reading current meters are more convenient for the local velocity measurements than the standard horizontal bucket meter, both in time and in the number of field notes that have to be recorded. As shown in Table 2-8, local velocity and depth measurements may be mapped together as the Froude Number (F_r), a useful descriptor of the state of the flow.

The Froude Number is the velocity divided by the square root of the product of the depth and gravitational acceleration, or,

$$F_r = \frac{v}{(g \times d)^{1/2}}$$

where

F_r = *Froude number of flow*
v = *velocity of flow (m/s)*
g = *gravitational acceleration (9.8 m/s^2)*
d = *depth of flow (m)*

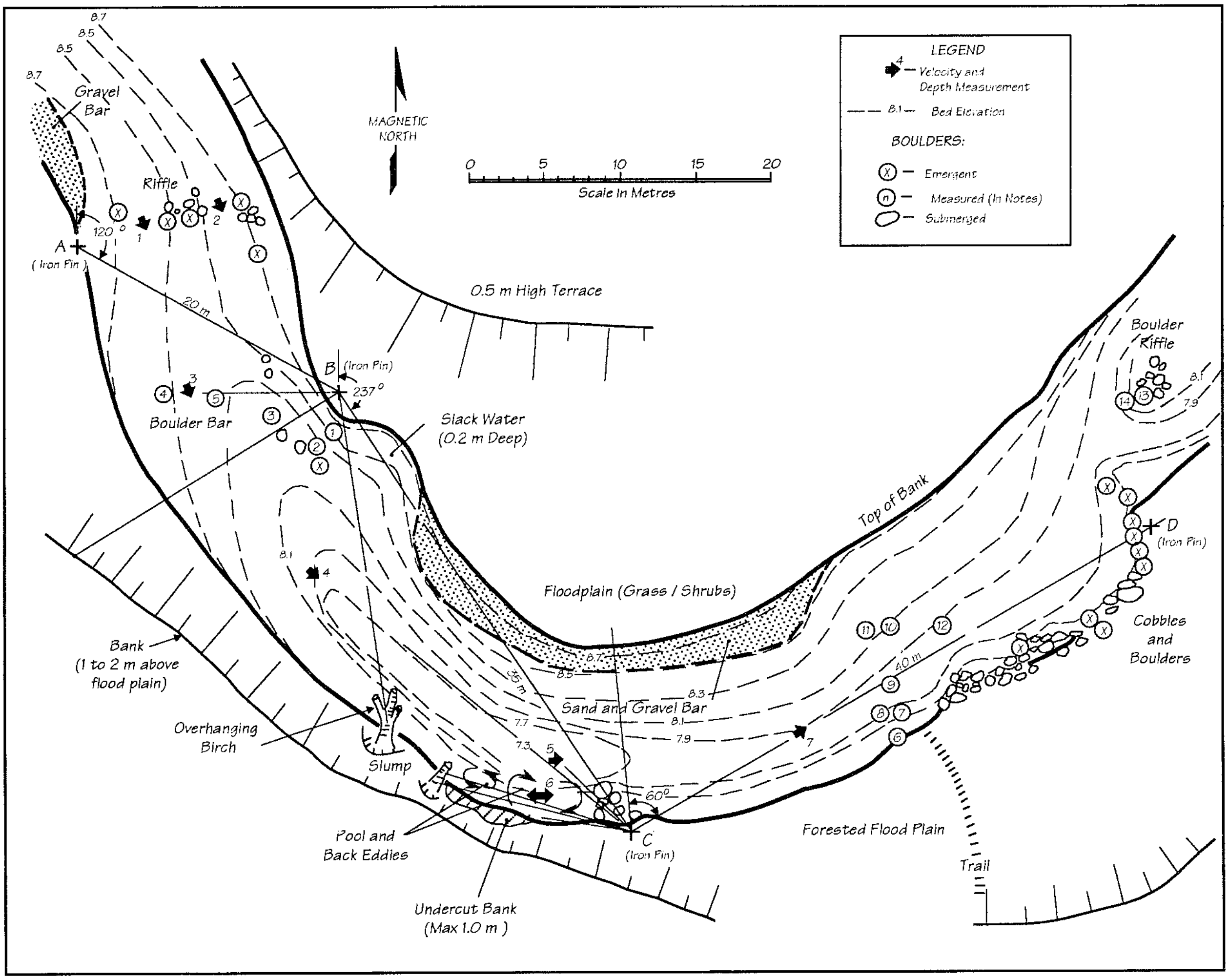


Figure 2-10: *A surveyed reach of preferred trout habitat on the lower Pine River (site PR3). The reach was used as a reference for habitat enhancement works on the North Pine River (Design Example 4, Chapter 4).*

To complete the habitat survey, water temperatures in the sample reach should be measured and water samples taken for analysis. Textural analysis of gravels, sands, silts, and clays may be undertaken later by sampling the materials and following standard soil evaluation methods.

The field notes of bearings, distances, and features for accurate mapping are extensive. Before leaving the reach, it is a good idea to plot the distances and bearings between reference points to be sure there are no missing segments of the baselines or unmapped areas of the reach. If a plane table is available, it may be convenient to plot the entire map in the field. This allows sketches and local observations to be added directly to the map. A surveyed reach map with habitat features on the Pine River is shown in Figure 2-10. The field crew and plane table is shown in Figure 2-11. The bearing and distance of habitat features is being plotted directly on the plane table map using the simple alidade and a scale. Elevations taken with the survey level are recorded on the map directly, allowing contours of the stream and floodplain to be sketched and checked in the field. The rod and metering crew are just visible on the left bank.

Figure 2-11: *Plane table survey at site PR3, Pine River.*

Chapter 3

The Evaluation of Stream Behaviour and Characteristics

The measurements and observations taken in the field can be used to determine the hydraulic characteristics and the habitat conditions in a stream reach. If several stream reaches have been sampled throughout the drainage basin, the whole channel network may be characterized by relationships between the area of the drainage basin tributary to a sample reach and its bankfull or characteristic channel maintenance discharge. The sample reach drainage area or the bankfull discharge may also be used to develop relationships between the bankfull channel width, mean bankfull depth, reach slope, and the bed materials. These relationships, referred to as the hydraulic geometry of the channel, are the basic reference for evaluating streams and man-made channels and designing stream habitats with natural characteristics. With biological sampling, the geographical distribution of biotic habitats may become evident as well. Such a basin-wide comparison is useful in identifying preferred, rare, and altered habitats and in developing habitat preference regression models. In Chapter 4, the natural characteristics of channels with preferred habitats will be used in designing stream enhancement and rehabilitation works.

Stream geometry data are also used in two common instream flow assessment methods, the "wetted perimeter method" and the "instream flow incremental method". A short discussion and references for these methods are included in Appendix D.

Methods for evaluating field observations are presented in the following five sections with a discussion of their significance to the stream's behaviour, form, and habitats:

3.1 Channel hydraulics
3.2 Flow frequency
3.3 Channel stability
3.4 Channel geometry and pattern
3.5 Flow conditions and hydraulic habitats

3.1 Channel hydraulics

The discharge (Q) flowing through a reach may be determined by multiplying the cross-sectional area of the flow (A) by the average velocity (v) flowing at right angles through the cross-section, or

$$Q = v \times A$$

where Q = *discharge* (m^3/s),
v = *mean velocity of flow* (m/s),
A = *cross sectional area of flow* (m^2)

The average velocity and depth of water flowing through a sample reach are governed primarily by gravity, expressed as the slope of the reach, and the resistance offered by the stationary channel boundaries on the "wetted perimeter" of the flow.

Manning's uniform flow equation

There is no complete analysis of the variety of flow conditions that occur in the reach. Consequently, an empirical relationship, commonly called the "Manning Equation" in North America, has been adopted to describe average flow conditions with some rather severe assumptions about the uniformity of the flow. The metric form of the equation is:

$$v = \frac{R^{2/3} \times s^{1/2}}{n}$$

$$R = A / p$$

Note: *the average depth of flow may be used as the approximate hydraulic radius **R** in wide and shallow natural channels.*

where v = mean velocity (m/s)
R = hydraulic radius of flow (m)
s = average reach slope
n = Manning's roughness factor ($m^{1/6}$)
A = cross-sectional area of flow (m^2)
p = wetted perimeter of flow (m)

Local variations in the average flow occur due to turbulence and obstacles on the streambed that cause the flow to accelerate and decelerate. The local flow conditions create important habitat and aeration conditions . Variations in the average velocity and depth may also occur because of the influence of high or low water depths (backwater effects) from the next reach downstream. The backwater effects may be analyzed also, but more detailed hydrometric surveys are required.

For the Manning equation to apply, it is assumed that the depth is uniform throughout the reach, the velocity is constant, and the slope of the water surface and streambed are parallel. These conditions of flow commonly occur in very large rivers and in smoothly graded excavated channels. In fact, Manning adapted the Chezy canal flow formula for more rugged natural channels by defining a range of channel resistance factors (Manning's "n" values). The original formula was developed by Chezy from observations of the Seine River in 1769.

Manning's roughness factor "n"

The most difficult part of applying the Manning equation is the choice of the channel resistance or roughness factor "n". The resistance to the flow varies widely for different sizes of the bed paving material and depths of flow. If the depth of flow is much greater than the size of the bed materials, the resistance is primarily due to drag on the substrate surface. However, if the depth of flow is shallow and the bed materials protrude into and through the flow, as in a boulder-bed stream, the resistance is much higher as it is caused by both drag and the physical obstruction of the flow.

If possible, the average velocity, depth, and slope should be measured in the reach for several different discharges to determine the relationship between discharge and the actual "n" value. However, this is seldom possible and other methods must be used to estimate the roughness factor for a given depth of flow.

In natural stream channels, three typical situations occur when estimating Manning's "n":

Case I: when the depth of flow is 3 or more times greater than the size of the median size of the bed paving materials,

Case II: when the depth of flow is less than 3 times the median bed material size, and

Case III: when the depth of flow shifts from less than 3 times to more than 3 times the median bed material size as the discharge increases.

Which case to apply may be determined by sampling the size of the bed paving materials (Chapter 2, Observation 4) and estimating the depth of flow.

Manning's "n" Case I: depth of flow > 3 x median bed material

If the flow is deep relative to the bed paving material size, the roughness may be estimated with an empirical relationship derived by Strickler in 1923

$$n = .04 \times d_{50}^{1/6}$$

where n = Manning's roughness factor ($m^{1/6}$)

d_{50} = median bed paving material size

This case occurs in streams with fine bed materials (sands, shales, gravels, small cobbles). For example, in the lower reaches of Wilson Creek, the bed materials consist primarily of pebbles and weathered shale particles with a median diameter of 6 cm. The slope of the reach is 0.8%. To estimate the bankfull discharge an "n" value must be chosen as there are no direct observations of the flow at that stage. The average bankfull depth was observed to be 0.35 m. At this stage, the ratio between the depth and median bed material size is .35/.06 = 5.8 and the Strickler approximation of "n" may be applied, where:

$$n_{\text{strickler}} = .04(.06)^{1/6} = .025.$$

From the Manning equation, the velocity is:

$$v = (.35^{2/3} \times .008^{1/2})/.025 = 1.8 \text{ m/s}.$$

The observed bankfull width was 4.3 m, producing a cross-sectional area of flow of 4.3 x .35 = 1.5 m^2. The bankfull discharge estimate is therefore 1.8 x 1.5 = 2.7 m^3/s.

Even though the depth of flow in Case I conditions is relatively deep, other factors may increase the resistance to the flow such as fallen trees in the channel, sharp bends, and emergent vegetation. When these conditions occur, "n" values must be adjusted upwards using tables or photographs of different channel conditions and their observed resistance values. A few common examples (Chow 1959) of typical resistance factors for different channel conditions are listed in Table 3-l. A photographic index of stream reaches and "n" values has been prepared by Barnes (1967) as well.

Table 3-1: Manning's "n" resistance factors

Channel Type	"n" value
1) clean, straight, fine bed materials with few isolated boulders	.03
2) clean, winding, cobble bed with some boulders, pools and riffles	.04
3) sluggish, weedy, deep pools	.05
4) weedy, fallen or flooded vegetation in stream	.08

(note: if substrate is greater than the depth of flow n = .08 - 0.5)

Manning's "n" Case II: depth of flow < 3 x median bed material

This case commonly occurs in rugged headwater streams where the water flows over and through cobbles, boulders, and logs. In these channels, Strickler's approximation does not apply because the flow is obstructed by the large bed paving materials. The "n" values may be 5 to 10 times greater than the case I deep-water flow values. In these streams, metering the discharge and measuring the average depth and slope (Observations 1 to 4 in Chapter 2) should be done to directly determine the resistance factor for the observed stream stage.

For example, in the North Pine River sample reach described in Chapter 2, the metered discharge was 0.89 m^3/s (observation 1). The average cross-sectional area of the flow was 2.5 m^2 (observation 2). The average velocity in the reach was therefore 0.89/2.5 = 0.36 m/s. The average depth of the flow was 0.25 m (observation 2), and the slope of the reach was 2.2% (observation 3). If the observed values are substituted in the Manning equation, the present resistance factor may be solved for as follows:

$$.36 = (.25^{2/3} \times .022^{1/2})/n, \text{ or } n = 0.16$$

This is not surprising for such a steep boulder-filled stream. The size distribution of the bed paving materials shown in Figure 2-7 (observation 4) indicates that over 90% of bed materials are larger than the depth of flow at the observed stage.

For other stages, the relationship between the depth of flow and bed material size will indicate whether the observed value should be increased or decreased. If possible, these estimates should be confirmed with direct metering as well. As these rocky channels are generally stable, the cross-sections measured in the first survey may be used for subsequent determinations of "n" if an elevation reference point is established. Subsequent surveys may be reduced to measuring the stage, water surface slope, and discharge.

For example, at the bankfull stage in the North Pine sample reach of 0.84 m in Figure 2-7, the 3:1 Strickler requirement would apply to streambeds with a median bed material size of 0.84 / 3 = 0.3 m. From the North Pine bed material size distribution, it is apparent that this condition would occur over less than 10% of the bed materials at the bankfull stage. Therefore, the obstructed flow conditions would not change significantly from the lower stage and the observed "n" value of 0.16 should be used to estimate the bankfull flow as well. If possible, further measurements at higher stages should be made to confirm the bankfull "n" estimate.

With an "n" value of 0.16, the bankfull velocity estimate is:

$$v_{bf} = (.84^{2/3} \times .022^{1/2}) / \; 0.16 = .83 \text{ m/s}$$

The bankfull discharge estimate is:

$$Q_{bf} = .83 \times .84 \times 9.7 = 6.7 \text{ m}^3\text{/s}$$

Manning's "n" Case III: depth of flow shifts from < 3x to > 3 x the median bed material size at low and high stages

Streams with pools of fine bed materials and riffles of cobbles, boulders and debris often have a wide shift in "n" values between low and high stages. At very low stages, the stream flows through low-gradient quiescent pools across steeply-sloping boulder-obstructed riffles. The "n" values may be as high as 0.4 to 0.6, using the average slope and dimensions of the channel. At high flows, the pools and riffles are "drowned out" as the depth increases and the slope of the water surface parallels the average slope of the whole reach. At higher depths of flow, the boulder and cobble sections of the reach no longer obstruct a significant portion of the flow and the "n" values shift dramatically downwards. If the high stage depth of flow is 3 or more times greater than the median bed material size, the case I Strickler values may be used.

The following example is typical of a pool and riffle reach with shifting "n" values. Stream survey data were gathered in a sample spawning reach on Hamilton Creek, a tributary of Falcon Lake in eastern Manitoba (Figure 1-2). The survey was undertaken during a low flow period in September 1989. The data are summarized below:

	Depth	Width	Slope
Observed:	.24 m	3.1 m	.47%
Bankfull estimate:	.36 m	4.6 m	.47%

The median diameter of the cobbles paving the streambed was 12 cm. The discharge measured at the time of the survey was 0.05 m^3/s.

Based on the observed cross-section and discharge measurement, the average velocity at the time of the survey was only 0.07 m/s. The channel resistance factor under these low-flow conditions was 0.38. The ratio of the depth to the median bed material size was only 2:1.

At the bankfull stage, the ratio of the depth to the median bed material size is 3.0, just meeting the criteria required for a Case I estimate. The predicted bankfull “n” value is .028 using the Strickler equation. From the Manning equation, the average velocity is predicted to increase to 1.3 m/s at the bankfull stage. Based on the observed dimensions, the bankfull discharge estimate would be 2.1 m^3/s.

The reduction of flow resistance at high stages in Hamilton Creek has been observed in other streams as well. Where frequent stage and discharge measurements have been taken, a relationship may be developed between the depth of flow or discharge and Manning's resistance factor as shown in Figure 3-1 for Oak Creek, Oregon (Bovee and Milhous 1978). Similar observations have been made in Bald Hill Creek, the boulder/cobble channel that is tributary to Wilson Creek. The resistance factor shifts from .23 to .08 as the flow increases from .002 to .9 m^3/s.

In these difficult transitional cases, the best insight is gained by comparing the estimated stage to the bed material size distribution to see how much of the paving material will be obstructing the flow...and by some imaginative use of the descriptive and photographic guides.

3.2 Flow frequency

The bankfull flood is the maximum discharge that may be conducted through the reach within the main channel or channels. This is also referred to as the characteristic, channel-forming, or bankfull flow. Within a stream network, several useful relationships may be developed between the bankfull flow and the tributary drainage area, the width and depth of the channel, and the substrate stability.

Flood flows that exceed the bankfull depth spill into the floodplains above the channel. In this case, the discharge through the reach

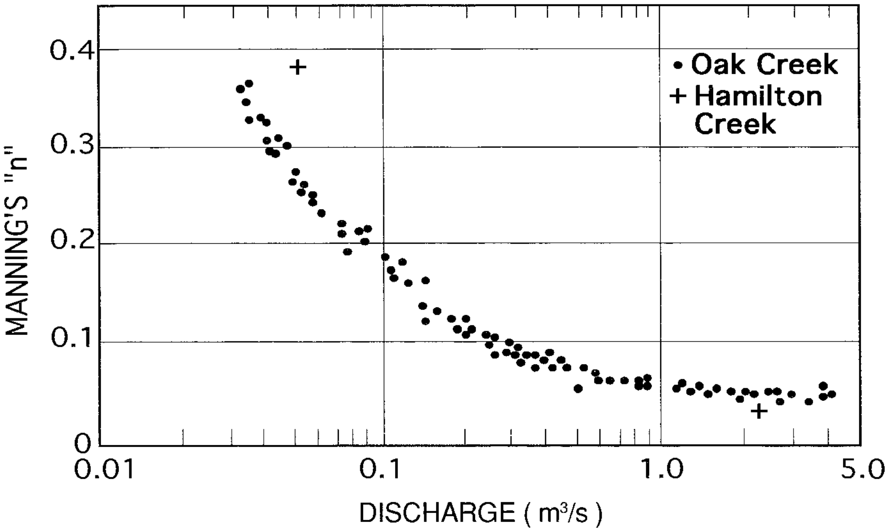


Figure 3-1: *The reduction in Manning's resistance factor "n" as the discharge and depth of flow increase (after Bovee and Milhous 1978).*

must be evaluated as a series of parallel channels, each with its own dimensions and flow resistance. The main channel or channels usually carry the bulk of the flow because the shallow depth and high resistance on the floodplains limit the overbank velocities.

Flows that are less than the bankfull stage may be estimated using Manning's equation with an appropriate allowance for changes in the resistance factor as the depth changes. The flows corresponding to a range of depths may be plotted to produce a channel rating curve (depth versus discharge).

Minimum flows in an ungauged reach are more difficult to determine because they are site-specific. These very low flows may disappear within the reach as groundwater recharge or they may simply flow through coarse materials on the streambed. Further downstream, they may reappear in zones of groundwater discharge or when finer bed materials are encountered. In these cases, a reconnaissance along the stream in low flow periods is required to map the sources and sinks of flow. In summer, reaches with groundwater inflows may be detected by measuring the difference between temperatures in the flow and in the substrate. The substrate temperatures will often be cooler because the inflowing groundwater temperature will be close to the mean annual temperature of the region. This can be checked in nearby wells. Inflow reaches are particularly distinct in mid-winter as the sensible heat of the groundwater will suppress ice growth and maintain open water conditions. Further downstream, ice dams formed by successive layers of freezing are often found.

Annual flood frequency

A convention for describing the frequency of occurrence of flood flows has been adopted for mid-latitude streams that generally produce a flood peak once a year during or just following the Spring snowmelt period or peak rainfall event. The convention consists of choosing the maximum flood each year as a sample of all floods that can occur. The cumulative probability of exceedence of the annual peaks is then plotted on log-normal graph paper, and a line is fitted to the data to define the relationship between discharge and the annual flood frequency.

Table 3-2: Wilson Creek annual flood peaks recorded at the lower gauging station in the years 1959 to 1977.

Flow (m^3/s)	Year	Rank	Plotting Position (%)
44.8	1975	1	5
20.7	1971	2	10
19.8	1969	3	15
14.2	1977	4	20
10.2	1970	5	25
8.2	1974	6	30
7.2	1963	7	35
7.1	1965	8	40
4.7	1968	9	45
4.5	1962	10	50
4.5	1972	11	55
4.2	1976	12	60
3.4	1966	13	65
3.3	1960	14	70
2.7	1964	15	75
2.0	1967	16	80
1.8	1973	17	85
1.2	1961	18	90
1.0	1959	19	95

For example, the annual flood peaks recorded at the Wilson Creek gauging station for a 19 year period (Table 3-2) have been arranged in descending order. The largest peak of 44.8 m^3/s has been assigned a rank of 1, the second largest, 2 etc. The plotting position, or cumulative frequency is calculated using a convention proposed by Weibull (in Chow 1964) for incomplete data sets as follows:

$$p = \frac{rank}{n+1} \times 100\%$$

where p = *plotting position*
n = *total number in sample*

The data from Table 3-2 are plotted in Figure 3-2. A straight line fitted through the data points on the graph assumes that the logarithm of the flood peaks is normally distributed, as is often the case for natural basins. From the plot, it is apparent that a flow of 14 m^3/s is equalled or exceeded by 20% of the flood peaks. This implies that there is a 20% chance each year that the peak flow will be 14 m^3/s or more. A widely adopted, but misleading, expression of this probability is that this is the "5 year return period flood", based on the rationale that in 100 years, floods of this magnitude or greater will occur 20 times, or 1 for every 5 years. Of course, it simply means that there is a 20% chance every year with no "flood-free" return period implied.

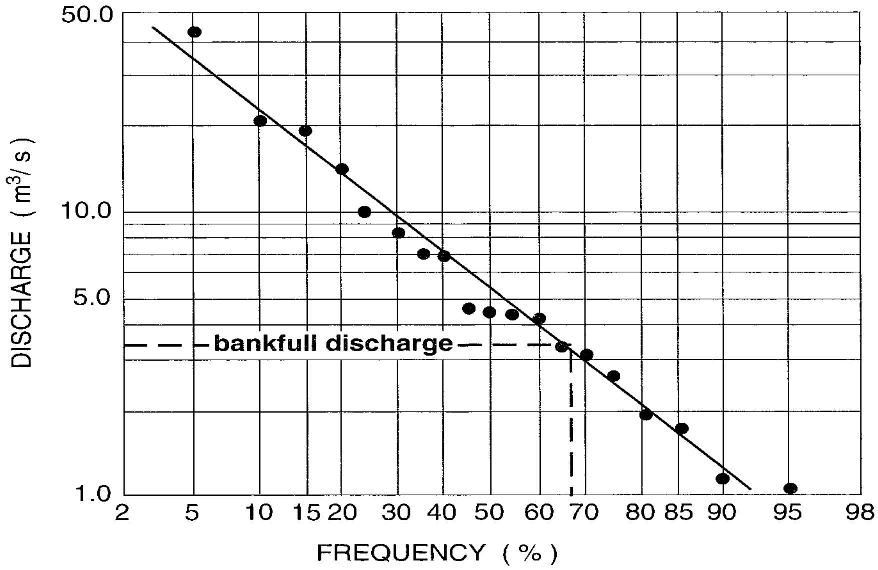


Figure 3-2: *Annual flood frequency curve for Wilson Creek for the period 1959-1977 (Table 3-2).*

Estimating flood frequency

In most streams, there are no long-term gauging records available for a sample reach. Consequently, the flow records must be transferred from a nearby gauging station in a similar basin by making the assumption that the flood peak produced per unit area of tributary drainage area is the same for both basins. This assumption should be checked by measuring a few flood peaks in the sample reach and comparing them to the recorded peaks at the gauging station, particularly where the tributary areas differ widely. In many cases, the peak flow per unit area increases in smaller tributary areas as there is less surface storage available and the water collects more rapidly in the channel.

For example, flood flow records must be transferred to the North Pine sample reach (see sample field data in the preceding chapter) as there is no gauging station for the upper Pine River basin. The nearest gauging station is near the town of Pine River as shown in Figure 1-3. Table 1-3 contains a sample of the records. The drainage area tributary to the sample reach is 100 km^2 and to the gauging station, 210 km^2. Assuming that the basins have similar unit area flood peaks, the transferred sample reach flows will have 100 / 210 = 0.48 x the flood peaks that have been recorded at the gauging station. The cumulative frequency curves for the North Pine sample reach and the Pine River gauging station are plotted in Figure 3-3 using the data listed in Table 3-3.

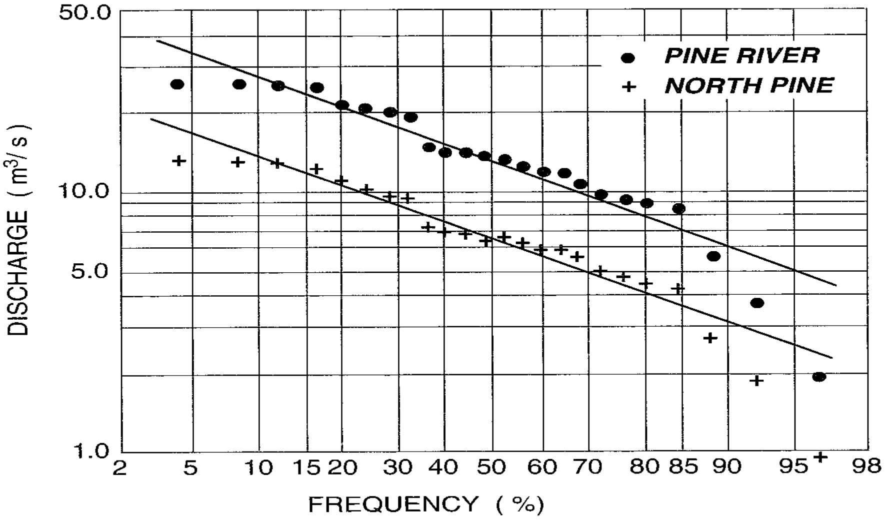


Figure 3-3: *Annual flood frequency curves for the Pine River gauging station and the North Pine rehabilitation site for the period 1958-1982 (see Table 3-3).*

Table 3-3: Pine River annual flood peaks recorded near the town of Pine River in the years 1958 to1982. The North Pine flood peaks are estimated using the ratio of tributary drainage areas.

Rank	Year	Plotting Position	Flow (m^3/s)	
			Pine River	North Pine
1	1973	4	26.4	12.7
2	1976	8	26.2	12.6
3	1970	12	25.7	12.4
4	1979	16	25.3	12.1
5	1982	20	21.6	10.4
6	1974	24	20.5	9.8
7	1959	28	19.8	9.5
8	1965	32	19.3	9.3
9	1969	36	14.5	7.0
10	1958	40	13.6	6.5
11	1966	44	13.5	6.5
12	1960	48	13.1	6.3
13	1975	52	13.1	6.3
14	1971	56	12.5	6.0
15	1972	60	11.8	5.7
16	1967	64	11.6	5.6
17	1977	68	10.8	5.2
18	1980	72	9.4	4.5
19	1963	76	9.1	4.4
20	1981	80	8.6	4.1
21	1968	84	8.3	4.0
22	1964	88	5.4	2.6
23	1978	92	3.6	1.7
24	1962	96	1.9	0.9

Bankfull flow frequency

From field observations, the bankfull flow for a sample reach near the gauging station on Wilson Creek was estimated to be 2.7 m^3/s (see "n" Case I). In Figure 3-2, this peak is equalled or exceeded by 75% of the annual floods, implying that the bankfull condition occurs in 3 out of 4 years.The bankfull flow estimate for the North Pine sample reach was 6.7 m^3/s (see "n" Case II). From the estimated cumulative frequency curve in Figure 3-3, this flow would be equalled or exceeded by 50% of the annual flood peaks, implying that the channel-forming bankfull condition occurs regularly in 1 out of 2 years, similar to the Wilson Creek case. This regularly recurring bankfull flood maintains the central channel or channels and may be used as the channel "characteristic" or "maintenance" flow in relationships that describe the width, depth, and bed materials in sample reaches. In many basins, a strong correlation exists between the bankfull discharge and the tributary drainage area. As shown in Figure 3-4, the relationship may be used to compare the runoff characteristics of different basins. The dashed lines in Figure 3-4 bracket the range of relationships for streams with high and low runoff regimes in the United States.

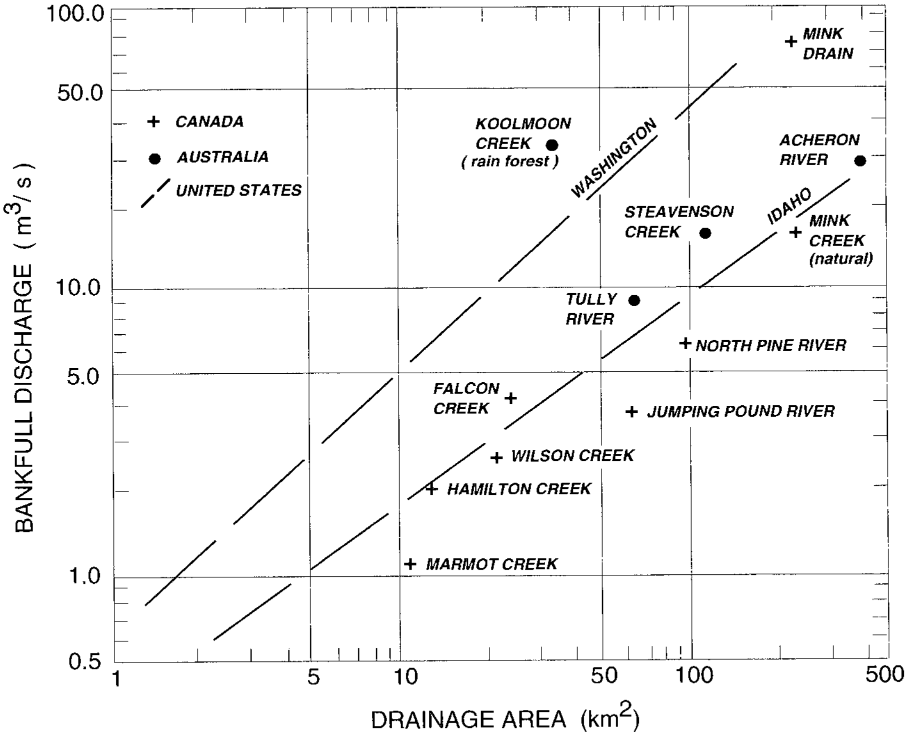


Figure 3-4: *Bankfull flow and tributary areas for several streams in Canada and Australia. The bankfull discharge was estimated using the field methods presented in Chapter 2.*

3.3 Channel stability

Shear stress

The movement of coarse sediments by rolling and bouncing along the channel bed has been studied by many researchers concerned with stable channel design. The shear stress exerted by the flow on individual particles just at the point at which they begin to move (incipient motion) has been measured in laboratory flumes but only observed indirectly in canals and natural channels. In research studies, shear stress on the surface of the streambed or on an individual particle on the bed is determined by measuring the adjacent velocity profile with miniature current meters.

Tractive force

In canal and stream studies, a more general measure of shear stress, the "tractive force", is used to characterize the average shear stress in a reach. In the following relationship, the tractive force in kg/m^2 of the streambed may be determined from two simple field measurements, the average slope of the water surface in the reach and the depth of flow.

$$\tau = 1000 \times d \times s$$

where τ = tractive force of flow (kg/m^2)
(x 9.8 for Newtons/m^2)
d = depth of flow (m)
s = slope of water surface

The tractive force can be related to the size of material at incipient motion as shown in Figure 3-5. The field observations and recommended design guidelines were compiled by Lane (1955) for a wide range of canals and river channels. The data are widely scattered for several reasons, for example; smooth channels with cohesive bed materials (clays and fine silts) tolerate high shear stresses until they start to erode and then become highly mobile, coarser silt and sand bed streams form ripples and dunes that move along the streambed, and gravel and cobble bed streams may develop an erosion resistant "paving" of cemented or closely packed bed material. However, for non-cohesive bed materials greater than 1 cm in diameter (fine gravel), the relationship is less scattered and may be approximated as:

$$\text{tractive force (kg/m}^2\text{)} = \text{incipient diameter (cm)}$$

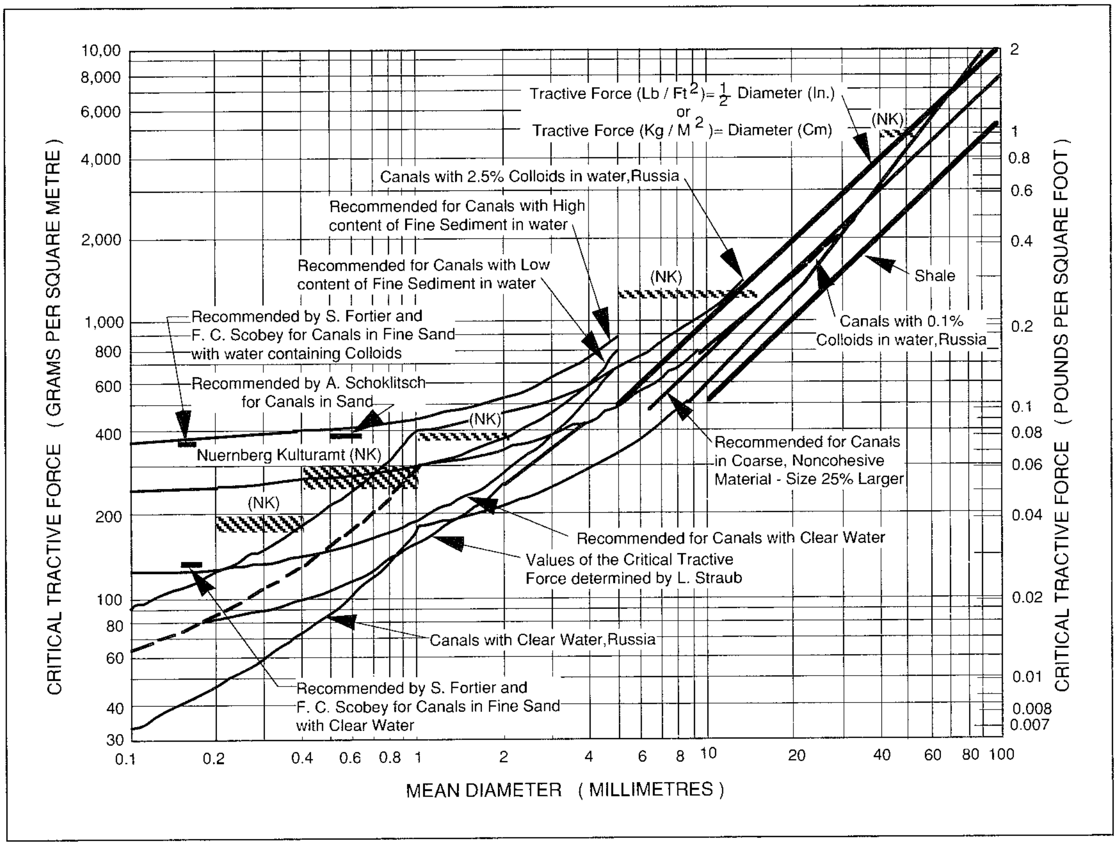


Figure 3-5: ***Relationships between the tractive forces on the streambed and size of bed material that will erode (Lane 1955, Magalhaes and Chau 1983).***

Flat shale gravels and cobbles have been observed to move at approximately half of the tractive force required for an equivalent rounded particle (Magalhaes and Chau 1983).

Bed stability

The degree of stability of a stream channel may be estimated using the bed paving material sample and reach slope observations described in Chapter 2. For coarse non-cohesive bed paving materials, the mean diameter at incipient motion may be determined for different depths of flow using Lane's general relationship. The percent of the bed paving materials that lie above or below this value may be determined from the cumulative frequency of mean bed material size plot. For example, using the sample observations in

Chapter 2, the tractive force at the bankfull stage in the North Pine sample reach is 1000 x .84 x .022 = 18 kg/m^2. From Lane's relationship for gravels and cobbles, this will move particles as large as 18 cm in mean diameter. In Figure 2-7, all of the sampled bed materials exceeded this diameter, implying that at the bankfull stage, the channel shape and profile remain stable while materials less than 18 cm in diameter move through the reach. However, there may be some local adjustments in the channel as the cobbles and boulders are undermined in this reach of large glacial deposits.

In channels with finer bed materials, some fraction of the bed may be eroded at the bankfull stage but the channel cross section is maintained by equivalent materials moving into the reach from upstream. For example, on Bald Hill Creek, a tributary of Wilson Creek, the bankfull tractive force is 13 kg/m^2. In the upper bed material size distribution shown in Figure 3-6, an equivalent diameter of 13 cm occurs at a cumulative frequency of 68%. In the Bald Hill sample reach, 68% of the bed paving materials will be stable, or, the stream is capable of moving 32% of the surface materials at the bankfull stage. In unstable reaches with smaller bed materials, a larger portion of the bed may be eroded at the bankfull stage. The channel dimensions are maintained as the eroded materials are replaced by materials transported from upstream that are deposited in the reach as the flood peak passes (unless there is a reservoir or some other sediment trap constructed above the reach). For

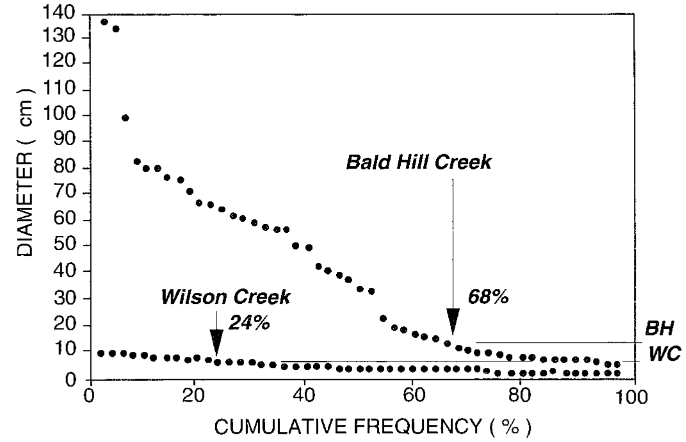


Figure 3-6: *Bed paving materials in stable and unstable reaches of Wilson Creek (Cobb 1990).*

example, in the sample reach at the head of the Wilson Creek alluvial fan, the bankfull tractive force is only 3 kg/m^2. As the channel is formed of flat shale gravels, the equivalent diameter that can be eroded at the bankfull stage is 6 cm. This diameter occurs on the lower bed material distribution curve in Figure 3-6 at a cumulative frequency of 24%, implying that 76% of the bed material can be eroded by the bankfull flows.

Stream deposition

A reach by reach analysis of the tractive force and bed paving materials is a useful insight into the stream's behaviour and the hydraulic habitats created in the channels. In streams with sharply concave profiles like Wilson Creek, the slope of each successive reach downstream decreases more rapidly than the bankfull depth of flow increases. Consequently, the tractive force decreases as the stream moves down through the basin. If the stream flows through deposits with a wide range of sizes, such as the glacial tills in the upper reaches of Wilson Creek, the regular flood flows will sort the bed materials into decreasing sizes in successive downstream reaches. In the steep headwater reaches of Wilson Creek for example, large cobbles and boulders that cannot be transported accumulate in the streambed as the stream downcuts into the valley bottom. The bed paving materials cover a wide range of sizes, from car-sized boulders to fine sediments washed in from the valley walls. Further downstream in the mid-reaches of the basin, the upper limit of the size of the bed material becomes uniform. Typically, the channel is paved with cobbles that have been transported from the upstream reaches. Further downstream, as the reach slopes decrease even more, the stream is paved with materials whose upper size limits are pebbles and coarse shale gravels. Finally, in the lowest reaches, the slope and tractive force decrease until only fine sediments are transported by suspension into the reach. The coarser suspended sediments are deposited as the stream enters a lake or estuary or encounters a flat-lying segment of low slope. In Wilson Creek, the shale gravels are deposited in an alluvial fan as the stream enters the flat glacial Lake Agassiz plain below the Manitoba escarpment. Finer sediments are carried in suspension across the plain and deposited in the Turtle River delta on the southern shore of Dauphin Lake (Figure 1-6).

Stable channel design

Lane's tractive force graph may be used in design to select stable materials with mean diameters that are greater than the observed and recommended limits for a given tractive force. For a design discharge and slope, the channel depth (and consequent tractive force) may be adjusted by varying the channel width.

Natural channel cross-sections are relatively wide and shallow as compared to most excavated canals, with ratios of width to depth of 10:1 to 15:1 as the drainage area increases (see section 3.4). However, the wide natural channels do not have the "most efficient" cross-section for conducting a given discharge. The most efficient section maximizes the hydraulic radius for a given cross-sectional area, producing a circular cross-section. This is often approximated in man-made canals with narrow, steep-sided trapezoidal and rectangular channels. The canal sections minimize the land required for the channel and the amount of excavation but may require larger than natural bed materials to protect the channel from erosion due to the increased tractive force. In wider natural channels with the same discharge capacity, the tractive force is limited by the decreased depth of flow.

3.4 Channel geometry and pattern

The dimensions used to characterize channel size and shape, stream pattern or planform, and the longitudinal profile of a stream segment provide a natural template for evaluating impacted stream reaches and designing stream enhancement and rehabilitation works. All of the hydrological background and survey data described in Chapters 1 and 2 are required to evaluate and characterize the stream channels and habitats in a basin or region. The following discussion of this important aspect of stream behaviour has been extended with data from other river basins in addition to the Manitoba examples presented in Chapter 2. Stream enhancement and rehabilitation projects based on natural hydraulic geometry are discussed in Chapter 4.

Channel width and depth

The cross-section of the main channel of a natural stream (central channel, Figure 2-4) is maintained by regularly occurring flood flows that fill the channel to the bankfull stage. The width and depth of the channel at the bankfull stage, called the "channel geometry", are the basic dimensions used to define the relationship between stream size and the bankfull discharge. Similar relationships have been observed in man-made canals in erodible materials after the channels have had time to adjust their geometry to the design flows.

The relationship between the bankfull channel size and the bankfull discharge may be determined by surveying sample reaches throughout the drainage network using the methods described in Chapter 2. For basins with uniform hydrologic conditions, correlations with drainage area alone may be adequate to define the width and depth relationships. This eliminates the need to introduce an estimated value for Manning's roughness.

To obtain a well-distributed sample, the reaches should be chosen with a geometric ratio of tributary drainage areas up to the maximum basin size. For example, for a 200 km^2 basin, sample reaches may be chosen that have tributary areas of 200, 100, 50, 25, 12, 6, and 3 km^2. The sample reaches should reflect the variability of channel conditions in the basin (discussed in Chapter 1) particularly where there are reaches of interest for habitat or fish passage studies.

Bankfull dimensions and drainage areas for sample reaches in several Canadian streams are listed in Table 3-4. The hydraulic geometry data are plotted in Figure 3-7. The bankfull width observations follow a trend line similar to that observed in mid-western US streams. The bankfull depth observations show a similar trend but with more scatter because the bankfull stage is more variable than the width and more difficult to estimate. The depth observations for sample reaches in the same stream exhibit less scatter. For example, the Jumping Pound Creek depth observations follow a trend line that is parallel to, but lower than, the general trend line for all other sites. This is also the driest basin in the sample.

Natural channel guidelines

Establishing the natural channel geometry relationships for a stream is an important step in understanding the stream's behaviour and characteristics. Based on the drainage area the channel geometry measurements may be linked to the channel pattern and profile and used to dimension stream rehabilitation works that mimic natural conditions. Even a preliminary estimate of the hydraulic geometry based on an abbreviated field survey in which only the bankfull width

Table 3-4: Bankfull stream dimensions surveyed in several Canadian streams.

Stream and Reach	Order No.	Drainage Area (km^2)	Slope	Bankfull Width (m)	Bankfull Depth (m)
Wilson Creek (Manitoba)					
Conway Creek	1	0.7	.06	2.0	0.29
South Branch	2	3.0	.06	3.0	0.30
Bald Hill	3	8.6	.04	3.8	0.32
Junction	3	12.7	.015	3.6	0.33
Weir Site	4	22.1	.008	4.3	0.35
Jumping Pound Creek (Alberta)					
Moose Mountain	1	7.3	.02	3.1	0.17
Coxhill Creek	2	36.0	.02	5.1	0.24
Pinetop Hill	3	59.0	.019	10.9	0.35
Gauging Station	5	455.0	.007	13.4	0.38
Don River (Ontario)					
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
Hamilton Creek (Man.)	2	12.5	.005	4.6	0.36
Pine River (Man.)	4	100.0	.022	9.7	0.84
Mink Creek (Man.)					
natural	4	230.0est	.0019	16.0	1.10
channelized	5	250.0	.0022	20.0	1.60

* order unknown because the urban tributaries are conducted underground.

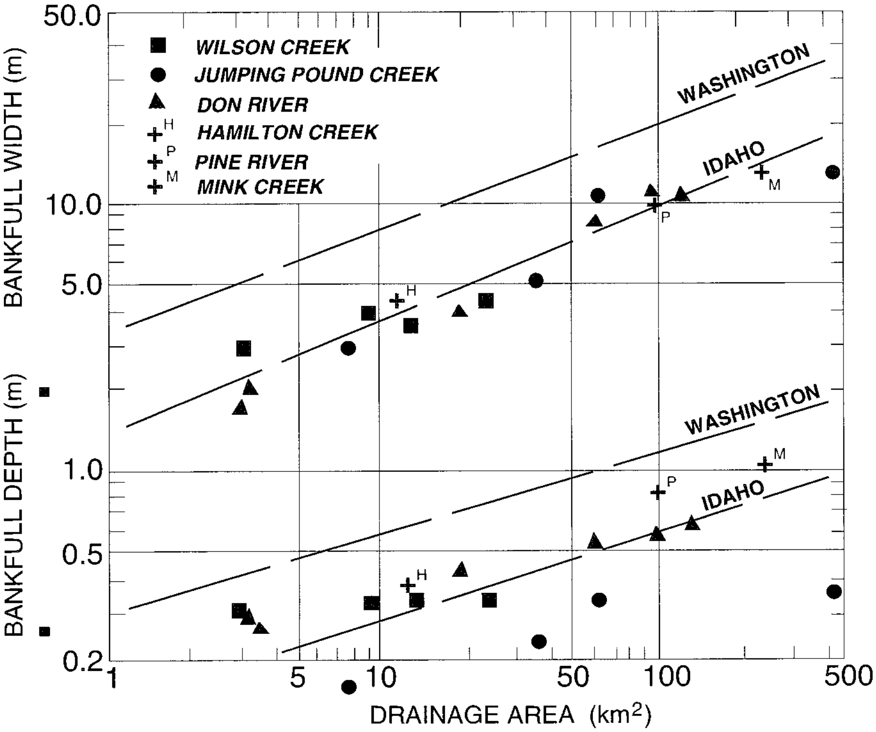


Figure 3-7: *Bankfull channel geometry and tributary drainage areas surveyed in several Canadian streams. The dashed lines bracket the relationship for streams in the United States.*

and depth are measured will provide useful guidelines. Sample reaches with known drainage areas may be chosen for ease of access, for example, following a network of regional roads.

Channel patterns

Stream patterns are seldom uniform throughout a drainage basin. For example, in streams with steep headwater reaches and low-gradient lower reaches, the channel often shifts from a straight or braided pattern to a meandering pattern. A relationship between the reach slope, bankfull discharge, and channel pattern has been observed by Leopold and Wolman (1957) as shown in Figure 3-8. Two sample reaches in the Wilson Creek basin illustrate the shift in pattern from straight to meandering as the stream leaves the escarpment and enters the flat Lake Agassiz plain. In this segment of the stream, the bankfull discharge does not increase significantly but the slope decreases from .01 to .001. Many other factors such as large stable bed material, bedrock outcrops, and local gradient controls affect the channel pattern as well. These may be suggested in the preliminary evaluation of the stream pattern and geology described in Chapter 1 and verified with the reach surveys and sketches described in Chapter 2.

Pools and riffles

The overall longitudinal profile of a stream in erodible materials is generally concave (see Chapter 1). However, within a stream segment the profile is broken into a series of smaller steps that form pools and riffles under low flow conditions as shown in Figure 3-9. This naturally stepped profile forms a vertical wave form that has been observed for all channel patterns. In straight channels, the length of the pool or distance between riffles is equal to the straight line distance between the riffles that occur at points of inflection in a meandering channel.

Stepped profiles of natural channels surveyed by Leopold and Wolman (1957) with straight, meandering, and braided patterns are shown in Figure 3-10. The pool and riffle profile creates the diverse hydraulic habitat conditions that are required in streams with healthy habitats.

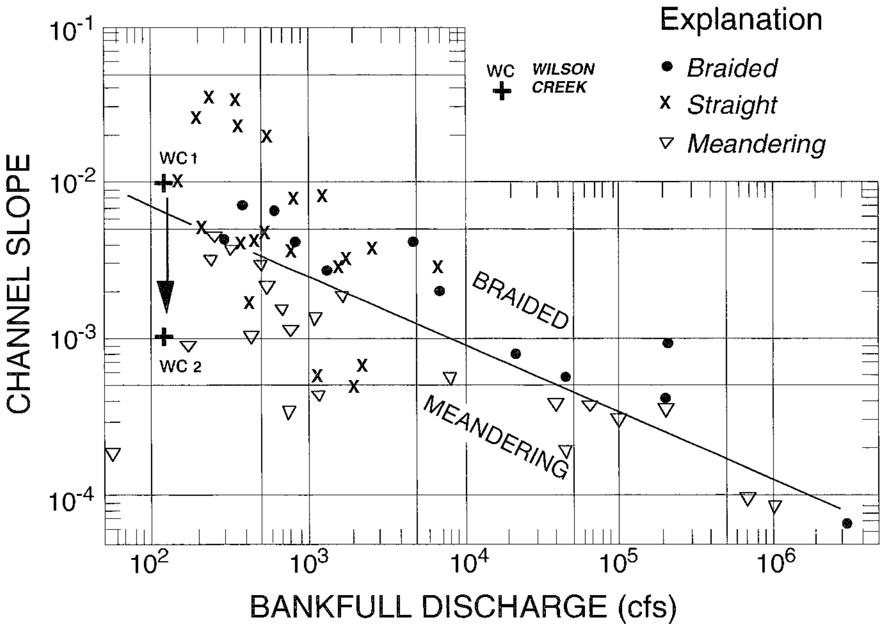


***Figure 3-8:** Relationship observed between slope, bankfull discharge, and channel pattern (Leopold and Wolman 1957).*

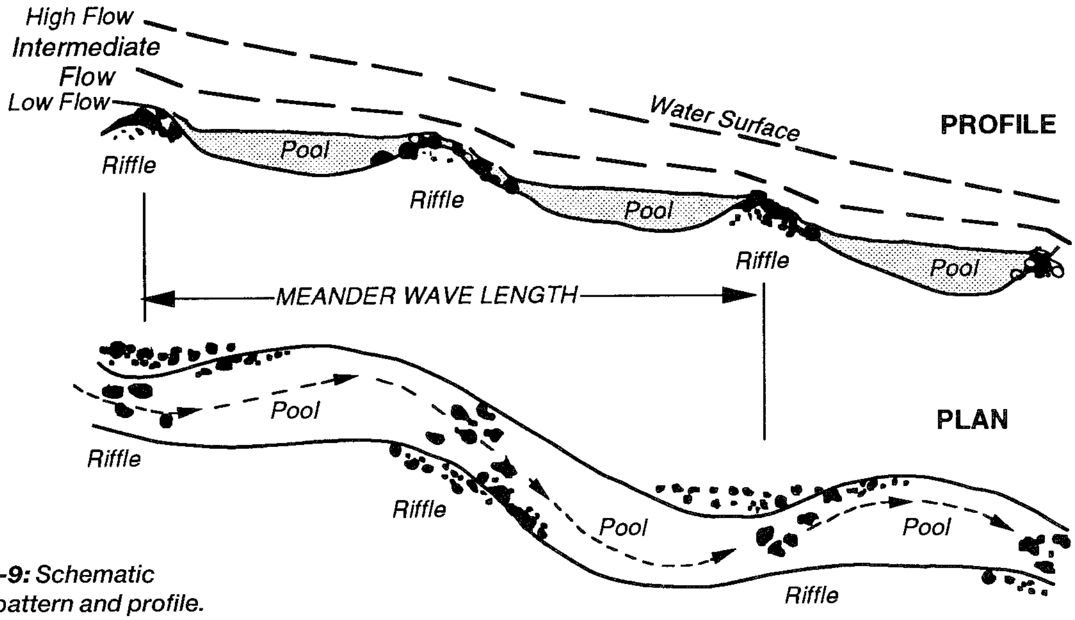


***Figure 3-9:** Schematic channel pattern and profile.*

Pool and riffle profiles often develop in channelized streams as well, in spite of their uniformly constructed gradients. For example, the meandering Mink Creek channel was straightened and graded with a smooth profile in 1950 as shown in Figure 3-11. A resurvey in 1982 showed that the eroding channel had developed a stepped profile with the same pool and riffle spacing that existed before the channel was straightened. The redeveloped natural profile was used to design the spawning rehabilitation works discussed in Chapter 4.

The geometry of meanders and the pool and riffle profile for all river patterns in erodible materials may be related to the bankfull width. A full meander wavelength, that is, the distance between two riffles or two similar points along the channel where the wave form is repeated, has been observed to occur between 7 and 15 times the bankfull width for rivers ranging from 0.3 to 300 m wide. The mean spacing of pools, half a meander wavelength, has been measured as 5.6 and 6.7 times the bankfull width for alluvial and bedrock streams by Roy and Abrahams (1980). The distributions and standard deviations of observed pool spacing/width ratios are shown in Figure 3-12.

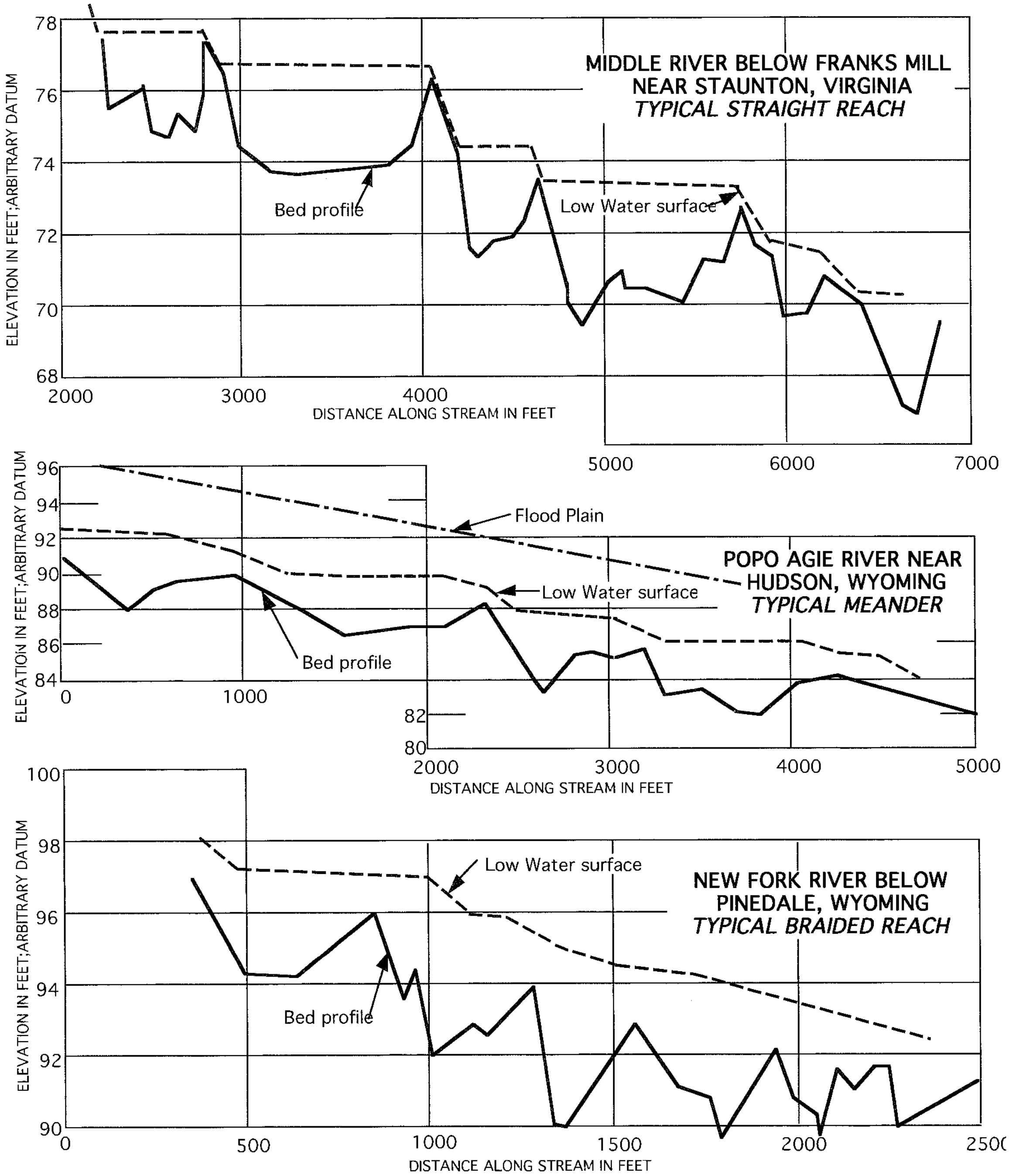


Figure 3-10: *Naturally stepped bottom profiles in straight, meandering, and braided rivers (Leopold and Wolman 1957).*

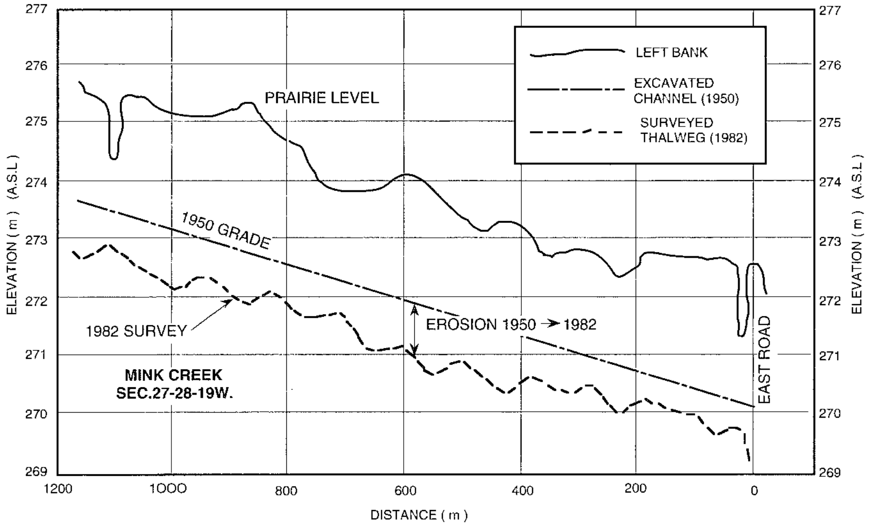


Figure 3-11: *The pool and riffle profile developed by Mink Creek after straightening and uniformly grading the channel.*

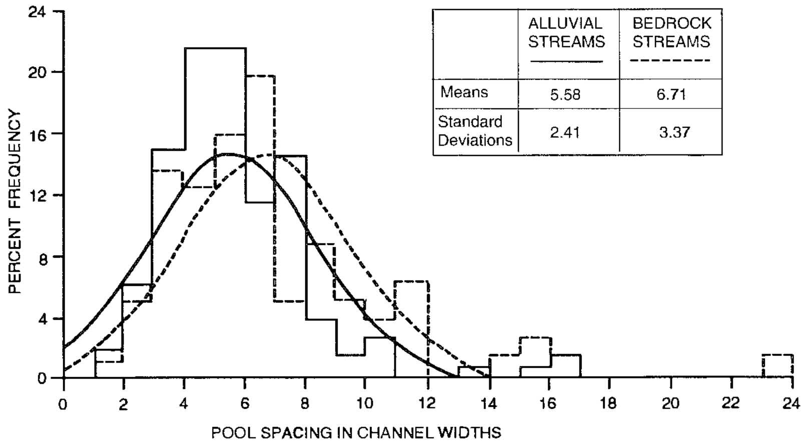


Figure 3-12: *The range of pool spacing in bankfull widths observed by Roy and Abrahams (in Chang 1988).*

Channel pattern measurements

The dimensions of meanders, pools and riffles, and channel widths may be determined from the sketches prepared in the sample reach surveys discussed in Chapter 2. For example, in the North Pine River (Figure 2-10), the distance between major riffles in the sample reach was about 60 m. The bankfull width was 9.7 m, making the ratio slightly greater than 6:1 for the length of a pool and riffle segment or 12:1 for a full meander wavelength with two pool and riffle segments. In the Wilson Creek sketch (Figure 2-9), the ratio is similar with an average straight line distance between riffles that is 6 times the bankfull width. Channel pattern measurements may be extended to whole stream segments by using air photos if the bankfull width can be distinguished. The surveyed sample reaches then provide useful ground truthing measurements.

Meander patterns

The amplitude of the meanders and their radius of curvature (Figure 3-13) may also be determined using sample reach surveys that have been prepared to scale. For example, in the surveyed reach of preferred trout habitat on the Pine River shown in Figures 2-10 and 3-16, one half of the meander wave length was 66 m. This was scaled from the field drawing as the straight line distance between successive major riffles in which the stream crossed from one side of the channel to the other. The riffle spacing is approximately 5.5 times the bankfull width of 12 m. The amplitude of the meander bend was

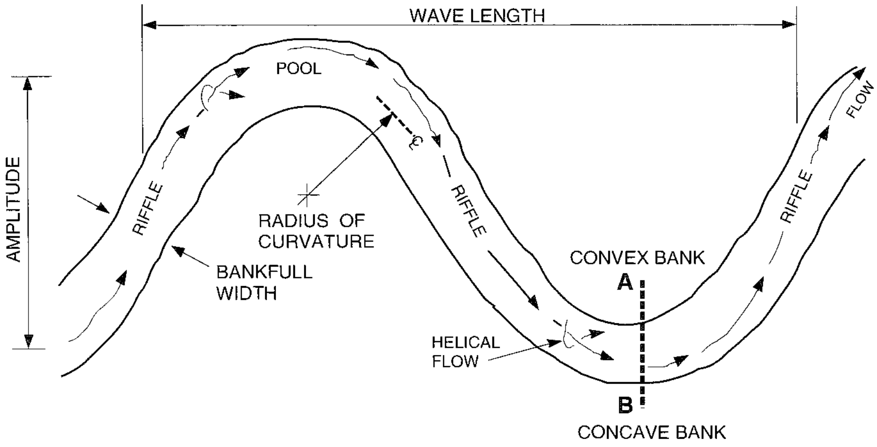


Figure 3-13: *Definition sketch for meander dimensions. The main flow crosses from one side of the channel to the other in the major riffles between successive bends. (See Figure 3-15 for cross-section AB).*

60 m, with a radius of curvature of 27 m, about 2.3 times the bankfull width. This is approximately the radius of curvature that has been observed in rivers with fully developed meanders and flows that smoothly shift from bank to bank in successive bends (Chang 1988).

3.5 Flow conditions and hydraulic habitats

Gradually varied uniform flow (backwater curves)

The depth of flow and velocity may vary gradually through several reaches along a stream segment if the depth is changed by a downstream condition as shown in Figure 3-14. For example, as a stream approaches a lake or reservoir, the slope of the water surface gradually decreases with increasing depth along the channel until it is horizontal. The smooth curving profile from the channel slope to horizontal is called an M1 backwater curve. If the depth of flow decreases at the downstream control section, the slope of the water will increase as the depth decreases. In this case, the profile of the water surface follows an M2 backwater curve. The M1 and M2 curves are the two commonest backwater conditions that occur in natural streams. Other backwater curves for steeper channels with super-critical flows and hydraulic jump transitions (M3) have also been defined (see Chow 1959).

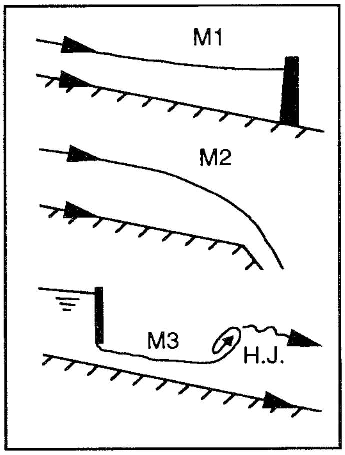


Figure 3-14: *Typical backwater curves.*

The extended backwater curve conditions occur under uniform flow conditions that are governed by the channel resistance to flow. Consequently, Manning's equation may be used to determine the profile along the stream by analyzing the backwater zone in a series of short reaches that have small incremental changes in depth (Chow 1959).

Helical near-uniform flow

The estimate of mean flow velocity obtained with the Manning equation is based on the assumption that uniform flow occurs throughout the reach, where the mean velocity is constant for a given discharge and the water surface, velocity vectors and the channel bottom are all parallel. However, in all open channels regardless of their pattern, secondary currents occur as well. The secondary currents cause the central thread of the flow (called the thalweg) to move regularly from side to side in the channel and up and down within the depth of the wetted cross-section. In effect, the flow moves in a three dimensional wave along the thalweg. Similar forms of wave flow occur in atmospheric and oceanic flows. In channels flowing through erodible materials, the wave form is reflected in the channel pattern as meanders and in the longitudinal profile as pools and riffles.

The secondary currents also cause the flow to rotate as it moves downstream. In meandering reaches, rotation of the flow is accentuated as the water flows around a bend. In the bend, the momentum of the higher velocity surface flow carries the water to the outside of the bend and rotates the flow as shown in Figure 3-15. Looking downstream, as the stream moves through a bend to the right, the rotation is counter-clockwise. As the flow moves into the next bend in a meander that turns to the left, the rotation is clockwise. Between bends, the flow crosses the centre of the channel in the shallow riffle zone. Thus in a meandering reach, viewed in the downstream direction, the bottom water is rotated to the surface, turbulently aerated and mixed in the riffle zone, and then rotated in the opposite direction in the next bend. As each bend is passed, the bottom water and its detritus is repeatedly moved upwards through the deeper pools to the surface of the stream. This is an important mechanism for transporting drifting benthic organisms from riffle zones past predators in the pools.

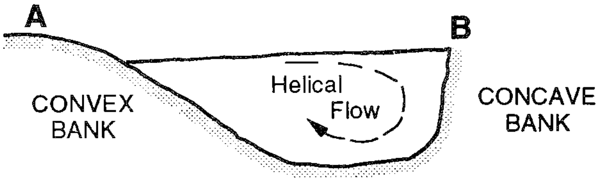


Figure 3-15: *In a fully developed meander, the flow slowly rotates as it moves around each bend.*

Investigations of the kinetic energy of secondary flows in meanders suggest that the minimum energy expended by the spiralling flows occurs when the radius of curvature of the bend is between two and three times the bankfull width of the stream, with a median value of 2.4 (Chow 1959, Chang 1988). It has been argued that the minimum energy condition is the "most probable state" for the curvature of a natural meander bend. In a sample of meander bends in 50 rivers, the median value was found to be 2.7 (Leopold et al. 1964).

In surveys of proven trout habitats in meander bends on three Manitoba escarpment streams, the mean ratio of the radius of curvature to the bankfull width was found to be 2.5, regardless of the size of the stream. For example, at trout habitat site PR3 on the Pine River shown in Figure 3-16, the radius of curvature is 2.3 times the bankfull width.

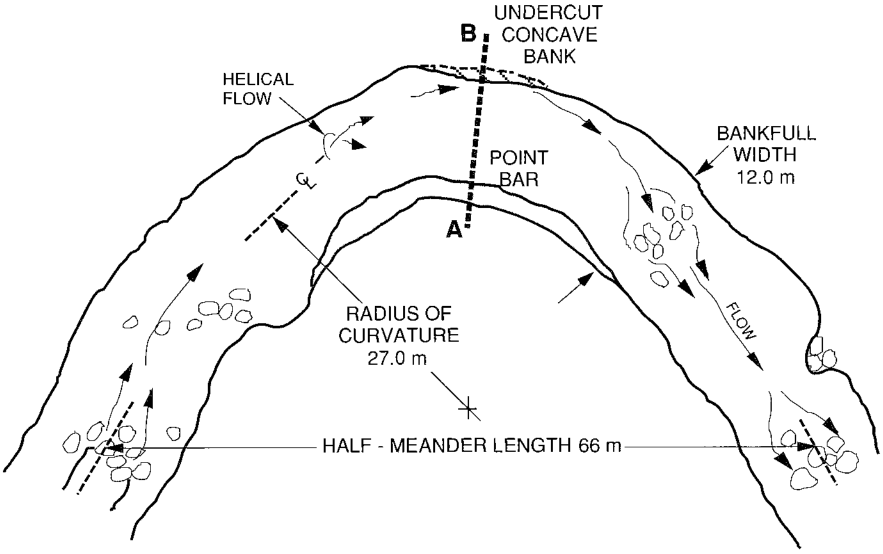


Figure 3-16: *Trout habitat meander bend on the North Pine River. The radius of curvature is 2.3 times the bankfull width, similar to meanders in many rivers. (See Figure 3-15 for cross-section AB).*

A photograph of the Pine River site looking upstream is shown in Figure 3-17. The main thread of flow leaving the upstream riffle completes a half revolution in the bend. Upwelling water was observed along a shear zone that followed the right side of the pool in the centre of the stream opposite the survey tripod. Fine materials from the outside concave bank were carried across the bottom of the channel by the rotating flows and deposited on the convex bank,

Figure 3-17: *Rotational flow in a trout habitat meander bend on the lower Pine River.*

forming a sandy point bar. Observers reported that trout moved from the deep pool under the concave bank in the early evening to feed along the shear zone and edge of the point bar.

The strong tendency for natural streams to follow meandering paths and to form pool and riffle profiles suggests that straightened and uniformly channelized rivers with erodible beds can only be maintained by repeated reconstruction. Alternatively, Henderson concluded in 1966 "...the river engineer should look when planning to simulate natural meanders in river training works" (p 470).

Varying states of local flow conditions

In an open channel, many combinations of depth and velocity will conduct the same discharge. However, the combinations fall into only two categories, sub-critical and super-critical. Critical flow is the dividing point between them. Critical flow occurs when, for a given discharge, the total combination of velocity energy and depth are at a minimum. This combined term, called the specific energy of the flow, is expressed as the sum of the depth (d) and the kinetic or velocity energy ($v^2/2g$) for a unit width of channel as shown in Figure 3-18. In the central diagram, the critical depth of flow $d_c = 2/3$ H. The critical velocity energy $v_c^2/2g = 1/3$ H or $1/2\ d_c$.

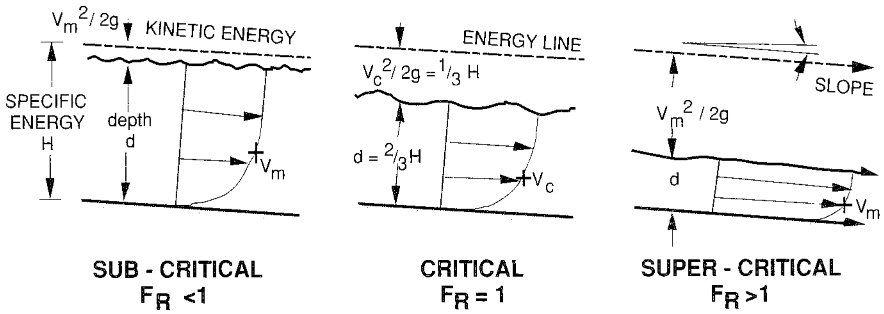


Figure 3-18: *States of flow in an open channel. Critical flow occurs when the velocity energy is one-half of the depth of flow, or* $v_c = (gd)^{1/2}$ *(Froude no. = 1).*

The critical velocity is also equal to the velocity of a wave generated by a disturbance in a still shallow pond, where $v_{wave} = (gd)^{1/2}$. Consequently, there are often accentuated "standing waves" on the surface of the stream that move slowly up and down the channel when the flow velocity and depth are close to the critical state.

The state of flow is characterized by the Froude number which has a value of 1 only at critical flow. If the Froude number is less than 1, the flow is sub-critical, and greater than 1, super-critical, where:

$$F_r = \frac{v}{(g \times d)^{1/2}}$$

where F_r = *Froude number of flow*
v = *velocity of flow (m/s)*
g = *gravitational acceleration* ($9.8\ m/s^2$)
d = *depth of flow (m)*

How does this apply to natural stream flow? Suppose there was a mildly sloping channel for which the Manning equation predicted a relatively deep depth of flow and low velocity. The Froude number of this sub-critical flow would be less than 1. If the channel steepened in the next reach downstream, so much so that the Manning equation predicts that the flow will be shallow and faster than the critical velocity, the state of the flow will be super-critical with a Froude number greater than 1. At the point where the channel changes slope, the flow will pass through a critical velocity section with local standing waves on the stream surface. The acceleration of the flow occurs smoothly between the mild and steep reaches, with the stream surface following a smooth vertical curve to the shallower depth downstream. In the next reach downstream, if the flow deepens again and becomes sub-critical, the flow must decelerate. However, this transition is abrupt and tumultuous because of the negligible shear strength of water. The shallow super-critical flow leaps upwards to the deep sub-critical depth in a flow phenomenon called the "hydraulic jump". The high velocity flows penetrate and circulate on the upstream face of the jump, sweeping air into the flow. The air bubbles froth to the surface and break, causing the noise that is associated with babbling brooks or roaring rapids, depending on the size of the hydraulic jump. In a stream or river, this is the only flow condition that produces noise. Without hydraulic jumps, the stream would move silently downstream with limited re-aeration of the flow and limited habitat opportunities.

Hydraulic jump

Flow in rapids and riffles

In natural streams, particularly at intermediate and low flows, the sequence of smooth acceleration from sub-critical through critical to super-critical flows followed by abrupt noisy deceleration to sub-critical flows in hydraulic jumps occurs between pools in a steep shallow riffle section (shown schematically in Figure 3-19).

If the pool above the riffle is deep, the velocity energy will be relatively small and the specific head can be estimated as the difference in elevation between the top of the point of overflow and the flow immediately upstream.

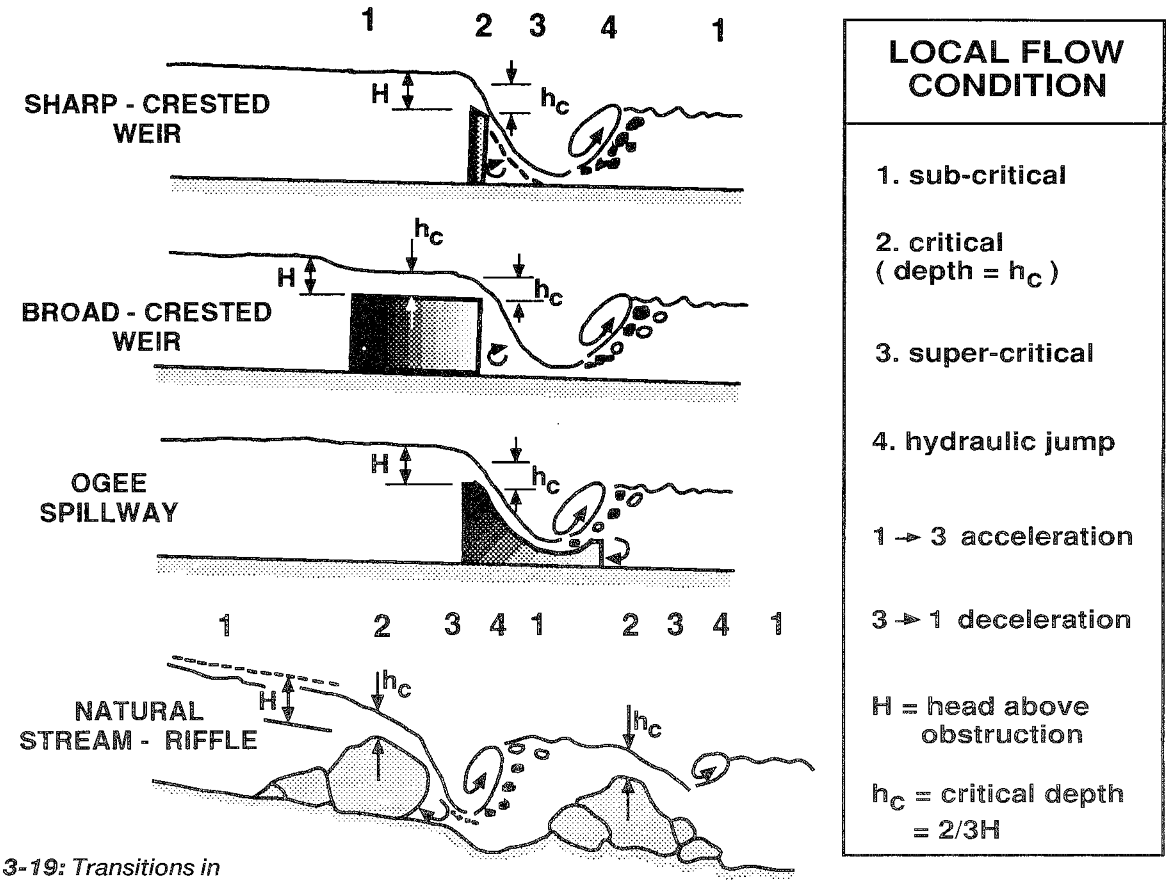


***Figure 3-19:** Transitions in rapidly-varied local flow conditions over weirs and a schematic riffle profile.*

In uniformly constructed weirs and spillways, the critical velocity occurs close to the point of overflow. These structures are used for measuring flows because the velocity can be determined from the specific head measurement, avoiding direct velocity observations. In the schematic stream riffle sequence, the transitional conditions are repeated with each obstruction and local pool, producing a “field” of local accelerating chutes and overflows followed by an array of hydraulic jump conditions.

A typical steep riffle section with local rapidly-varied states of flow is shown in Figure 3-20. The flow smoothly accelerates from the sub-critical state in the upstream pool to the critical velocity and depth that occurs above the boulders and chutes that form the crest of the riffle. Super-critical flow occurs below the crest on the downstream face of the boulders and in the major chutes. As the flow enters local pools and the sub-critical reach below the riffle, hydraulic jumps occur that violently mix and aerate the flow.

Fish passage

Regular velocity, pressure, and tractive force distributions that occur with uniform flow conditions are disrupted by rapidly-varied flow conditions. The abruptly changing bed configurations cause the main flow to separate from the substrate, forming local eddies with velocity reversals and pockets of low or negative pressure below and behind boulders and cobbles. This diversity of flow conditions allows more opportunities for fish passage through riffle sections than uniformly-constructed chutes with the same mean slope. Pockets of flow

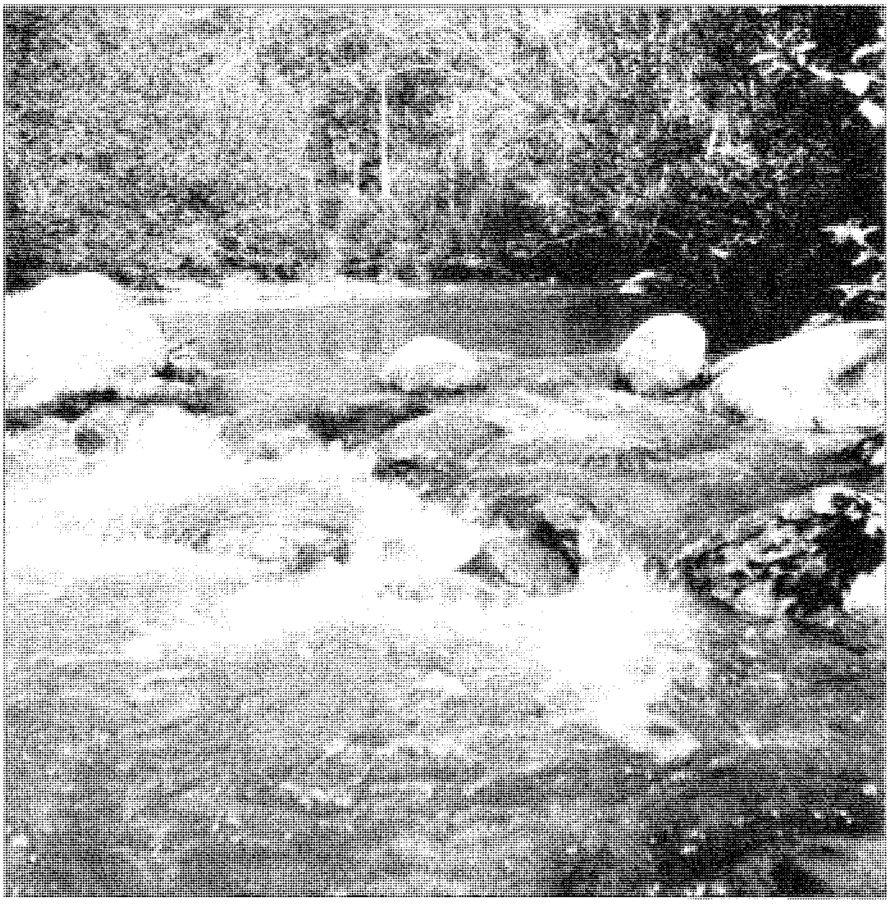


Figure 3-20: *Rapidly-varied flow between pools in a natural riffle on the Pine River. The noisy hydraulic jump below the riffle re-aerates the flow.*

reversal in horizontal eddies and hydraulic jumps create resting areas in the steep riffle reach. The coarser substrate and aerated flows also create preferred fish spawning habitats for many species (see Appendix A).

Benthic habitats

Some benthic organisms select specific positions within the geometry of the local flow conditions. For example, the caddis fly Brachycentrus occidentalis was found to prefer the hydraulic habitat shown in Figure 3-21 in studies made in Wilson Creek (Wetmore et al. 1990). The preferred feeding habitat was located on the top of cobbles and boulders in the zone of accelerating and converging flows that is slightly upstream from the critical flow section. The mean Froude number for these locations was observed to be 0.6. Black fly larvae (Simulium) were found to prefer similar sites located further downstream closer to the critical flow section with a higher Froude number of 0.7.

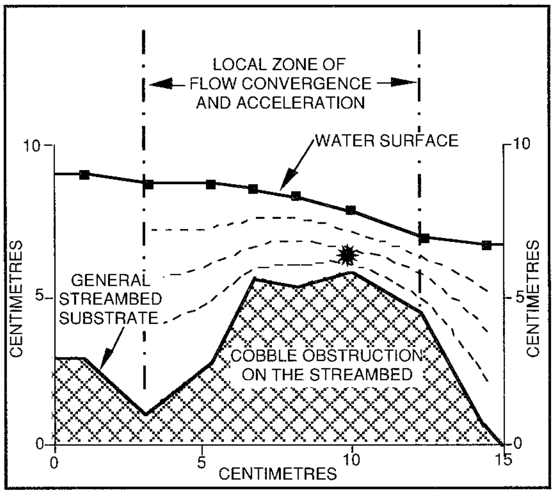


Figure 3-21: *A caddisfly hydraulic habitat.*

Mapping local hydraulic conditions

The distribution of flow conditions in a reach may be determined by measuring the velocity and depth and plotting the Froude number at that location (see Observation 6, Chapter 2). The discharge at the time of the observations should also be measured. Local flow phenomena such as surface eddies, hydraulic jumps, and zones of velocity reversal on the streambed require careful observation. The location of the thalweg and other flow phenomena may be plotted in the field on a separate transparent sheet that overlays the reach map. Supplementary photographs should also be taken, particularly if the reach is to be used as a template for designing stream rehabilitation works. If possible, the flow observations should be repeated over the range of discharges that occur in the central channel to determine the persistence of hydraulic habitat conditions. These observations may be applied in assessing instream flow requirements (Appendix A). With biological monitoring, the discharge record for the stream may be compared to organism abundance or year class strength to determine the magnitude and timing of streamflows that support preferred habitats. Methods for examining the preferred flow regimes using a "mass curve" of historical flows are discussed in Chapter 4 (instream flow requirements).

3.6 Stream analysis summaries

An inventory of stream characteristics and selected habitats may be made by extending the sample reach survey data to whole stream segments. The data may be projected by using stream segments of similar drainage area or the stream order number. For more detailed inventories, reach by reach analyses may be carried out to determine the total available habitat ("weighted useable area") that is available at different discharge rates (Bovee 1982).

An useful overview of the stream characteristics in a drainage basin can be gained by compiling the stream sample reach surveys and evaluations in a graphical poster. Three sample reaches in a Wilson Creek summary poster are shown in Figure 3-22. The photographs, sketches, and channel geometry data allow the sample reaches to be compared easily.

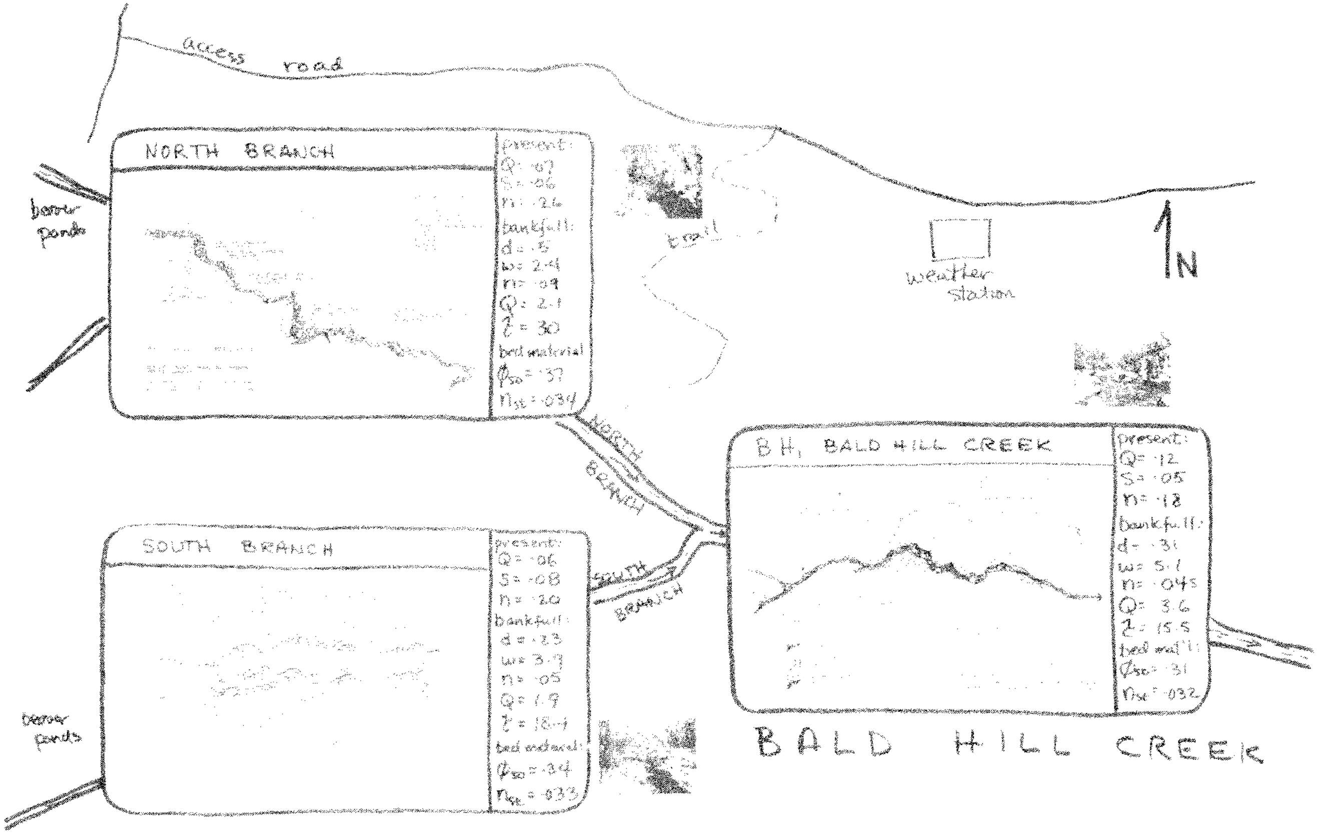


Figure 3-22: Summary poster of sample reaches surveyed on Bald Hill Creek, a tributary of Wilson Creek on the Manitoba escarpment.

Chapter 4

Design and Construction of Stream Habitat Works

Design principle

The design of stream rehabilitation and enhancement works is based on evaluating the present state of the stream and adjusting the channel geometry and slope to a new form that can be maintained by the available streamflow. The biological habitats that are created are a complex combination of the flow hydraulics and physical characteristics of the streambed, banks, and riparian vegetation that defies complete analysis. Where possible, surveys of natural stream reaches with preferred and proven habitats are used as design guidelines that will allow the habitat factors to be re-created naturally. In most cases, the observed design templates and stream construction works must be sized to fit the capability of rehabilitation stream.

Ten steps in the design and construction process

The major stages in designing and constructing stream habitat works have been divided into ten steps (Figure 4-1). The procedures and analyses used in the first six steps are discussed in the preceding chapters of the manual: Planning, Field Surveys, and Evaluation. The last four steps are presented in the following five stream habitat projects:

Example 1: Hamilton Creek - walleye spawning habitat at a stream crossing,
Example 2: Mink Creek - walleye spawning habitat and stabilization in a drainage canal,
Example 3: Wilson River - walleye spawning habitat and stabilization in a channelized river,
Example 4: Pine River - trout habitat creation in a naturally uniform mobile bed stream,
Example 5: Whiteshell River - trout habitat enhancement in a bedrock controlled river.

1) Drainage Basin	Trace watershed lines on 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 the relationship between the channel geometry, drainage area, and bankfull discharge.
5) Rehabilitation Reach Survey	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. Where possible, undertake reach surveys in reference streams with proven populations to identify local flow conditions, substrate, refugia, etc.
7) Selecting and Sizing 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 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 re-constructed channel ages.

Figure 4-1: *Design and construction process for stream habitat projects.*

Design Example 1: Hamilton Creek

Graded Stream Crossing

Project background

Hamilton Creek is typical of many small streams tributary to lakes in the Canadian Shield (Figure 1-4) where the drainage basin boundaries and the longitudinal profile of the stream are governed by bedrock outcrops. The basin and profile of Hamilton Creek are shown in Figure 1-1.

In the upper 4 km of the basin, the profile is concave upwards as the stream flows through an overburden of partially-erodible glacial deposits. However, a bedrock outcrop interrupts the profile and impounds the stream in Edgar Lake. Below Edgar Lake, a short section of the stream flows into a man-made bog caused by an elevated culvert under the Trans-Canada highway. Below the highway, the stream flows across the steep bedrock surface into Falcon Lake.

Fish migration from Falcon Lake is limited to the lower segment of the stream below the highway. Several pools and riffles near the top of the lower segment are used by walleye from the lake as spawning habitat. A profile of the upper reaches is shown in Figure 4-2. Part of the lower half of the spawning area has been excavated and graded for a gas pipeline crossing similar to that shown in Figure 4-3.

Below the pipeline crossing area, the reach was infilled with coarse gravels and cobbles (up to 15 cm in diameter) to maximize the spawning substrate suitability index (McMahon et al. 1984) in a previous rehabilitation project. The infill widened the channel profile causing siltation and increased growth of grasses on the streambed.

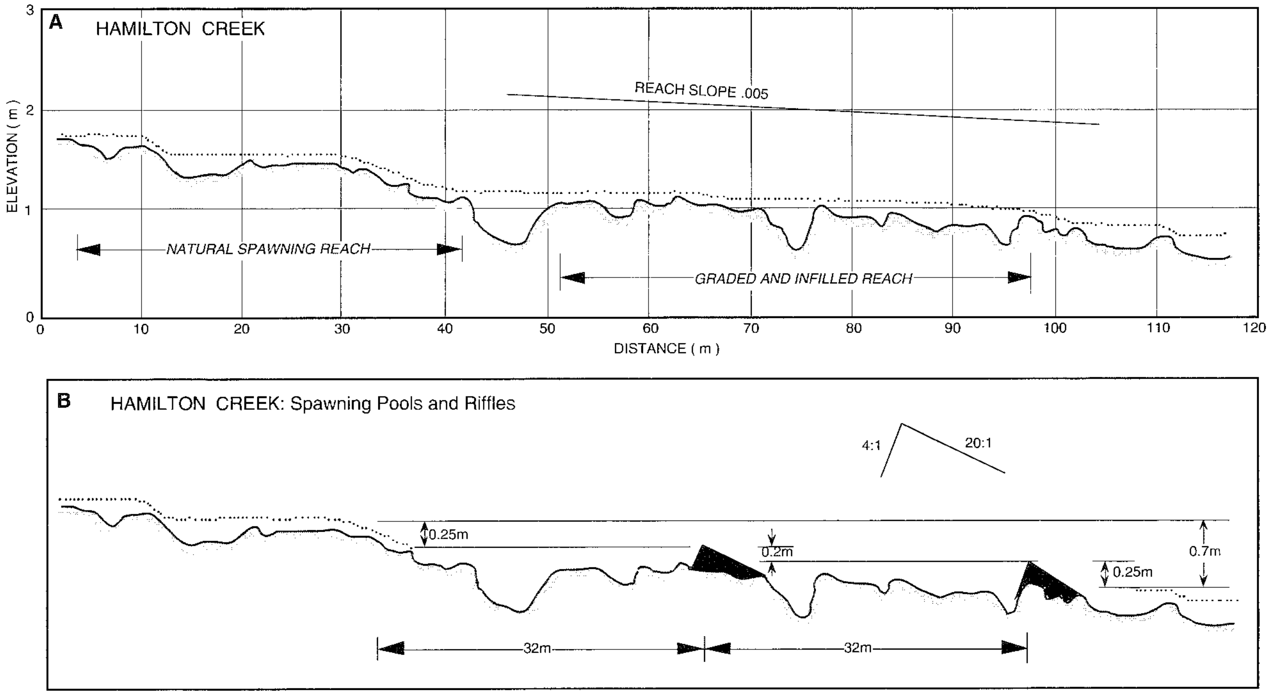


***Figure 4-2:** (A) graded profile of the walleye spawning reach in Hamilton Creek, (B) reconstructed profile with pools and riffles for spawning enhancement.*

Pools, riffles, and other irregularities in the profile were reduced. In the lower section, the stream is actively downcutting through the added cobbles and re-establishing a narrower bankfull width.

In 1989, two pool and riffle reaches were designed and constructed for the graded and infilled reaches to re-create natural spawning conditions. The rehabilitation project is summarized in the following sections using the design process steps summarized in Figure 4-1.

1) Drainage basin

The watershed line surrounding the drainage basin for Hamilton Creek was interpreted from the 25 ft interval contours on NTS 1:50,000 scale Map Sheet 52E11 (Figure 1-1). The drainage area tributary to the spawning zone in the lower reach is 12.5 km^2. The geological setting of the basin is shown in Figure 1-4.

2) Profiles

The longitudinal profile of the stream was drawn from the 25 ft contour intervals shown in Figure 1-1. The detailed profile in Figure 4-2 and the cross-sections in Figure 4-7 were surveyed in May, 1987.

Figure 4-3: *Typical re-graded stream profile at the pipeline crossing in the Whiteshell region (Falcon Creek).*

3) Flow

As is typical for many small streams, there are no flow records for Hamilton Creek. The nearest streamflow monitoring station is located on the Rennie River below the outlet of Brereton Lake. The drainage area tributary to the gauging station is 159 km^2. A discharge record summary is shown in Table 1-1.

The Rennie River peak flow records cannot be used to estimate the Hamilton Creek flood frequencies because there is a large discrepancy in the drainage basin sizes and potential storage effects. In small steep basins, the flood peaks produced by snowmelt and rainstorm events are usually greater than would be predicted from an equivalent fraction of the larger (Rennie River) basin. For example, the annual flood frequency curve estimated for Hamilton Creek in Figure 4-4 was derived from the frequency curve for a unit area of the Rennie River basin. The mean daily and instantaneous flood peaks do not differ widely because of the attenuating effect of regulated storage on Brereton Lake above the Rennie River gauging station. The 67% frequency annual flood peak that is typical of bankfull flows in many natural streams is predicted to be 0.36 m^3/s. However, the bankfull flow prediction based on measurements of the channel geometry was 2.1 m³/s (see Sec. 3.1, Case III). In cases such as this where the flood records cannot be proportionately transferred, the higher prediction should be used for the channel design.

Monthly flows predicted for Hamilton Creek are shown in Figure 4-5. The flows have been re-constructed from the Rennie River record from 1978 to 1990 by multiplying the monthly recorded flows by the ratio of the drainage areas (12.5/159.0). In this case, the records are more realistically transferrable because the peak flow events are averaged out over a month, although there may be some variation in timing because of the Brereton Lake dam operations.

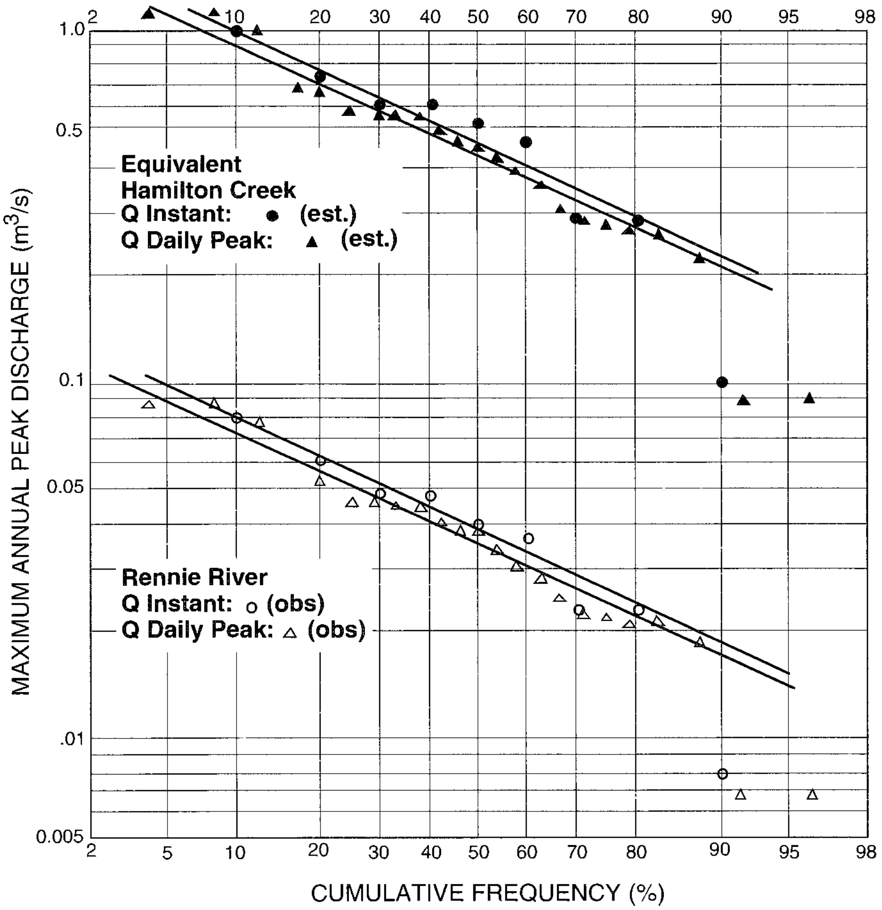


Figure 4-4: *Annual flood frequency curves for a unit area of the Rennie River basin and an underestimated curve for Hamilton Creek.*

Mass curve

The monthly flows are presented in two formats. In Figure 4-5A the discharge is plotted vs time to produce a standard hydrograph. From the hydrograph, it is apparent that monthly peak flows of 0.2 m^3/s or more have occurred in 5 of the 13 years. In the other years, the peak flows varied from almost zero to slightly greater than 0.1 m^3/s. The magnitude and duration of flow for a specific period, for example, the April-May walleye spawning season, may be determined by examining the flow records directly. Alternatively, a simpler graphical method may be used. In the plot of cumulative monthly discharges for the 1978-1990 period shown in Figure 4-5B (called the discharge mass curve), the slope of the line represents a rate of flow (m^3/s -months divided by months). Thus, the rate and duration of flows during the April-May periods may be read directly off the plot using the reference slopes plotted in the inset graph. From the mass curve analysis, it is apparent that for the April-May period, there were 5 years with sustained flows of 0.2 m^3/s or more, 5 years with flows between .04 and .08 m^3/s, and 3 years with negligible flows. In cases where there are fish population data, the magnitude and duration of flows during the Spring spawning and incubation period may be compared to walleye year class strengths to determine the minimum flows required for successful reproduction.

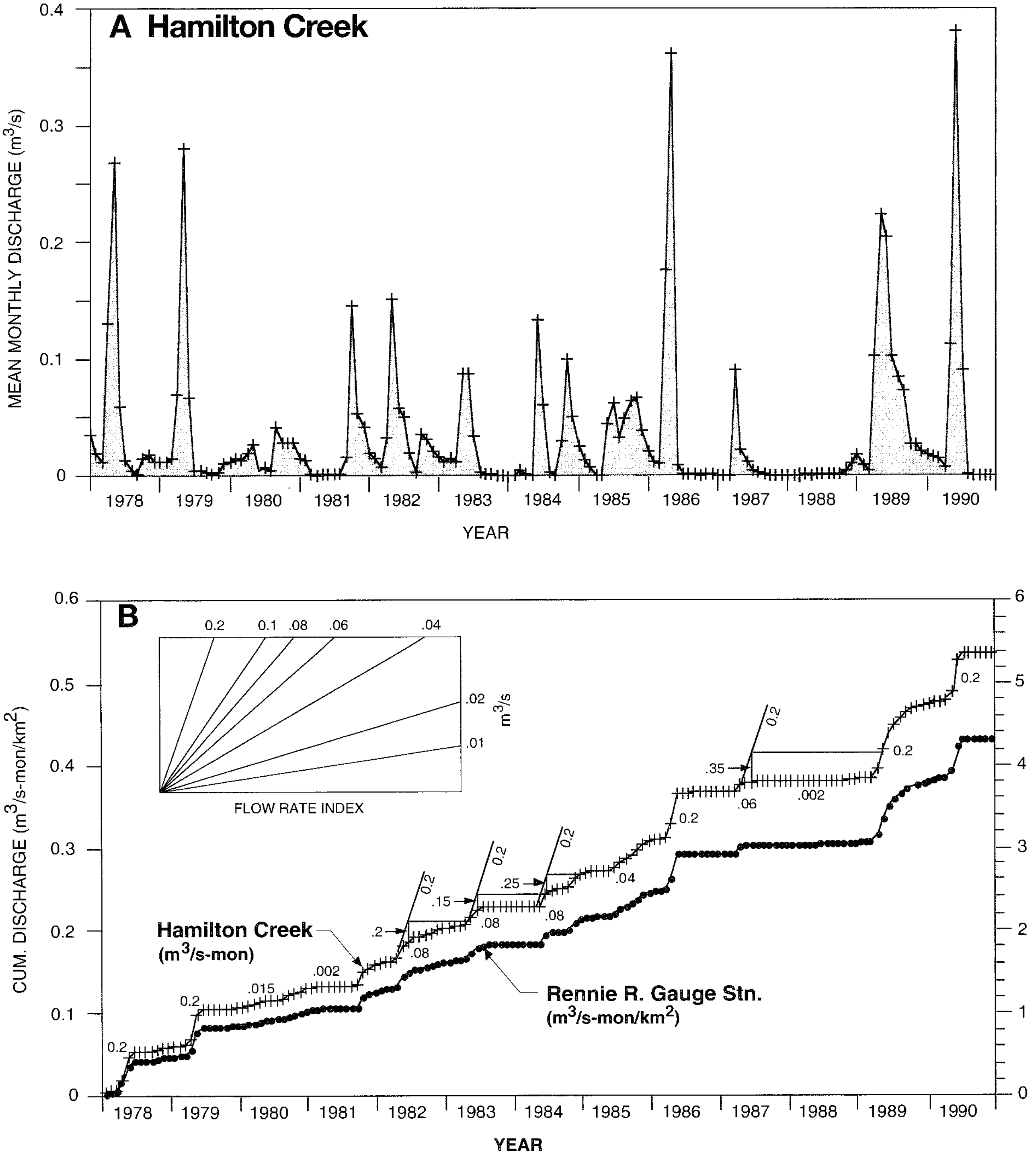


Figure 4-5: *Rennie River and Hamilton Creek discharges for 1978-1990 shown as (A) a mean monthly discharge hydrograph and (B) as a cumulative plot of discharge (mass curve).*

4) Channel geometry surveys

A channel geometry survey was undertaken in the unaltered upper half of the natural spawning area shown in Figure 4-2A. The channel geometry and characteristics are summarized in Table 4-I. The survey and evaluation methods are discussed in Chapters 2 and 3.

Table 4-1: Hamilton Creek natural channel characteristics

bankfull width	4.6 m
bankfull depth	0.36 m
average slope.	.005
median bed paving material size.	0.12 m
assumed bankfull roughness	0.028
predicted bankfull velocity	1.3 m/s
bankfull tractive force.	1.8 kg/m^2
bankfull Froude number	0.67
bankfull discharge.	2.1 m^3/s

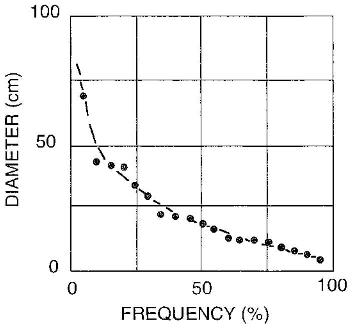


Figure 4-6: Natural bed paving size distribution in Hamilton Creek.

In Figure 3-4, the predicted bankfull discharge lies along a general line for the relationship between bankfull discharge and drainage area for small southern Manitoba basins. The bankfull width and depth lie within the range of similar relationships shown in Figure 3-7. This is a useful check on the survey measurements and analysis.

The size distribution of cobbles and boulders paving the streambed in the spawning reach is shown in Figure 4-6. At the bankfull stage, the stream is capable of moving gravels up to 1.8 cm mean diameter. As this lies well below the minimum size of bed paving material (5 cm), the natural streambed is stable at the bankfull stage.

5) Rehabilitation reach survey

The profile of the graded and infilled reach in the lower section of the spawning area is shown in Figure 4-2A. Since the earlier rehabilitation project and pipeline excavation, two minor pools have formed at a spacing of 28 m and 22 m in the gravels and cobbles that were placed on the streambed. Typical channel cross-sections at station 65 and station 105 are shown in Figure 4-7. At station 105, the stream has downcut through the infilled materials, forming a 4 m wide rectangular cross-section.

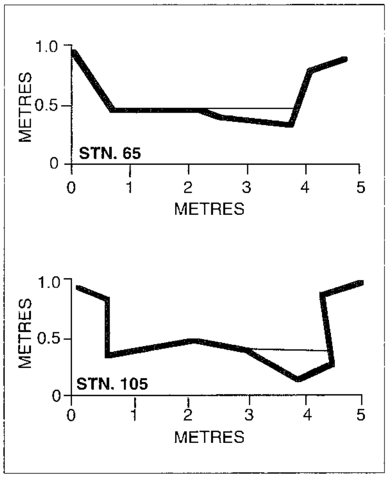


Figure 4-7: *Channel cross-sections in the infilled reach of Hamilton Creek.*

6) Preferred habitats

Four factors that affect walleye spawning success in streams were identified in reference studies of habitat suitability (McMahon et al. 1984). The optimum conditions for each factor are:

1) dissolved oxygen levels of 6 mg/l or more,

2) water temperatures between 10°C and 20°C during egg incubation,

3) substrate of gravel and cobbles in riffles with depths of flow between 0.3 m and 1.5 m deep, and

4) rising or steady water levels during spawning and embryo development phases.

These four habitat criteria may be achieved in both the natural and infilled reaches in Hamilton Creek depending on Spring runoff conditions but spawning has been observed to take place preferentially in the natural reach. During the spawning run, fish pass through the uniform flows in the graded and infilled reaches to the natural pools and riffles at stations 45 and 15. Local flow conditions vary as large emergent and near-emergent boulders are encountered.

A short section of the riffle zone sampled in the spawning reach survey is shown in Figure 4-8. Approximately 20% of the substrate paving the channel bed is greater than the bankfull depth of 0.36 m (Figure 4-6). Consequently, super-critical overflows and chutes are formed in the riffle with aerated hydraulic jumps in local pools. The chutes formed between larger boulders vary from 20 to 30 cm in width.

The slope of the downstream face of the natural riffles at stations 10 and 35 is 0.05, or 20:1. Similar slopes and diverse flow conditions have been observed in preferred spawning riffles in other Manitoba streams (Figure 4-16). As in Hamilton Creek, the preferred riffles were adjacent to well-developed pools which provided spawning and resting areas above and below the riffles.

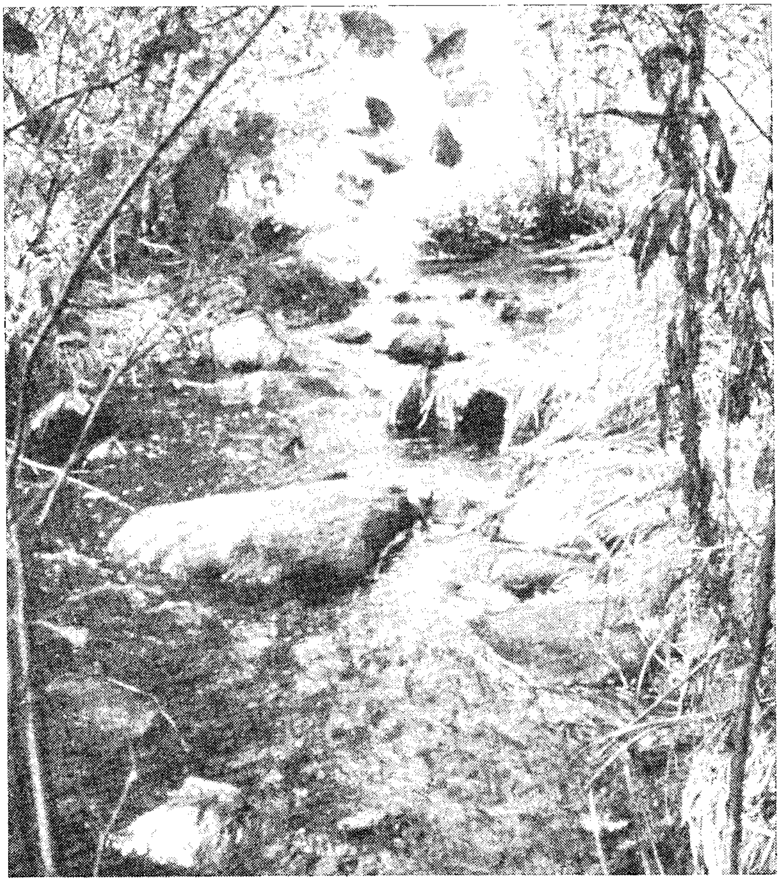


Figure 4-8: *Bouldery natural spawning riffle at low flow in Hamilton Creek.*

7) Selecting and sizing rehabilitation works

The total fall in the altered reach below the natural riffle at station 35 is 0.45 m. To create additional pools and spawning riffles, the fall was divided into two reaches 32 m in length as shown in Figure 4-2B. The length of the pool and riffle reach is 7 times the observed bankfull width, which is only slightly greater than the mean value of 6.7 observed in bedrock streams (Figure 3-12). The riffles were placed to take advantage of the existing stream profile to create pools that were 0.5 m to 0.8 m deep under low flow conditions. The crest elevations of the riffles were set to allow a shallow depth of water to be impounded over the infilled and graded channel sections under low flow conditions. This reduces the stranding of adult fish in the upper spawning reaches after the Spring flood peak has passed and later assists in the passage of fry back to Falcon Lake.

The spawning riffle structures were built with 4:1 upstream and 20:1 downstream slopes using angular rock ranging in size from 20 cm to 60 cm mean diameter. The riffles are shown schematically in Figure 4-9. Larger boulders were placed on the crest and downstream face of the riffle to create the same range of chute dimensions that were observed in the natural riffles.

The upstream riffle and pool are shown in Figure 4-10 immediately following construction in September, 1989. The stream discharge is 0.05 m^3/s.

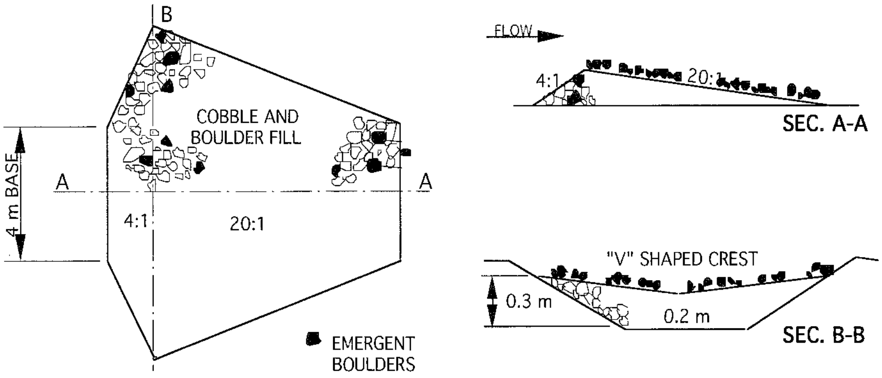


***Figure 4-9:** Schematic diagram of spawning riffles constructed on Hamilton Creek (located in Figure 4-2).*

Figure 4-10: *Upper spawning riffle and pool constructed in Hamilton Creek.*

The stability of the riffle materials under bankfull flow conditions was tested for two cases: 1) where the average channel slope and bankfull depth occur throughout the reach (the high flow case shown in Figure 3-9), and 2) where critical flow is assumed to occur on the riffle face at the 20:1 slope (the intermediate flow case). The tractive force in the first case is 1.8 kg/m^2 (Table 4-1). In the second case, the critical depth in the 4.6 m wide channel at the bankfull discharge of $2.1 m^3/s$ would be 0.28 m (from solving the continuity equation $Q = v \times d \times w$ with $v_c = (g \times d)^{1/2}$ substituted for v). In this case, the tractive force on the face of the riffle would be $1000 \times .28 \times .05 = 14$ kg/m^2. The minimum rock size of 20 cm used to construct the riffles would be stable under both conditions (see Figure 3-5). Only minor settling and re-arrangement of the surface materials occurred in the first few years following construction.

8) Instream flow requirements

In the 1978-1990 period, there were 5 years in which the April/May spawning season flows equalled or exceeded 0.2 m^3/s. Although the year class strength of walleye in Falcon Lake was not monitored directly, local fishermen recall an abundance of adult fish 3 and 4 years after the high flow spawning years. This view is supported by the observation of a high level of larval production in 1986 when the April-May flows slightly exceeded 0.2 m^3/s.

In the other 8 years of record, the flows were .08 m^3/s or less (Figure 4-5B). By utilizing storage on upstream lakes, the flow may be augmented during some of the lower flow years. For example, in 1982, 1983, and 1984, a flow of 0.2 m^3/s may be maintained with upstream storage of 0.2, 0.15, and 0.25 m^3/s-mon. This is determined from the mass curve (Figure 4-5B) by drawing a line sloping at a discharge rate of 0.2 m^3/s from the beginning of April to the end of May. The water required from storage is then represented by the vertical distance between the actual accumulated flow and the 0.2 m^3/s line at the end of May. A horizontal line drawn from the end of May on the 0.2 m^3/s line to the actual accumulated flow line represents the number of months that would be required to replenish the storage if the same flow pattern were to occur. In the three years analyzed, the storage would be replenished within the following year. A similar analysis of the next lowest flow year, 1987, shows that the storage would require over two years to restore, prohibitively stopping the flow in Hamilton Creek in the following spawning season.

From this analysis of the mass curve, assuming that similar flow patterns will occur in the future, the number of successful spawning period flows may be increased from 5 out of 13 years to 8 out of 13 years with a maximum upstream storage of 0.25 m^3/s-mon. This represents a storage volume of: 0.25 x 30.5 days x 24 hours x 3600 seconds = 658,800 m^3. This represents a depth of storage of 0.66 m on Barren Lake, assuming a surface area of approximately 1 km^2. The flow records used in this analysis were not adjusted for the drainage area of Barren Lake as it is close to the spawning reach in the lower part of the drainage basin. However, if the storage is to be developed in the headwaters, a mass curve of inflows to the lake must be used to evaluate the storage potential.

9) Supervise construction

The upstream riffle and part of the downstream riffle were constructed by hand using rock that was delivered to the pipeline right-of-way by the TransCanada Pipeline construction crew. The rock was moved to riffles with an all-terrain vehicle and trailer and placed in the stream by Fisheries employees attending a workshop on stream rehabilitation (the field exercise).

The riffle crest and toes of the upstream and downstream slopes were marked with survey stakes and flagging. The crest elevations were established with a surveyors level referenced to a benchmark established when the stream profile was surveyed. The crest elevations were marked by driving iron fence posts (T-bars) into the streambed on either side of the crest until the tops of the bars coincided with the design elevation. The cobbles and boulders required re-alignment and packing in the crest area to achieve the desired upstream water level.

The costs and materials for the project in 1990 $ and person-days (pd) are summarized in Table 4-2.

Table 4-2: Materials and costs for Hamilton Creek spawning riffle construction.

Materials	
20 yards blast rock	donated
16 pr leather gloves.	$ 50.
Labour	
surveys	4 pd
arranging for rock	1 pd
placing of rock.	8 pd

10) Monitor and adjust design

In 1990 and 1991, the monthly discharge in the spawning reach of Hamilton Creek basin exceeded 0.2 m^3/s. The completed upstream riffle and pool were actively used for spawning in both seasons. The upper spawning riffle is shown in Figure 4-11 in May 1990 at a peak discharge of 0.8 m^3/s. There were no major changes in the riffles or sedimentation in the pools since construction.

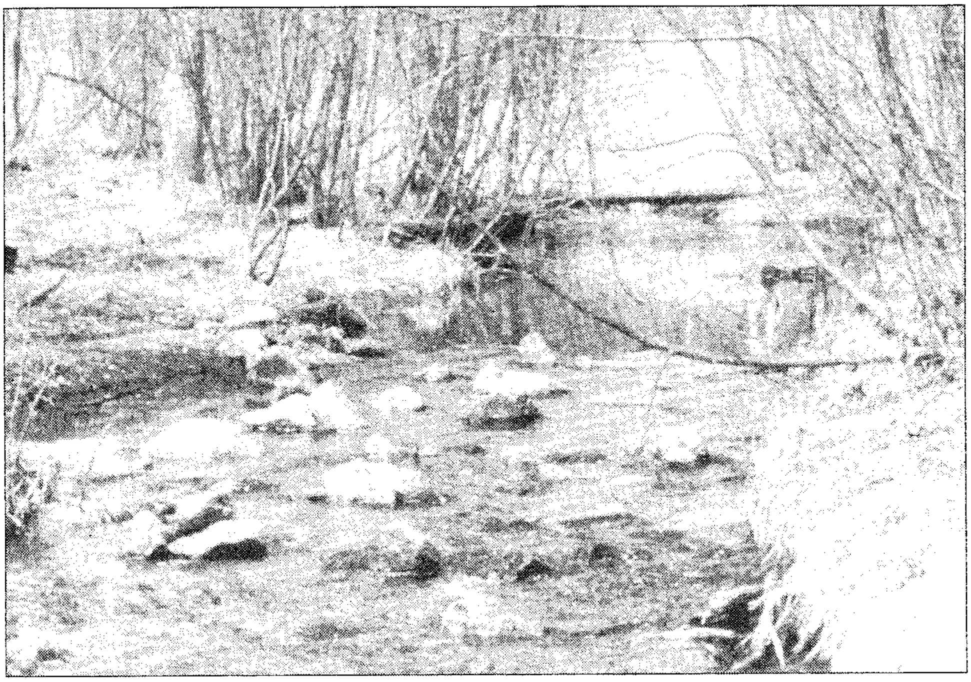


Figure 4-11: *Upper constructed pool and riffle on Hamilton Creek at a discharge of 0.8 m^3/s during the walleye spawning period in May, 1990.*

Design Example 2: Mink Creek

Walleye Spawning Reaches in a Channelized Stream

Project background

The headwaters of Mink Creek start on the southern slope of Baldy Mountain in the Duck Mountain section of the Manitoba escarpment (Figure 1-2). At the foot of the escarpment, the stream flows across the upper levels of the abandoned basin of glacial Lake Agassiz and enters the north-western corner of Dauphin Lake (Figures 1-5 and 1-6).

Dauphin Lake supported a large commercial and sport walleye fishery up to 1950. After 1950, the fish harvests declined dramatically to produce walleye yields of only 5 to 10 % of the pre-1950 values. One of the major causes of the decline was the extensive channelization of the tributary streams to improve agricultural drainage and reduce Spring flooding. The stream channels were straightened and uniformly graded to increase their discharge capacity for higher runoff peaks from the increasingly cleared and ditched basin in the agricultural zone below the escarpment. The channelization shortened the duration of the Spring runoff period and eliminated the pool and riffle habitats used by walleye for spawning and incubation (Gaboury 1985). The sediment input to the lake dramatically increased from the re-graded and diverted stream channels. One-quarter (0.8 m) of the mean depth of the shallow lake was infilled with sediments in the 1950 - 1980 period.

The Mink Creek rehabilitation project commenced in 1985 with the construction of a series of pools and riffles in three experimental segments of the channelized stream that extended from 4 km to 6 km above Dauphin Lake. The central experimental segment is shown in Figure 4-12.

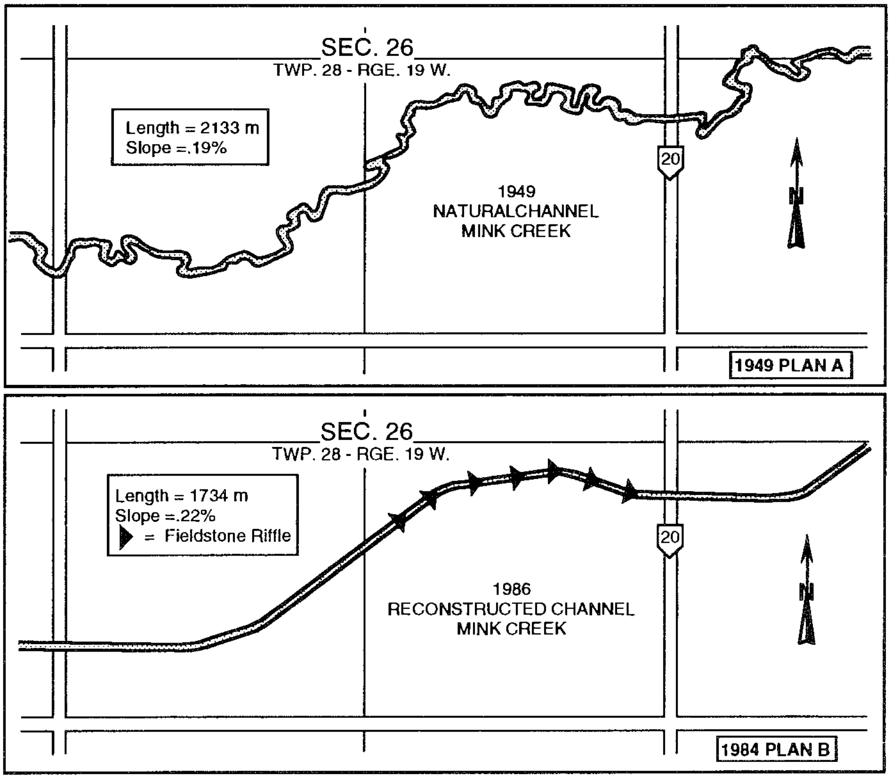


Figure 4-12: *The naturally meandering reaches of Mink Creek (A) were straightened and graded in 1951 to improve agricultural drainage (B).*

In the upper diagram (A), the natural meandering pattern of the stream was traced from pre-channelization air photos. The channelized stream and rehabilitation segment is shown in the lower diagram (B).

Elimination of the meanders shortened the length of the stream and increased the gradient from .19 % to .22 % in the rehabilitation reach. The graded channel followed a mean path through the meander pattern, exposing new substrate materials to the flow which rapidly eroded. The sequence of channel erosion and re-building at a typical cross-section is shown in Figure 4-13.

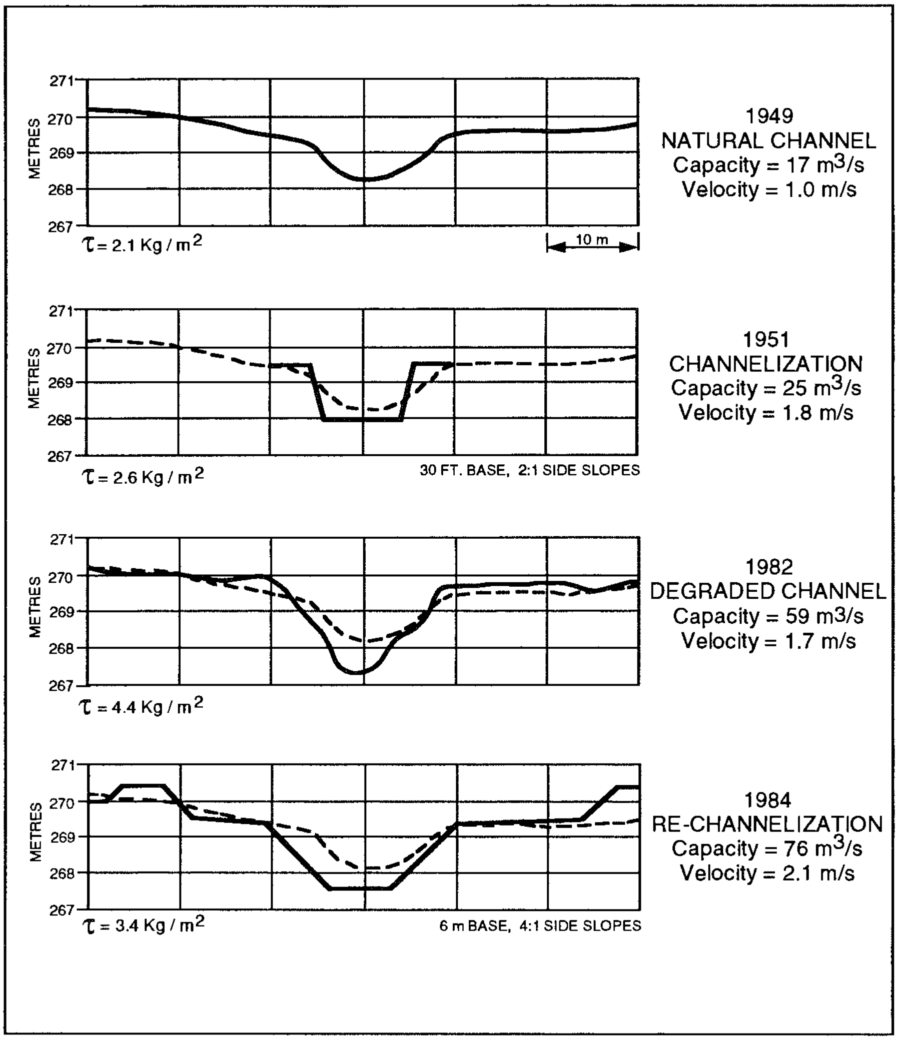


Figure 4-13: *Downcutting and widening in a typical cross-section of Mink Creek following channelization and re-excavation for channel maintenance.*

Surveys undertaken in 1949 before channelization showed that the stream followed a regular meandering pattern with an average wave length of 200 m, about 12 times the bankfull width. The average pool and riffle spacing was 100 m. The stream ran through outwash deposits from the escarpment composed of silts, sands, gravels, and cobbles that were re-sorted as the shoreline of Lake Agassiz retreated towards Dauphin Lake. The riffles were paved with rounded cobbles and angular limestone boulders scoured from the local bedrock surface.

A typical natural channel cross-section is shown in the upper diagram of Figure 4-13. The stream was straightened and channelized in 1951 to a trapezoidal cross-section with a 9 m base and 2:1 side slopes as shown in the second diagram. The increased slope and depth of the stream and the exposure of finer substrate materials in the straightened segments caused the stream to downcut and the steepened banks to slump into the channel. By 1982, the channel had deepened by 0.6 m and widened by 8 m in the channelized reach as shown in the third diagram. The eroded materials were transported to Dauphin Lake, forming a small delta at the mouth of the creek. In 1984, the stream was re-excavated to the larger cross-section shown in the bottom diagram. The last cross-section more closely approximates the original natural cross-section. However, erosion and bank slumping continue in the re-excavated reaches.

The Mink Creek rehabilitation project is based on restoring the more stable pre-channelized geometry of the stream. The original stream characteristics were compiled from early surveys, air photographs, and the recollections of local fishermen and farmers. The project is summarized in the following sections of the design process presented in Figure 4-1.

1) Drainage basin

In the escarpment area, the boundaries of the drainage basin shown in Figure 1-2 were interpreted from 100 ft contour intervals on NTS 1:250,000 Map Sheet 62N. Provincial drainage maps were used to locate tributaries and new ditches that have been excavated and joined to the main stem of the stream in the lower half of the basin. The total drainage area of the stream tributary to the rehabilitation reach was increased from 230 km^2 to 250 km^2. The geological setting is discussed in the Project Background section.

2) Profiles

The longitudinal profile of the main stem of Mink Creek (Figure 1-2 inset) was drawn from the 100 ft contour intervals on the topographic map sheet. Below the regular concave upward segment in the headwaters, two steeply sloping segments in the profile coincide with abandoned beach fronts that were established by long-standing levels on Lake Agassiz (Klassen 1979). Minor stands as the lake retreated caused the numerous smaller beaches shown in Figure 1-2 to form. A minor beach front with a corresponding increase in slope occurs in the lower half of the rehabilitation segment shown in Figure 4-16. Before channelization, the meander amplitude increased in this section to maintain a uniform slope along the thalweg of the river.

3) Flow

A long-term gauging station on Mink Creek is located in the middle segment of the basin near the town of Ethelbert. The records are summarized in Table 1-2. Annual flood frequency curves for the recorded and predicted flows for the rehabilitation segment are shown in Figure 4-14.

The drainage area above the gauging station for most of the period of record was 132 km^2 (to 1984). Consequently, the predicted flows for the rehabilitation segment further downstream must be increased by the ratio of the drainage areas, 250/132, a factor of 1.9x. This may underestimate flood peaks from snowmelt and rainstorm events because a large portion of the upper half of the basin lies in the Provincial Forest Reserve. The lower half of the basin that is tributary to the rehabilitation reach has been cleared and drained for agriculture. The bankfull annual flood in two out of three years would be 7 m^3/s. The bankfull flow capacity of the pre-channelized stream was estimated to be 17 m^3/s, suggesting that the lower half of the cleared basin did produce significantly higher flood runoff. However, this estimate is based on an assumed roughness value for the natural channel which could not be confirmed. In Figure 3-4, the trend shown for other Manitoba basins would predict a bankfull flow of 11 m^3/s for the drainage area tributary to the rehabilitation segment. The largest bankfull flow estimate of 17 m^3/s was adopted for the designed works (40% frequency).

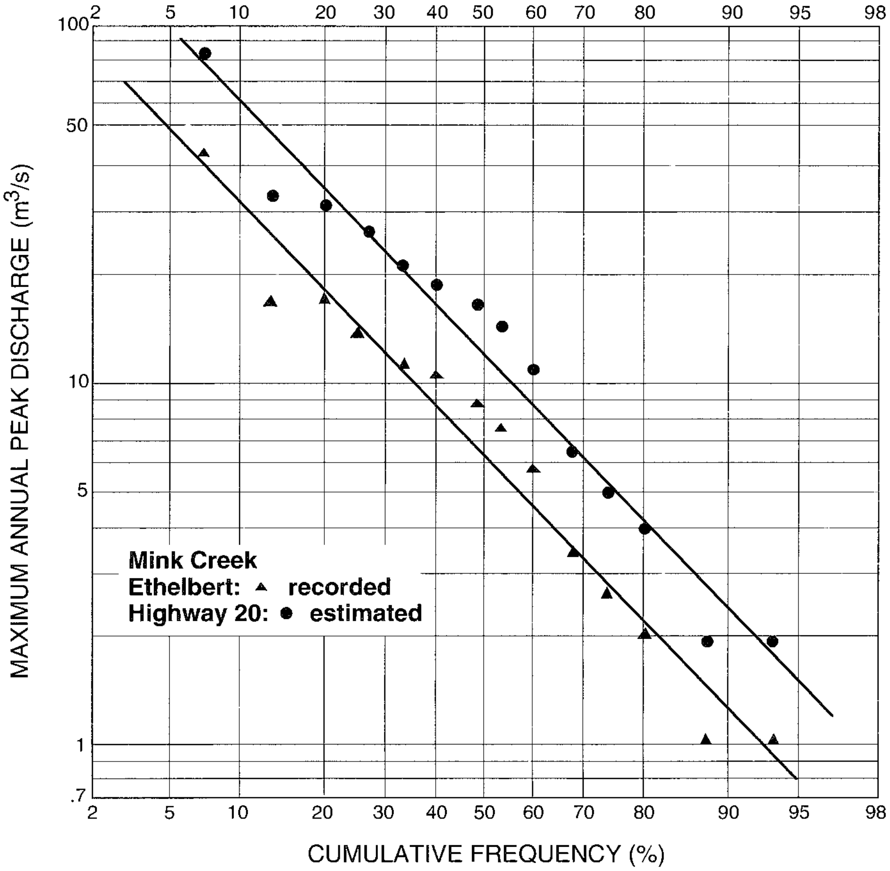


***Figure 4-14:** Annual flood frequency curve for Mink Creek at Ethelbert (recorded) with an estimated curve for the rehabilitation reach for the 1959-1988 period.*

The capacity of the excavated channel has increased as the streambed eroded and the banks collapsed. The present capacity is estimated to be 76 m^3/s, equivalent to an annual flood peak with a frequency of occurrence of less than 10%. A flood peak of 41 m^3/s was measured in 1987 that was contained within the channel in the rehabilitated reaches.

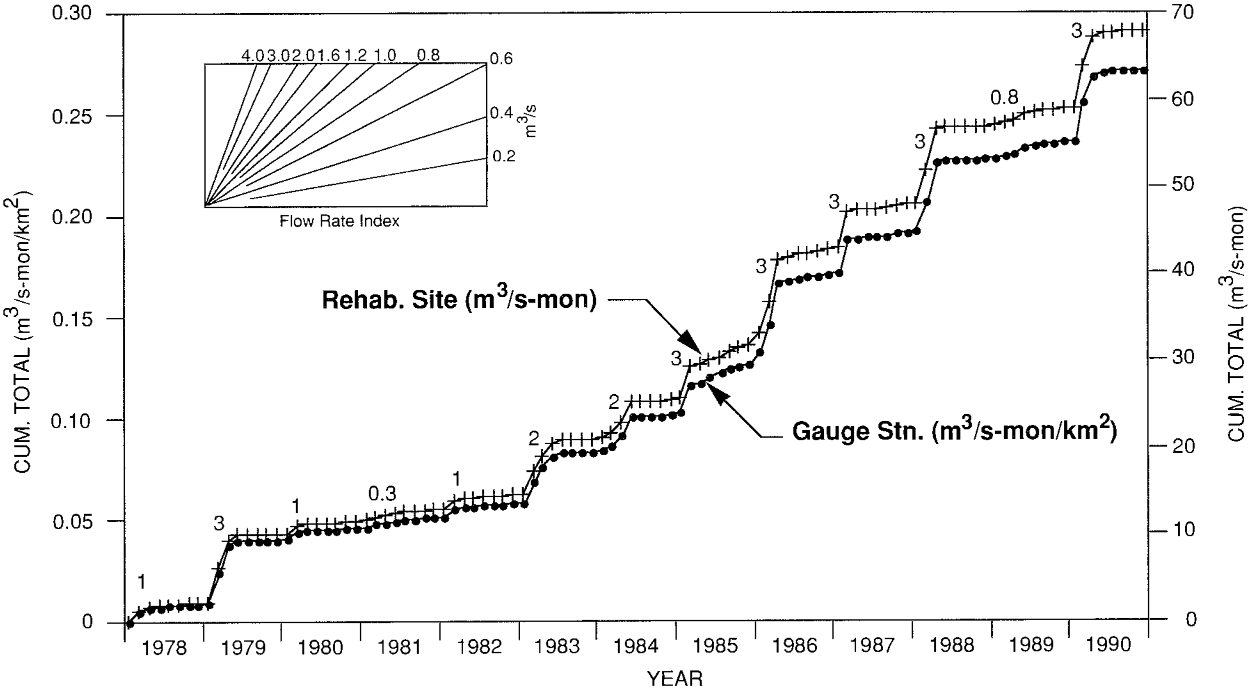
A mass curve of monthly flows during the open water season (April-November) is shown in Figure 4-15. The curve is based on flows recorded at the Ethelbert gauging station (Table 1-2) adjusted for the area tributary to the rehabilitation segment. The average open water monthly flow for the years 1978-1990 is 0.65 m^3/s.

Analysis of the mass curve (Figure 4-15) using the inset flow rate curves for the April/May spawning cycle indicates that there are 8 years with flows of 2.0 m^3/s or more and 5 years with 1.0 m^3/s or less. In the low-flow, short-duration years, there would not be sufficient time for incubation and passage of the fry back to Dauphin Lake. This can be altered with the development of an upstream storage reservoir on Mink Creek. The storage would allow flow augmentation and extension during the short dry Spring runoff years. However, the supply of water is limited in the basin. Assuming that water released from upstream storage must be restored each year, the maximum flow that can be sustained during the April-May period for the 1978-1990 period is 1.0 m^3/s. A maximum storage of 1.5 m^3/s-mon is required in 1981 when the natural flows were only 0.3 m^3/s during the April-May period (see expanded segment of Figure 4-15). This represents a storage volume of 4 million m^3. A storage reservoir of this magnitude might be developed on nearby public lands immediately above the spawning reaches. For a section of land (260 ha), an active storage depth of 1.5 m would be required.

4) Channel geometry surveys

The geometry and characteristics of the natural and channelized Mink Creek rehabilitation segment are summarized in Table 4-3. Natural channel cross-sections were available in the pre-construction surveys undertaken in 1949. The channelized characteristics are based on the cross-sections which were re-excavated in 1984. As shown in Figure 3-7, the bankfull dimensions of the natural channel lie along a general relationship for streams in southern Manitoba.

The larger dimensions of the present channelized stream are not related to the bankfull discharge but have evolved as the stream deepened and widened. The streambed in the rehabilitation segment is composed of sands and gravels derived from the re-worked beach deposits of Lake Agassiz with occasional short sections of small cobbles. The cobble sections occur where the straightened channel crosses the route of the old natural channel, particularly where the crossing occurs in a previous riffle zone. As the maximum cobble size seldom exceeds 4 cm, a large fraction (>90 %) of the channelized bed erodes at the bankfull stage. The deepening channel is re-graded periodically to stabilize the slumping side-slopes.



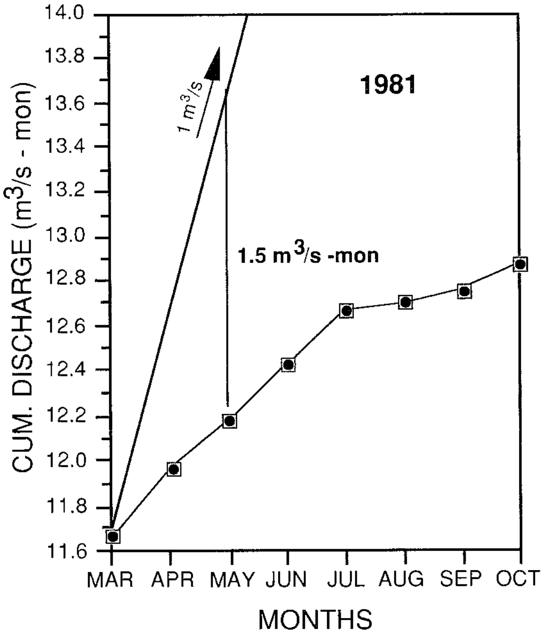


Figure 4-15: *Mass curve of monthly flows for the period 1978-1990 showing April-May flow rates and storage requirements for a sustained flow of 1 m^3/s during low-flow years.*

5) Rehabilitation reach survey

The profile of the rehabilitated stream segment shown in Figure 4-16 was surveyed in 1985. The segment crosses a minor Lake Agassiz beach front (Figure 1-2) with a mild backshore slope of .0015 and a steeper foreshore slope of .003. Uniform meanders were developed across the steeper segment before channelization. The channel cross-section of the central segment of the rehabilitation area was recently re-graded to uniform 4:1 side slopes with a 9 m base as shown in Figure 4-13.

6) Preferred habitats

The four preferred walleye spawning habitat characteristics (dissolved oxygen, temperature, substrate, and sustained flows) discussed in the Hamilton Creek example are more difficult to attain in the channelized stream for several reasons:

1) dissolved oxygen levels decline slightly as the Spring runoff peak subsides because the flow is uniformly sub-critical in the evenly-graded channel, particularly in the sections that have been recently re-graded. In the older sections, there are only a few re-establishing riffle sections to create flow diversity and re-aeration conditions. The problem is accentuated in low flow years when higher concentrations of organic loading from the lower agricultural basin occurs,

Table 4-3: Mink Creek channel characteristics before (natural) and after channelization.

	Natural	Channelized
bankfull width	15.5 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/m^2	3.4 kg/m^2
bankfull Froude number	0.31	0.54
bankfull discharge	17 m^3/s	76 m^3/s

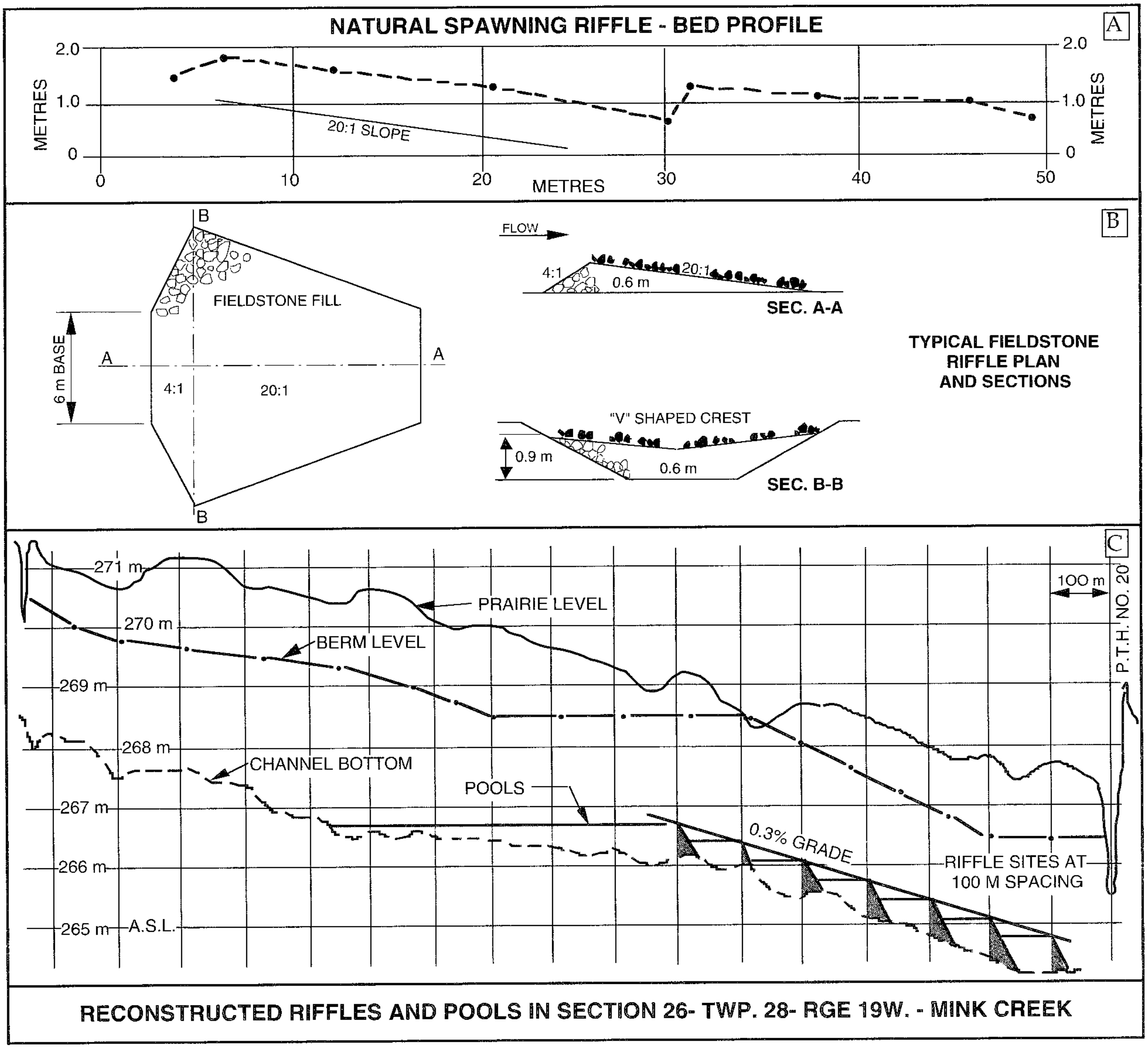


Figure 4-16: *Profiles of a natural spawning riffle (A) (Valley River), constructed riffles (B), and the Mink Creek profile (C) before and after pools and riffles were created in the rehabilitation reach 3 km from Dauphin Lake.*

2) water temperatures are generally higher but fluctuate widely as a consequence of a wider, unshaded channel and a shorter duration of Spring flows. The channel banks and berms are regularly mowed to gather hay and to prevent woody vegetation from developing,

3) the straightened channel has been uniformly graded through finer sands and gravels with shallow pools and gradually re-forming riffles,

4) the duration of the Spring flood peaks has been shortened by removing the tree cover in the agricultural part of the basin and by increasing the efficiency of water collection with drains and local ditches.

As only a few re-developing spawning habitats remained in the Mink Creek, the geometry and characteristics of two long-term natural pool and riffle spawning reaches in the nearby Valley River were surveyed. A photograph of one of the sample reaches is shown in Figure 4-17. The profile of this reach is shown in Figure 4-16A.

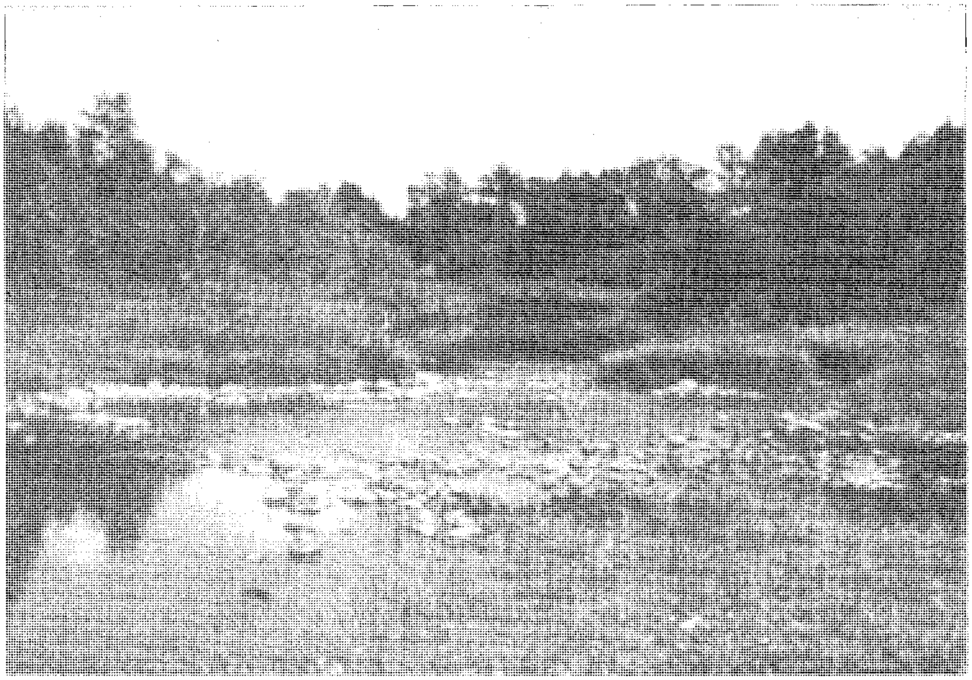


Figure 4-17: *Hidden Valley natural walleye spawning site on the Valley River upstream from Provincial Highway 20.*

The spawning reaches were studied for several years prior to the Mink Creek project to gather information on walleye spawning behaviour. The fish spawned near the crests of the riffles, behind emergent boulders on the riffle surface, and in large horizontal eddies in the upstream pool. The fertilized walleye eggs drifted into the riffle sections and settled into quiet water zones behind and at the base of large cobbles and boulders. Some of the eggs were carried through the riffle and deposited in the upper end of the downstream pool.

The maximum slope of the downstream face of the riffles was 5 % (20:1). The crest of the riffles was less than 0.5 m above the mean reach gradient while the bottom of the pools was less than 2 m below the mean reach gradient. The cobbles and boulders ranged in size from 0.1 m to 0.9 m mean diameter. At the bankfull stage, the tops of one to two boulders per 10 m^2 were emergent.

The rugged surface of the riffles created locally-varied flow conditions. Hydraulic jumps and aeration zones occurred in different areas on the riffle surface as the Spring flood stage rose and fell. At the lowest stages, the flow dwindled into two or three smaller channels crossing the riffle surface between the larger cobbles and boulders.

7) Selecting and sizing rehabilitation works

To achieve the pool depths, riffle gradients, and flow diversity observed in the Valley River riffles, the higher gradient lower half of the rehabilitation segment was divided into six reaches by rock-fill riffles as shown in Figure 4-16. Riffle crest elevations were set to follow the average slope of the stream segment of 0.3 %. The crests were elevated from 0.5 to 0.8 m (average 0.6 m) above the channel bottom to create pools that extended to the mid-point of the upstream riffle slope. This ensured that a continuous water course would be maintained through the spawning reaches for returning fry to Dauphin Lake. The impounded water on the face of the riffles ensured that a stilling basin would be formed in the pools to reduce scouring of the fine-grained channel bottom.

The riffles were located at 100 m intervals, creating a net drop at each riffle of 0.3 m. The spacing is 6.4 times the 1949 natural channel bankfull width and 4.5 times the 1984 excavated width. In several cases, the riffles were placed at the same locations as the riffles had occurred between the natural meander bends before the channel was straightened.

The riffles were constructed of cobbles and boulders up to 1 m in diameter that were hauled to the sites from local collections of fieldstone. The largest boulders were placed on the channel bottom along the crest of the riffle. Smaller boulders were set aside until the downstream slope of the riffle was nearly completed. They were then carefully placed on and in the surface to create the rugged conditions observed on the surface of the natural spawning riffles. A straight segment of the rehabilitated channel under mid-summer low-flow conditions before and after construction is shown in Figures 4-18 and 4-19.

The stability of the cobbles and boulders used to construct the riffles was tested for two flow assumptions at the natural channel capacity of 17 m^3/s: 1) that the flow would be uniform in the reach with an average slope of .003; and 2) that critical flow would occur on the downstream face of the riffles with an average slope (water surface) of 20:1. In the first case the depth of flow is 1.0 m and the average tractive force is 3.0 kg/m^2. In the second case, critical depth of flow on the riffle face would be 0.7 m, with a tractive force of 35 kg/m^2. To ensure the stability of the riffles, spaced boulders that were larger than 35 cm were placed on the crest and downstream face of the riffle. In May 1987, the first Spring runoff period following construction, a peak flow of 41 m^3/s occurred (annual frequency 20 %). After the flood, when the riffles were re-surveyed it was apparent that only local settling had occurred (see Step 10 Monitoring, Figure 4-21).

Figure 4-18: *The uniformly channelized reach of Mink Creek below Highway 20 in September 1985, prior to the addition of spawning riffles and pools.*

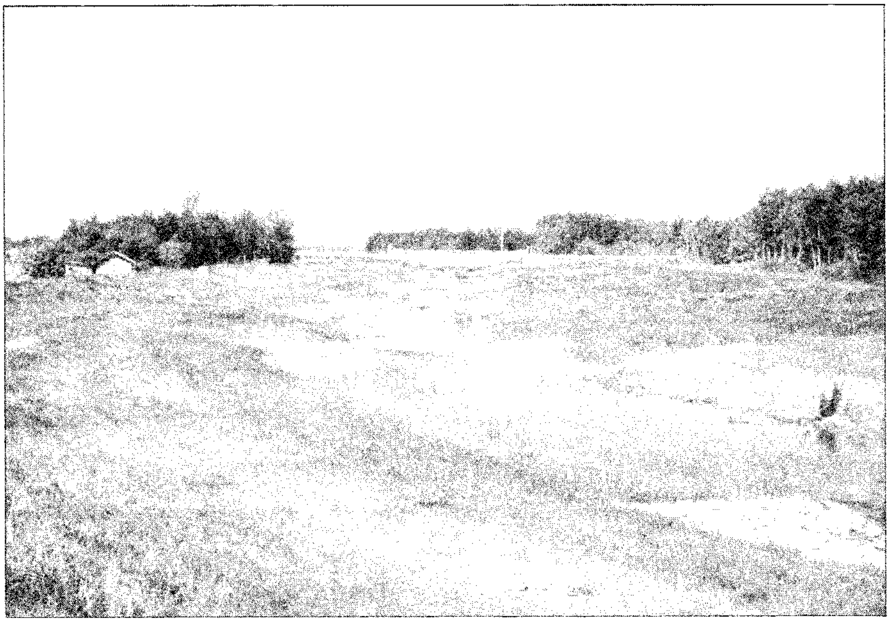


Figure 4-19: *Stable spawning riffles and pools added to the rehabilitated reach of Mink Creek below Highway 20 under low-flow conditions in July 1988, two years after construction.*

8) Instream flow requirements

During 5 of the 13 years of record analyzed in the mass curve (Figure 4-15), monthly flows during the April/May spawning and incubation period were either too low or not of sufficient duration. The supply of water to the lower Mink Creek channel is very limited, with no mid-winter flows and often no mid-summer flows. However, some of the low-flow spawning periods may be alleviated by storing water upstream. In the mass curve analysis, the maximum potential flow that could be achieved through storage is 1.0 m^3/s. At this discharge, the depth of flow (critical) on the 6 m wide riffle crests would be 14 cm at a velocity of 1.2 m/s. This is sufficient flow to create combinations of sub-critical flow velocities and depths similar to those observed in the Valley River natural spawning riffles by arranging larger cobbles and boulders on the surface of the riffles. In higher flow years, the spawning area on the riffles would expand beyond the central 6 m zone.

9) Supervise construction

The riffles were constructed with a 1 m^3 bucket track-mounted backhoe (Figure 4-20). Fieldstone was gathered from local stone piles and transported to the sites with two 10 m^3 dump trucks after freeze-up occurred in November and December 1985. The crest elevations and the upstream and downstream toes of the riffles were marked with survey stakes. Marker stakes were placed on the berms beside the stream that showed the volume of rock that was to be delivered to each site.

The elevation of the riffle crests was checked as the construction proceeded from temporary elevation benchmarks established beyond the working area. The materials and costs for the construction of 7 riffles in the rehabilitation segment above Highway 20 in 1990 $ and person-days (pd) are summarized in Table 4-4.

Figure 4-20: *Mink Creek riffle construction above Highway 20 in November,1985. A completed riffle is shown upstream.*

Table 4-4: Materials and costs for riffle and pool construction on the central experimental segment of Mink Creek.

Materials	
700 m^3 of field stone	donated
Machine Rental	
40 hours trucking	$1300.
38 hours backhoe	$3160.
33 hours loader	$2000.
Labour	
surveys	20 pd
design	10 pd
arrangements	4 pd
supervision	20 pd
monitoring	120 pd

10) Monitor and adjust design

Channel Geometry Surveys: The rehabilitated reach was re-surveyed following the Spring flood peak for several years. A typical profile surveyed in June 1989 after the Spring flood peak had passed is shown in Figure 4-21. Riffles W1 to W7 occur in the rehabilitation reach above Highway 20.

During the first flood peak following construction (41 m^3/s peak), 0.3 m of settling occurred in the upper two riffles when finer materials were washed from the rock infill. In addition, one bank of riffle W4 required 40 m^3 of additional rock to fill a scoured section near the crest of the riffle. Immediately below the riffles, the sands and gravels on the channel bed were scoured to an average depth of 0.5 m, forming pools that were up to 1.5 m deep under high flow conditions during the spawning season. No further scouring occurred after the pools were formed by the first flood peak. In contrast, the streambed has continued to erode in the channelized reaches above and below the rehabilitation segments, causing sections of the recently re-graded 4:1 side slopes to collapse.

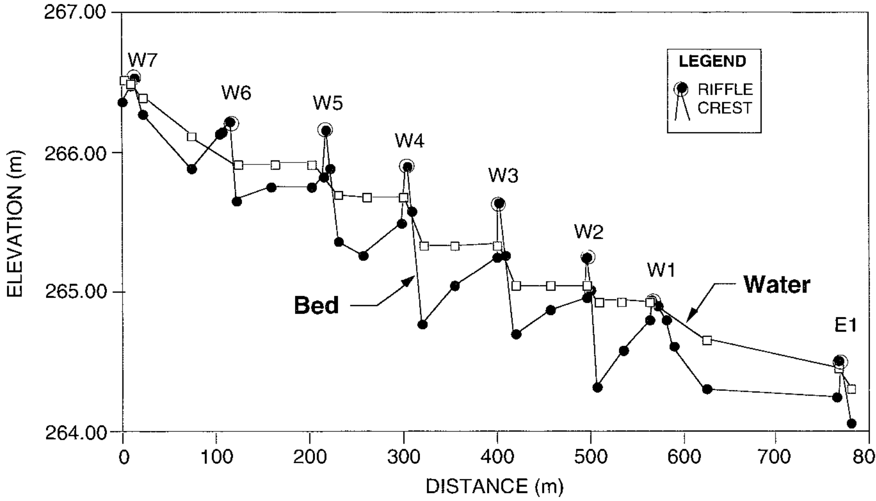


***Figure 4-21:** Profile of the stable Mink Creek rehabilitation reach under low-flow conditions three years after riffles and pools were constructed.*

Biological Sampling: Walleye spawning performance was monitored by sampling the riffle and pools sections for fertilized eggs during and following the spawning period. The general framework for pre- and post-development fisheries evaluations is based on five components:

A. Pump/Surber Egg Sampling

B. Local Hydraulic Conditions

C. Egg Scour and Drift

D. Larval Fish Drift

E. Discharge and Temperature

A. Pump/Surber Egg Sampling: In order to determine egg density and distribution in rapids and pools within Mink Creek, an egg sampling pumping device was constructed consisting of a diaphragm pump, a 10 m long vacuum hose, and two brass sieves in a filtering bucket with openings of 2.27 mm and 1.10 mm (Figure 4-22).

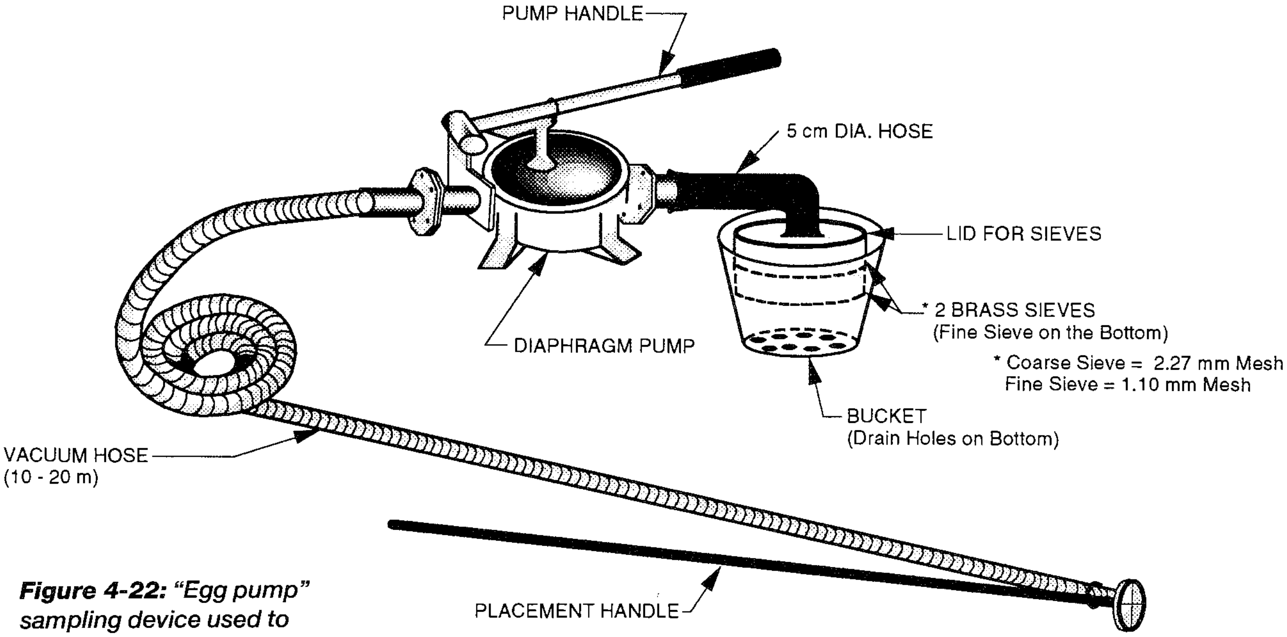


Figure 4-22: *"Egg pump" sampling device used to collect fish eggs deposited on the streambed.*

Figure 4-23: *Using the "egg pump" sampling device on a constructed spawning riffle crest in Mink Creek.*

At each riffle, three egg samples were collected from 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. The pumped water passed through the brass sieves, sorting the eggs into two size groups. The larger pore sieve held white sucker eggs while the smaller pore sieve caught walleye, quillback and other percid eggs. Any eggs dislodged from the streambed and not collected by the pump were caught in a surber placed immediately downstream of the sampling area. Without the pumping device, egg densities can be determined by surber samplers only when the substrate is regular and there is sufficient water depth for their effective use. Sampling with the egg pump on a riffle crest is shown in Figure 4-23.

The number of live and dead walleye eggs were counted in the field using a concentrated sugar solution to float the eggs, separating them from the sand and gravel.

B. Local Hydraulic Conditions: Local flow conditions are important in prescribing specifications for enhancement designs, in this case for walleye spawning and incubation habitats. During egg sampling, measurements of site-specific depth and velocity were recorded. Also, an examination of riffle roughness, water surface slope, substrate diameter, pool depth and stream discharge at specific riffle-pool sites where egg sampling was carried out helped to quantitatively describe preferred spawning/incubation habitats. Egg density, egg survival and hydraulic condition measurements could then be used to modify and improve artificial riffle/pool designs.

C. Egg Scour and Drift: Egg drift is a function of discharge, channel gradient, channel roughness and bed profile, and is an indicator of how well incubation habitats retain eggs. Total daily estimates of egg scour and drift from the pool and riffle zones were extrapolated from catches in drift nets (Figures 4-24 and 4-25) set for short periods (0.5-1 h) during the day. The volume filtered by the drift net was calculated from a velocity measurement taken at the net mouth multiplied by the mouth opening area and by the time fished.

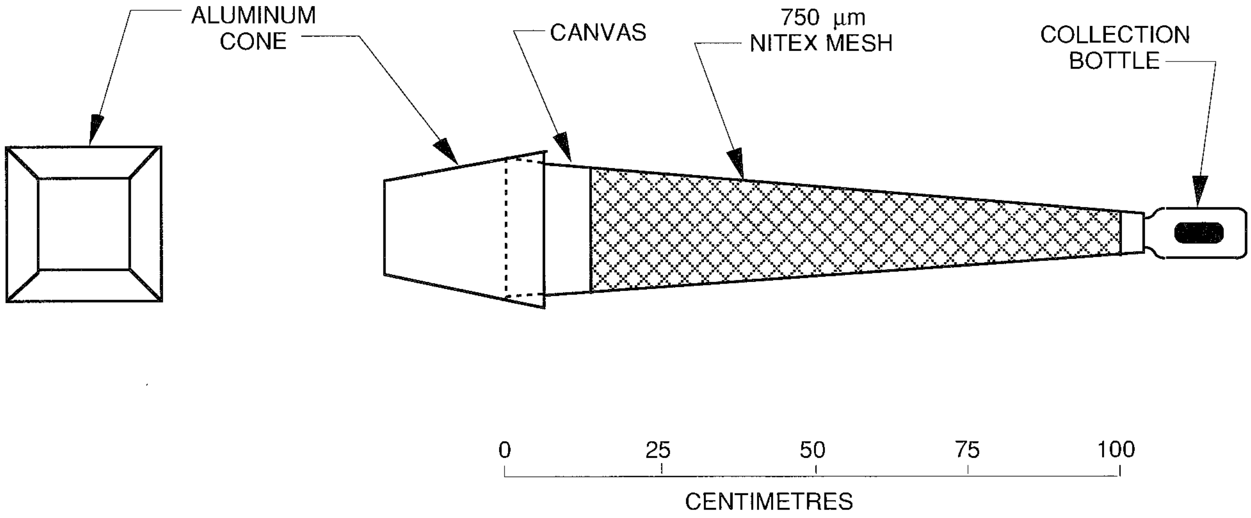


Figure 4-24: *Egg and larval drift trap with conical net and aluminum hood.*

Total daily discharge was calculated from published records of mean daily flows or from a present discharge measurement taken at the time of netting. Total drift estimates of live and dead eggs were obtained by extrapolating the actual egg catches in the volume filtered to the total streamflow volume of the day.

D. Larval Fish Drift: Larval fish were captured with drift nets set for continuous 24 h periods beginning about two or three days prior to the onset of hatching. A single net was set in the centre of the stream channel, downstream of a rapids, and approximately 10 cm below the water surface. Velocity at the net mouth was measured before and after collection of the drift sample. During the peak period of larval drift, samples were collected twice a day to ensure fresh specimens. Similar to daily egg drift estimates, daily larval drift was estimated using the proportion of filtered water volume to streamflow volume.

E. Discharge and Temperature: Published mean daily discharge records were used in calculations of total egg and larval drift. Occasionally a present discharge measurement was taken to verify the published records.

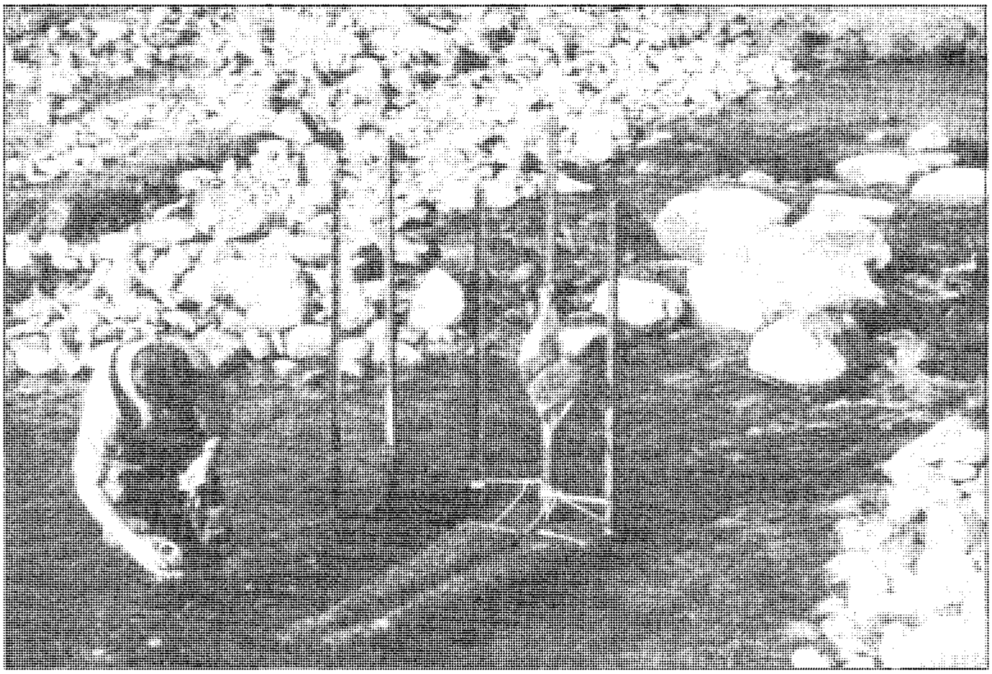


Figure 4-25: *The egg and larval drift trap installed at the foot of a constructed spawning riffle on Mink Creek.*

A submersible thermograph provided continuous temperature records for the study stream, from ice-out to the end of larval drift. Maximum daily water temperatures were used in a relationship developed by Hartman (unpubl.) that determined the elapsed development time of the incubating eggs. By estimating the probable start date of hatching, larval drift nets could be installed at the appropriate time.

Biological Evaluation: Mink Creek was monitored for six years following riffle construction in the winter of 1985 (Janusz 1993). A summary of the results is presented in Table 4-5. To evaluate the rehabilitation technique, comparisons were made between artificial and existing channelized riffle-pool habitats. Both riffle-pool habitats had similar pool depths, riffle slopes and median substrate sizes. Few classic riffle-pool habitats existed within the channelized Mink Creek and this was considered to be one of the factors limiting walleye reproductive success.

Spring discharges in the Mink Creek controlled the occurrence and location of walleye spawning activity. In two years, 1989 and 1991, discharges were insufficient for walleyes to ascend the stream to spawn. Low spawning flows in 1988 limited the extent of walleye migration upstream. As a result, a lower egg density was recorded for the channelized section in comparison to the rehabilitation zone, located in the lower reaches of the creek. Conversely, in high discharge years such as 1987 and 1990 the egg densities were greater 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.

It was apparent in all years that egg drift from the three habitat types was positively correlated with egg density and discharge. Egg drift increased as egg density increased and as discharges exceeded 2.5 m^3/s. Egg scour and drift was considered a serious problem as viable eggs could settle and die in high siltation areas near Dauphin Lake. Relative to egg densities, mean egg drift was 1.5 times greater from the channelized versus the rehabilitated section (Table 4-5). In addition, the rehabilitated section appeared to trap and retain eggs that entered from the upstream channelized reach.

Table 4-5: Summary of walleye spawning success information for Mink Creek.

Measurement	Reach Type	Year 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/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^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)	2.82	7.96	1.09	0.48	9.04	0.34
	Mean incubation flow (m^3/s)	5.61	1.36	7.92	0.19	3.09	0.36
	Mean larval drift flow (m^3/s)	2.43	0.27	1.00	0.10	6.07	0.92

In comparisons between artificial and existing habitats it was evident that except in low spawning flow years egg densities were greater for existing channelized riffle-pool habitats. However, larvae were produced by both rehabilitated and existing channelized riffle-pools with roughly equal frequency and magnitude. Of the two types of artificial riffle design, double riffles tended to produce the most larvae.

Minimum or preferred flows can be prescribed by inference from the data collected during the egg and larval studies. Flow requirements can be partitioned into the three phases of walleye reproduction: 1) spawning flows- to allow fish access to upstream spawning areas, 2) incubation flows- to provide high dissolved oxygen concentrations, low sedimentation rates, and minimal daily temperature fluctuations, and to minimize egg scour, 3) larval drift flows- to provide sufficient discharges so that larvae can reach a suitable nursery environment in the lake before exhausting their yolk sac. In Mink Creek, with storage in an upstream reservoir, the mean monthly flows that could be sustained in low flow years for April and May are 1.0 m^3/s. These flows would be further partitioned to allow for moderate flows (~1.5 m^3/s) in the spawning period, decreasing flows in the incubation period and increasing flows in the larval drift period.

Bed and bank erosion has declined in the rehabilitated reaches where the channel gradient has been controlled. Consequently, sedimentation rates on incubation habitats and in Dauphin Lake have been reduced. However, the upper pools above the artificial structures have tended to infill because of the high sediment loads from the upstream non-rehabilitated sections. Paired riffles partially alleviated infilling by creating a deep plunge pool between two closely spaced crests.

Design Example 3: Wilson River

Channel Stabilization With Walleye Spawning Riffles

Project background

The Wilson River flows from the northern slope of the Riding Mountain portion of the Manitoba escarpment to Dauphin Lake through an intensively developed agricultural region. The valley materials consist of highly erodible glacial deposits of clays, silts, sands, and gravels. The river had been shortened to only two-thirds of its natural length through channel straightening and the removal of meander loops. Erosion of the consequently steeper channel bed has occurred throughout the lower reaches of the river. The channel has rapidly down-cut as much as 2 m, causing extensive bank slumping, increased turbidity, and sedimentation in Dauphin Lake. Walleye spawning activity has been dramatically reduced because of the loss of pool and riffle habitat associated with the abandoned meanders, increased sedimentation in the remaining spawning areas due to channel erosion, and shortening of the length of time that water persists in the channel because of the increased drainage efficiency in the basin.

In 1988, a pilot project was undertaken to investigate the effectiveness of placing nine rock-fill spawning riffles to re-stabilize a reach that had been shortened by a straight cutoff channel. One km of the Wilson River was selected for the re-stabilization and spawning project in the 8 km reach above Dauphin Lake (Figure 4-26). The straightening caused severe downcutting and bank collapse as shown in Figures 4-27 and 4-28.

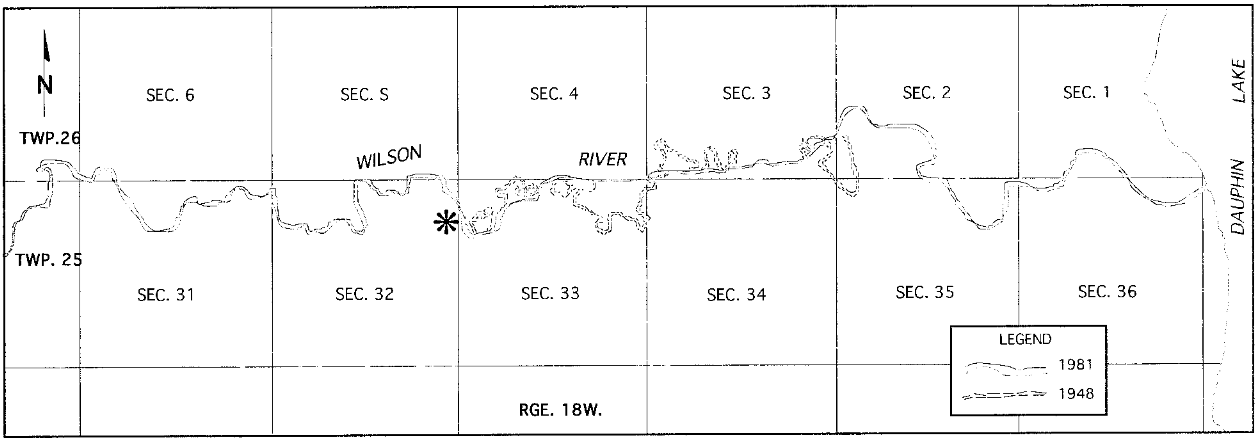


Figure 4-26: *Lower section of the Wilson River prior to straightening in 1948 (dashed line), and in 1981 (solid line). Channel lengths for both conditions are shown on the upper scale. The experimental restabilization and spawning reach is marked* ✻.

The following sections summarize the steps taken in the analysis and design process presented in Figure 4-1.

1) Drainage basin

The area of the Wilson River drainage basin from the escarpment to the river mouth on Dauphin Lake is 931 km^2 as shown in Figure 4-29. The drainage area tributary to the rehabilitation reach is 919 km^2.

2) Profiles

The longitudinal profile of the Wilson River main channel drawn from 100 ft contours on the 1:250,000 topographic map is shown in Figure 4-29. The profile is broken into two concave upward segments. The upper segment ends at approximately elevation 1200 ft ASL (366m), which corresponds to the maximum elevation of glacial Lake Agassiz. The second segment has developed as the glacial lake fell to the present level of Dauphin Lake. The gradient in the headwaters is steep (0.6 %). In the remainder of the basin, with the exception of the steeper upper section of the re-set profile below the upper level of Lake Agassiz, the gradient of the channel is generally less than 0.2%.

3) Flow

Historic flow records similar to those shown for the Ashville station (Table 4-6) are available at several short-term sites in the basin. The frequency curve (Figure 4-30) is based on all records reduced to the Ashville station drainage area of 669 km^2. The estimated bankfull flow for the larger drainage area (919 km^2) tributary to the rehabilitation reach is 24.0 m^3/s.

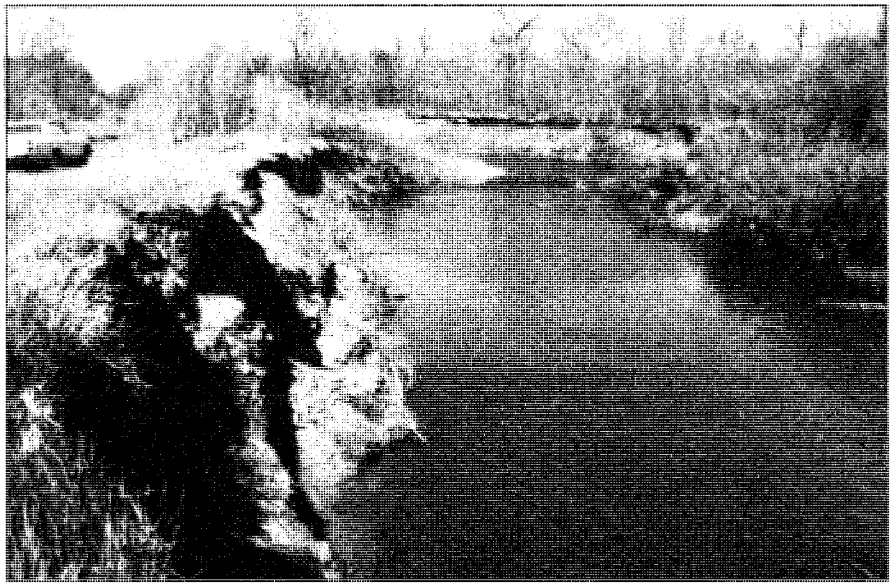


Figure 4-27: *The actively downcutting lower reaches of the Wilson River near the rehabilitation reach.*

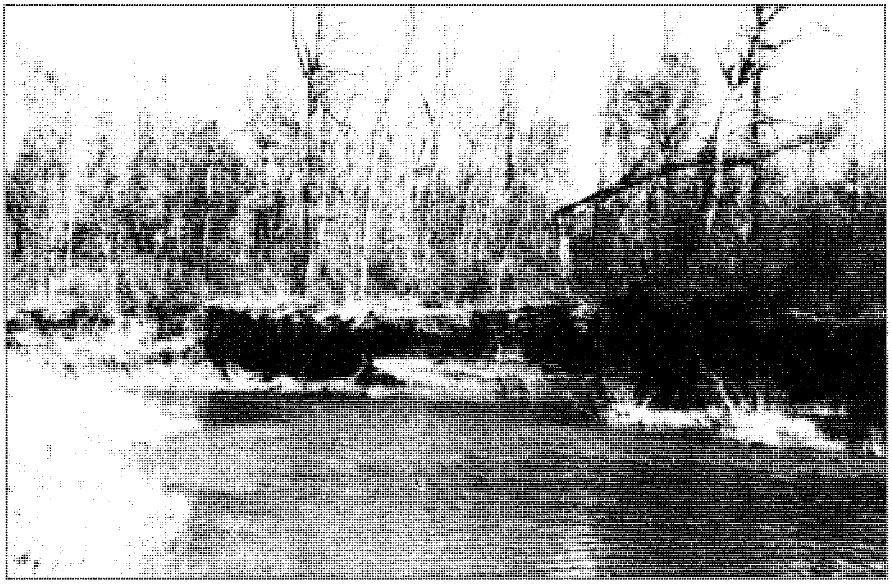


Figure 4-28: *Progressive bank undercutting and slumping in the rehabilitation reach of the lower Wilson River.*

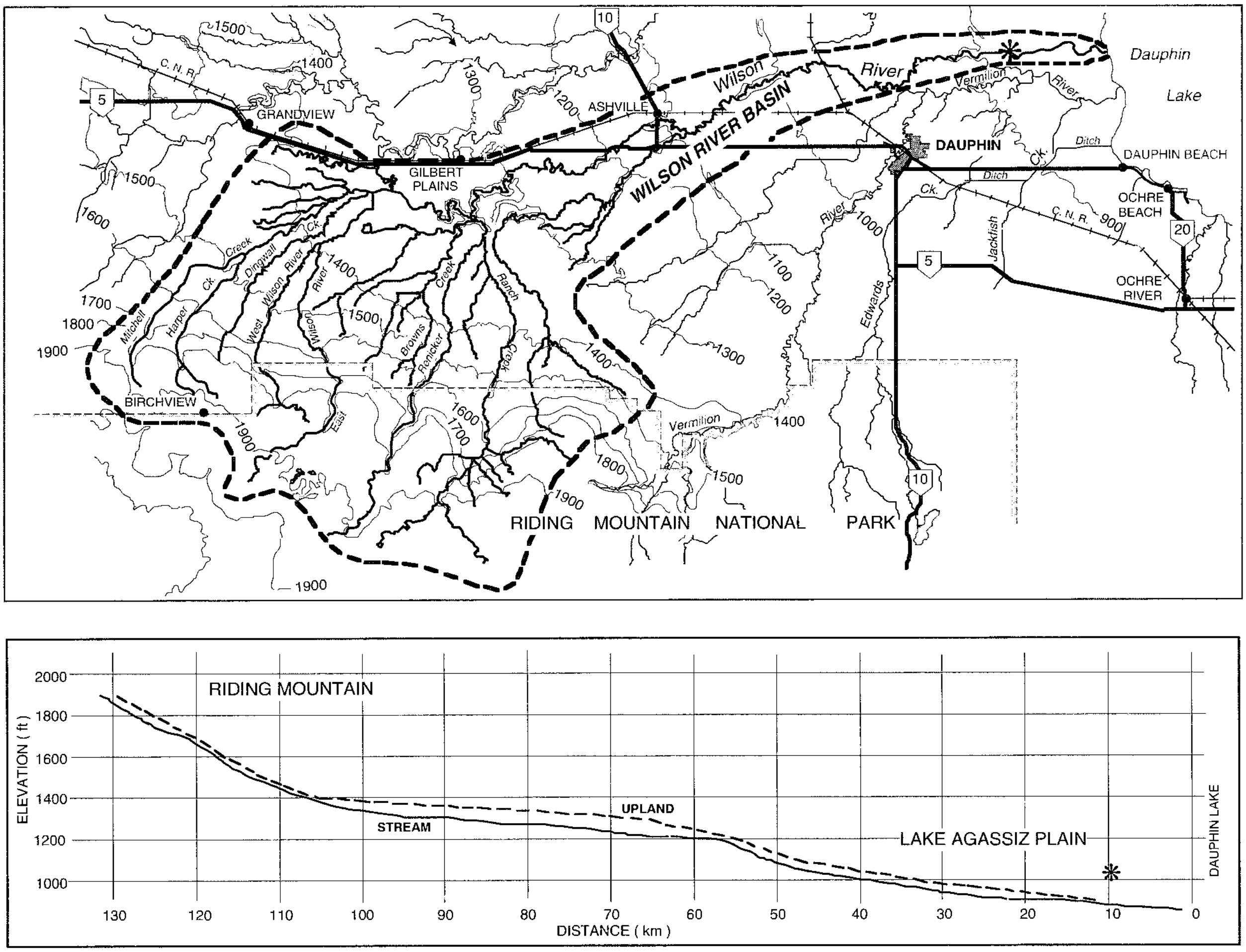


Figure 4-29: *Wilson River drainage basin and profile (NTS Map Sheet 62N, 1:250,000). The rehabilitation reach is marked ✻.*

Table 4-6: Wilson River at Ashville discharge summary (Water Survey of Canada 1990).

WILSON RIVER NEAR ASHVILLE - STATION NO. 05LJ045

MONTHLY AND ANNUAL MEAN DISCHARGES FOR MAR TO OCT IN CUBIC METRES PER SECOND FOR THE PERIOD OF RECORD

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	MEAN	YEAR
1979	---	---	0	22.8	12.5	1.45	0.036	0.001	0	0	---	---	4.56	1979
1980	---	---	0.017	4.85	0.088	0.002	0	0.152	0.131	0.113	---	---	0.658	1980
1981	---	---	0.550	0.770	0.787	1.43	0.104	0.001	0.001	0.003	---	---	0.453	1981
1982	---	---	0.076	5.15	0.518	0.078	0.008	0.232	0.004	0.317	---	---	0.787	1982
1983	---	---	0	19.5	4.82	0.941	0.327	0.010	0.001	0.001	---	---	3.15	1983
1984	---	---	0.216	0.546	0.814	0.194	0.019	0.001	0.001	0.010	---	---	0.225	1984
1985	---	---	0.003	15.2	0.733	0.756	0.068	1.10	0.799	2.48	---	---	2.61	1985
1986	---	---	4.79	10.2	13.4	0.235	0.074	0.066	0.005	0.003	---	---	3.60	1986
1987	---	---	0.874	6.36	0.113	0.012	0.001	0	0	0.001	---	---	0.906	1987
1988	---	---	0.039	4.91	7.14	0.090	0.007	0.001	0	0.001	---	---	1.52	1988
1989	---	---	0.006	0.806	0.024	1.21	0.065	0.001	0.001	0.001	---	---	0.260	1989
1990	---	---	0.508	10.7	3.88	0.710	0.297	0.014	0.001	0.002	---	---	1.99	1990
MEAN	---	---	0.590	8.48	3.73	0.592	0.084	0.132	0.079	0.244	---	---	1.73	MEAN

LOCATION - LAT 51 09 30 N DRAINAGE AREA, 669 km²
LONG 100 20 00 W NATURAL FLOW

WILSON RIVER NEAR ASHVILLE - STATION NO. 05LJ045

EXTREMES OF DISCHARGE AND TOTAL DISCHARGE FOR MAR TO OCT FOR THE PERIOD OF RECORD

YEAR	MAXIMUM INSTANTANEOUS DISCHARGE (m³/s)	MAXIMUM DAILY DISCHARGE (m³/s)	MINIMUM DAILY DISCHARGE (m³/s)	TOTAL DISCHARGE (dam³)	YEAR
1979	187 AT 03:53 CST ON APR 22 *	163 ON APR 22 *	0 B ON MAR 01 *	96 500	1979
1980	---	13.0 B ON APR 07	0 B ON MAR 01	13 900	1980
1981	8.26 AT 04:00 CST ON MAY 30	7.32 ON MAY 30	0 ON AUG 11	9 580	1981
1982	---	16.9 ON APR 18	0 B ON MAR 01	16 700	1982
1983	182 AT 06:21 CST ON APR 24	154 ON APR 24	0 B ON MAR 01	66 800	1983
1984	2.48 AT 15:32 CST ON APR 03	1.83B ON APR 04	0 B ON MAR 01	4 760	1984
1985	29.8 B AT 15:01 CST ON APR 05	27.5 B ON APR 16	0 B ON MAR 01	55 200	1985
1986	105 A AT 16:30 CST ON MAY 06	79.8 A ON MAY 06	0.001 ON SEP 20	76 200	1986
1987	58.9 AT 18:34 CST ON APR 05	39.3 ON APR 06	0 ON JUL 17	19 200	1987
1988	58.0 AT 00:46 CST ON MAY 03	43.8 ON MAY 03	0 B ON MAR 01	32 200	1988
1989	14.0 AT 18:50 CST ON JUN 13	9.67 ON JUN 13	0 B ON MAR 01	5 490	1989
1990	29.9 B AT 16:22 CST ON APR 04	25.2 B ON APR 01	0 B ON MAR 01	42 100	1990
				36 600	MEAN

A - MANUAL GAUGE B - ICE CONDITIONS * - EXTREME RECORDED FOR THE PERIOD OF RECORD
(SEE REFERENCE INDEX)

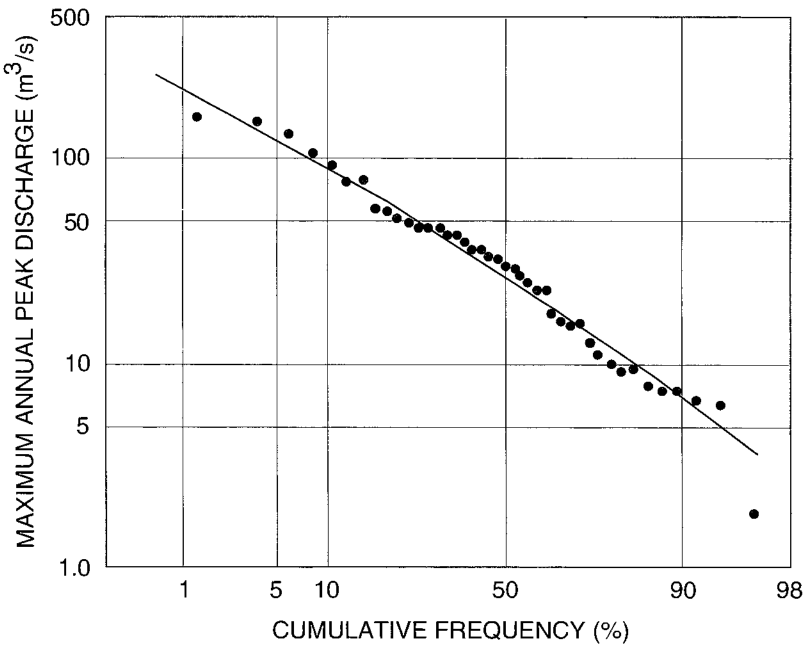


Figure 4-30: *Annual flood frequency curve for the Wilson River at the Ashville gauging station.*

4) Channel geometry surveys

Sample reaches were surveyed in the lower shortened reaches of the Wilson River in June, 1988 (Table 4-7). The width of the sample reaches averaged 9.8 m and 11.8 m, about half the width that would be predicted for natural streams in this region with similar drainage areas (24 m, Figure 3-7). In the abandoned meander channels the average bankfull width was 15.5 m. The narrow excavated channel was steeper than the historic channel and, as a result, is actively eroding its bed and banks.

Table 4-7: Channel characteristics of the lower Wilson River

	Site 1	Site 2
drainage area	924.	922.km^2
bankfull width	11.8	9.8 m
bankfull depth	0.9	1.1 m
average slope.	0.001	0.002
medium bed paving	2.7	4.7 cm
bankfull roughness est	0.021	0.024
bankfull velocity	1.4	2.0 m/s
bankfull tractive force	0.9	2.2 kg/m^2
bankfull Froude number	0.47	0.60
bankfull discharge	14.9	21.4 m^3/s

5) Rehabilitation reach survey

Characteristics of the rehabilitation segment were measured in June, 1988 prior to riffle construction (Table 4-8). Water surface and streambed profiles are shown in Figure 4-31. Three representative cross-sections are shown in Figure 4-32.

Table 4-8: Wilson River channel characteristics in the rehabilitation reach.

drainage area	919 km^2
bankfull width.	17.1 m
bankfull depth	1.1 m
average slope	.002
median bed paving	12.0 cm
bankfull roughness est	0.028
bankfull velocity.	1.7 m/s
bankfull tractive force	2.2 kg/m^2
bankfull Froude number	0.51
bankfull discharge.	32.0 m^3/s

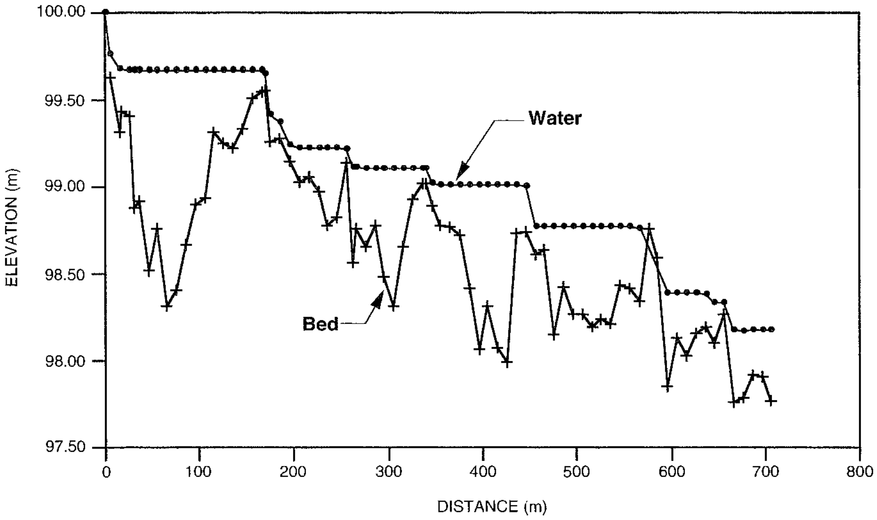


Figure 4-31: *Water surface and streambed profiles surveyed in the Wilson River rehabilitation reach in June 1988 prior to re-construction.*

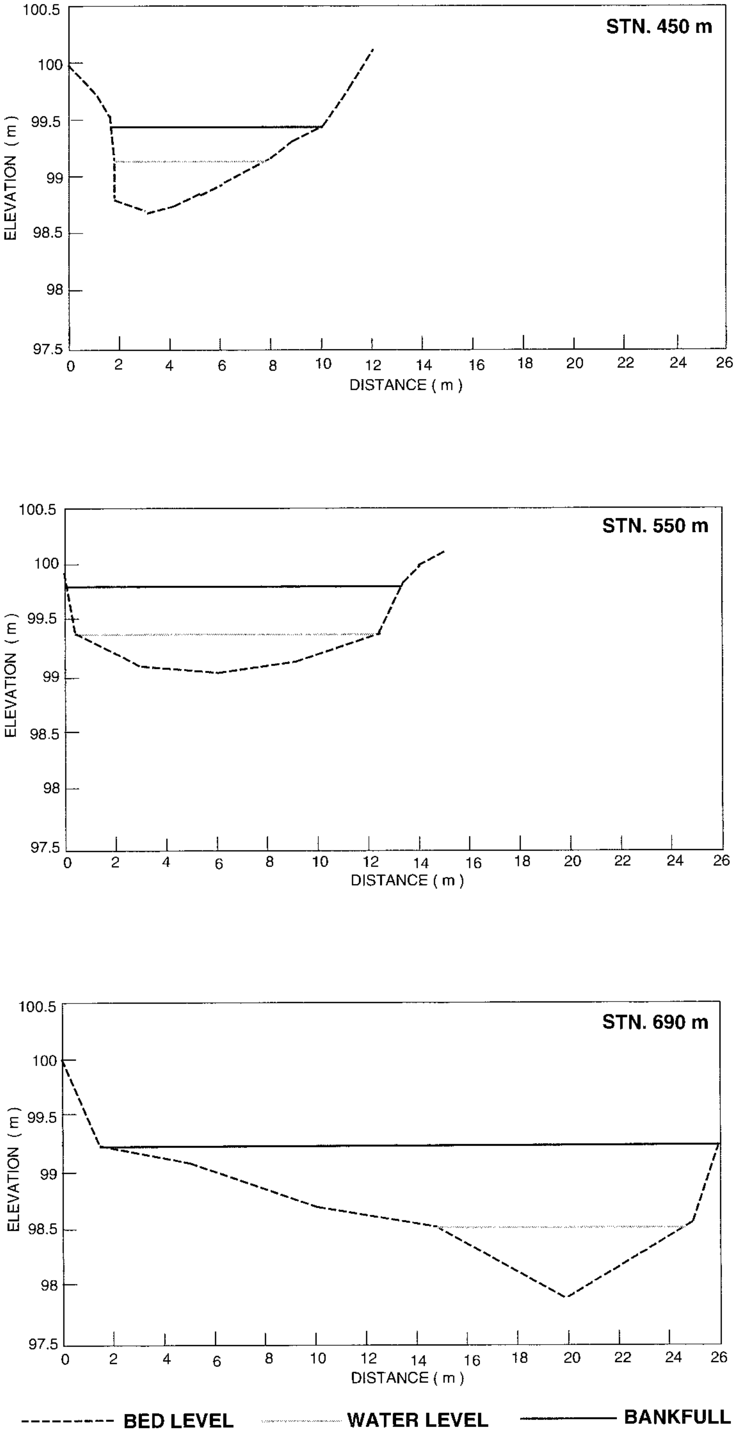


Figure 4-32: *Typical cross-sections in the Wilson River rehabilitation reach.*

6) Preferred habitats

The shortened lower reaches of the Wilson River experience similar habitat problems to the channelized reaches of Mink Creek (Example 2). However, the larger drainage basin of the Wilson River provided greater sustained flows during the walleye spawning period. Channelization has reduced spawning and incubation habitats from historic levels, but flow conditions still exist to allow for reproductive success in most years.

A brief study was conducted in the spring of 1988 to quantify the distribution of walleye spawning activity and reproductive success in the lower 30 km of Wilson River (Cann 1991). The general distribution of walleye spawning activity in the lower 30 km of Wilson River was determined by random egg collections using surber samplers. Walleye eggs were collected from six of nine sampling sites. Mean egg densities were between 36 and 667 eggs/m^2. The density at the proposed rehabilitation site was 562 eggs/m^2.

The rate and incidence of egg scour were measured at six drift net sites. Walleye eggs were caught at the rehabilitation site station (Table 4-9) in numbers comparable to egg drift catches in other channelized streams (Mink Creek) and in greater numbers than from a natural stream (Valley River). This suggested that morphological conditions of the incubation habitat had been altered by channelization, subjecting the eggs to increased dislodgement.

Larval drift samples were collected from three sites encompassing the sections of stream where walleye eggs were collected by the surber sampler. Walleye larvae were caught in only the rehabilitation site net (Table 4-9).The estimated total number of drifting larvae caught at the rehabilitation site was similar to those for Mink Creek but significantly lower than for the Valley River.

Walleye spawning activity and egg incubation occurred successfully in the proposed rehabilitation site, but existing channel morphology resulted in high egg dislodgement. It was apparent that improvements could be made to spawning and incubation habitats in the Wilson River by creating a channel morphology that was similar to preferred spawning and incubation habitats in the Valley River.

Table 4-9: Walleye egg and larval drift summary for the Wilson River at the proposed rehabilitation site, May 1988.

Date	Effort (h)	Net Flow (m^3/s)	River Discharge (m^3/s)	Percent Sampled	Number Caught		Est. Total Number	
					Eggs	Larvae	Eggs	Larvae
8	0.50	0.018	20.60	0.09				
10	1.58	0.029	8.48	0.34	5		1471	
11	12.00	0.024	4.77	0.50	25		5000	
12	19.00	0.039	3.16	1.22	22		1803	
12	6.00	0.039	3.16	1.22	9		738	
13	19.50	0.037	2.59	1.44	5		347	
14	18.50	0.035	2.14	1.64	8		488	
15	22.80	0.035	2.15	1.63	8		491	
15	7.70	0.033	2.15	1.56				
16	16.80	0.039	3.92	0.99	8		808	
17	24.00	0.039	3.30	1.18	3	12	254	1026
17	8.10	0.039	3.30	0.99		2		203
18	15.20	0.037	2.56	1.45		10		690
18	8.50	0.040	2.56	1.57		8		510
19	14.50	0.051	3.76	1.36		30		2206
19	8.33	0.039	3.76	1.03		6		583
20	21.70	0.051	3.63	1.41		9		638
20	3.50	0.026	3.63	0.72		3		415
21	14.40	0.034	2.55	1.32		3		227
21	10.30	0.067	2.55	1.46		3		205
22	16.00	0.029	1.88	1.56		1		64
22	7.75	0.031	1.88	1.64		6		366
23	14.60	0.030	1.46	2.08		16		769
23	7.95	0.029	1.46	1.99		2		101
24	16.60	0.025	1.08	2.28		10		439
25	23.80	0.027	0.80	3.36				
26	24.90	0.019	0.62	3.07				
27	24.00	0.008	0.52	1.59		2		126
28	24.10	0.012	0.45	2.71				
29	24.60	0.011	0.40	2.85				
				Totals	93	123	11400	8568

7) Selecting and sizing rehabilitation works

Nine riffle structures similar to those constructed on the Mink Creek were designed for the rehabilitation reach (Figure 4-33). To imitate the swirling eddies and deep pools found in natural meanders, the upper six riffles were constructed in pairs. In each pair the upstream riffle had a v-notch crest, which concentrated the flow to the centre to scour a deep plunge pool between the riffles. Eddies were formed as the concentrated flows were confined and directed laterally by the horizontal crest on the downstream riffle. A typical riffle pair immediately after construction is shown in Figure 4-34. Crest elevations were selected to create pools 0.5-1.5 m deep at bankfull flows and to allow for unobstructed access during upstream spawning migrations. Elevation drop between the crests of each pair was either 0.15 or 0.25 m. The upstream and downstream riffles were located 40 m apart. The average distance between each pair of riffles was 83 m or 4.8 times the bankfull width. The last three v-notch riffles had net elevation drops of 0.2 m and were spaced approximately 68 m apart or 4 times the bankfull width to take advantage of the pre-existing profile peaks.

Local velocity and depth variations were created by arranging larger cobbles and boulders on the riffle surface to direct the flow. Minor adjustments in the crest elevations were also required to create pools and back-eddies that were similar to those observed in natural spawning rapids. This required on-site supervision during construction. The local flow variations shown in Figure 4-35 were created by arranging boulders on the uniform riffle surface shown in Figure 4-34.

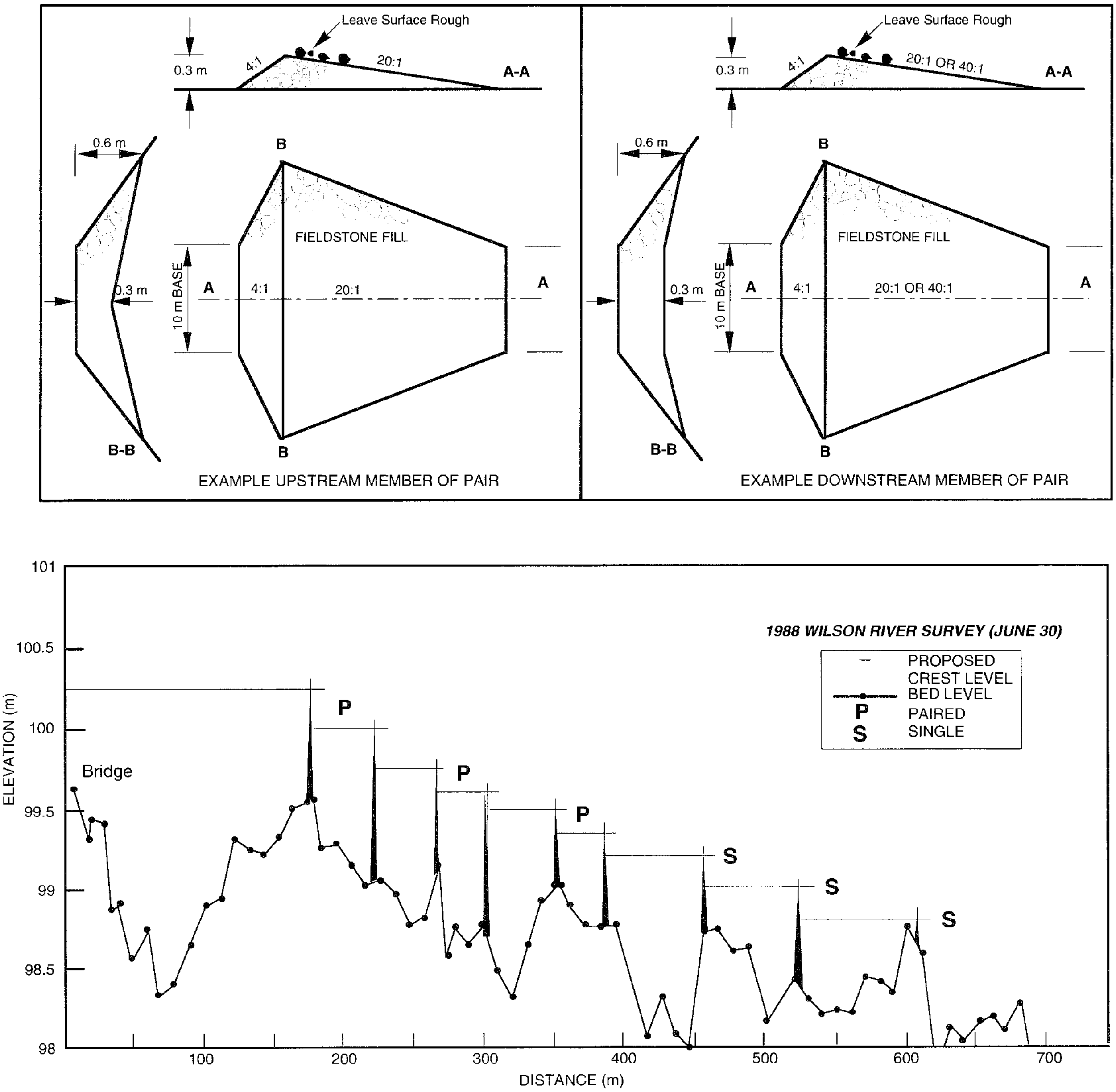


***Figure 4-33:** Riffle design and locations for the Wilson River rehabilitation site.*

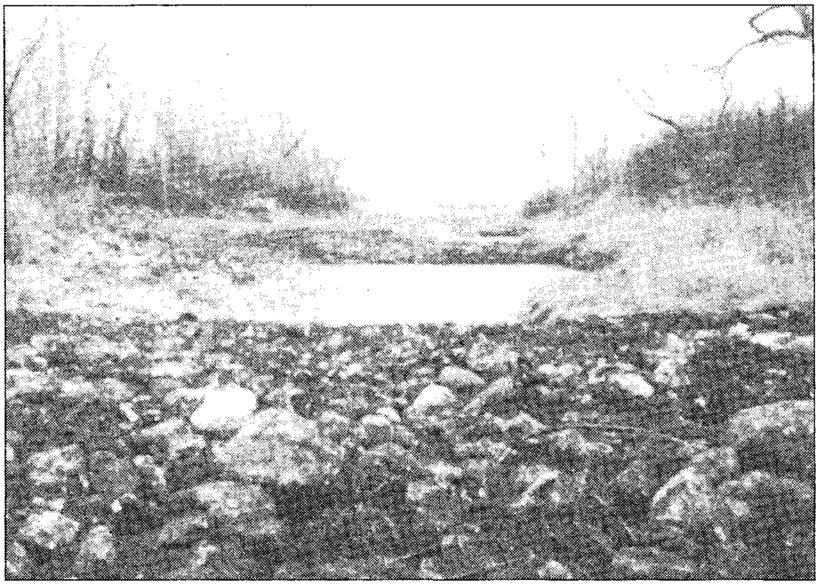


Figure 4-34: *Riffle pair on the Wilson River following construction under low flow conditions.*

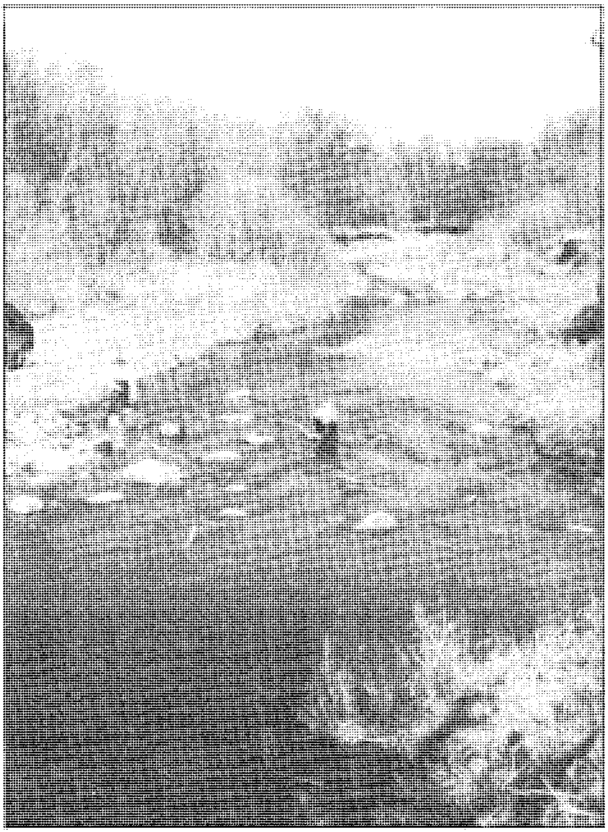


Figure 4-35: *Sampling egg densities in varying local flow conditions created by placing large boulders on the riffle surface.*

Table 4-10: Summary of walleye egg density, survival, and hydraulic conditions on artificial and natural riffles in the Wilson River, 1991.

Location	No. of Samples	Mean (M) Range (R)	Density (no./m^2)	Percent Live	Depth (m)	Velocity (m/s)	Froude Number	Water Surf. Slope (m/m)
Upstream Pool	18	M	147.7	56.6	0.61	0.07	0.034	0.0003
		R	0-2008.1	0-100	0.21-0.81	0-0.22	0-0.132	0-0.007
Riffle Face	17	M	144.9	55.8	0.34	0.18	0.107	-
		R	0-1510.8	0-100	0.14-0.48	0.04-0.39	0.025-0.249	-
Riffle Crest	8	M	85.4	70.6	0.17	0.41	0.310	-
		R	0-281.1	50-100	0.09-0.30	0.18-0.82	0.166-0.558	-
Mid-Riffle	26	M	105.0	71.3	0.21	0.32	0.258	0.0077
		R	0-756.8	6-100	0.04-0.55	0.04-0.99	0.026-0.953	0.0023-0.0189
Back Eddy	8	M	198.6	60.2	0.57	0.18	0.085	-
		R	5.4-1281.1	33-100	0.34-0.88	0-0.47	0-0.224	-

8) Instream flow requirements

The data collected during the evaluation of artificial and non-rehabilitated riffles in the Wilson River are summarized in Table 4-10. The egg survival and density data showed that all locations on the riffles provided suitable egg incubation conditions. Egg survivals ranged from 56 to 71%, and densities ranged from 85 to 199 eggs/m^2.

When the data were grouped, optimum egg survival and density occurred at a mean Froude number of 0.13 (Table 4-11). This corresponded to a mean velocity of 0.2 m/s, and mean depths between 0.3 and 0.4 m. It was assumed in doing this analysis that preferred depths and velocities for incubation occurred where egg survival and density were highest.

The discharge required to produce average hydraulic conditions for successful walleye spawning was estimated using the optimum depth of 0.35 m for egg density and survival. For an average depth of flow

Table 4-11: Local hydraulic conditions at egg incubation sites grouped by three ranges of (a) percent live and (b) egg density.

	Percent Live	n	Depth (m)	Velocity (m/s)	Froude Number	Egg Density (no./m^2)
(a)						
	0-49	17	0.41	0.11	0.065	385.53
	50-75	23	0.39	0.21	0.132	84.60
	76-100	25	0.27	0.31	0.227	59.12
(b)						
	71.50	24	0.38	0.28	0.182	1-24
	60.43	21	0.33	0.19	0.133	25-99
	54.40	20	0.33	0.20	0.133	>100

of 0.35 m, the discharge required would be 4.8 m^3/s using the slope, roughness, and width in the rehabilitation reach (Table 4-8).

Analysis of the mass curve of monthly flows during the incubation period (Figure 4-36) indicates that in the last 12 years, there have been only 3 years with flows less than 4.8 m^3/s. With the improvements to local flow conditions produced by added riffles and pools, the large drainage basin of the Wilson River appears to be capable of maintaining adequate flows for successful walleye reproduction in most years assuming there are no other water temperature or quality limitations.

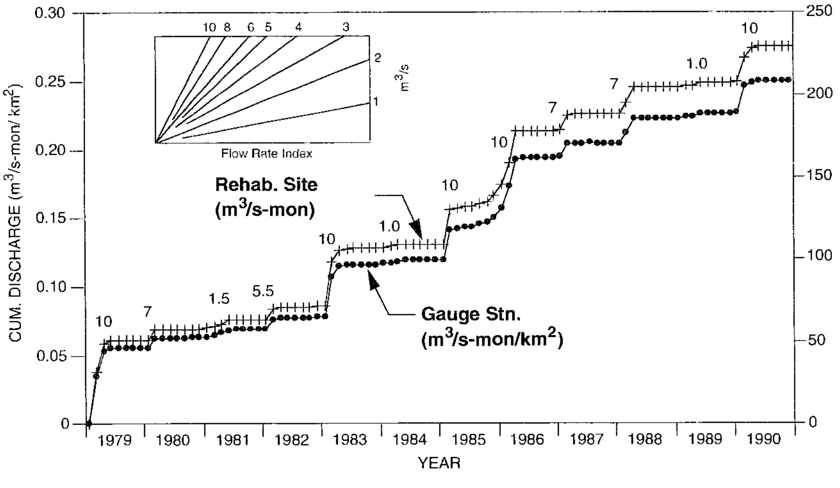


Figure 4-36: *Mass curve of Wilson River monthly flows for an eight month open-water season. The unit drainage area curve for the gauging station is extrapolated to estimate the discharges at the rehabilitation reach.*

9) Supervise construction

The riffles were constructed using equipment and fieldstone as described for the Mink Creek project (Design Example 2). The costs and person-days (pd) for surveys, design, and construction of nine riffles are summarized in Table 4-12.

Table 4-12: Materials and costs for Wilson River pool and riffle construction (1990$).

Materials		
2290 m^3	of field stone	donated
Machine Rental		
147	hours trucking	$ 4600.
86	hours backhoe	6900.
76	hours loader	4000.
Labour		
	surveys.	10 pd
	design	2 pd
	arrangements	2 pd
	supervision	9 pd
	monitoring	20 pd

10) Monitor and adjust design

Channel Geometry (1988-1991): The rehabilitated reach was re-surveyed in 1989. As a result of the field stone settling and underfilling at the time of construction, additional fill was required on several riffles to meet design elevations for the crests. Following this initial adjustment, no further deformation of the structures has occurred. A maximum discharge of 25.2 m^3/s was recorded in September 1991. This corresponds to the bankfull discharge estimate based on the frequency curve of annual flows (Figure 4-30) and is in the range of the bankfull discharge estimates for the lower reaches (Tables 4-7 and 4-8). The low and moderately sloped streambanks in the rehabilitation reach have stabilized.

Biological Evaluation(1989-1991): Two of the objectives of the habitat rehabilitation project on Wilson River were to provide preferred hydraulic conditions within artificial riffles and pools that would entice walleye to spawn, and to provide the correct physical conditions to ensure a high degree of survival during egg incubation through to larval drift. In the assessment of these objectives the techniques used concentrated on determining egg survival and larval production of walleye and measuring the physical conditions associated with these early development stages. Comparisons of egg survival, egg density, egg drift and larval drift were made between non-rehabilitated and artificial habitats to determine preferred spawning locations and preferable hydraulic conditions for spawning and incubation habitats.

The Wilson River was monitored for three years following riffle construction in 1988. A summary of the results is presented in Table 4-13. The data indicate that mean egg density was greater at artificial riffle-pool sites than at non-rehabilitated locations, but that survival of the eggs during the incubation period was similar in both reach types.

Table 4-13: Summary of walleye egg and larvae data for rehabilitated and non-rehabilitated reaches in Wilson River, 1989-1991.

Year	Reach Type	Eggs			Larva	
		Mean Density (no./m^2)	Percent Live	Estimated Total Drift	Number per Vol. (no./m^3)	Estimated Total Drift
1989	Rehab	162.23	86.3	-	0.726	29474
	Non-Rehab	11.38	83.0	-	0.085	5585
1990	Rehab	98.20	86.8	-	[1]0.048	41537
	Non-Rehab	77.84	86.1	-	[1]0.049	71140
1991	Rehab	162.05	44.7	663422 [2](451071)	0.137	426388 [2](185945)
	Non-Rehab	76.35	52.3	321158 [2](172708)	0.101	313575 [2](74508)

1. High stream flows prevented a complete assessment of larval drift
2. In parentheses are the estimated values for one riffle-pool sequence

In the Wilson River, the reconstructed reach was situated downstream of the non-rehabilitated reach. As a result drift catches did not quantify the production within the rehabilitated reach type alone or within a specific length of stream. In 1991, egg and larval production were estimated for one riffle-pool sequence in each reach type so that a more direct comparison could be made between artificial and non-rehabilitated habitats. The preliminary results indicated that the artificial riffle-pool had a higher egg and larval drift production than non-rehabilitated habitat. Further testing of drift net sampling efficiency and the effect of net siting in the channel is being undertaken to obtain more conclusive drift estimates.

Design Example 4: North Pine River

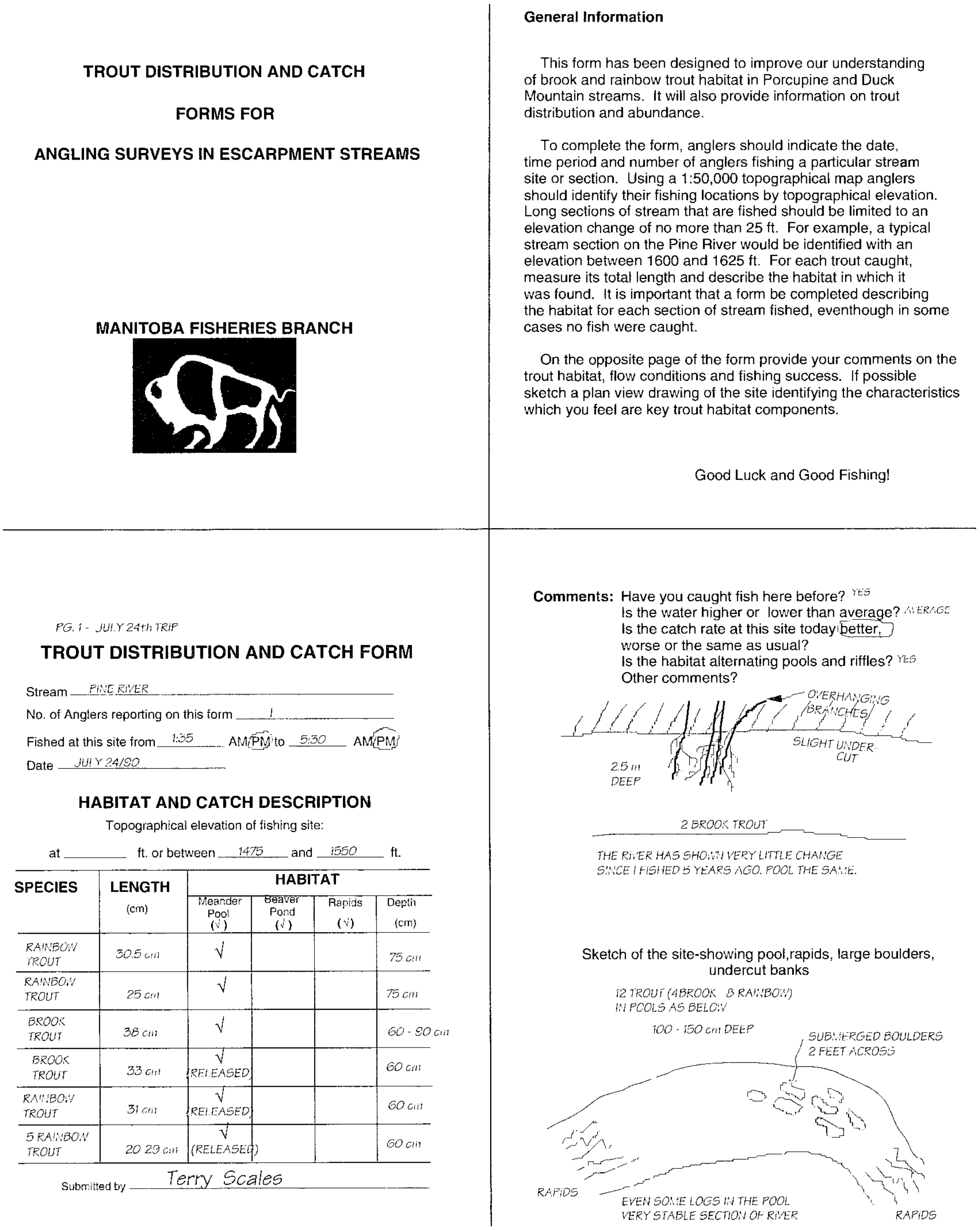
Trout Habitat Enhancement

Project background

The Pine River flows from the foot of Baldy Mountain in the Duck Mountain portion of the Manitoba escarpment to Lake Winnipegosis (Figures 1-3 and 1-5). A topographic model of the basin is shown in Figure 1-7.

The Pine River supports one of the few resident rainbow trout (Oncorhynchus mykiss) and brook trout (Salvelinus fontinalis) populations in south-western Manitoba. Adult trout are widely distributed in the lower river, particularly in meandering reaches with pools that are greater than 0.7 m deep under low flow conditions. Under higher flow conditions, some trout have been caught in the middle reaches of the stream in tributaries to the main stem, particularly in beaver dam impoundments in Middle Creek and Clearwater Creek. However, with low and moderate flows, there are rapidly-flowing shallow reaches paved with large boulders and cobbles that obstruct fish passage and do not allow meanders or pools to form. A typical straight reach in the Upper Pine River is shown in Figures 2-8 and 4-40. The characteristics of the reach are discussed as survey and evaluation examples in Chapter 2 and Chapter 3.

In 1990, Swan Valley Sport Fishing Enhancement Inc. raised funds to create more trout habitat in the middle reaches of the Pine River. To gather information for designing the enhancement works, the members of the Association described ”ideal” trout fishing reaches on the lower Pine and adjacent streams. Based on these initial interviews, probable sites were chosen along several streams for sample fishing. The “trout distribution and catch form” shown in



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!

PG. 1 - JULY 24th TRIP

TROUT DISTRIBUTION AND CATCH FORM

Stream PINE RIVER
No. of Anglers reporting on this form 1
Fished at this site from 1:35 AM/[✓ PM] to 5:30 AM/[✓ PM]
Date JULY 24/90

HABITAT AND CATCH DESCRIPTION

Topographical elevation of fishing site:

at ______ ft. or between 1475 and 1550 ft.

SPECIES	LENGTH (cm)	HABITAT			
		Meander Pool (√)	Beaver Pond (√)	Rapids (√)	Depth (cm)
RAINBOW TROUT	30.5 cm	√			75 cm
RAINBOW TROUT	25 cm	√			75 cm
BROOK TROUT	38 cm	√			60 - 90 cm
BROOK TROUT	33 cm	√ (RELEASED)			60 cm
RAINBOW TROUT	31 cm	√ (RELEASED)			60 cm
5 RAINBOW TROUT	20 29 cm	√ (RELEASED)			60 cm

Submitted by Terry Scales

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

THE RIVER HAS SHOWN VERY LITTLE CHANGE SINCE I FISHED 5 YEARS AGO. POOL THE SAME.

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

12 TROUT (4BROOK 8 RAINBOW)
IN POOLS AS BELOW

EVEN SOME LOGS IN THE POOL
VERY STABLE SECTION OF RIVER

***Figure 4-37:** Sample trout distribution and catch forms used by volunteer anglers to identify preferred trout habitats.*

Figure 4-37 was completed for each sample reach by the volunteer anglers. Obtaining volunteers was not difficult and the quality of sketching and reporting was outstanding.

The best trout sites occurred in meanders with deep pools and helical flows as shown in Figures 2-10, 3-16, and 3-17. On the lower Pine, two of the sites were surveyed in detail. The characteristics of the pools, riffles, and meanders were then used as design guidelines for constructing two experimental meanders in a straight reach of the North Pine River. The meanders were constructed in November 1990.

The North Pine River project is summarized in the following sections in the design steps presented in Figure 4-1.

1) Drainage basin

The boundaries of the Pine River drainage basin shown in Figure 1-3 were sketched using 100 ft contours on 1:250,000 NTS Map Sheet 62N. The area of the Pine River basin that is tributary to the gauging station is 210 km^2. The area tributary to the North Pine sample reach was estimated to be 100 km^2.

2) Profiles

The general profile shown in Figure 1-3 is concave upwards with three distinct segments on and below the escarpment. To define the cusp segments in more detail, a larger scale profile was prepared using 25 ft contour intervals on 1:50,000 NTS maps. The profile was combined with a geologic cross-section of the escarpment prepared by Klassen (1979) to determine where and at what elevations the streambed intersected different surficial deposits and bedrock formations. The basin plan and cross-section are shown in Figure 4-38.

In the glacial till on top of the escarpment, the bases of local cusps coincide with beds of coarse stratified deposits that are more resistant to erosion than the overlying deposits in the upstream reaches. The stable North Pine River enhancement site flows through a bouldery stratified deposit at elevation 549 ASL (1800 ft). The local slope in this stable reach is 2.2%, about 1.5 times the average slope in the middle segment of the profile.

The elevation of the base of the cusps in the lower half of the profile coincide with the upper bedrock surface and the upper levels of more resistant bedrock units in the geological cross-section. The two

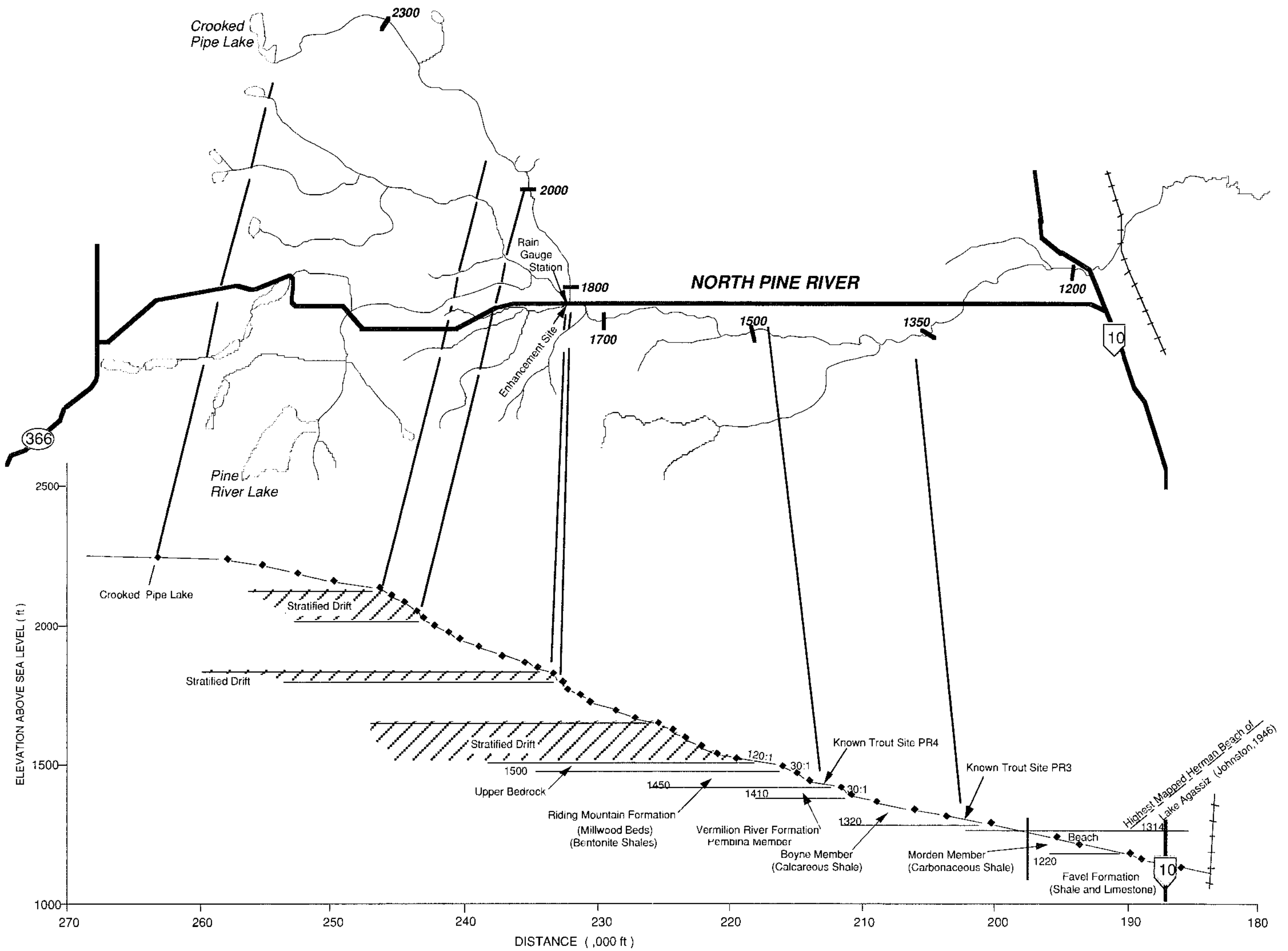


Figure 4-38: Plan, long profile, and geologic cross-section of the Pine River basin. Local cusps in the profile are formed as the stream encounters resistant glacial deposits and bedrock outcrops.

preferred trout habitat survey sites occur in meandering reaches of the lower half of local cusps in the profile. The average slope of the profile in this segment of the stream is 1% while the slope of the habitat reaches is only 0.6 %.

3) Flow

The Pine River gauging station is located at the base of the escarpment near the town of Pine River. The records are summarized in Table 1-3. Annual flood frequency curves for the gauged site and for the North Pine site were shown as examples in Figure 3-3. Based on the reach surveys presented in Chapter 2, the estimated bankfull flow for the North Pine site was 6.7 m³/s. On the annual flood frequency curve, this flow represents the average annual flood peak. The estimated bankfull flow was adopted as the design flow for the channel enhancement works.

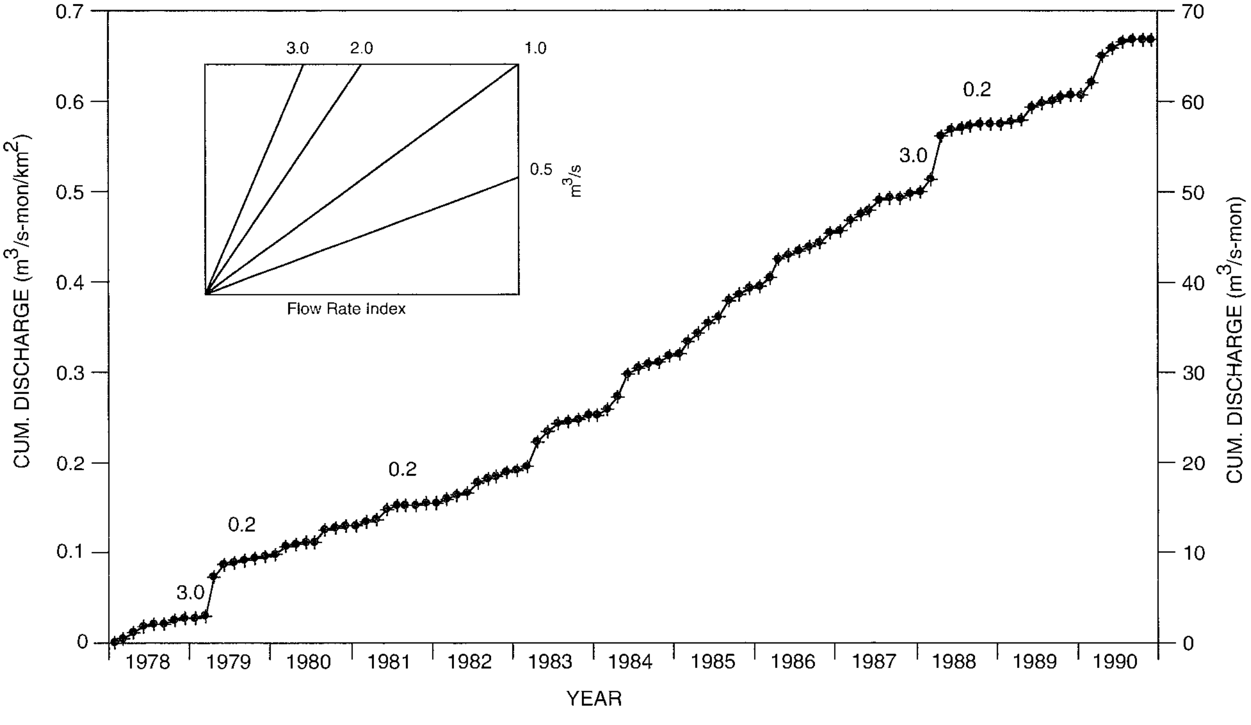


Figure 4-39: *Mass curve of monthly flows for the North Pine River 1978-1990.*

The mass curve of monthly flows for the North Pine site is shown in Figure 4-39. The flows are steady in the open-water season because of natural regulation by upstream storage in small lakes and marshes on the top of the escarpment. The average monthly flow for the open water season in the 1978-1990 period was 0.6 m^3/s. The lowest monthly mid-summer flows were maintained at 0.2 m^3/s and Spring runoff flows did not exceed 3 m^3/s. The lowest flow period occurs in mid-winter. During this period, resident fish populations have been observed in beaver ponds above and below the North Pine site. Open water is maintained only in reaches with inflowing groundwater. This condition occurs in the upper half of the North Pine site.

4) Channel geometry surveys

The channel geometry surveys and evaluations for the North Pine site are discussed in Chapters 2 and 3. The characteristics of the channel are summarized in Table 4-14.

In Figure 3-4, the predicted bankfull discharge lies along a general line for the relationship between bankfull discharge and drainage area for small southern Manitoba basins. The bankfull width and depth lie within the range of similar relationships shown in Figure 3-7.

Table 4-14: North Pine River channel characteristics.

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

The size distribution of the boulders and large cobbles paving the streambed was shown in Figure 2-7. At the bankfull stage, all of the bed paving materials are stable.

5) Enhancement reach survey

The North Pine survey reach and a similar straight segment of the stream above the Beaver Lake Provincial Road crossing was used for the experimental trout habitat meander project. The natural reach prior to construction is shown in Figure 4-40. The plan and profile of the project reaches are shown in the upper diagram in Figure 4-41.

6) Preferred habitats

Reference studies of preferred adult trout habitats show the highest probability of use for stream reaches with flow velocities of 0.4 m/s (1.4 ft/s), depths of 0.6 m (2 ft) or more, water temperatures of 13 - 21 °C (55 to 70 °F), and a substrate of gravels, cobbles, and boulders (Bovee 1978). A typical trout habitat reach on the lower Pine was used as a template for the design. The meandering reach is shown as a survey example in Figure 2-10. The pattern and hydraulic habitat characteristics are discussed with Figures 3-16, 3-17, and 3-20 in Chapter 3.

7) Enhancement works

The existing channel alignment in the project reach was determined using baselines and channel cross-sections (see Observation 6, Chapter 2, Figure 2-8). The channel alignment in the reaches

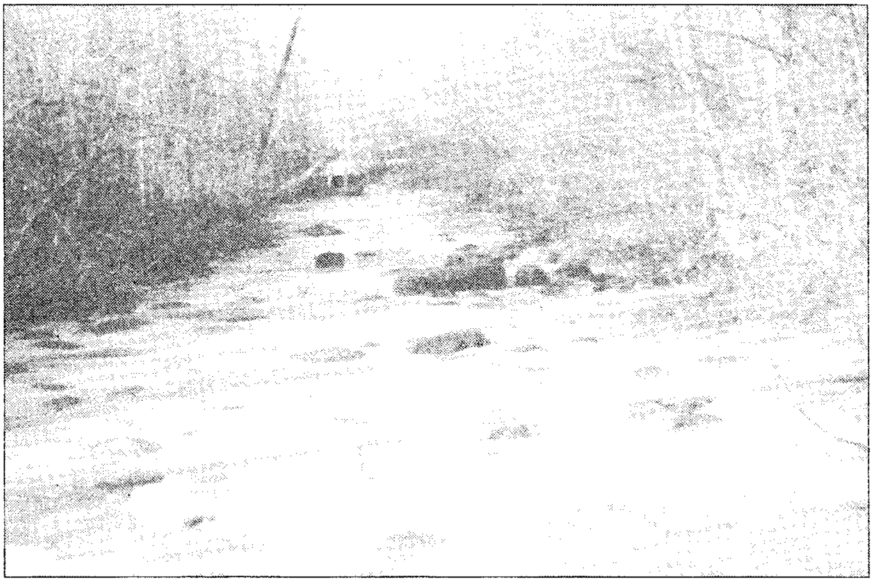


Figure 4-40: *The uniform straight channel of the North Pine enhancement reach prior to construction. A highway bridge is located in the middle of the reach.*

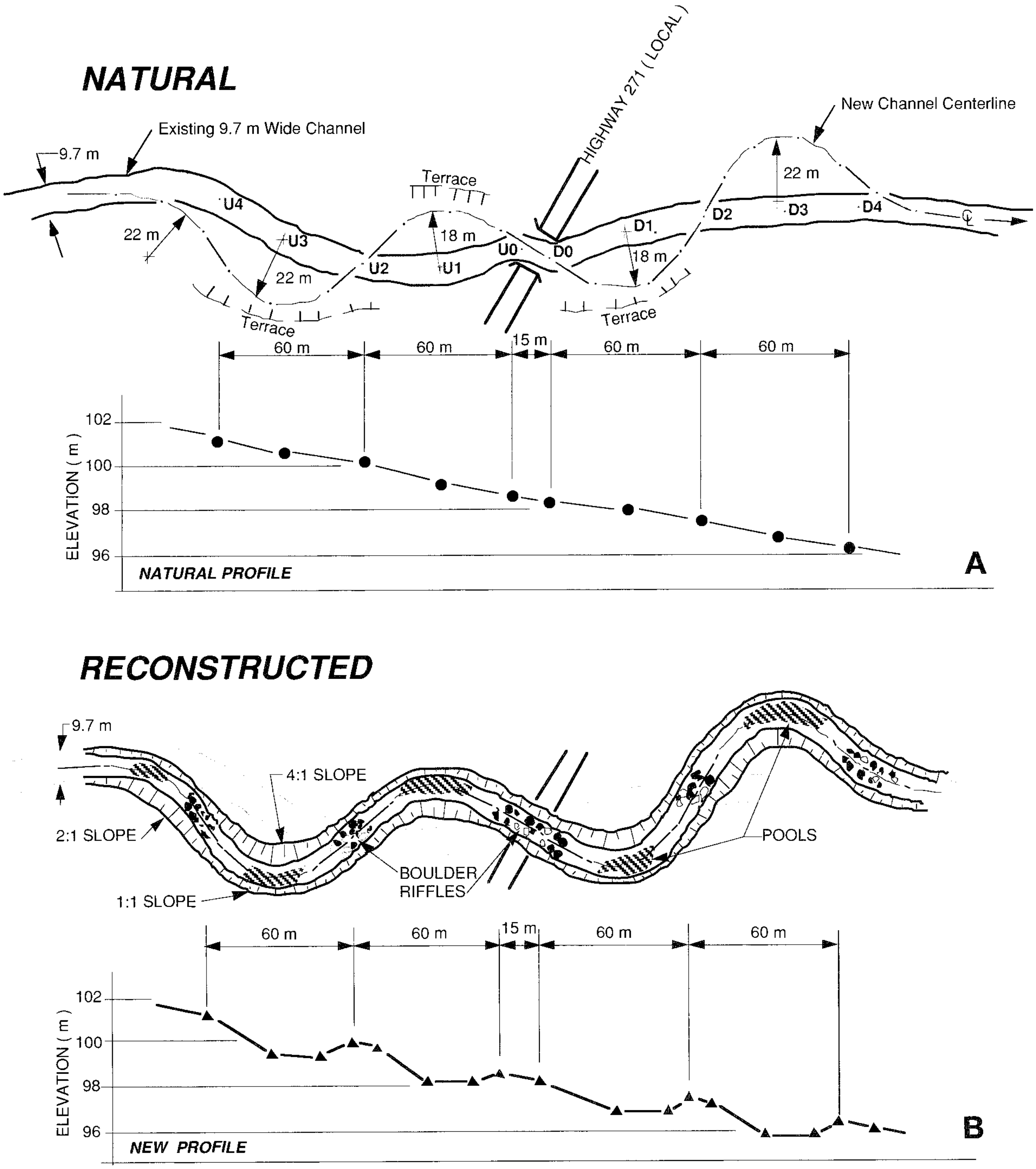


Figure 4-41: *North Pine trout habitat enhancement reach before (A) and after (B) re-alignment into meanders and excavation of a pool and riffle profile.*

upstream and downstream from the project area was scaled from air photos. Cross-sections of the channel and floodplain were surveyed every 30 m upstream and downstream from the highway bridge. The stations are shown as U0 to U4 upstream and D0 to D4 downstream in Figure 4-41A.

Meanders were designed at a spacing of 120 m, or 12.4 times the bankfull width of 9.7 m. The riffles were spaced at 60 m, or 6.2 times the bankfull width. The ratio of width to depth is slightly greater than the template site shown in Figure 3-16, but close to the average for bedrock and alluvial streams (Evaluation 5, Chapter 3).

The amplitude of the meanders was selected to fit between terraces that rose 1 to 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. The mean radius observed in many meanders is 2.4 times the bankfull width (Chang 1988). The radius was reduced to 18 m in the central bends to produce a straight alignment with the highway bridge. The centreline and geometry of the meander loops are superimposed on the existing channel in Figure 4-41A.

A pool and riffle profile was designed for the meandering channel (Figure 4-41B). The original riffle sections were used as cross-over points for the meanders, although some additional large rocks were added at 0.2 m to 0.5 m spacing to produce chutes at low and intermediate flows. Pools were excavated between the riffles to depths varying from 0.5 m to 0.7 m below the riffle crests. The channel cross-sections were varied as shown in Figure 4-42. In the meander pools, the cross-section is designed with 1:1 slopes on the outside of the bend and 4:1 slopes on the inside of the bend to mimic naturally skewed sections. In the riffle zones, the cross-sections are regular, with 2:1 slopes on both sides of the stream. It is anticipated that the cross-sections will become more continuously rounded as the channel sides erode with subsequent bankfull flows. A short 15 m reach with a regular cross-section was developed in an extended riffle that passes under the highway bridge.

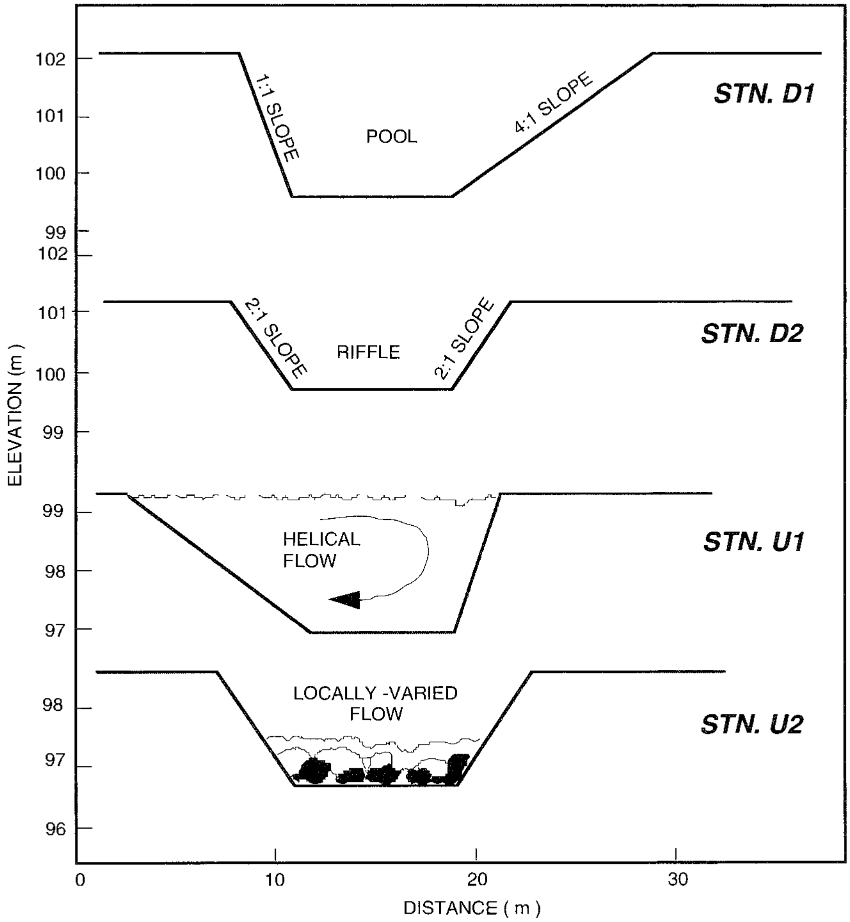


Figure 4-42: *Variation in excavated cross-sections through the excavated meanders in the North Pine River project.*

The natural straight channel was stable at the estimated bankfull flow of 6.7 m^3/s. The constructed meanders in the stream segment decreased the average slope in the reach from .022 to .018, increasing the stability even further. The local slope of the riffle sections was not changed but the average size of the bed paving materials was increased by adding spaced boulders to create aeration zones and diverse local flow conditions.

8) Instream flow requirements

The existing naturally regulated flow regime of the Pine River (Figure 4-39) presently supports the resident trout population and requires no augmentation (discussed in Section 3). In low-flow years the excavated pools in the meandering reach would decrease to an average depth of 0.6 m. Assuming the beaver population will not be removed, ponds above and below the enhancement reach should continue to act as winter refuge. Fish passage between the ponds has been improved by increasing the mean depth and creating narrow chutes through the riffle sections in the enhanced reach.

9) Supervise construction

The alignment of the new meandering channel was established by measuring offsets from the centre of the existing channel. The tops of the channel banks were marked with survey stakes, allowing for an 8 m base and varying side slopes. The meander path was then cleared by hand by members of the Swan Valley Sport Fishing Enhancement group and students of the Swan Valley Regional High School (Figure 4-43).

Figure 4-43: *Volunteers clearing the meander path as it crosses the original channel of the North Pine enhancement reach.*

The channel was excavated with an 0.5 m^3 bucket track-mounted backhoe assisted with a small bulldozer to infill the old channel (Figure 4-44).

Where possible, existing trees along the new course of the channel were saved, particularly on the outside of the meander bends to provide cover over the newly excavated pools. The completed meander upstream from the highway bridge is shown in Figure 4-45. In 1991, the project reach was re-planted with local trees and shrubs by volunteers from the Swan Valley Regional High School.

Project labour, costs and materials are summarized in Table 4-15.

Table 4-15: Materials and costs for the North Pine trout habitat project.

Machine Rental	
96 hours backhoe	$7200.
70 hours bulldozer	$3850.
Labour	
surveys	15 pd
design	3 pd
clearing	15 pd
re-planting	5 pd
arrangements	2 pd
supervision.	11 pd

10) Monitor and adjust design

In 1991, a moderate spring flood peak was observed at the Pine River gauging station of 5.74 m^3/s, equivalent to an annual flood peak frequency of 92 % (Figure 3-3). The flood peak in the excavated meandering reach was estimated to be 3 m^3/s. Following the peak, a small delta of coarse sands was observed in the upper pools. There was no movement of the cobbles and boulders in the riffle zones. Trout were observed and caught in the project reach in the 1991 open-water season. An aerial view of the excavated meanders under low flow conditions following the first flood peak is shown in Figure 4-46.

Figure 4-44: *Excavation of the first upstream meander bend above the highway bridge in the North Pine project (Figure 4-40 shows the pre-excavation channel).*

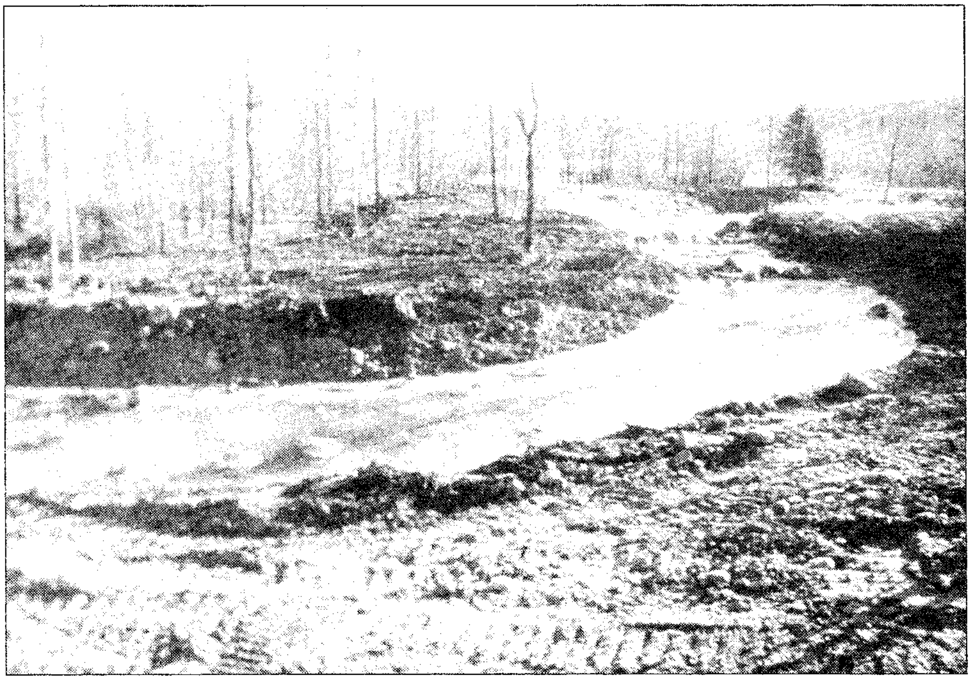


Figure 4-45: *The completed upstream meander bend of the North Pine River trout habitat enhancement project (December 1990).*

Figure 4-46: *Aerial view of the North Pine River trout habitat enhancement reach. The meandering channel mimics successful trout angling reaches surveyed on the lower Pine River and adjacent streams.*

Design Example 5: Whiteshell River

Trout Habitat Enhancement

Project background

The Whiteshell River is a southern tributary of the Winnipeg River that rises on the western edge of the Canadian Shield in south-eastern Manitoba. In the headwater portion of the basin shown in Figure 4-47, a 4.5 km reach of the Whiteshell River connects West Hawk Lake to Caddy Lake in the Whiteshell Provincial Park. The reach is bedrock-controlled with a steep boulder-filled section in the first km below West Hawk Lake followed by a shallow gradient section with frequent beaver ponds in the last 3.5 km above Caddy Lake. The reach is inhabited by minnow species and occasionally by spawning pike, walleye, and white sucker that migrate upstream from Caddy Lake during the Spring spawning season.

In 1991, the Manitoba Fly Fishers Association and Fish Futures Inc. proposed that channel modifications be undertaken in the first kilometre of the natural channel below West Hawk Lake to create adult habitat for rainbow and brown trout. In the existing reach, habitat limitations for trout included a lack of cover and deep pools. There were no undercut banks, overhanging and submerged vegetation, or large organic debris to provide cover in the bedrock channel. Under average flow conditions, the pool depths were only 0.3 to 0.4 m deep, less than the minimum of 0.7 m observed in productive trout streams in the Duck Mountains (see Pine River, Design Example 4).

High water temperatures and inadequate flows in mid-summer, normally a problem in small streams in this region of the Shield, can be avoided in the enhanced reach by utilizing upstream storage on West Hawk Lake and by cold water releases from the Whiteshell Fish

Hatchery located adjacent to the reach. To maintain cool water for the hatchery, supply water is withdrawn from the hypolimnion of West Hawk Lake, passed through fish tanks and discharged to the river. In mid-summer, the water entering the hatchery is about 13 °C and when discharged, less than 18 °C. In winter, water entering and exiting the hatchery is between 2 and 4 °C. Consequently, water temperatures in the enhanced reach below the hatchery discharge point could be maintained in the optimal range for brown and rainbow trout for summer and winter conditions with appropriate releases. The hatchery is also a convenient stocking source for the reach.

A stoplog dam at the outlet of West Hawk Lake controls discharges to the Whiteshell River. In most years releases from the dam occur only in early Spring and late Fall. At present, the only discharge in the river during summer and winter is provided by hatchery releases, which average 0.11 m^3/s. To provide higher continuous discharges during seasons when fish would be stressed by either high water temperatures or a limited number of overwintering pools, a new release schedule for the stoplog dam on West Hawk Lake was prepared by the Manitoba Water Resources Branch with a minimum release of 0.14 m^3/s in mid-winter and 0.28 m^3/s in mid-summer (see Step 8, Instream flow requirements).

The design process for the Whiteshell River reach enhancement project is summarized in the 10 steps presented in Figure 4-1 as follows:

1) Drainage basin

The Whiteshell River connects a series of lakes in Ontario and Manitoba, and has a total drainage area of 1683.5 km^2. The watershed boundaries of the Whiteshell River up to Caddy Lake are identified on the 1:250,000 NTS Map Sheet 52E (Figure 4-47). The area tributary to the enhancement reach is 174.0 km^2.

2) Profiles

The longitudinal profile of the main river channel as it flows from its headwaters in Ontario to the confluence with the Winnipeg River at Nutimik Lake was drawn from the 100 ft contours on 1:250,000 NTS Maps (Figure 4-48). The overall channel gradient is 0.08% . The gradient in the steep local section of the enhancement reach is 0.6 %.

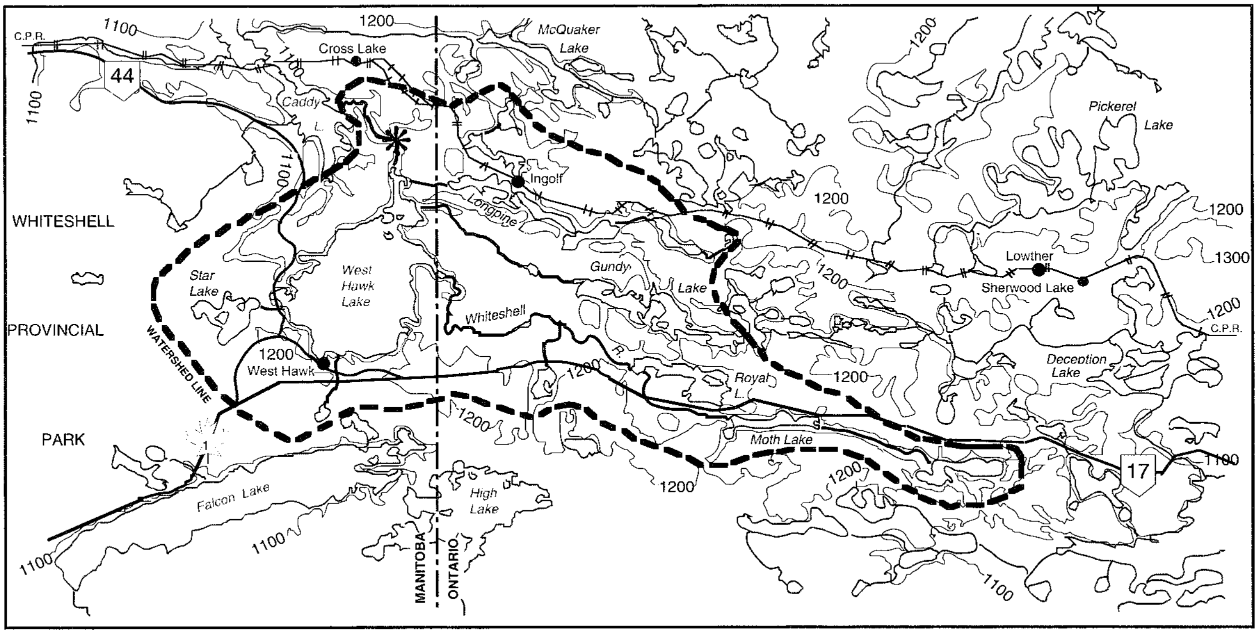


Figure 4-47: *The southern headwater portion of the Whiteshell River drainage basin shown on NTS Maps 52 E and 52L at a scale of 1:250,000. The project reach is marked as* ✳.

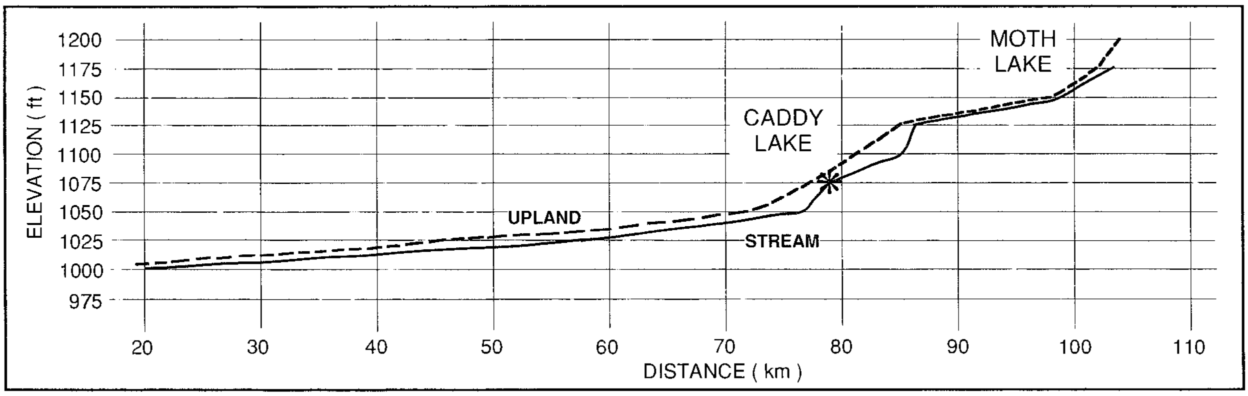


Figure 4-48: *Generalized profile of the Whiteshell River. The project reach is marked as* ✳.

Table 4-16: Whiteshell River discharges monitored at the outlet of Jessica Lake (Water Survey of Canada 1990).

WHITESHELL RIVER AT OUTLET OF JESSICA LAKE - STATION NO. 05PG001

MONTHLY AND ANNUAL MEAN DISCHARGES IN CUBIC METRES PER SECOND FOR THE PERIOD OF RECORD

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	MEAN	YEAR
1960	---	---	2.31	5.00	10.1	5.85	2.87	1.50	1.02	0.770	---	---	---	1960
1961	---	---	1.37	1.53	2.81	1.71	0.269	0.245	0.082	0.217	---	---	---	1961
1962	---	---	---	---	15.1	21.8	8.28	8.49	8.82	---	---	---	---	1962
1963	---	---	---	6.09	7.56	9.14	7.14	3.97	1.62	---	---	---	---	1963
1964	---	---	---	4.03	11.0	6.30	5.06	5.79	6.00	5.67	4.96	3.58	---	1964
1965	2.59	1.97	2.43	7.55	14.1	12.5	9.61	7.00	6.10	8.97	---	---	---	1965
1966	0.441	0.268	0.466	10.7	19.8	18.0	11.7	4.43	4.39	3.11	1.95	1.60	6.42	1966
1967	1.43	1.39	1.57	9.31	14.0	6.64	1.25	1.02	3.32	1.02	1.12	1.66	3.64	1967
1968	1.21	1.18	1.14	5.16	5.22	6.58	8.15	4.19	3.34	4.13	6.35	4.39	4.26	1968
1969	3.27	2.67	2.62	5.15	8.74	2.77	3.02	2.50	1.92	1.78	3.98	2.48	3.41	1969
1970	0.440	0.898	0.774	3.44	15.8	13.9	3.38	1.60	1.87	2.28	8.53	5.59	4.88	1970
1971	3.38	1.84	1.88	7.90	12.5	5.69	1.59	0.685	0.131	0.093	4.10	2.81	3.56	1971
1972	1.76	1.15	1.32	3.43	3.79	2.67	0.475	0.381	0.550	0.830	5.17	2.03	1.96	1972
1973	1.53	1.24	0.777	0.104	0.084	0.339	1.23	2.47	5.35	10.1	10.5	6.99	3.40	1973
1974	4.03	2.97	2.53	10.6	34.4	28.4	4.27	1.75	6.04	6.59	4.01	2.76	9.04	1974
1975	2.30	2.02	2.08	4.30	11.1	7.19	5.72	1.47	1.92	2.01	0.977	0.979	3.52	1975
1976	1.09	1.03	1.09	5.82	8.52	4.39	1.59	0.213	0.243	0.160	0.096	0.084	2.03	1976
1977	0.081	0.073	0.079	0.069	0.531	6.42	5.75	2.81	3.24	5.52	5.43	6.61	3.07	1977
1978	5.55	3.89	2.90	6.42	19.7	8.72	2.00	0.760	0.781	1.98	1.95	1.57	4.69	1978
1979	1.08	1.02	1.18	3.09	14.4	10.4	1.22	0.347	0.326	1.74	1.97	1.91	3.24	1979
1980	1.51	1.16	0.932	1.28	2.39	1.12	0.332	0.229	1.71	2.59	2.77	2.28	1.53	1980
1981	1.56	1.28	0.276	0.074	0.085	0.454	1.34	0.940	1.77	5.26	5.35	3.75	1.85	1981
1982	2.08	1.39	1.49	3.47	10.3	7.25	2.46	1.49	1.13	3.86	3.08	2.09	3.35	1982
1983	1.66	1.42	1.62	1.27	2.37	5.42	2.10	0.411	0.390	2.37	1.76	1.15	1.83	1983
1984	0.649	0.540	0.489	0.177	0.130	3.92	5.24	1.97	0.365	1.65	4.39	4.13	1.98	1984
1985	4.10	2.80	2.32	0.379	8.59	3.85	3.23	1.77	4.74	5.03	5.76	4.78	3.96	1985
1986	3.58	2.62	2.38	6.38	19.2	5.31	1.13	0.918	0.712	2.74	0.598	0.772	3.88	1986
1987	0.744	0.687	0.873	3.79	2.44	1.10	0.449	0.516	0.295	0.258	0.256	0.219	0.966	1987
1988	0.135	0.167	0.225	0.496	0.336	0.272	0.571	0.391	0.280	0.178	0.269	0.392R	0.310R	1988
1989	0.636	0.697	0.705	3.71	12.6	11.2	11.5	5.07	3.80	2.81	2.33	1.91	4.78	1989
1990	---	---	1.44	1.14	3.57	12.3	14.3	5.49	2.16	1.11	0.708	0.629	---	1990
MEAN	1.87	1.45	1.40	4.06	9.40	7.47	4.10	2.28	2.40	2.93	3.40	2.58 R	3.40 R	MEAN

LOCATION - LAT 50 02 20 N
LONG 095 30 20 W

DRAINAGE AREA, 884 km²
REGULATED

R - REVISED SINCE JAN 01 1989

WHITESHELL RIVER AT OUTLET OF JESSICA LAKE - STATION NO. 05PG001

ANNUAL EXTREMES OF DISCHARGE AND ANNUAL TOTAL DISCHARGE FOR THE PERIOD OF RECORD

YEAR	MAXIMUM INSTANTANEOUS DISCHARGE (m^3/s)	MAXIMUM DAILY DISCHARGE (m^3/s)	MINIMUM DAILY DISCHARGE (m^3/s)	TOTAL DISCHARGE (dam^3)	YEAR
1960	---	11.9 ON MAY 04	---	---	1960
1961	---	6.60 ON APR 02	0.028E ON SEP 03	---	1961
1962	---	31.4 ON JUN 04	---	---	1962
1963	---	9.85 ON JUN 12	---	---	1963
1964	---	12.7 ON MAY 15	---	---	1964
1965	---	16.1 ON MAY 17	---	---	1965
1966	---	21.1 ON MAY 07	0.210E ON MAR 23	203 000	1966
1967	---	15.2 E ON MAY 07	0.289 ON JUL 27	115 000	1967
1968	---	13.4 ON JUN 17	1.13 E ON FEB 26	135 000	1968
1969	9.77 AT 07:38 CST ON MAY 05	9.74 ON MAY 05	1.03 ON JUN 04	108 000	1969
1970	19.8 AT 08:36 CST ON JUN 01	19.7 ON JUN 01	0.153 ON JAN 22	154 000	1970
1971	14.8 AT 18:18 CST ON MAY 11	14.7 ON MAY 15	0.074 ON SEP 26	112 000	1971
1972	14.5 AT 19:44 CST ON OCT 31	12.6 ON NOV 01	0.278 ON AUG 11	61 900	1972
1973	12.9 AT 22:39 CST ON OCT 13	12.5 ON OCT 14	0.071 ON MAY 13	107 000	1973
1974	42.5 AT 15:00 CST ON MAY 24 *	42.2 ON MAY 24 *	0.665 ON AUG 09	285 000	1974
1975	12.0 AT 11:55 CST ON MAY 19	11.9 ON MAY 19	0.739 ON AUG 07	111 000	1975
1976	14.7 AT 14:01 CST ON APR 26	13.9 ON APR 27	0.079 ON NOV 23	64 100	1976
1977	15.3 AT 20:11 CST ON JUN 20	14.2 ON JUN 21	0.026 ON APR 29 *	96 800	1977
1978	25.8 AT 15:47 CST ON MAY 03	24.5 ON MAY 04	0.606 ON OCT 12	148 000	1978
1979	21.1 AT 17:47 CST ON MAY 17	20.0 ON MAY 18	0.293 ON SEP 10	102 000	1979
1980	5.57 AT 19:54 CST ON SEP 22	5.20 ON SEP 23	0.169 ON SEP 05	48 200	1980
1981	11.5 AT 15:55 CST ON OCT 13	10.3 ON OCT 14	0.027 ON MAY 02	58 300	1981
1982	13.3 AT 17:52 CST ON MAY 19	13.0 ON MAY 20	0.871 ON AUG 17	106 000	1982
1983	7.89 AT 17:56 CST ON OCT 11	7.53 ON JUN 02	0.268 ON APR 29	57 700	1983
1984	9.77 AT 13:02 CST ON OCT 24	7.71 ON OCT 25	0.040 ON MAY 06	62 500	1984
1985	15.3 AT 17:25 CST ON MAY 14	14.4 ON MAY 15	0.166 ON APR 10	125 000	1985
1986	24.4 AT 23:33 CST ON MAY 09	23.4 ON MAY 10	0.373 ON NOV 03	122 000	1986
1987	6.78 AT 14:54 CST ON APR 22	6.37 ON APR 23	0.145B ON DEC 30	30 500	1987
1988	0.743 AT 14:33 CST ON APR 16	0.722 ON APR 16	0.124 ON JAN 05	9 800	1988
1989	18.9 AT 16:40 CST ON JUN 26	17.7 ON JUN 27	0.488 ON JAN 01	151 000	1989
1990	17.8 AT 03:11 CST ON JUL 07	17.5 ON JUL 07	0.587 ON DEC 31	---	1990
				107 000	MEAN

B - ICE CONDITIONS
E - ESTIMATED

* - EXTREME RECORDED FOR THE PERIOD OF RECORD

3) Flow

Flow records are maintained for a gauging station at the outlet of Jessica Lake (Table 4-16). The drainage area tributary to the station is 884 km^2. From the flood frequency plot for the gauging station, the bankfull discharge (67% event) is 10.5 m^3/s (Figure 4-49). The bankfull discharge of the enhancement site calculated using drainage area ratios only is 2.1 m^3/s. Although this approximation may be used for unregulated rivers, in this case it must be modified to allow for upstream storage on West Hawk Lake and the releases made at the stoplog dam located on the lake outlet.

Using lake elevation and dam operation records, typical discharges in the reach were hindcast for the 1984 to 1990 period by Manitoba Water Resources Branch. Between 1984 and 1990 the maximum flow was estimated to be 5.5 m^3/s. With appropriate operation of the stoplog dam, the natural bankfull or channel maintenance discharge of 2.1 m^3/s could be regularly attained. Adjustments to the timing of the releases will be required as well to assure mid-winter and mid-summer flows.

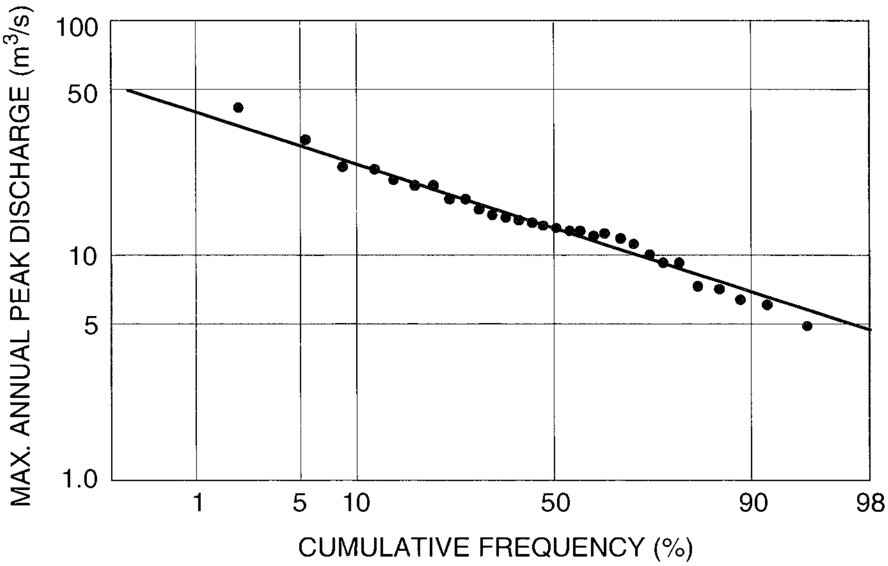


Figure 4-49: *Whiteshell River annual flood frequency curve (gauging station).*

4) Channel geometry surveys

A survey of the natural Whiteshell River channel downstream of West Hawk Lake was made prior to enhancement. The channel geometry measurements are summarized in Table 4-17.

In the upstream portion of the enhancement reach the river width is controlled by outcrops of Precambrian granitic rock in a narrow steep-walled valley (Figure 4-50). In the lower gradient downstream portion of the reach, the valley widens and the channel meanders through a narrow floodplain composed of clays and sandy silts that shallowly (< 2 m) overly the bedrock surface (Figure 4-51). Bankfull width in the upstream portion is 9.0 m and in the downstream section is 13.2 m. For streams in this region, the estimated bankfull width for a drainage area of 174 km^2 is approximately 11 m (Figure 3-7).

Table 4-17: Whiteshell River natural channel characteristics.

bankfull width	10.3 m
bankfull depth	0.3 m
average slope	0.006
median bed paving material size	10.0 cm
assumed bankfull roughness	0.027
predicted bankfull velocity.	1.3 m/s
bankfull tractive force	1.7 kg/m^2
bankfull Froude number	0.74
bankfull discharge.	4.0 m^3/s

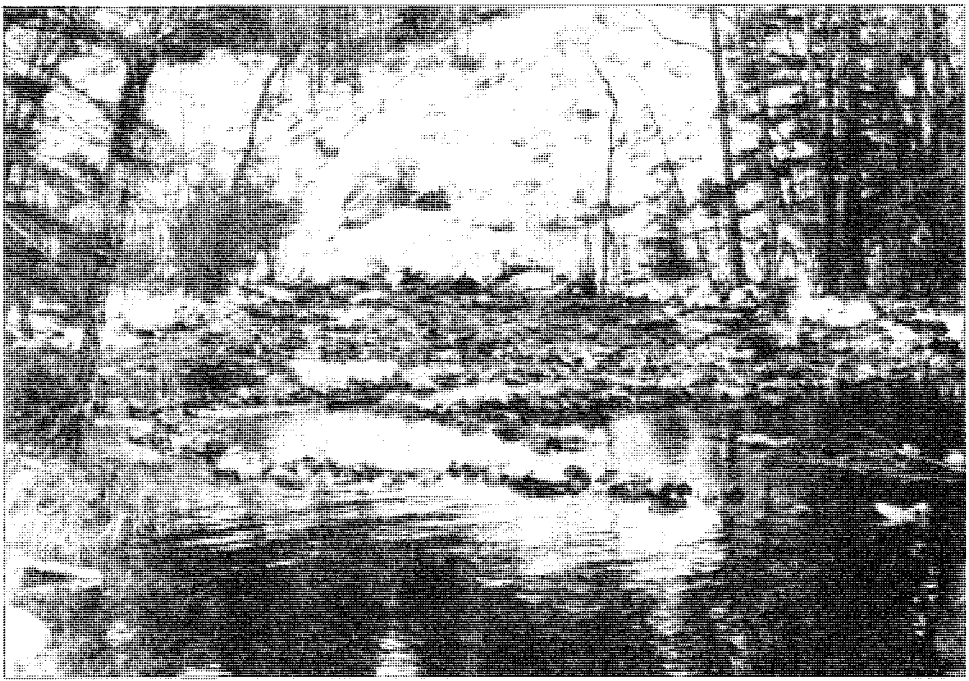


Figure 4-50: *Rocky upstream segment of the Whiteshell River trout habitat enhancement reach.*

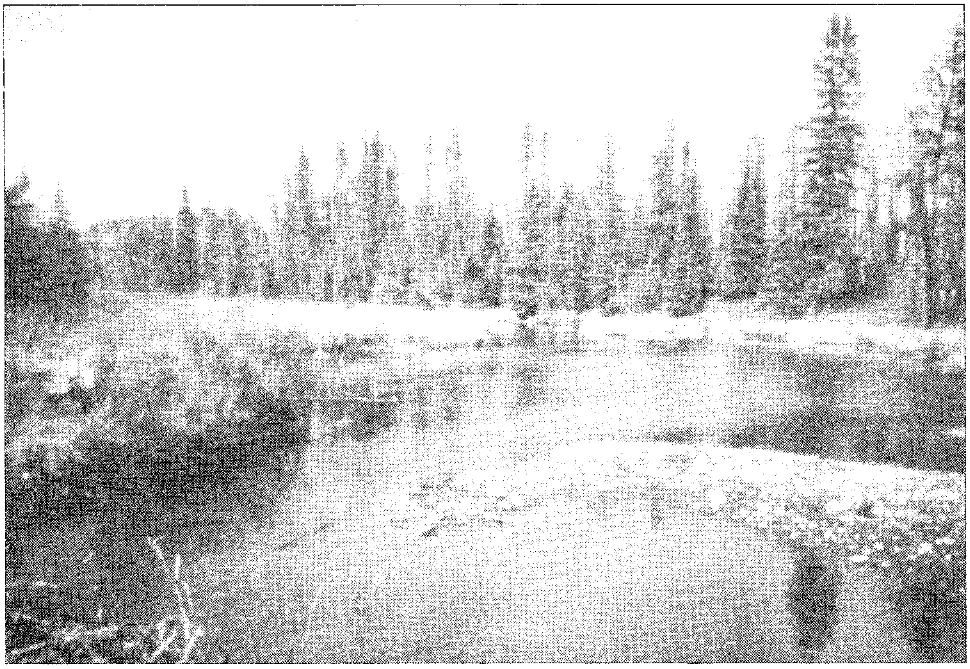


Figure 4-51: *Meandering low gradient segment of the Whiteshell River trout enhancement reach.*

5) Enhancement reach survey

Channel bed and water surface profiles and cross sections were surveyed in February 1991. The profiles and representative cross sections are shown in Figures 4-52 and 4-53.

6) Preferred habitats

All life stages of rainbow and brown trout are dependent on the cover created by overhanging vegetation, undercut banks, debris piles, logs, etc. (see Raleigh et al. 1984 and 1986, Appendix A). They also prefer stream channels with pools to retain water during low flow periods, riffles for re-aeration of the flows and clear, cold water. Although the enhancement site had riffles primarily in the upstream reach and shallow pools in the lower reach there were very few riffle-pool combinations. All types of cover including deep pools were limited in the enhancement reach.

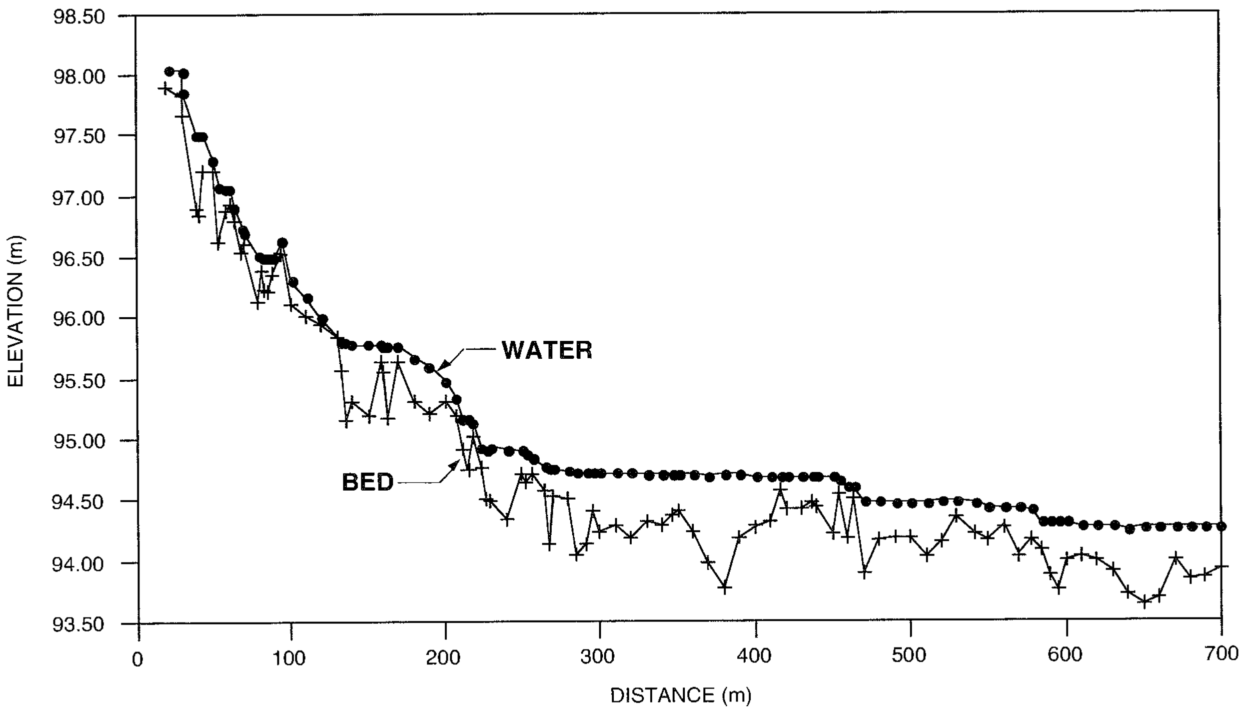


Figure 4-52: *Water level and bed profiles at the trout habitat enhancement site on the Whiteshell River.*

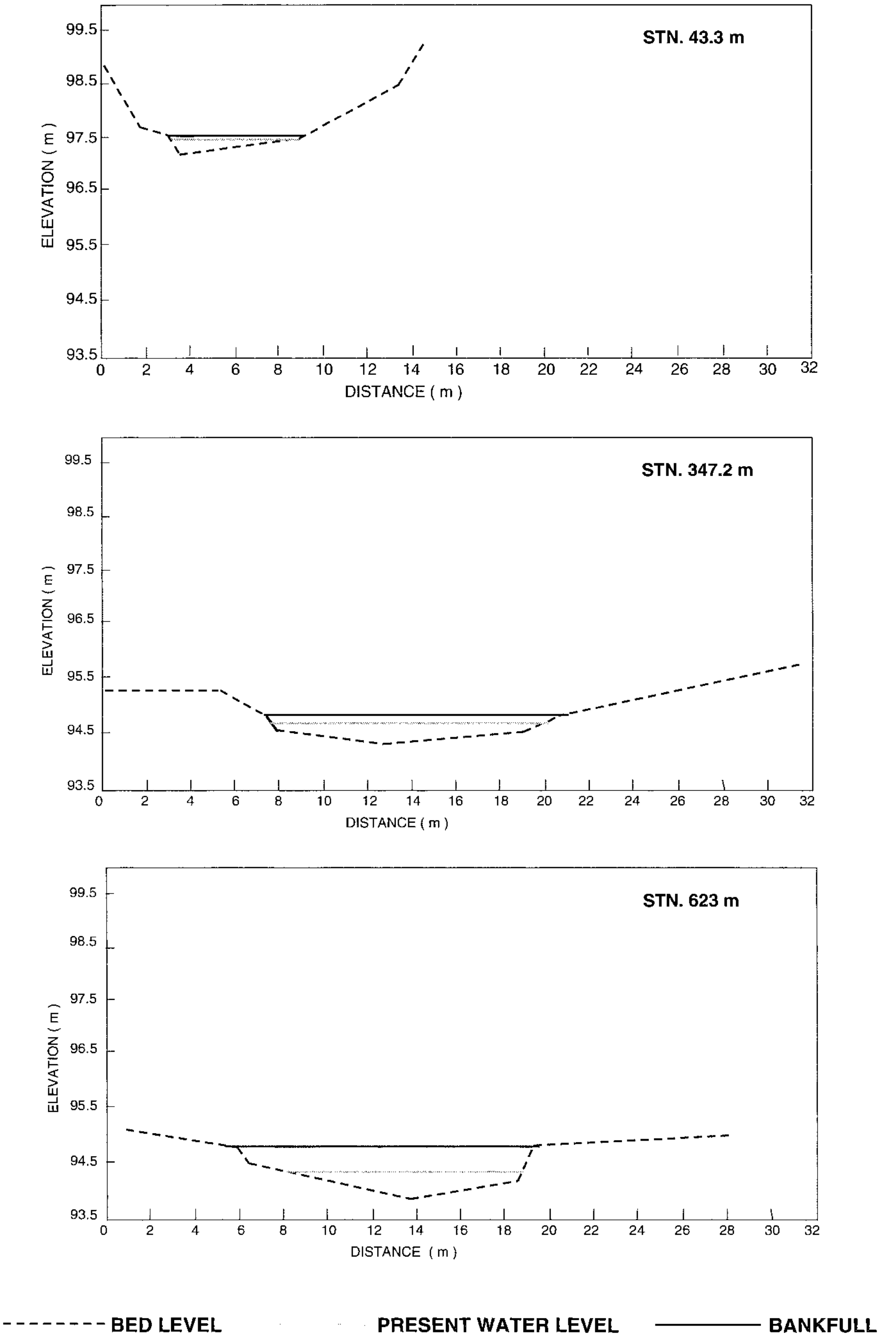


Figure 4-53: *Typical cross-sections in the trout enhancement reach on the Whiteshell River.*

For the Whiteshell site, optimal temperatures and sustained flows can be provided by utilizing cool water releases from the Whiteshell Fish Hatchery and by operating the stoplog dam on the outlet of West Hawk Lake to improve flows in all seasons (see Step 8, Instream flow requirements).

7) Selecting and sizing enhancement works

The overall plan of the enhancement project is shown in three parts in Figures 4-54, 4-55, and 4-56. To create pool-riffle sequences over the upper 350 m of the enhancement reach, seven rock riffles were constructed with local bed material.

The total fall in the upper reach was redistributed into seven steps, averaging five times the channel width as shown in Figure 4-57. The riffle design was similar to that used in other rehabilitation and enhancement projects with a steep upstream face and shallower downstream face (Figure 4-16).

The riffle crest elevations were set to create a minimum upstream pool depth of 0.7 m with limited flooding of the existing floodplain. Further excavation of the pools to depths of 1.0-1.5 m was undertaken in locations where bedrock was absent.

Cover structures were made from spruce trees that were felled nearby and placed in excavated cuts in the streambank (Figure 4-58). Excavated material from the pool and bank was used to cover and secure the overhanging trees.

The meandering channel pattern was reinforced by constructing point bar extensions and blocking shallow side channels. Excavated bed materials were used to build up the banks and islands (see Step 9, Supervise construction).

8) Instream flow requirements

A mass curve of estimated monthly flows for the Whiteshell River enhancement reach based on the tributary drainage area and the gauging station records for the years 1979 - 1990 is shown in Figure 4-59. In the sample period of 12 years, the maximum continuous flow

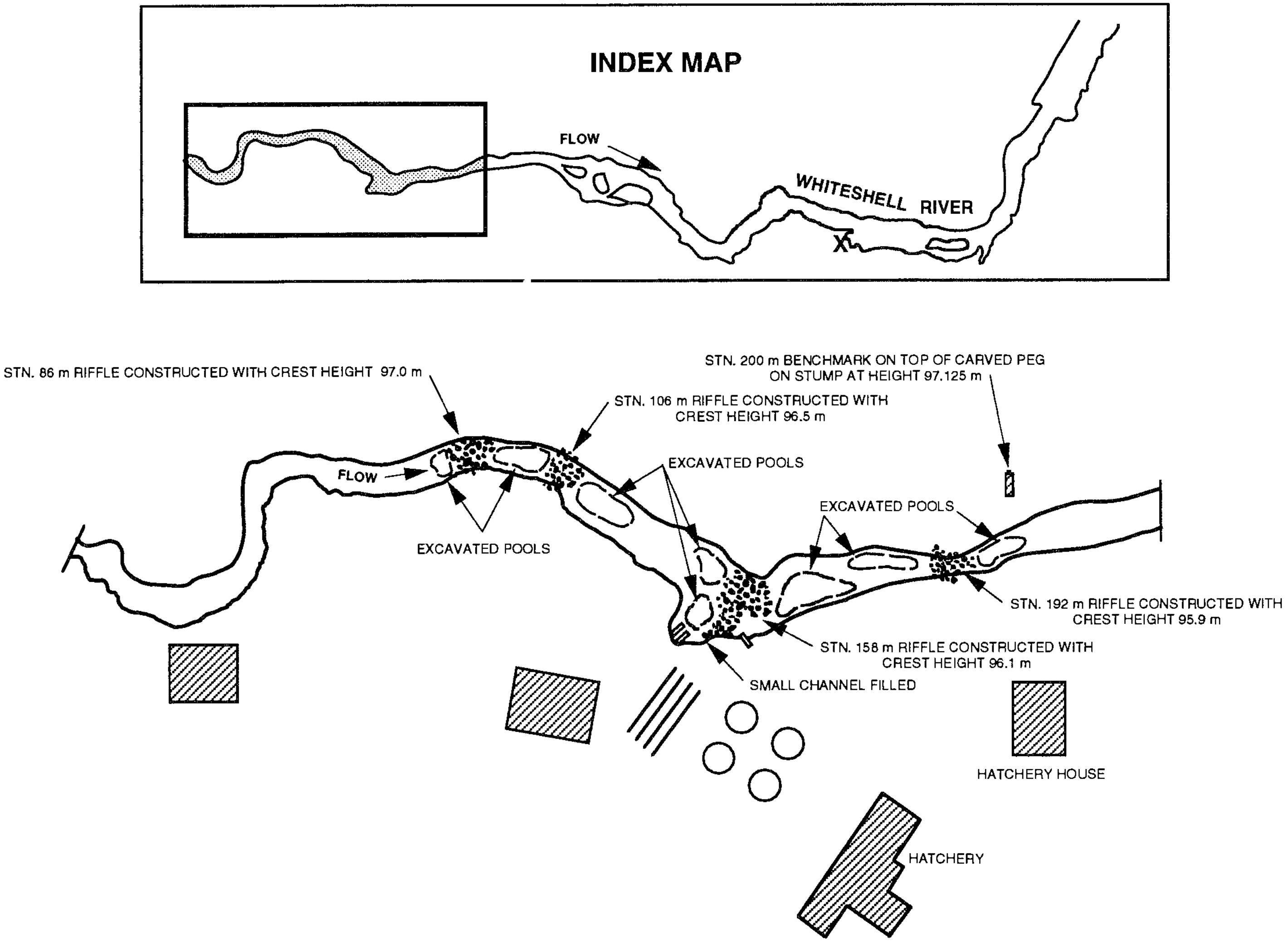


Figure 4-54: *Plan of channel reconstruction in the upper third of the trout enhancement reach on the Whiteshell River.*

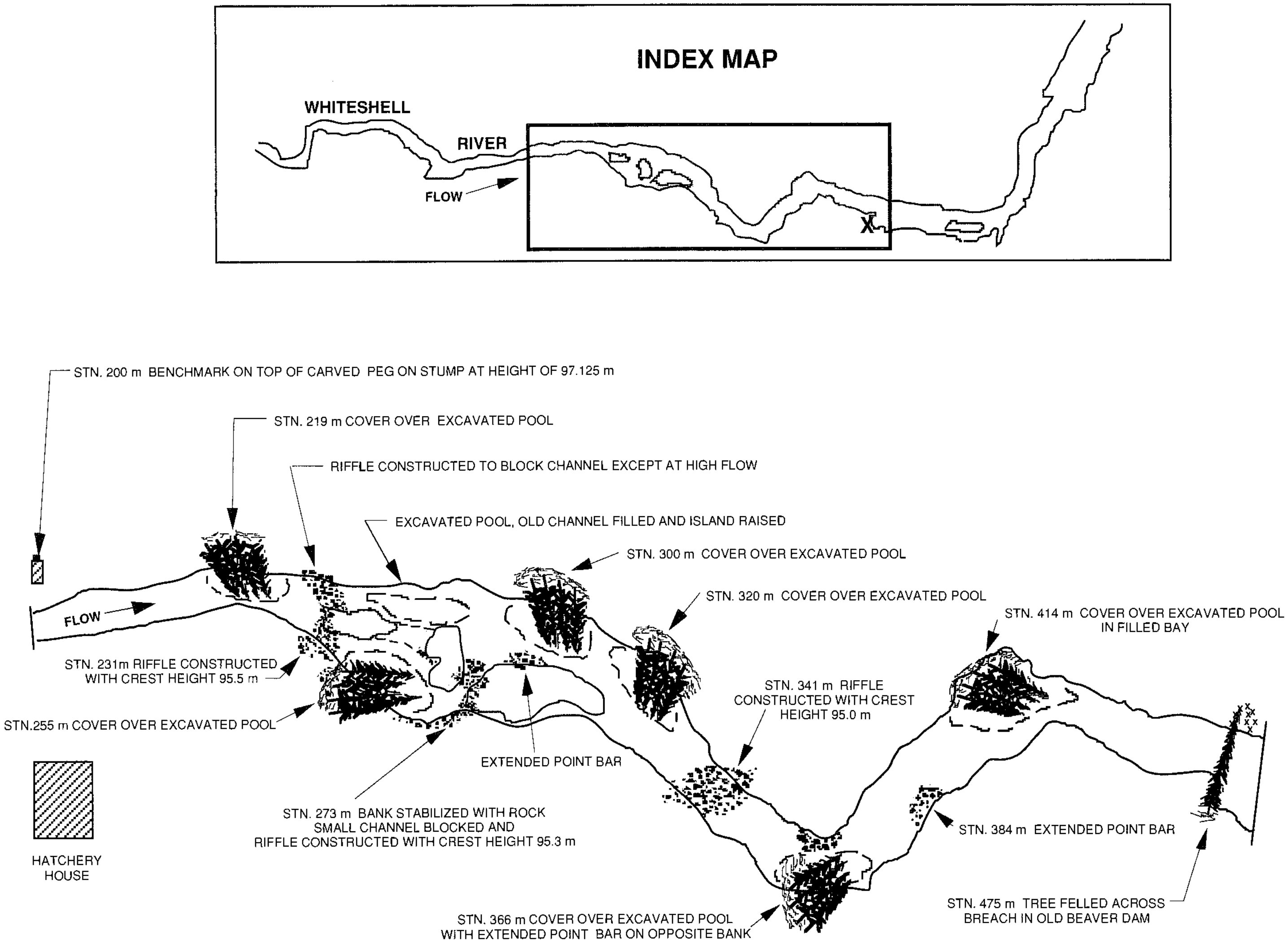


Figure 4-55: *Plan of channel reconstruction in the middle third of the trout enhancement reach on the Whiteshell River.*

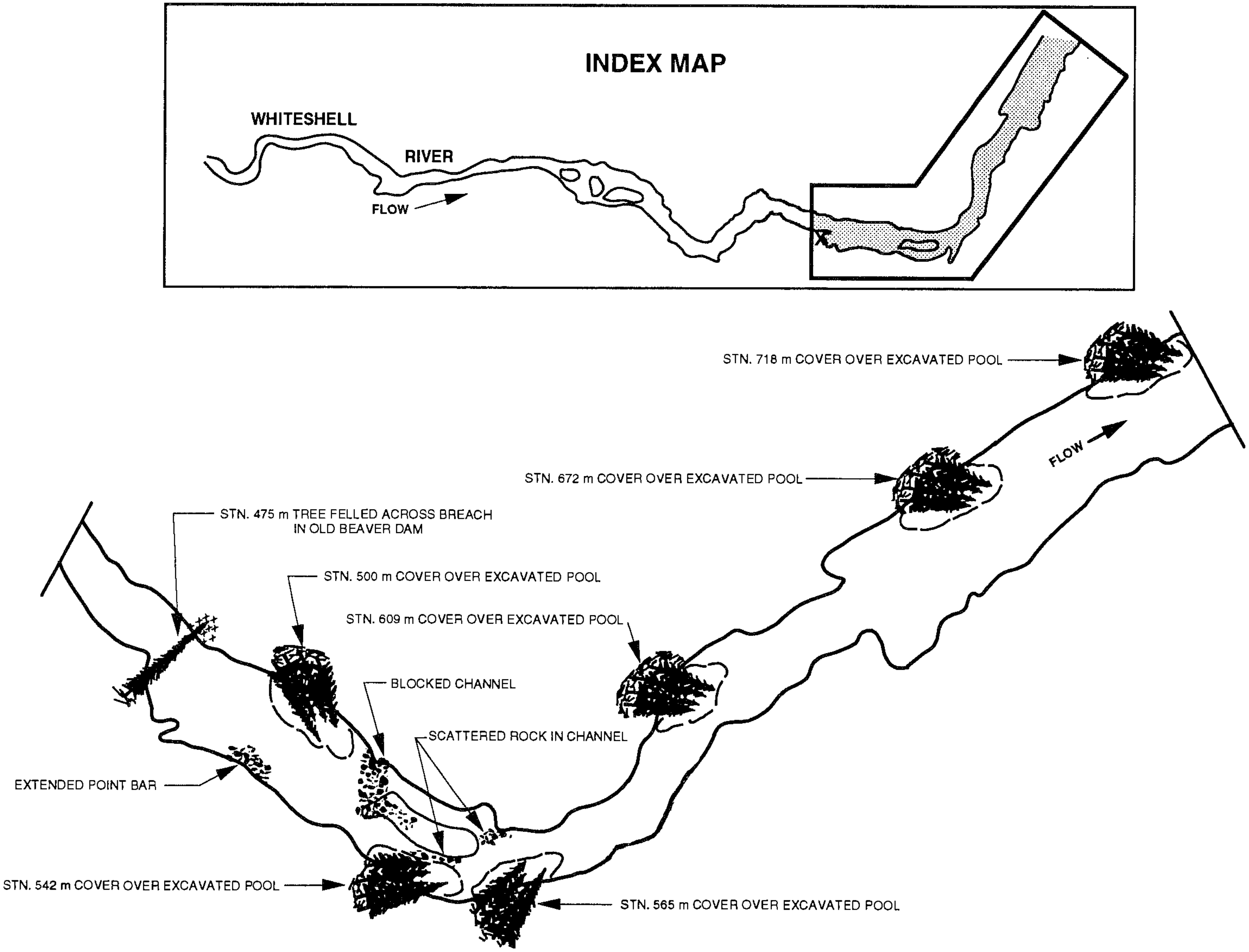


Figure 4-56: *Plan of channel reconstruction in the lower third of the trout enhancement reach on the Whiteshell River.*

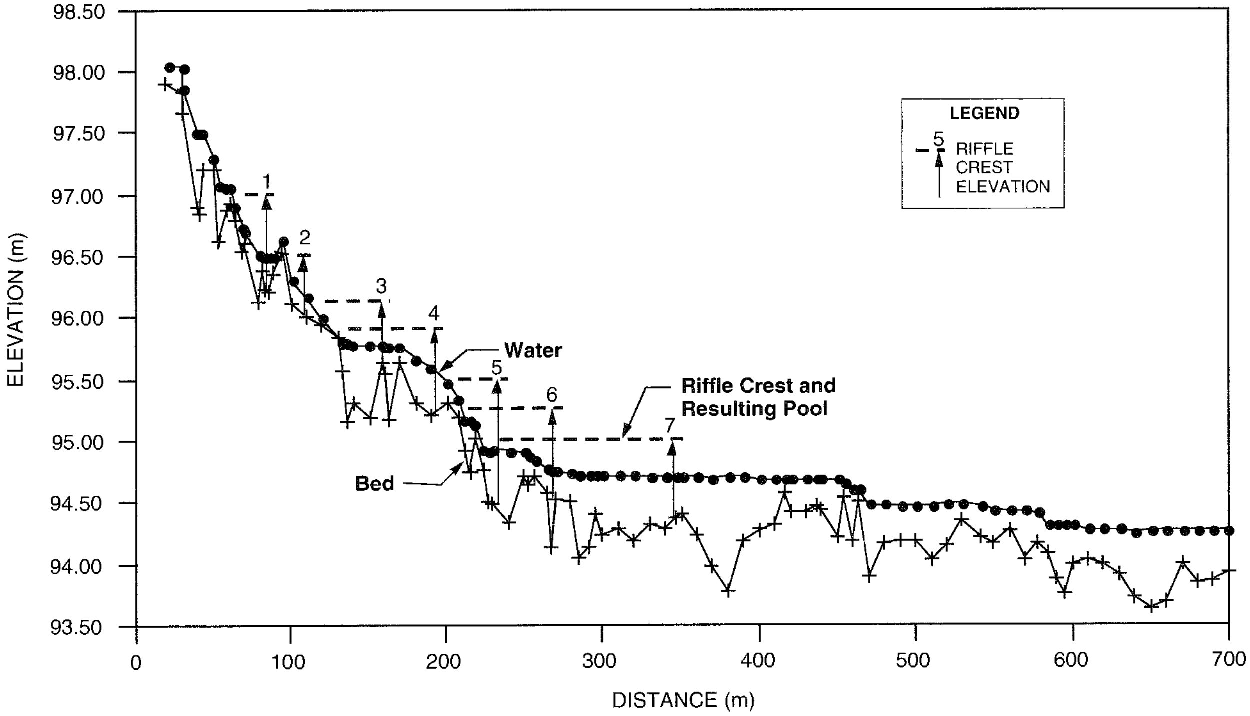


Figure 4-57: *Channel and water surface profiles showing the location and elevations of seven riffles constructed in 1991 on the Whiteshell River.*

was approximately 0.5 m^3/s. In the 12 Spring runoff periods, the flows exceeded 1.0 m^3/s in 5 years, 0.3 to 0.8 m^3/s in 5 years, and 0.15 m^3/s in 2 years.

In the two low flow years, higher sustained flows are required to maintain year-round trout habitat in the enhancement reach. The low flow years (1987 and 1988), could be alleviated by utilizing the storage capacity on West Hawk Lake. For example, for a continuous flow of 0.3 m^3/s, 4.0 m^3/s-months of stored water would be required (see 1989, Figure 4-59). The equivalent storage volume of 4 m^3/s-mon is approximately 10.5 million m^3. The area of West Hawk Lake is 14.95 km^2 or 14.95 million m^2. The storage depth required is therefore 10.5/14.95 = 0.7 m. Releases from storage could be made as a combination of hatchery outflows and spillage from the stoplog dam. Less storage would be required if the mid-winter flows were reduced. For example, a flow of 0.14 m^3/s in winter and 0.28 m^3/s in

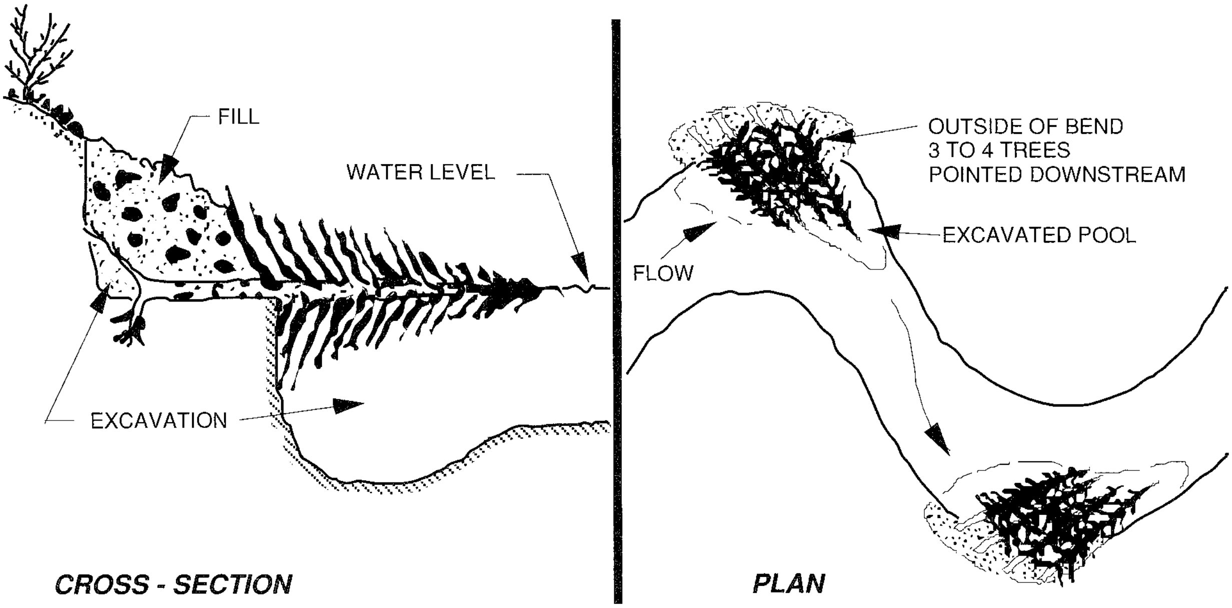


Figure 4-58: *Design and placement of overhanging cover structures made from local black spruce in the Whiteshell River trout habitat enhancement reach.*

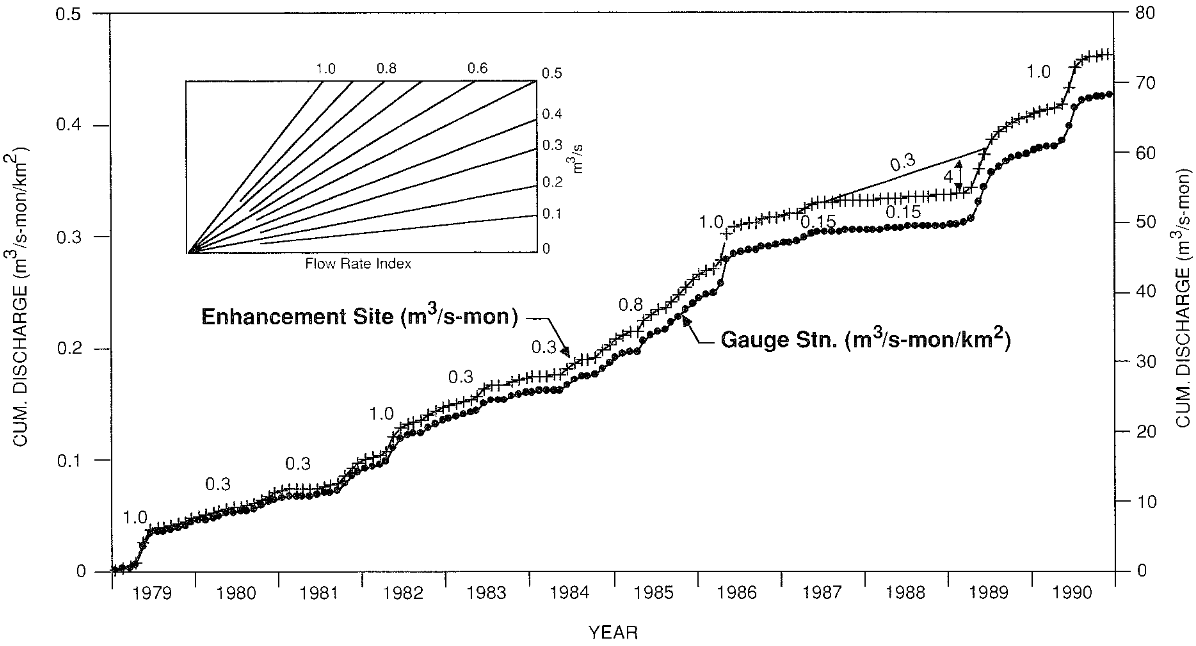


Figure 4-59: *Mass curve of Whiteshell River flows. The project reach discharges are based on a tributary drainage area of 174 km^2.*

the open water period can be supplied by utilizing the storage on West Hawk Lake within the regulation range of 332.38 to 332.54 m (Manitoba Water Resources Branch). In mid-winter, discharges of 0.14 m^3/s would maintain the pool depths above the preferred minimum of 0.7 m. In the open-water period, discharges of 0.28 m^3/s would maintain an overflow depth of 0.1 m for fish passage over the crest of the riffles for a width of channel of 3 m, assuming that critical flow occurs. This may require some re-alignment of boulders on the riffle crests after several flood peaks have passed.

9) Supervise construction

A track excavator was used to construct all the components of the project (Figures 4-60 and 4-61). Rock was transported from the upstream section to the riffle sites with a small bulldozer. The costs and person-days (pd) required for surveys, design and construction in 1991 $ are summarized in Table 4-18.

Table 4-18: Materials and costs for the Whiteshell River trout habitat enhancement project.

Machine Rental	
51 hours hydraulic excavator	$4386.
24 hours bulldozer	1008.
Labour	
surveys.	4 pd
design	3 pd
arrangements.	3 pd
supervision	6 pd

Figure 4-60: *Pool excavation prior to constructing cover structure at Station 500. Fill used to re-direct the flow from the original channel is shown in the foreground.*

Figure 4-61: *Overhanging cover structure constructed at Station 366.*

10) Monitor and adjust design

During the first flood period following construction in April 1992, erosion occurred only where finer materials dredged from the river bottom were used to divert the flow. There was no erosion in the riffle structures (Figure 4-62).

Following the spring flood peak, pool depths of 1 m to 2 m have been maintained in the enhancement reach. A view of the lower end of the upper reach (from riffle R7, Figure 4-64) under moderate flow conditions is shown in Figure 4-63. The cover structure in the pool (right foreground) was not affected by high flows.

A creel census similar to that made on Duck Mountain streams will be undertaken by members of the Manitoba Fly Fishers Association in 1992 using project census sheets and a site identification map (Figure 4-64).

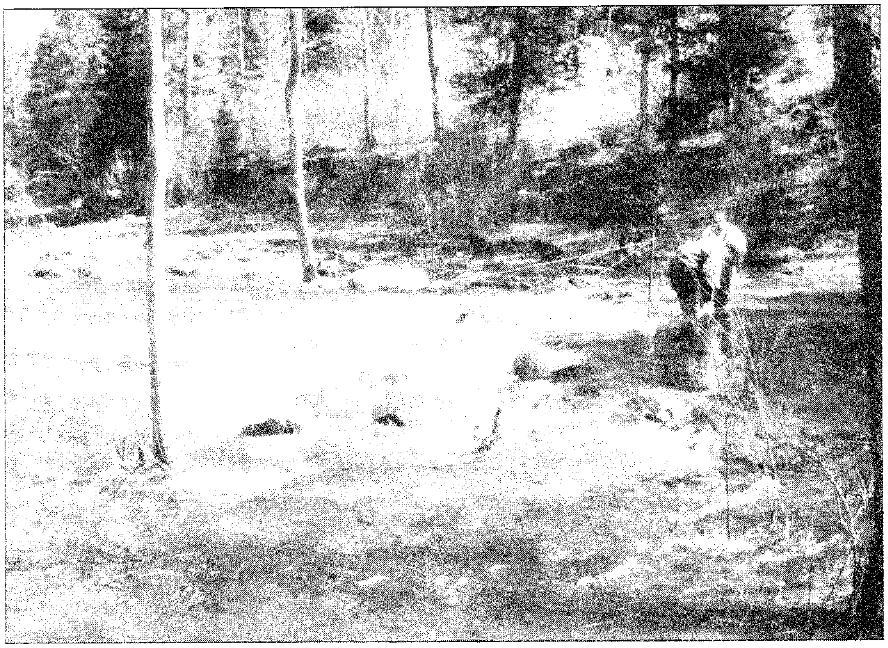


Figure 4-62: *Moderate flows passing over the riffle constructed at station 192 (R6) in early May 1992.*

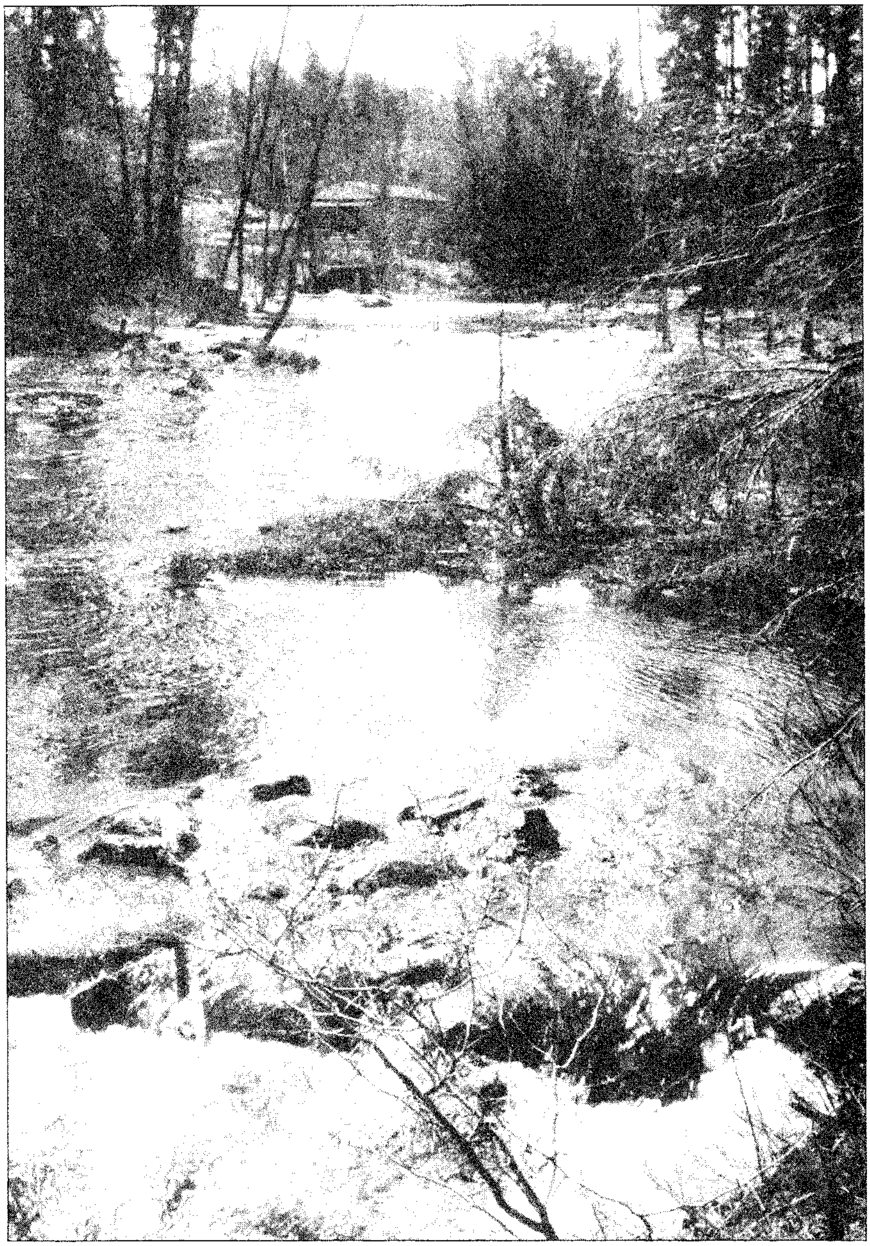


Figure 4-63: *View upstream from riffle R7 in the middle section of the Whiteshell River trout habitat enhancement reach. A constructed cover structure is in the pool (P5) in the right foreground. Riffles R6 and R5 and pools P4 and P3 are visible in the background adjacent to the fish hatchery. Pools and riffles are identified in the site map in Figure 4-64.*

WHITESHELL RIVER

TROUT DISTRIBUTION AND CATCH FORM

Date ____________________

No. of Anglers reporting on this form ____________________

Fished at this site from________ AM/PM to ________ AM/PM

Stream section: Upper_______ Middle_______ Lower _______

HABITAT AND CATCH DESCRIPTION

SPECIES	LENGTH (cm)	HABITAT		
		Pool (P1-P14)	Riffle (R1-R9)	Depth (cm)

Submitted by ____

General Information:

This form has been designed to improve our understanding of brown and rainbow trout habitat in the Whiteshell River. It will also provide information on trout distribution and abundance.

To complete this form, anglers should indicate the date, time period and number of anglers fishing a particular stream site or section. By consulting the map in the center of the booklet, anglers should identify on the form the section of stream they are fishing - upper, middle, or lower sections. A separate form should be used by the angler(s) for each section fished.

For each trout or other species caught (eg. walleye) 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. Also identify the catch site by referring to specific pool or riffle locations shown on the index map in the center of the booklet. Then, on the catch form, record the appropriate pool or riffle identifier (eg. P1 or R3)

On the opposite page of the form provide your comments on the trout habitat, flow conditions and fishing success.

Good Luck and Good Fishing!

Comments:

Have you caught fish here before? Yes___ No___

Is the water higher___ or lower___ than average?

Is the catch rate at this site today better___

worse___ or the same___ as usual?

Other comments?

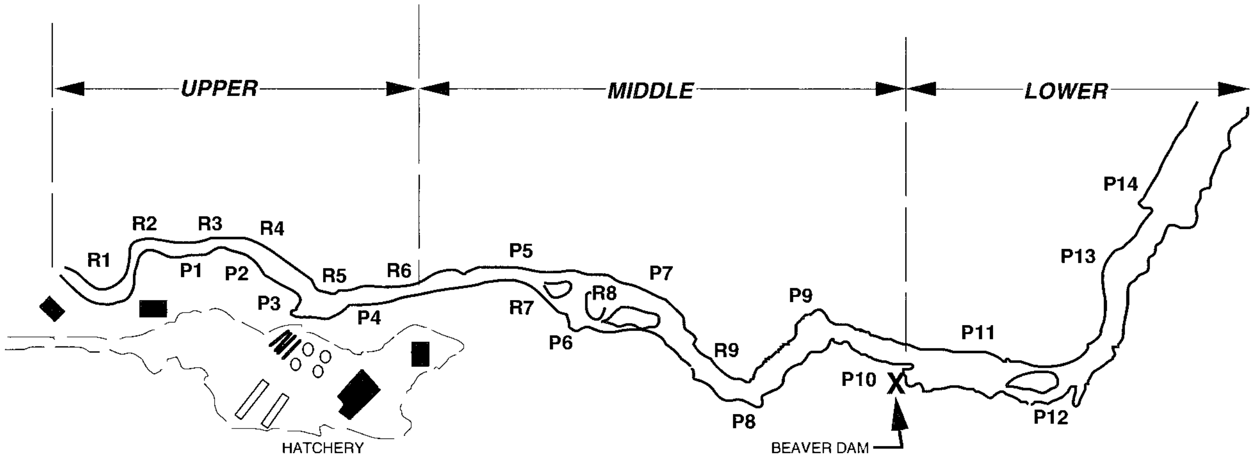


Figure 4-64: Creel census sheets and site identification map for the Whiteshell River trout habitat enhancement reach. The habitat works are identified in more detail in Figures 4-54, 4-55, and 4-56.

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Appendix A

Summary of Manitoba Fish Behaviour and Habitat Conditions

BEHAVIOUR AND HABITAT PREFERENCE

Species	Life Stage	Behaviour
Lake Sturgeon	Larvae	After 16 days, at 21mm, begin feeding (18)
	Juvenile	
	Adult	Bottom feeders, generally dispersed; food sucked up with mud, sticks and gravel and nonedible materials rejected (18)
Rainbow Trout	Larvae	Remain in gravel about 2 weeks after hatching (18)
	Juvenile	Young of the year inhabit riffles; may remain in natal streams for first 2 or 3 yrs (9)
	Adult	Dependent on cover such as, overhanging vegetation, submerged vegetation, undercut banks, debris piles, logs, large rocks, deep pools and surface turbulence (16); feed on bottom mostly but will feed on surface for emerging or egg laying insects (18); adults inhabit deeper pools or areas around boulders, etc. (9)
Brook Trout	Larvae	May drift downstream after emergence; stay close to streambanks (4)
	Juvenile/Adult	Free swimming at 38mm long; tend to feed primarily off the stream bottom, but will rise for insects at the surface; feed in riffle until temp. forces them into cooler pools downstream (15)
Northern Pike	Larvae	Remain in shallow spawning areas for several weeks after hatching (18); attach to vegetation using papillae on front of their heads (7)
	Adult	Occur in shallower water in spring and fall, and retreat to deeper, cooler water in summer; sedentary, establish a vague territory; omnivorous (7)
Brown Trout	Larvae	Disperse immediately after emergence; aggressive and territorial (17)
	Juvenile/Adult	Dependent on cover, overhanging and submerged vegetation, undercut banks, instream objects, such as debris piles, logs and large rocks, and deep pools or surface turbulence for predator avoidance and resting; in winter move into deep, low-velocity water (17)

Habitat Preferences
May reside on gravelly shoals near river mouths (18); in rivers or shallower waters for first one or two years (6)
In large lakes and large rivers, in depths of 4.6-9.2m, with bottoms of mud or a combination of mud and gravel (18)
Prefer shallow areas with velocities < 8 cm/sec; require cover (veg., debris, rocks); pool area 40-60% of total stream area (16)
Velocities of between 10 and 12 cm/sec; prefer instream substrate cover (16)
Velocities of 10-14 cm/sec; in rivers prefer clear cold water; a silt-free rocky substrate in riffle-run areas; ~1:1 pool to riffle ratio, with areas of slow, deep water; well vegetated streambanks; abundant instream cover; and relatively stable water flow, temperature regimes and streambanks; preferred lake type - oligotrophic; for salmonids baseflow ≥ 50% of average annual daily flow considered excellent, 25-50% fair to good and < 25% poor (16)
Associated with cover along streambanks (4)
Y-O-Y overwinter in shallow, low velocity areas with rubble as cover; optimum size of substrate used as winter cover by fry and juveniles was 10-40cm, ≥ 10% of total habitat area; prefer clear, cold spring-fed water; silt free rocky riffles; 1:1 pool-riffle ratio; well vegetated streambanks; abundant instream cover and relatively stable water flows, temps. and banks; cover area > 25% for adults and > 15% for juveniles of the entire stream area appears adequate; major limiting factor probably overwintering habitat (15)
Marshes and shoreline areas with dense submergent/emergent vegetation (7)
Not adapted to strong currents; in rivers, inhabit backwaters and pools; found in gradients < 5 m/km (0.5%); currents > 1.5 m/sec can block migrations; prefer depths in lakes < 8m or above the thermocline; prefer interface between vegetation and open water (7); clear, warm, slow meandering, heavily vegetated habitat in rivers (18)
Shallow areas with a smooth bottom and banks; prefer pools and rock substrates but are excluded by older trout; found at edge of riffles or margins of a river with depths of 20-30cm; cover is essential; may burrow into substrates that are 10-40cm in diameter (17)
Velocities < 15 cm/sec and depths > 15cm; pools and riffles; adequate cover provided when cover area is > 15% (juvenile) or > 35% (adult) of total stream area; for salmonids annual base flow > 50% of average annual daily flow considered excellent, 25-50% fair to good, and < 25% poor; clear, cool to cold water; relatively silt-free rocky substrates in riffle-run areas; 50-70% pool: 30-50% riffle-run with areas of slow, deep water; well vegetated, stable banks; stable annual water flow and temperature regimes; occupy lower reaches of low to moderate gradient areas (< 1%) (17)

BEHAVIOUR AND HABITAT PREFERENCE (CON'T)

Species	Life Stage	Behaviour
Lake Trout	Juvenile/Adult	Y-O-Y and older tend to remain in deep waters of lakes; tend to be nomadic, some sedentary (10)
Channel Catfish	Larvae/Juvenile	Remain in nest for 7-8 days after hatching then disperse to shallow water areas with cover; strong shelter seeking tendencies; larvae initially lie in mass on the bottom and begin to make forays to the surface as they grow (11)
	Adult	Move to riffles and runs at night to feed; concentrate in warmest sections of river; strongly seek cover (11)
Smallmouth Bass	Larvae/Juvenile	Exhibit strong, cover seeking behaviour and prefer protection from light in all life stages (3)
	Adult	Use deep, dark quiet water for cover, as well as boulders, stumps, trees and crevices (3); remain inactive or near the bottom during winter (13)
Yellow Perch	Larvae	Move to open water during first 2 months (8); remain in upper .9-1.2m of lake for 3-4 weeks until about 25mm, then spends more time near bottom (13)
	Juvenile/Adult	Adults and young are gregarious, often 50-200 individuals; active during the day and all winter (18)
Walleye	Larvae	Drift passively to lake after hatching from tributaries; photopositive and probably pelagic in lakes until about 2.5-4.0cm; begin feeding at temp. > 15°C (12)
	Juvenile/Adult	Found under cover during the day, move inshore to feed at night, photo-sensitive (12); tend to school (2)
Sauger	Larvae	Remain on bottom for 7-9 days after hatching and absorb yolk (18)
	Juvenile/Adult	Photosensitive, sight predators (18)

Habitat Preferences
Oligotrophic lakes, mean depths > 6m; TDS < 50 mg/L; hypolimnion D.O. > 6 mg/L and metric MEI < 6; uses rocky shorelines, inflowing streams and deep waters (10)
Protected, slow flowing (< 15 cm/sec) areas of rocky riffles, debris-covered gravel, sand bars in clear streams, and in shallow (< .5m) mud or sand substrate edges of flowing channels along turbid rivers; overwinter in riffles or move to cover in deeper water (11)
Diversity of velocities, depths, and structural features that provide cover and food; found in large, deep pools with cover; optimum river habitat with 40-60% pools (11)
Most remain in shallow water, but have been found in 4-6m depths; usually in quiet water near or under a dark shelter, such as brush or rocks (3)
As with juveniles, prefer low velocity water near a current, but in slightly deeper water than juveniles; cool, clear mid-order streams > 10.5m wide, with abundant shade and cover and deep pools, moderate current, and a gravel or rubble substrate; gradient .75-4.7 m/km; prefer pools deeper than 1.2m (3); and riffles comprising 40% of channel area (13)
Larvae < 9.5mm unable to maintain position in current velocities > 2.5 cm/sec (8)
In rivers, occupies pools and slack water areas with moderate amounts of vegetation (> 20% of area) (8); adults and juveniles prefer open water of lakes with clear water, moderate vegetation and bottoms ranging from muck to sand and gravel; found in quiet rivers (18); occupies the area at the open-water edge of weed beds, during the summer feeding period; present at .2-1.2% stream gradients but absent where lowest slope is > .4% (21)
Tributaries must have sufficient discharges to transport larvae to suitable rearing habitats; after becoming photosensitive seek shelter of dim light such as deep or turbid water and typical cover habitats (12); occupy waters .3-1.2m deep (14)
Prefer large, shallow turbid lakes; large streams or rivers are suitable if deep and turbid enough to provide shelter in daylight; uses sunken trees, boulder shoals, weed beds, and thick ice and snow as shelter from sunlight; usually found at at < 15m depths (12); most abundant in water between 1.2 and 3.7m deep (14)
Large, shallow lakes and large, slow flowing (low gradient) rivers that are turbid with colloidal clay; northern range limited by 15°C July isotherm; young fish may frequent shallow mud flats (18)

THREATS TO HABITAT

Species	Cause	Effect
Lake Sturgeon	Major dam construction on large rivers for hydroelectric, water supply and recreational purposes; major water diversions; pulp and paper mill effluents	Barriers to migration; alteration in flow regime affecting spawning, incubation and feeding habitats; toxins, PCBs and mercury affecting survival and marketability
Rainbow Trout	Logging; stream crossings; low base flow as a result of diversion, channelization or drought	Loss of riparian vegetation and soil erosion can lead to siltation of spawning habitat and insect production areas; low flow can result in winterkill, increased competition due to crowding; migration blockage
Brown Trout	Channelization; clearcut logging; overgrazing; dams; removal of streamside vegetation; instream logs and boulders	Reduces amount of cover; increases siltation (fines); increases temp. through a loss of shading; loss of productive invertebrate habitats; removal of rocky substrates; alteration in flow regime
Lake Trout	Water level drawdown; mine effluents	Dessication of eggs; toxins; heavy metals
Brook Trout	Stream crossings; loss of riparian zones; de-stabilized streambanks; logging; dams; low base flow	Migration blockage; siltation of spawning habitat and insect production area; reservoirs change from preferred lotic habitat to lentic
Northern Pike	Channelization; drawdown and excessive water level fluctuations; eutrophication; stream crossings; dams; waterfowl developments; diversion	Removal of pools; backwaters; veg.; negatively affects development of near shore veg. and may strand/dessicate embryos or larvae; oxygen depletion in summer or winter; obstructs migration; loss of feeding, spawning, nursery habitat
Channel Catfish	Dams and reservoirs; channel alteration; thermal plant operations	Blocks migration; high siltation rates decrease quality of feeding habitats; attracts fish to outflow area and kills by thermal shock after rapid shutdown

Waterbody Affected In Manitoba
Winnipeg River; lower and upper Nelson River system; North Saskatchewan River; Red River; Assiniboine River; Churchill River
Pine River; Steeprock River; North Duck River
Steeprock River and its tributaries; North Duck River; Nelson River and its tributaries; Churchill River and its tributaries
Pembina River system; Otter Lake; Souris River
Pembina River; numerous lake marshes; Whitemud River
Lower Churchill River
Red River; Assiniboine River; Winnipeg River
Cooks Creek

THREATS TO HABITAT (CON'T)

Species	Cause	Effect
Smallmouth Bass	Regulated streams	Rapid drop in water level may leave fry in areas where they will dessicate; rise in discharge may displace fry from the nest (3)
Yellow Perch	Waterlevel drawdown (8);	Eliminates inundated terrestrial vegetation used for spawning (8);
	numbers will decrease in a body of water in which turbidity increases or vegetation decreases (18);	reduces feeding efficiency, reproductive success and escape cover;
	waterfowl developments	blocks movements into/out of lakeside marshes
Walleye	Channelization/diversion;	Loss of pool-riffle sequence, hydraulic habitat diversity, and substrate; altered water flow regime causing a shorter duration of flows in spring and summer; destabilization of stream channel causing excessive bed and bank erosion and consequent siltation;
	reservoir management;	cold water releases during spawning and incubation (12)
	dams; stream crossings	migration blockage
Sauger	Increases in turbidity	Limits feeding

Waterbody Affected In Manitoba
Lake Winnipegosis; Lake Manitoba
Mink Creek; Wilson River; Edwards Creek; Icelandic River; Wavey Creek; Toutes Aides Creek
Vermilion River
Whitemud River; Pembina River; Assiniboine River; Souris River; Little Saskatchewan River; Valley River; Turtle River; Rat River; Morris River; and others

MOVEMENT

Species	Life Stage	Description
Lake Sturgeon	Larvae	
	Juvenile	
	Adult	When shallow waters warm, move to deeper water and return in autumn (18); upstream migration to spawn or enter shoal waters of large lakes and rivers (13)
Rainbow Trout	Larvae	Downstream, upstream or dispersive movement to rearing areas (16)
	Juvenile	Movement out of natal stream after 2 or 3 yrs (9) or 0 to 3 yrs (18)
	Adult	Migration to streams to spawn (18); movement to beaver ponds to overwinter (5)
Brown Trout	Juvenile	May spend 2 or 3 yrs in stream before moving to lake (9)
	Adult	Migration to streams to spawn (17)
Lake Trout	Larvae	May stay near shore for extended periods (13); move from spawning areas within 1 month after hatching to deeper waters of the lake (10)
	Juvenile/Adult	Rocky shallows to spawn; dispersed; surface waters; hypolimnion (18)
Brook Trout	Larvae	Drift downstream after emergence (4)
	Juvenile/Adult	Move out of rapids and hold in cooler channels and pools (9); movements into small streams (20) and into beaver ponds; evidence of anadromy; may move to larger rivers or beaver ponds to overwinter (4,20)
Northern Pike	Larvae	Leave spawning area within 10 to 42 days (7)
	Juvenile	
	Adult	Extensive spawning migrations reported (18); up to 322km (7)

Season	Environmental Factors	Comments
Out of shallows in July and August, return in September or October; May-June (spawn)	Movements related to water temp. and perhaps oxygen (18)	Strong homing tendencies reported; migrations often 129km, max. 530km (18)
Summer		Genetically controlled (16)
April-May (spawn); September-November	Movements related to water temp.	
Late September-early November (17)		High homing accuracy (17)
Spring	Avoid higher light intensities or predation (10)	
Autumn; winter; spring; summer	Water temperature controlled, limited to waters < 12°C (10)	Evidence of homing; movements up to 160km (18)
Early spring	Increases in temp. and discharge (4)	
Mid-summer; spring to fall; late fall	Water temperature controlled; unfavourable temp.; rise in water level and crowding initiate movement (9); triggered by low temperatures (15)	Evidence of homing (4)
May-June	Inhibited by low light intensity; may be controlled by water level and food supply (7)	
Late March-April	Increases in temp. and discharge	Degree of homing unclear (7)

MOVEMENT (CON'T)

Species	Life Stage	Description
Channel Catfish	Larvae/Juvenile	Move from spawning areas back to lake (11)
	Adult	Migration up rivers for spawning; move to shoreline or tributaries at night to feed (11)
Smallmouth Bass	Adult	Migrate upstream to spawn at ~5°C (13); restricted to a single pool during a single season (3); seek deep, dark areas (3)
Yellow Perch	Juvenile/Adult	Movements inshore and out; up and down over the day and seasonal movements out of and into deeper water (18)
	Adult	Migrate into tributaries to spawn and return to lake after spawning (18)
Walleye	Larvae	Passive movement from spawning area downstream to lake; at 24mm move inshore to depths of .3-1.2m (2)
	Juvenile/Adult	Spawning migrations of up to 100km to shallow shoals and tributary streams; daily vertical and lateral movements(13)
Sauger	Larvae	Passive movement from spawning area downstream to lake (2)
	Adult	Move little in the summer but make migration to spawn (13)

Season	Environmental Factors	Comments
July-August		
May-June; open water		
Late May-June;		Strong homing to spawning grounds (13,18)
summer	Temperatures drop to 15-20°C (3)	
All year	Movements in response to temperature and to distribution of food (18)	
April; late April-May		
Spring	Dispersion controlled by discharge	
Spring		Evidence of homing (2)
All year	Daily movements in response to light, temp. and food (13)	
Spring		Dispersion controlled by discharge

PHYSICO-CHEMICAL PREFERENCES/TOLERANCES

Species	Oxygen	Turbidity
Lake Sturgeon	Moderate level required (6)	
Rainbow Trout	Lethal < 3 mg/L; optimal 7 mg/L @ 15°C (16)	
Brown Trout	Minimal and optimal: > 3 and > 7 mg/L @ < 15°C > 5 and > 9 mg/L @ > 15°C (17)	
Lake Trout	Min. hypolimnion, D. O. > 6 mg/L (10)	
Brook Trout	Optimum > 7 mg/L @ 15°C and > 9 mg/L @ 15°C (15)	Optimum 0-30 JTU; range 0-130 JTU (15)
Northern Pike	Minimum .1-.4 mg/L for a few days; prolonged exposure, min. = 1.0 mg/L (7)	Avg. Secchi = 2-4m (7)
Channel Catfish	Optimal > 7 mg/L; adequate 5-7 mg/L (11); lethal .95-1.08 mg/L (13)	< 100ppm optimal (11)
Smallmouth Bass	Optimal > 6 mg/L; lethal 1 mg/L @ 20-25°C (3)	Optimal < 25 JTU; larva can tolerate 250 JTU (3)
Yellow Perch	Optimal > 5 mg/L (8); min. 1.1-1.3 @ 16°C, .4-.9 @ 15.5°C, and 2.25 @ 20-26°C (21)	Numbers decrease with increased turbidity (21)

	Temperature		
Velocity	Low	High	Comments
Preferred range .6-2.5 m/sec; median 1.2-1.5 m/sec (22)		23.8°C (6)	May enter brackish water; papermill effluents, PCB and mercury have reduced pop. (6)
Adults prefer .1-.6 m/sec; fry tolerate .08-.3 m/sec, prefer < .08 m/sec (16)	0°C Optimal 12-18°C (16)	25°C	Optimal pH of 6.5-8.0; tolerant pH range of 5.5-9.0 (16)
Prefer < 15 cm/sec (fry and juvenile) (17)	5°C Optimal 7-15°C (fry) 0°C optimal 7-19°C (juvenile) optimal 12-19°C (adult) (17)	25.5°C (fry) 27°C (juv. and adult)	Optimal pH of 6.8-7.8; tolerant pH range of 5.0-9.5 (17)
	Lethal 23.5°C optimal < 12°C range 4-18°C (10)		Least tolerant of all chars to salt water, upper limit 11-13 ppt (18)
Observed focal point velocity range 7-11 cm/sec with max. .25 cm/sec (15)	Lethal 25.3°C common in waters < 20°C upper lethal (eggs) 12°C optimal 11-16°C tolerance 0-24°C (15)		Optimal pH 6.5-8.0; tolerant pH range of 4.0-9.5 (15);
Require < 1.5 m/sec in stream (7) and < 1.0 m/sec in culverts (9)	Lethal 32°C optimal for growth 19-20°C; optimal for incubation 6.4-17.7°C (7)		Lake mean depths 2-6m; littoral (< 6.1m deep) areas 60-80% of total surface area; tolerant pH (5.0-8.9) (7)
Prefer < 15 cm/sec in deep pools and backwaters (11)	Optimal 26-29°C (11) lethal 30.3-33.5°C (13)		Tolerate salinities ≤ 8ppt; TDS of 100-350ppm associated with high standing crops (11)
Fry cannot tolerate > 200 mm/sec; adults found in currents of 10.9-32.0 cm/sec (3)	Larva: lethal 4.0°C juvenile: optimal 28-31°C : lethal 0 and 35°C adult: optimal 21-27°C : lethal 0 and 32.2°C (3)		Tolerate pH of 5.7-9.0; optimum 7.9-8.1 (3)
Larvae (8.5mm) can swim against 2.5 cm/sec; max. sustained level is .54 m/sec at 20-25°C (21)	Upper lethal 33°C (18); 31°C; optimal 18-21°C (21)		Found in brackish waters in Manitoba up to 10.3ppt; tolerant pH of 3.9-9.5, but require pH > 5.5 for successful reproduction (8)

PHYSICO-CHEMICAL PREFERENCES/TOLERANCES (CON'T)

Species	Oxygen	Turbidity
Walleye	Adult min. 3-5 mg/L; adult lethal < 1 mg/L; optimal for fry ≥ 5 mg/L (12)	Moderate turbidity preferred; max feeding at 1-2m secchi, poor feeding at < 1 or > 5m (12)
Sauger		

Velocity	Temperature Low	 High	Comments
Critical velocity of fish 20 cm long is .6 m/sec, 30cm - .74 m/sec; fry can withstand only slight currents (12)	Embryo: lethal 19°C fry: optimal 22°C : lethal 31-32°C adult: optimal 20-24°C : lethal 29-32°C; 34-35°C (12)		Stream velocities must be sufficient to transport fry downstream to lake within the period of yolk-sac absorption (3 to 5 days) (12)
	Optimal 18.6-19.2°C (18)		

FECUNDITY AND INCUBATION PERIOD

Species	Egg Number	Egg Size
Lake Sturgeon	Calculated minimum of 107510 and maximum 885360 (18); 50000-700000 (1)	Diameter : 2.7-3.5mm (18); 3.2-3.5mm (1)
Rainbow Trout	Range 500-3161; 935-4578; average 2028 (16); range 1315-3894; 3120-5302 (1)	Mean diameter of 3.5mm (18); 4.46 ± .19mm (1)
Brown Trout	107-2419 (1)	4.4-4.5mm (1)
Lake Trout	628 to 1710/Kg of total wt (10); 919-14766; 1093-10746; 411-2640 (1)	5-6mm (10); 5.0-5.6mm (1)
Brook Trout	100-300 @ 3 yrs; up to 2000 @ 6 or 7 yrs (9); up to 5604 @ 8 yrs (4); 99 to 4765 (1)	3.5-5.0mm (18); 1.0-4.7mm; mean diameter of 3.3mm (4); 4.1mm (1)
Northern Pike	7691-97273; 28000-290000 (1); average 32000; maximum 595000 (18)	2.2-3.0mm (1); 2.5-3.0mm (18)
Channel Catfish	2660-52000 (1)	Mean diameter of 3.5mm (1)
Smallmouth Bass	2000-20825 (1)	1.8-2.8mm (1)
Yellow Perch	23000-48000 (1)	Mean diameter of 3.5mm; 2.3mm (1)

Egg Description	Incubation Period	Size of Larvae on Hatching	Comments
Black, adhesive, demersal, deposited singly (1)	At 15.6-17.8°C, eggs hatching in 5-8 days (18); at 15°C, 7 to 9.6 days (1)	8mm (18); 8.0-8.5mm (1)	Larvae nourished by yolk for 9-18 days (18)
Demersal and pink-orange (18)	4-7 weeks (1, 16); optimal temp. of 7-12°C (16)	12.4-13.2mm (1)	Average depth of egg deposition =15cm (16); range 10-20cm (1); optimal velocity above redds, 30-70 cm/sec (16); emerge when temp. 4.4-10°C (1)
Amber (1)	33 to 66 days at temps. of 7-11°C (1)	13.7-15.0mm (1)	Optimal temp. 2-13°C; tolerance 0-15°C (17)
Pink, orange; semibuoyant (1)	10°C - 50 days; 5°C - 100 to 117 days; 2-2.5°C - 141 to 156 days (10)	15.2mm (1)	
Pink, orange (4)	10°C - 45 days; 2.8°C - 165 days (15); 4.5°C - 93 days; 14.0-14.8°C - 28-31 days (1)	11.3-11.8mm (1)	Dissolved oxygen (D.O.) > 50% saturation for successful incubation (15)
Demersal, adhesive, amber (18)	120 degree-days (1); 17 days @ 8°C; 12 days @ 10°C; 5 days @ 16-20°C (7)	7-9mm (7); 6-10mm (1)	Sensitive to high siltation rates (> 1mm/day); D.O. should be > 35% saturation; .2-1.0m drop in water level decreases embryo and fry survival; eggs die < 5°C (7)
Demersal, adhesive, deposited in gelatinous mass, yellow, opaque (1)	6-7 days @ 27°C (11); 9-10 days @ 15.6-18.4°C (1); 8-10 days @ 23.9°C (1)	6.0-9.8mm (1)	No development with temp. < 15.5°C; optimal temp. 27°C; range 15.5-29.5°C (11)
Demersal, adhesive, greyish-white, opaque, light amber or pale yellow, oil globule large (.9-1.7mm) and single numerous small oil droplets present (1)	6 days @ 15.6°C; 5 days @ 18.9°C; 4 days @ 21.1°C; 2.5 days @ 22.2°C (1)	4.6-5.0mm (1); 5.6-5.9mm (18)	D.O. > 6 mg/L necessary for max. survival (3)
Semi-demersal, released in long bands; flat ribbon-like accordian, folded, transparent, semi-buoyant, gelatinous masses .6-2.0m long and 51-76 mm wide, oil globule (.4-.9mm)(1)	51 days @ 5.4°C; 27 days @ 8.3°C; 6 days @ 19.7°C (1)	4.7-6.6mm (1)	Aeration of eggs is accomplished by means of water circulation thru holes and a central canal (18)

FECUNDITY AND INCUBATION PERIOD (CON'T)

Species	Egg Number	Egg Size
Walleye	23-227181; average 50000-60000 (1)	1.5-2.1mm; 1.9-2.3mm (1)
Sauger	9360-152110; average 15871 (1)	Mean diameter of 1.7mm; 1.3mm; range 1.0-1.9mm (1)

Egg Description	Incubation Period	Size of Larvae on Hatching	Comments
Demersal, adhesive prior to water hardening; translucent and pinkish; oil globule single, diameter .67mm (.6-.77mm) (1)	25-29 days @ 5.6-15.6°C; 12-18 days @ 12°C; 8-11 days @ 15.0°C (1)	5.8-8.7mm (1)	Embryos require D.O. levels ≥ 5 mg/L (12); preferred velocities of .2-1.0 m/sec, depths of .3-.9m and substrate diameters of 2-250mm; preferred Froude number .03 and .04; preferred riffle gradient of 2.5% (5)
Demersal, adhesive after water hardening or semi-buoyant and non-adhesive after water hardening (1)	25-29 days @ 4.5-12.8°C; 12-18 days @ 10°C; 8-13 days @ 15°C (1)	4.5-5.8mm (1)	

SPAWNING REQUIREMENTS AND BEHAVIOUR

Species	Age/Size at maturity	Season	Induction	Temp.
Lake Sturgeon	Males mature between 12-19 yrs (18); 8-19 yrs (6), 85-95cm, 3.9-5.2kg (18); females mature between 14-23 yrs (6); 20-30 yrs; 90-100cm; 4.3-9.0kg (18)	Late May to late June (6,1)	Depends on water temp. (6)	Between 8.5 and 18°C (18); 13-21°C (6); 11-15°C, with optimum between 14-16°C (1)
Rainbow Trout	Mature at 3-5 yrs with males usually a year younger than females; size at maturity extremely variable (18)	Mid April to late June (18)	Temp. related (16)	Between 10.0 and 15.5°C (18)
Brown Trout	Females mature at 5 or 6 yrs (18)	October-November (18)	Decreasing day length; increased late fall flows; drops in temp. to < 9°C (17)	Between 7 and 9°C (17); 6.7 and 8.9°C (1)
Lake Trout	Age 6 or 7 (18)	Sept.-Oct. over a two week period (18)	Water temp.; photoperiod; strong onshore winds (10)	4.5-14°C; usually 9-14°C; begins at < 4.4°C and occurs between 2.8-14.4°C (1)
Brook Trout	Earliest age male 2 yrs, 222mm; female 3 yrs, 320mm (4); varies among populations with males maturing as early as 0+ (15)	Sept.-Oct. (4)		4.5-10°C (15); near 9.4°C (1); 3-13°C (4)
Northern Pike	Males 34-42cm (7), 2-3 yrs (18); females 40-48cm (7), 3-4 yrs (18); in north, male 5 yrs and female 6 yrs (18)	April-May shortly after ice-out (18)	Water temp.; water level/discharge change (18)	8-12°C; completed by 13°C (7); 4-11°C (1)

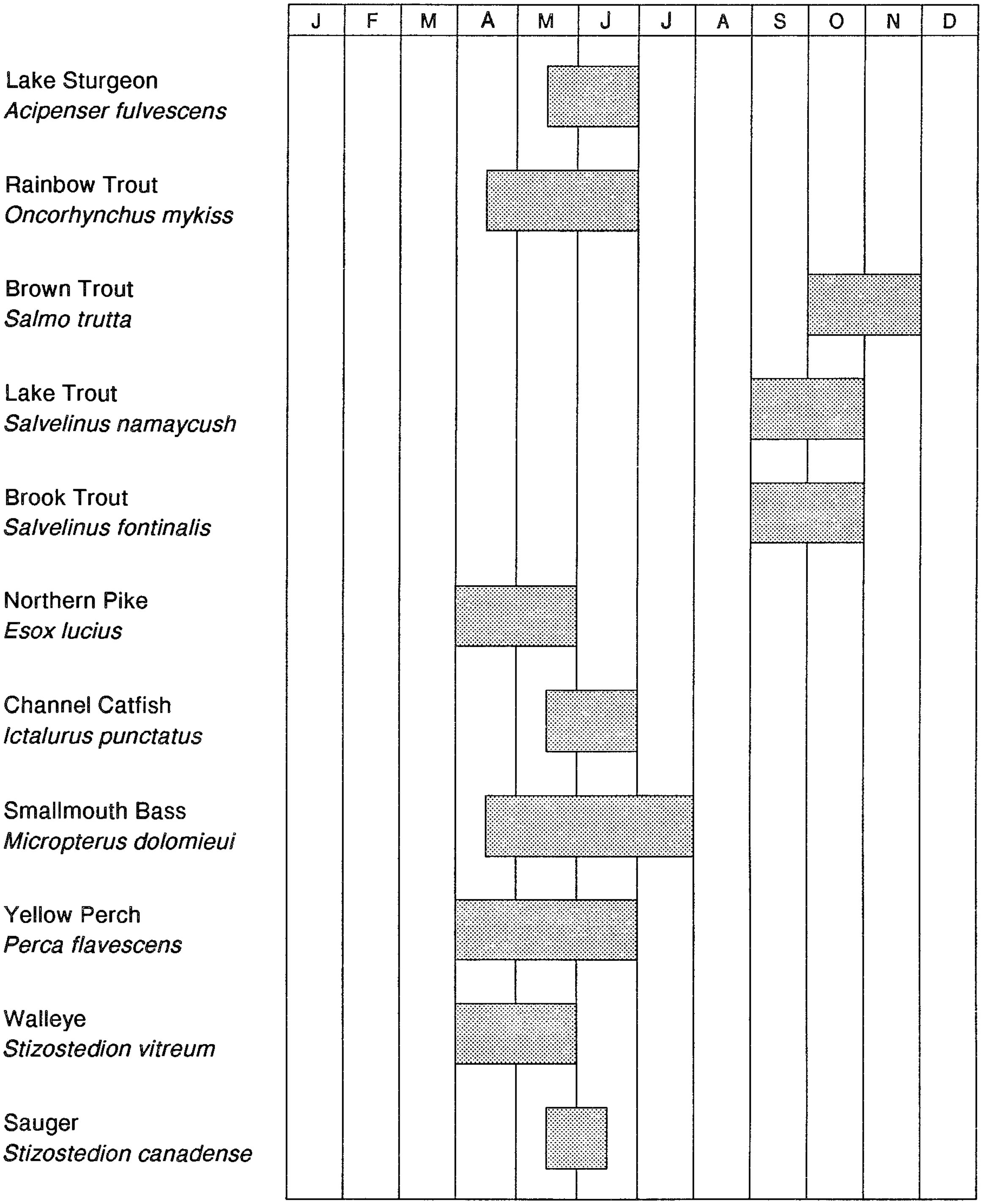
Site	Behaviour	Comments
In rivers in swift water or rapids 0.3-4.6m deep; at base of impassable falls (18); in large clean rubble; areas of upwelling currents; outside bends and rapidly moving water of rivers; near dams; in 1.0-5.0m depth (1); in lakes on rocky shoals (6)	Migration begins just prior to or soon after spawning rivers are free of ice; males arrive first; eggs shed over several days; spawning groups of 1 or 2 males to each female (18)	No feeding during spawning period; interval between spawning 4-9 yrs (18); substrates of cobble, boulder and bedrock outcrops; ≥ 16cm in diameter; must be silt-free and not covered with algae; .6-2.5m/sec with a median of 1.5 m/sec (22)
Small tributaries of rivers; inlet or outlet streams of lakes; spawn in fine gravel at head of riffle or downstream edge of pool (18)	Female constructs redds; spawning several nests; 1 or 2 males for each spawning female (18)	Prefer velocities of .2-.9 m/sec, and depths of .09-.9m (19); often groundwater flow; strong homing tendency; gravel substrate size 1.5-6.0cm for fish < 50cm long and 1.5-10cm for spawners ≥ 50cm (16)
Typically stream spawners; redds often located at the head of riffles or tail of pools where gravel slopes upward; groundwater upwelling (lakes) or currents flowing downward into the gravel selected as spawning sites (17)	Fall spawning migrations begin at temps. of 6-13°C ; construct redds; high homing accuracy (17)	Depth > 15cm; adequate spawning habitat ~5% of total trout habitat area; gravel substrate with ≤ 5% fines; prefer gravel diameter 1.0-7.0cm but will utilize 0.3-10.0cm; optimal velocity of 0.4-0.7 m/sec, but will tolerate 0.15-0.9 m/sec (17)
In lakes, depth range: 15cm-55m; rubble substrate 2.5-30cm or .25-1m in diameter (1); angular rock (10); usually in <12m (13); exposed shores facing prevailing winds (9); may occur in rivers among coarse gravel and large boulders (1)	1 or 2 males per female; eggs cast indiscriminately among large rocks and settle in crevices; male may precede female and clean the substrate of silt by fanning (1)	Evidence of homing; will utilize artificial spawning grounds (18); intermittent spawning behaviour common in north (10)
Typically stream spawners, but also lakes/ponds at spring upwellings (18); coarse sand, gravel and stones, 7.6-10.2mm (1); 30% sand (.42-4.8mm); 70% gravel (4.8-18.0mm) (4)	Eggs deposited in redd; constructed by female; 1 or 2 males per female with 2 or 3 subordinate males (18)	Groundwater upwelling highly preferred; lakes and river velocities 1-92 cm/sec (15), depths of.09-.6m (19); evidence of homing (4)
Over dense vegetation in calm, shallow water i.e. flooded marsh, wetland, shallow pool or backwater; depths of 0.2-.45m (7)	Gametes broadcast; no parental care; eggs adhere to veg.; 5-60 eggs released per spot; larvae attach to veg. (10 days) (7)	Spawning interrupted by cold weather, water level drawdowns, strong wind or rain (7)

SPAWNING REQUIREMENTS AND BEHAVIOUR (CON'T)

Species	Age/Size at maturity	Season	Induction	Temp.
Channel Catfish	Males > 6 yrs; females > 8 yrs; size 267-406mm (11)	Late May - mid June (11)	Temperature	21°C (11);21.1-29.5°C (1)
Smallmouth Bass	Males 3-5 yrs; females 4-6 yrs (18)	April 15 - early May (18); mid April - July (3)		12.8-21°C (3); 12.8-23.9°C (1); egg deposition 16-18°C (13);
Yellow Perch	Males 3 yrs; females 4 yrs (18)	Early April - late June (1)	Migrate to shore as temp. rises from 1.5-6°C (1); photoperiod, rising water temp. and/or completion of maturation (8)	7.2-11.1°C (1)
Walleye	Males 2-4 yrs and > 279mm; females 3-6 yrs and 356-432mm (18)	April - late May (1)		3.3-14.4°C (1); initiated at 7-9°C; occurs between 6 and 11°C (12)
Sauger	Males 2-3 yrs; females 4-6 yrs (18)	Late May - early June (1)		3.9-6.1°C; 6.1-11.1°C; 3.9-11.7°C (1)

Site	Behaviour	Comments
Dark and secluded areas for nesting, usually cavities, burrows, under rocks; in shallow flooded areas in large rivers; near shore (11); in muddy ponds; in undercut banks; under logs at depths of 2-4m (1)	Males build and guard nests and larvae, fan the embryos (1)	Eggs may be deposited in submerged man-made containers such as milk cans and nail kegs (1)
Rocky lake shoals, river shallows, or backwaters, or move into creeks or tributaries to spawn; require clean stone, rock or gravel for spawning (3); or coarse sand; nests in water .30-6.10m deep (1); or .3-.9m deep (3); or .9-1.8m deep (19)	Nests are constructed between 13-20°C by male (13); males guard young for several days after hatching (3)	Stable, high water levels preferred for nesting (3); prefer velocities of .1 m/sec (19)
Over sand, gravel, rubble submerged veg. or debris covered bottoms (1); depths range from 0.6-3m (13)	Males move onto spawning grounds first and remain longer; spawning occurs at night and early morning (18)	Min. winter temp. of < 10°C needed for gonad maturation; occurs in < 5 cm/sec current velocity; velocities > 25 cm/sec; fragment egg strands (8)
Selects moving water and clean substrate; rocky areas in white-water, shoals and shorelines of lakes and streams; lake depths of .05-3m (1) or .05-4.6m (2), river depths .2-.9m (2); also utilize dense mats of vegetation (12)	Start to congregate and migrate at 3.3-3.9°C or just after ice-out; begin spawning at 7.7-10.0°C (1); eggs broadcast over substrate, usually at night (12)	Substrates include coarse gravel boulder and rock, sand and fine gravel (18); 2.5-15cm gravel and rubble (12); optimum temp. for fertilization is 6-9°C, and for incubation is 9-15°C (12)
Spawns in shallows, .6-3.7m, sand and gravel shoals or bars in turbid lakes or streams (1); prefer depths of 1.2-1.5m deep (19)	Usually spawn at night; eggs are broadcast; no parental care (18)	Substrates include sand, gravel, rubble shoals, bars or shorelines (1); prefer velocities of 0-.5 m/sec (19)

SPAWNING CALENDAR



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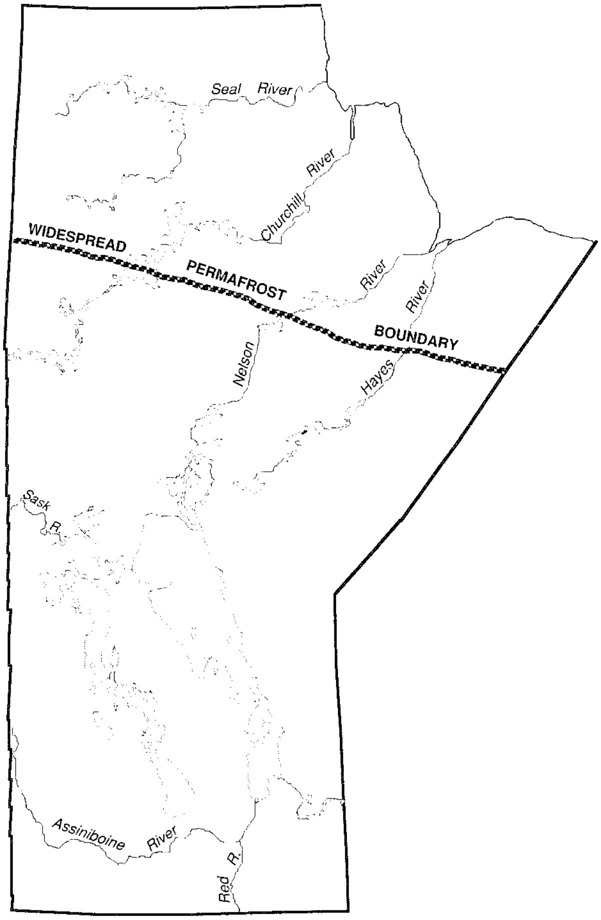
Appendix B

Overview of Manitoba Streams

STREAM REGIONS OF MANITOBA

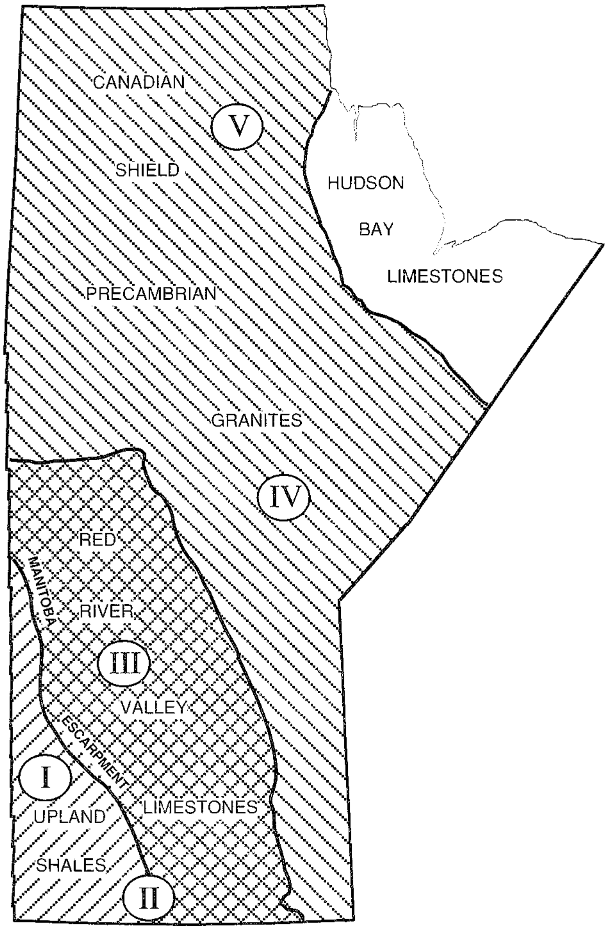
The streams of Region I, located above the Manitoba escarpment in south-western Manitoba, run across level sedimentary rocks through thick deposits of glacial till and gravelly outwash. The patterns of drainage often follow large abandoned valleys formed by glacial meltwater rivers. This is the driest agricultural region in the province and small streams may dry up during the summer after a spring snowmelt flood.



MAJOR HYDROLOGY

The streams of Region II originate on the Manitoba escarpment, a steep ridge of weathered Cretaceous shale that runs from the American border to the Saskatchewan River in western Manitoba. The escarpment was divided into four blocks by eroding glacial rivers. The blocks, named the Turtle, Riding, Duck and Porcupine "mountains", are separated by wide, glacial river valleys. Local streams have downcut into picturesque, rocky canyons on the face of the escarpment before emerging into the level alluvial plain on the western edge of Region III. These are the highest relief streams in Manitoba and are subject to flash floods from summer rainstorms and spring snowmelt water.

The streams of Region III slowly flow across one of the flattest areas in the world, the Lake Agassiz basin. Glacial Lake Agassiz was impounded in the Red River valley following the retreat of the last glaciers in Manitoba. Thick lake deposits of heavy clay ("Manitoba gumbo") overlie horizontal limestone beds to form a level plain of rich farmland and shallow lake basins. The stream valleys are subject to extensive flooding from spring snowmelt. As this is the lowest southern point in the prairie drainage basin of western Canada, water from outside Manitoba flows into Lake Winnipeg in the centre of the region from the Winnipeg, Red, Assiniboine, and Saskatchewan Rivers.



MAJOR GEOLOGICAL SUBDIVISIONS

The streams of Region IV flow across the exposed rocky surface of the southern Canadian Shield. Although the total relief is limited, moderately deep lakes are impounded in many depressions that are connected by short, turbulent, stream channels. Streamflows that persist year-round are moderated by the large storage capacity of the lake basins in the headwaters. Many of the lakes and streams in the southern part of the region are developed for summer sports fishing and recreation.

The streams of Region V also flow across the Canadian Shield (and a small portion of the Hudson Bay lowlands), but in the harsher climatic zone of widespread permafrost occurrence in northern Manitoba. Here, the rivers and streams have unique forms that are controlled by bedrock and the melting back of permafrost valley walls. Hydro-electric development has occurred on the major rivers that flow into Hudson Bay and commercial sports fisheries are located on a few of the large lakes in the region. The smaller lakes and rivers are generally unexplored.

Appendix C

Fisheries Inventory and Habitat Classification System – Survey Sheets

Fisheries Inventory and Habitat Classification System Waterbody Questionnaire

Name:________________	Watershed Unit:______	Map Sheet:______

INTRODUCTION

This package will form part of the Fisheries Inventory and Habitat Classification System database. Data compiled for waterbodies will provide an overview on the biological condition of the province's watershed units.

Five sections comprise this package including Biology, Water Quality, Morphology and Hydrology, Land Use, and Habitat Condition. In the Biology section, information on the fisheries resource has been requested to provide a background on species composition, sport and commercial fisheries, and stocking. The section on Habitat Condition identifies the adverse conditions that may be affecting fish and fish habitat in the waterbody, and provides a mechanism of rating (or classifying) fish habitat. "Source" refers to specific coded references for data and information listed in the Literature Cited section.

Your participation is extremely important. Please complete the tables and answer all questions.

Adapted from: Whitworth M.R., Ischinger L.S. and Horak G.C. 1985. Guidelines for implementing natural resource information systems: The River Reach Fisheries Information System. U.S. Fish Wildl. Serv. Biol. Rep. 85(8). 79 pp.

GENERAL INFORMATION

For question 1, please identify <u>who</u> compiled the data, <u>when</u> it was completed, and <u>what</u> regional jurisdiction the waterbody falls under (i.e. based on Manitoba Fisheries Branch regional boundaries). The updated portion of the form will be filled in by Fisheries Habitat Management staff at the appropriate time.

Compiled By:________________________

Date of Completion:________________________

Regional Jurisdiction:________________________

Updated(dd-Mon-yy):________________________

I. BIOLOGY

For this question, please print in the left hand column the common name of all species that occur in the waterbody at any time. Check or code all columns of the matrix that are applicable to these species. You may base your answer on personal experience through field sampling, discussion with colleagues or professional judgement.

For the purpose of answering this question, the following definitions apply:

<u>Sport fish</u>:	any fish with a legal limit (numbers, weights, or volume) set by our fishing regulations.
<u>Commercial</u>:	any fish harvested commercially.
<u>Special Concern</u>:	any fish species that is of particular concern to the waterbody for preservation and management; included are threatened or endangered species, rare and heritage species, species receiving special management attention, or of special concern for study and management.
<u>Introduced</u>:	any fish species not endemic to that waterbody.
<u>Nonsport</u>:	any fish species which is not considered a sport fish.

Population Codes	Check all that apply to the species											Refer to codes in left box		
	Fish Classes					Description or Use						A	B	C
A - Presence A=Abundant C=Common U=Uncommon R=Rare E=Expected X=Unknown Z=Extirpated B - Lifestage Stocked E=Egg L=Larvae F=Fingerlings S=Subcatchable C=Catchable C - Frequency Stocked 1=Less than once annually 2=Annually 3=More than once annually	Sport	Commercial	Introduced	Special Concern	Nonsport	Year Round Resident	Spawn Elsewhere	Spawn and Hatch	Nursery	Migration Route	Over Winter	Presence	Lifestage Stocked	Frequency Stocked
Common Name														
1.														
2.														
3.														
4.														
5.														
6.														
7.														
8.														
9.														
10.														
11.														
12.														
13														
14.														
15.														
16.														
17.														
18.														
19.														
20.														

Resource Access

The resource access form was designed to determine accessibility and/or distance to the waterbody. For the purpose of answering this question, the following definitions apply:

Aircraft on Wheels	- For undeveloped areas (i.e. Northern region) use air strips that are available. - For developed areas use D.O.T. strips or air strips identified on a 1:50,000 map.
Distance Measurements	- Zero indicates access right to the waterbody while a blank value indicates not applicable.

Access and/or Distance to (km):	
Aircraft on Wheels:	Aircraft on Floats:
Seasonal Road:	All Season Road:
Boat:	Walking:
Electrical Power:	FFMC Delivery Point:

Allocation

Please indicate year(s) in which present and historic allocations were made.

Year of Allocation	Commercial, Sport, Bait, or Domestic

General Fisheries Use

General Fisheries Use identifies the different types of fishing activities occurring within the waterbody. Please check (✓) off the appropriate fields, and if possible, provide an estimated harvest.

Fisheries Use	(✓)	Estimated Harvest(kg)
Recreational Angling		
Commercial Sport		
Commercial Net		
Domestic		
Bait		

Sport Fishing Lodges

Lodge/Outcamp Name	Boat Cache Lodge, Outcamp	No. of Beds	Estimated Harvest (kg)

Note: If estimated harvest is not available, use 375 kg/bed/season

Source:______

Creel Surveys

Species	Year of Census	Catch/Unit Effort

Source:______

Commercial Fishing Regulations

This section of the questionnaire was designed to provide baseline information with respect to years of operation, commercial seasons, and present harvest restrictions (i.e. closed time, type of gear, etc.). Present harvest restrictions fall under sections 4 and 45 of the Manitoba Fishery Regulations and are published annually in the Manitoba Gazette.

Years of Operation: _____ to _____

	Summer	Fall	Winter	Spring
Season of Fishery:	____	____	____	____

Present Harvest Restrictions:

____

____

____

____

Whitefish Classification

Please indicate year(s) in which present and historic classifications were made.

Year	Classification

Classification=Export, Continental, or Cutter

Source:_____

Commercial Fishing Summary on quota species harvests(in parentheses)

Years	Total Annual Quota	Total Annual Harvest	Percent of Total Harvest							Number of		Gross Landed Value ($)
			Whitefish	Walleye	Pike	Lake Trout	Sauger	Y. Perch	Other	Lic	Men	
1988												
1989												
1990												
1991												
1992												
1993												

II. WATER QUALITY

Summer Temperature

Date	Maximum Temp.(°C)	Thermocline Present	Thermocline Depth(m)	Max.Temp.(°C) Below Thermocline

Source:______

Dissolved Oxygen

Date	# of Stns.	Low	High	Avg.	Conductivity @ Temp.(°C)	pH

Source:______

Water Chemistry (Unless indicated, all measurements in mg/l)

	Number of Parameters Measured	Parameters that Exceed CWQ Guideline Level
Inorganic		
Organic		
Physical		

Source(s):________

Inorganic Parameters	Samples	Low	High	Average	MSWQO or CWQ Guideline
Aluminum[1]					.005-.01
Antimony					ID[3]
Arsenic					190 ug/l
Beryllium					ID
Boron					.02-1.8 ug/l
Cadmium					0.66-2 ug/l
Calcium					
Carbon(Total inorganic)					
Carbon(Total organic)					
Chlorine(Total residual)			?		11.0 ug/l
Chromium					11.0 ug/l
Cobalt(Ext.)					
Copper(Dissolved)					
Copper(Ext.)					
Copper(Total)					6.5-21 ug/l
Cyanide					5.2 ug/l
Dissolved Oxygen					5-9.5
Iron(Dissolved)					
Iron(Ext.)					
Iron(Total)					1.0
Lead					1.3-7.7 ug/l
Magnesium					
Manganese(Ext.)					
Mercury					.006
Nickel					56-160 ug/l
Nitrogen(TKN)					
Ammonia (Total)					.018-.05
NO_2-NO_3 Dissolved					
Nitrite					.06
Nitrate					
Nitrosamines					
pH(pH units)					6.5-9.0
Phosphorous(Diss. Ortho.)					
Phosphorous(Diss. Inorg.)					
Phosphorous(Total)					
Potassium					
Selenium					35 ug/l
Silica					
Silver					.1 ug/l
Sodium					
Sulphate					
Thallium					ID
Zinc(Dissolved)					
Zinc(Ext.)					
Zinc(Total)					47 ug/l

Organic Parameters	Samples	Low	High	Average	MSWQO or CWQ Guideline
Acrolein					ID
Aldrin/dieldrin					.0019 ug/l
Benzene[4]					.3
Chlordane					5 ng/l
Chlorinated Benzenes[4]					
Monochlorobenzene					15 ug/l
Dichlorobenzene					2.5-4.0 ug/l
Trichlorobenzene					0.5-0.9 ug/l
Tetrachlorobenzene					0.10-0.15ug/l
Pentachlorobenzene					.03 ug/l
Hexachlorobenzene					.0065 ug/l
Chlorinated Ethylenes[4]					
Tetrachlorethylene					260 ug/l
Di-and trichloroethylenes					ID
Chlorinated phenols					
Monochlorophenols					7 ug/l
Dichlorophenols					0.2 ug/l
Tetrachlorophenols					1.0 ug/l
Trichlorophenols					18.0 ug/l
Pentachlorophenols 1 ug/L					
Chlorophyll A					
Coliforms(Fecal)(no./100ml)					
Coliforms(Total)(no./100ml)					
DDT					1 ng/l
Dinitrotoluenes					ID
Diphenyllhydrazine					ID
Endosulfan					.0056 ug/l
Endrin					.0023 ug/l
Ethylbenzene[4]					0.7
Halogenated ethers					ID
Heptachlor+Heptachlor epoxide					0.0038 ug/l
Hexachlorbutadiene					0.1 ug/l
Hexachlorocyclohexane isomers					0.01 ug/l
Hexachlorocyclopentadiene					ID
Phenols(Total)					1 ug/l
Nitrobenzene					ID
Nitrophenols					ID
Phenony herbicides(2, 4-D)					4 ug/l
Phthalate esters					
DBP					4 ug/l
DEHP					0.6 ug/l
Other phthalate esters					0.2 ug/l
Polychlorinated biphenyls(Total)					.014 ug/l
Polycyclic aromatic hydrocarbons					ID
Toluene					0.3
Toxaphene					.013 ug/l

Physical Parameters	Samples	Low	High	Average	MSWQO or CWQ Guideline
Alkalinity(Total)					
Colour					
Conductivity(uho/cm)					
Hardness(Total)					
Oxygen(BOD)					
Residue(Filterable)					
Residue(Non-filterable)					
Residue(Total)					
Temperature(°C)					
Turbidity(NTU or JTU)					
Secchi disc(m)					

1. Canadian Water Quality Guideline (1987) concentrations of heavy metals reported as total metal in an unfiltered sample.

2. For more than one years data, amalgamate the samples and record the overall low, high, and average.

3. ID=insufficient data to recommend a guideline.

4. Tentative Guideline

5. Manitoba Surface Water Quality Objectives (1986) are applicable to Class 2 waters: Aquatic Life and Wildlife, and provide an upper level beyond which unacceptable adverse effects could occur to aquatic life. Where MSWQO were not available, Canadian Water Quality Guideline values were used.

III. MORPHOLOGY AND HYDROLOGY

Lake Morphology

Date: Lake Elevation (m):

Gauge Station Number	
Area (ha)	
Maximum Depth (m)	
Mean Depth (m)	
Volume (m^3 X 10^6)	
Length of Shoreline (km)	
Length of Island Shoreline (km)	
Total Length of Shoreline (km)	
Shoreline Development Index	

Source:_____

Stream Morphology

Date: Total Drainage Area (km^2):

Gauge Station No.: Stream Length (km):

Stream Order:_____

Avg. Bankfull Width (m):_____

Avg. Bankfull Depth (m):_____

QBF (m^3/s):_____ τBF:_____

Present n:_____ Estimated n:_____

Avg. Slope (%):_____ Riffle Slope (%):_____

Pool Slope (%):_____

Median Diameter of Substrate (m):_____

Avg. Depth (m):_____

Avg. Width (m):_____

Avg. Velocity (m/s):_____

Source:_____

IV. LAND USE

Summary of existing activities and developments within the waterbody. Check (✓) appropriate boxes.

	Class 1	Class 2	Class 3
Agriculture		—	—
Energy Production			
Fisheries		—	—
Forestry			—
Manufacturing		—	—
Mining			
Recreation			—
Transportation and Transmission			—
Waste Treatment/ Disposal			—
Water Development and Control			

Land use classification of specific activities and developments. Check (√) appropriate activities.

	Class 1	Class 2	Class 3
Agriculture	___ Farming(general) ___ Feedlots ___ Irrigation ___ Rendering Plants ___ Meat Processing/ Slaughter Plants ___ Dairy Plants ___ Food Processing Plants		
Energy Production	___ Thermal Plants ___ Nuclear Reactors	___ Electric Generating Station ≤ 100 MW	___ Electric Generating Stations > 100 MW
Fisheries	___ Fish Hatcheries ___ Sport Fishing Lodges and Outcamps ___ Commercial Fishing Stations and Camps		
Forestry	___ Insecticide and Herbicide Spraying ___ Logging ___ Wood Treatment Plants ___ Sawmills ___ Plywood and Particle Wood Plants	___ Pulp and Paper Plants ___ Main and Secondary Haul Roads	
Manufacturing	___ Cement Plants ___ Concrete Batch Plants ___ Building Products Facilities ___ Gasification Plants ___ Foundries ___ General Manufacturing/ Processing Plants		
Mining	___ Ongoing Exploration	___ Surface and Underground Mines	___ Potash and Metal Mines Producing >1000 tons/day of Sulfide Ore

Land use classification (cont'd)

	Class 1	Class 2	Class 3
Recreation	___ Cottage Development ___ Campgrounds ___ Fish and Wildlife Refugia and Management Area ___ Remote Cottaging	___ Major Recreation and Tourism Development ___ Provincial, Municipal and Federal Parks	
Transportation and Transmission	___ Seasonal Roads ___ All Season Roads ___ Railroads ___ Airports ___ Sea Plane Bases	___ Transmission Lines Crossing Sensitive Areas ___ Pipelines Crossing Sensitive Areas	
Waste Treatment/Disposal	___ Water Treatment Plants (wastewater)	___ Wastewater Treatment Lagoons ___ Sewage Treatment Plants	
Water Development and Control	___ Stock Watering Dams ___ Shoreline and Floodplain Development ___ Wetland Development	___ Irrigation ___ Channelization ___ Lake Regulation ___ Stream/River Regulation ___ Within Basin Diversions	___ Interbasin Water Transfers ___ Flood Control Works ___ Water Supply Impoundments

V. HABITAT CONDITION

Seasonal Habitat Suitability

Please check (√) the months the waterbody has water usable as fish habitat during a normal water year.

All Year	J	F	M	A	M	J	J	A	S	O	N	D	NONE

The next section identifies adverse conditions that may be affecting fish in the waterbody. Note that natural conditions are included in the tables. The tables should be completed one at a time. For example, if a waterbody is dammed and several adverse conditions result, each table (water quantity, usable habitat, fish community) should be completed as a unit. If the dam is causing gas supersaturation in the waterbody enter #46 beside #6, if the dam blocks fish access to spawning gravel upstream enter #71 beside #27. Use "other" only when necessary to explain conditions; keep explanations brief. If linkage between the Limiting Factor(s) and Probable Source(s) is unknown, use check (√) marks to indicate occurrence.

1. Is the survival, productivity, or use of the fish community being adversely affected by natural or manmade conditions in the waterbody? <u>Circle one number</u>

Yes, definitely	1	Answer A than B
Yes, suspected	2	
Doubtful	3	Answer B
No, definitely	4	
Unknown	5	

(A) If yes (definitely or suspected)

Please complete the following tables by identifying the probable source(s) for each applicable limiting factor. If possible, indicate with a circle if the factors and sources are of major 2 or minor 1 concern.

WATER QUALITY

A. Limiting Factor

Major Minor

1___Temperature too High....2......1
2___Temperature too Low.....2......1
3___Turbidity...............2......1
4___Salinity................2......1
5___Dissolved Oxygen........2......1
6___Gas Supersaturation.....2......1
7___pH too acidic...........2......1
8___pH too basic............2......1
9___Nutrient Deficiency.....2......1
10___Nutrient Surplus........2......1
11___Toxic Substances........2......1
12___Other (specify below)
_____________________________2......1

B. Probable Source

Major Minor

39___Primarily Upstream....2......1
40___Within Reach..........2......1
41___Point Source Discharge............2......1
42___Industrial............2......1
43___Municipal.............2......1
44___Combined Sewage.......2......1
45___Mining................2......1
46___Dam Release...........2......1
47___Nonpoint Source Discharge............2......1
48___Individual Sewage Disposal.............2......1
49___Urban Runoff..........2......1
50___Landfill Leachate.....2......1
51___Construction..........2......1
52___Agriculture...........2......1
53___Feedlot...............2......1
54___Silviculture/Logging..2......1
55___Mining................2......1
56___Natural...............2......1
57___Unknown...............2......1
58___Other (specify below)
2......1

WATER QUANTITY

A. Limiting Factor

Major Minor

13___Below Optimum Flows/ Levels...................2......1
14___Above Optimum Flows/ Levels...................2......1
15___Loss of Flushing Flows..2......1
16___Excessive Flows/Level Fluctuation.............2......1
17___Occasional Low Flow/ Level...................2......1
18___Other (specify below)
_____________________________2......1

B. Probable Source

Major Minor

59___Dam(Power)............2......1
60___Dam(Flood Control)....2......1
61___Dam(Storage)......... 2......1
62___Diversion(Agriculture)2......1
63___Diversion(Municipal)..2......1
64___Diversion(Industrial).2......1
65___Natural...............2......1
66___Other (specify below)
_____________________________2......1

USABLE HABITAT

A. Limiting Factor

Major Minor

19___Adult/Juvenile Habitat..2......1
20___Pools/Profundal Zone....2......1
21___Riffles/Littoral Zone...2......1
22___Undercut Banks..........2......1
23___Boulders................2......1
24___Snags...................2......1
25___Cover...................2......1
26___Egg/Larvae Habitat......2......1
27___Gravel..................2......1
28___Plants, Plant Debris....2......1
29___Other (specify below)
______________________________2......1

B. Probable Source

Major Minor

67___Excessive Siltation...2......1
68___Bank Erosion/Sloughing2......1
69___Channelization........2......1
70___Other Channel
Modifications.........2......1
71___Migration Blockage....2......1
72___Natural...............2......1
73___Unknown...............2......1
74___Other (specify below)
______________________________2......1

FISH COMMUNITY

A. Limiting Factor

Major Minor

30___Fish Kills..............2......1
31___Contamination...........2......1
32___Diseases/Parasites......2......1
33___Tumors/Lesions..........2......1
34___Overharvest.............2......1
35___Poaching................2......1
36___Underharvest............2......1
37___Fish Stocking...........2......1
38___Other (specify below)
______________________________2......1

B. Probable Source

Major Minor

75___Heavy Metals..........2......1
76___Pesticides............2......1
77___Other Noxious/Toxic
Substances........... 2......1
78___Crowding..............2......1
79___Other Stress..........2......1
80___Natural...............2......1
81___Unknown...............2......1
82___Other (specify below)
______________________________2......1

Source:_____

(B) Habitat Classification

The next few questions are a subjective but necessary part of this survey. To provide some standardization for response, four classes are shown below describing the spectrum of conditions that could exist in an aquatic ecosystem in terms of the fish community. Class 1 is the ideal situation of maximum ability to support a fish community of high interest, i.e. a community of sport fish or other species of special concern. Class 4 represents a waterbody that is incapable of supporting any fish community. Please use these classes as a reference in answering questions 1, 2, 3, 4, and 5.

CLASSES

Class 1	Waterbodies that have high capability for production of fish.
Class 2	Waterbodies that have slight limitations to production of fish.
Class 3	Waterbodies that have moderate limitations to production of fish.
Class 4	Waterbodies that have severe limitations to production of fish.

CHECK ONE FOR EACH QUESTION

1. Using the classes shown above, how would you intuitively rank the current conditions of the waterbody?

☐	☐	☐	☐
1	2	3	4

2. Again using these classes, how would you rank the conditions of this waterbody five years ago?

☐	☐	☐	☐
1	2	3	4

3. If present trends in the waterbody continue, how will it rank five years from now?

☐	☐	☐	☐
1	2	3	4

4. Should the man-caused limiting factors (indicated in the Habitat Condition section) be eliminated or controlled, how will the waterbody rank five years from now?

☐ 1 ☐ 2 ☐ 3 ☐ 4

5. Considering, as a standard, a waterbody in the same or adjacent watershed with the greatest ability to support sport fish, how would you rate that waterbody on the scale?

☐ 1 ☐ 2 ☐ 3 ☐ 4 Standard:______________

6. If an improvement in conditions is required, please use these lines to indicate the type of modification needed, the priority for implementation (critical, necessary, desirable, helpful), and if the modification is in progress, in planning, or discussion stage only:

____

____

____

7. Historic Improvements and Comments

Please identify activities, if any, that have occurred within the waterbody. This includes projects such as, riffles, shoals, etc. For the comments section, please acknowledge any other points of interest not included (Note: do not list stocking history under Historic Improvements).

Historic Improvements: ______________________________

____

____

____

Comments: ______________________________________

____

____

____

____

VI. LITERATURE CITED: (Please give a full citation of each source you used).

1.____

____

____

____

2. etc.____

____

____

____

Appendix D

Instream Flow Methods

Instream Flow Methods

The alteration of natural flow conditions, in volume and timing, often occurs downstream from water development projects for hydro-electric generation and irrigation because large volumes of water are either stored or diverted. Smaller projects that use the "run-of-the-river" flows, like municipal water supply and recreation dams or stock watering dams have little effect on flows, although the water temperature and quality may be altered. Extensive land drainage and channelization in a drainage basin alters streamflow regimes as well. The more efficient excavated system causes higher flood flows and consequently adjustments in the channel geometry of lower reaches and it reduces flow persistence by eliminating surface storage in small ponds and "pothole" lakes.

Consequently, a limit for the minimum flow and an occasional maximum or flushing flow may be required to maintain aquatic habitats in the stream (IFR). There are three common approaches to estimating IFR and the recommended "mass curve" method that was discussed in Chapter 4 (see design step 8: instream flow requirements). The three methods are described in order of their increasing analytical requirements in the following sections with references for their procedures:

1) Tennant Method: This is a practical method for a preliminary assessment of minimum flows based on the observations and extensive experience of D. L. Tennant, a fisheries biologist working in Montana, Wyoming, and Nebraska. Tennant observed that the amount of hydraulic habitat in his stream increased most rapidly in the flow range from 0 to 10% of the average annual flow. In his streams, at the 10% level, 60% of the substrate was covered with water. Consequently, Tennant recommended a range of flows based on the average annual flow. For example: minimum 10%, good 20 - 40%, excellent 30 - 50%, optimum 60 - 100%, flushing 200%.

The distribution and timing of the habitat maintenance flows have to follow the natural flow cycle for the stream and there may be short-term critical periods of migration with more specific requirements. Given these conditions, Tennant's method provides a good first estimate of IFR that more elaborate flow prediction methods may not improve.
Reference: Tennant, D.L. 1976. Instream flow regimens for fish, wildlife, recreation, and related environmental resources. Fisheries, 1(4).

2) Wetted Perimeter Method: Tennant's method worked by keeping water in the channel. The wetted perimeter method was proposed as a further elaboration of Tennant's observations. In this method the amount of wetted perimeter at several stages in sample channel cross-sections is plotted against the corresponding discharge rates to determine if the wetted perimeter increases abruptly with stage. If it does, this is taken as a minimum flow stage and discharge. The conditions of timing and critical periods must again be applied.

It seems that this method takes the first large step into field surveys by requring the choice of representative sample reaches in successful habitats (pools or riffles), surveying cross-sections, and estimating a flow rating curve for ungauged sites.
Reference: Orth, D.J. and O.E. Maughan. 1982. Evaluation of the incremental methodology for recommending instream flow for fishes. Trans. Am. Fish. Soc., 111(4).

3) Instream Flow Incremental Method (IFIM): The IFIM method is based on a more elaborate treatment of the sample reach data used in the wetted perimeter method, aided with a computer package for calculations, plotting, and bookkeeping. Sample reaches used to estimate rating curves and preferred reach characteristics are summarized as Habitat Suitability curves for depth, velocity, and substrate. Sample cross-sections in the study reaches are then used to prepare an estimate of how much of the channel area will meet the selected habitat parameters at different flow stages (the PHABSIM program). The minimum flows required to maintain a minimum “useable area” for selected time periods and different weighting of the suitability parameters is then recommended.

The IFIM provides the analyses required to complete the wetted perimeter rationale, once the step has been taken to use sample reaches to measure habitat conditions as a function of depth and discharge. There is often an additional advantage in applying the method as the field data may have been gathered already for channel flood capacity studies. The choice of a minimum “weighted useable area” must still be made.

Reference: Bovee, K.D. 1982. A guide to stream habitat analysis using the instream flow incremental methodology. Instream Flow Information Paper 12. U.S. Fish and Wildlife Service.

As discussed in Chapter 4, the use of historical records and reference streams for instream flow regulation is a fourth method where sufficient field support is available. In this case it is just an analogy method (JAM).

Appendix E

Abbreviated Stream Hydrology Survey Sheets

HYDROLOGY A

Date

Stream Name

Location

A. Present Discharge

Cross Section of Metered Flow

1 2 3 4 5 6

Velocity (m/s) at 0.6 · Depth

Average Velocity, $\overline{V}$ = m/s

Area, A = m^2

Q_{pres} = m^3/s

n_{pres} =

D. Bankfull Conditions

Width	Depth	Width	Depth

Average Bankfull Width, $\overline{W}$ = m

Average Bankfull Depth, $\overline{D}$ = m

n_{bf} =

τ_{bf} = Q_{bf} = m^3/s

B. Present Flow

x - sec 1

x - sec 2

x - sec 3

x - sec 4

x - sec 5

Present Average Depth, $\bar{d}$ = m

Present Average Width, $\bar{w}$ = m

	Riffles		Pools	
	Length	Slope	Length	Slope
1.				
2.				
3.				
4.				

Total Length = Average Slope =

C. Stream Bed

X_{cm}	Y	Z	$\overline{Ø}$	Rank

Observations & Calculations

Select a sample reach roughly 20-30 times the channel width including at least one pool-riffle sequence.

A. Measure present discharge at a convenient cross section of the flow as:

$$Q_{pres} = \overline{V} \cdot A \; m^3/s$$

B. Determine average cross section and stream gradient from 4 or 5 typical cross sections along the reach. Determine the present Manning resistance factor using average depth, $\bar{d}$, average slope, $\bar{s}$ and measured discharge, Q_{pres}

$$n_{pres} = \frac{\overline{W} \cdot \bar{d}^{\frac{5}{3}} \cdot \bar{s}^{\frac{1}{2}}}{Q_{pres}} \; m^{\frac{1}{6}} \quad \text{(Manning's Roughness Coefficient)}$$

C. Randomly select 24 or 32 samples of the bed paving materials along the reach and measure their x, y, z axes (cm). Rank, from largest to smallest, and plot the mean diameter Ø cm of each sample in a cumulative plot where the plotting position = rank/total no. in sample plus one x 100%. Using the median diameter ($Ø_{50m}$), estimate the Strickler n value for a deep channel using:

$$n_{st} = 0.04 \cdot (Ø_{50m})^{\frac{1}{6}} \; m^{\frac{1}{6}}$$

note: $Ø_{50cm}$ must be converted to $Ø_{50m}$

D. Measure 6 to 10 typical bankfull flow widths (high water marks) and depths along the reach. Estimate the bankfull discharge using your choice of n values determined from n_{st}, photographic keys, or observed present values:

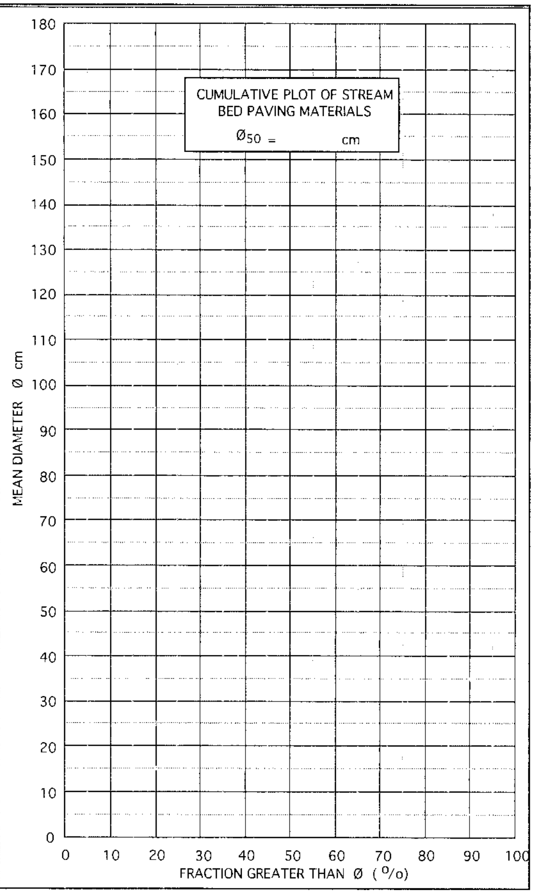
$$Q_{bf} = \frac{\overline{W} \cdot \overline{D}^{\frac{5}{3}} \overline{S}^{\frac{1}{2}}}{n_{bf}} \; m^3/s$$

E. Using the bankfull depth $\overline{D}$ and slope $\overline{S}$ calculate the tractive force τ, where $\tau_{bf} = 1000 \cdot \overline{D} \cdot \overline{S}$ (kg/m²). Determine the fraction of bed paving materials that would be in motion at the bankfull stage from τ_{bf} = Ø cm using the bed material plot developed (c).

Prepare a plan sketch on the Hydrology B form of the sample reach showing the pattern of the bankfull channel, floodplains and terraces. The sketch may be supplemented with photographs and other observations pertinent to the habitat.

HYDROLOGY B	Stream Name	Location	Date

Sketch



Appendix F

Other Applications of the 10 Step Analysis and Design Process

Wilson Creek Alluvial Fan Stabilization Project MB

Channelization for agricultural land drainage through a 0.8 % grade 2 km reach in a sub-escarpment shale fan in 1929 caused the stream to downcut 5 m into the fan surface. Sediments from the Wilson Creek fan and other nearby escarpment streams were deposited in downstream spawning habitats, leading to the collapse of a major walleye fishery on Lake Dauphin. The basin area tributary to the Wilson Creek fan is 22.1 km^2.

Beginning in 1980, five 2m rock-fill rapids were constructed in the fan reach to reduce the gradient by 50%. Although the pools rapidly filled with sediments, the reduction in gradient has stopped downcutting and widening of the stream. The design has been applied subsequently to the other escarpment streams.

reference: Newbury R. and M. Gaboury 1988. The use of natural stream characteristics for stream rehabilitation works below the Manitoba escarpment. Can. Water Resources Journal 13(4):35-51.

Roseau River Dam Fish Passage Project MB

A vertical 1.2 m high concrete spillway on the Roseau River dam near Dominion City, MB blocked fish passage at moderate and low flows. The catchment area for the project reach is 5200 km^2.

Two rock riffles (rapids at this scale) with pools were constructed in the reach below the dam. Each of the rapids raised the still water level in the upstream pool by 0.4 m. The remaining drop of 0.4 m at the dam spillway was graded with boulders on the downstream apron. Fish passage over the dam at low flows has been successful.

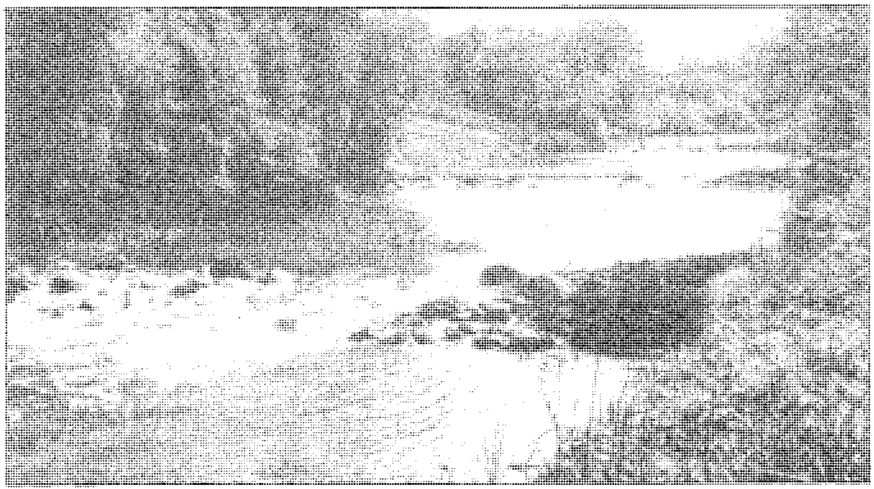


Figure F-1: two pools and rapids constructed below the Roseau River dam to facilitate fish passage over the vertical spillway.

Little Saskatchewan River Dam Fish Ladder Project MB

A vertical 3 m high spillway blocked all fish passage at the Rapid City earth-fill dam on the Little Saskatchewan River, MB. The basin area tributary to the dam site is 3910 km^2.

In 1992, eight 0.3 m high rock riffles were constructed on a diagonal channel leading from the tailrace to a headpond on the downstream face of the dam. The headpond was connected to the upstream reservoir with a 1.2 m diameter culvert through the dam crest. A maximum flow of 0.15 m^3/s is controlled with a timber gate on the upstream end of the culvert. The fish ladder channel was constructed on fill placed on the downstream face of the dam underlain by drainage rock.

Walleye, northern pike, and suckers readily ascend the pool and riffle fish ladder.

reference: Gaboury M. and R. Newbury in press. Two fish passage designs for small dams using natural rock riffles and pools. Manitoba Fisheries MS Report.

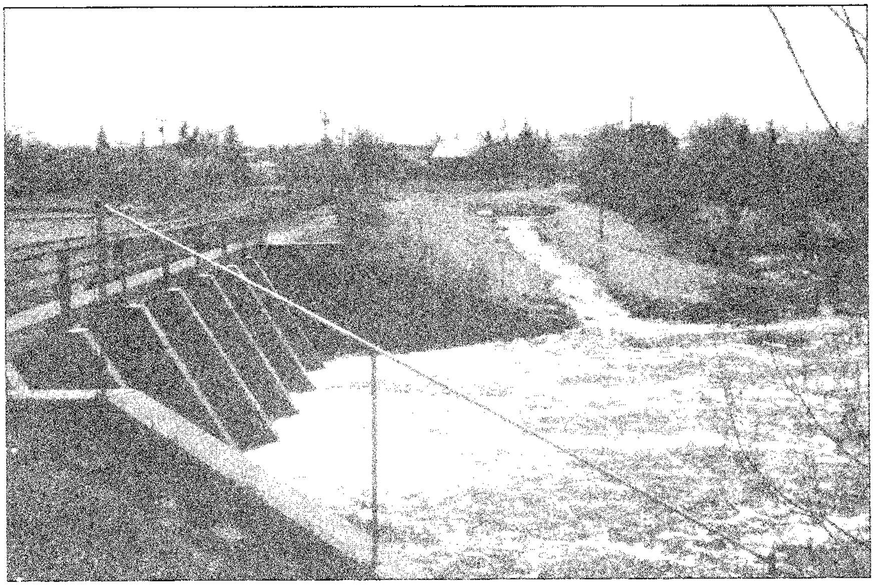


Figure F-2: pool and riffle fish ladder constructed on the downstream face of the Rapid City dam, Little Saskatchewan River MB.

Twin Creeks Project BC

Twin Creeks was diverted to either side of its alluvial fan to create a log sort station in 1960. In 1993, 7 rock riffles were constructed in the uniform southern channel to trap gravels and form spawning and rearing habitat for salmon and cutthroat trout.

Table F-1: Twin Creek project summary.

drainage area		5 km^2
mean annual rainfall		2590 mm
reach gradient		2.5%
bankfull discharge		14 m^3/s
bankfull width	natural	6.5 m
	diverted reach	11 m
bankfull depth	natural	0.7 m
	diverted reach	1.2 m
minimum flow		0.05 m^3/s
construction	surveys	4pd
	design	1 pd
	supervision	1 pd
	backhoe and loader	8 hours
	rock hauling	20 hours

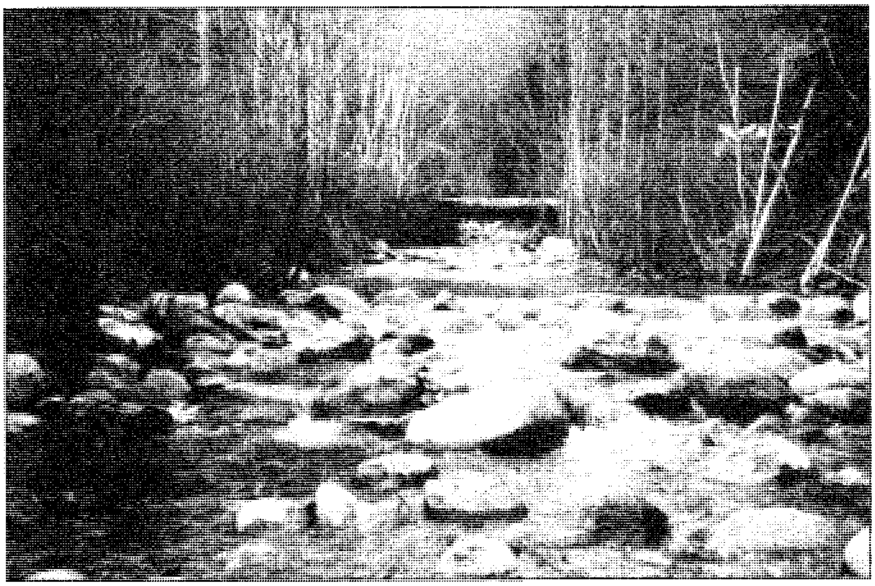


Figure F-3: *Second riffle and pool constructed in the southern diversion channel of Twin Creeks. Flood flows have re-sorted the surface rocks and deposited coarse gravels in the pools.*

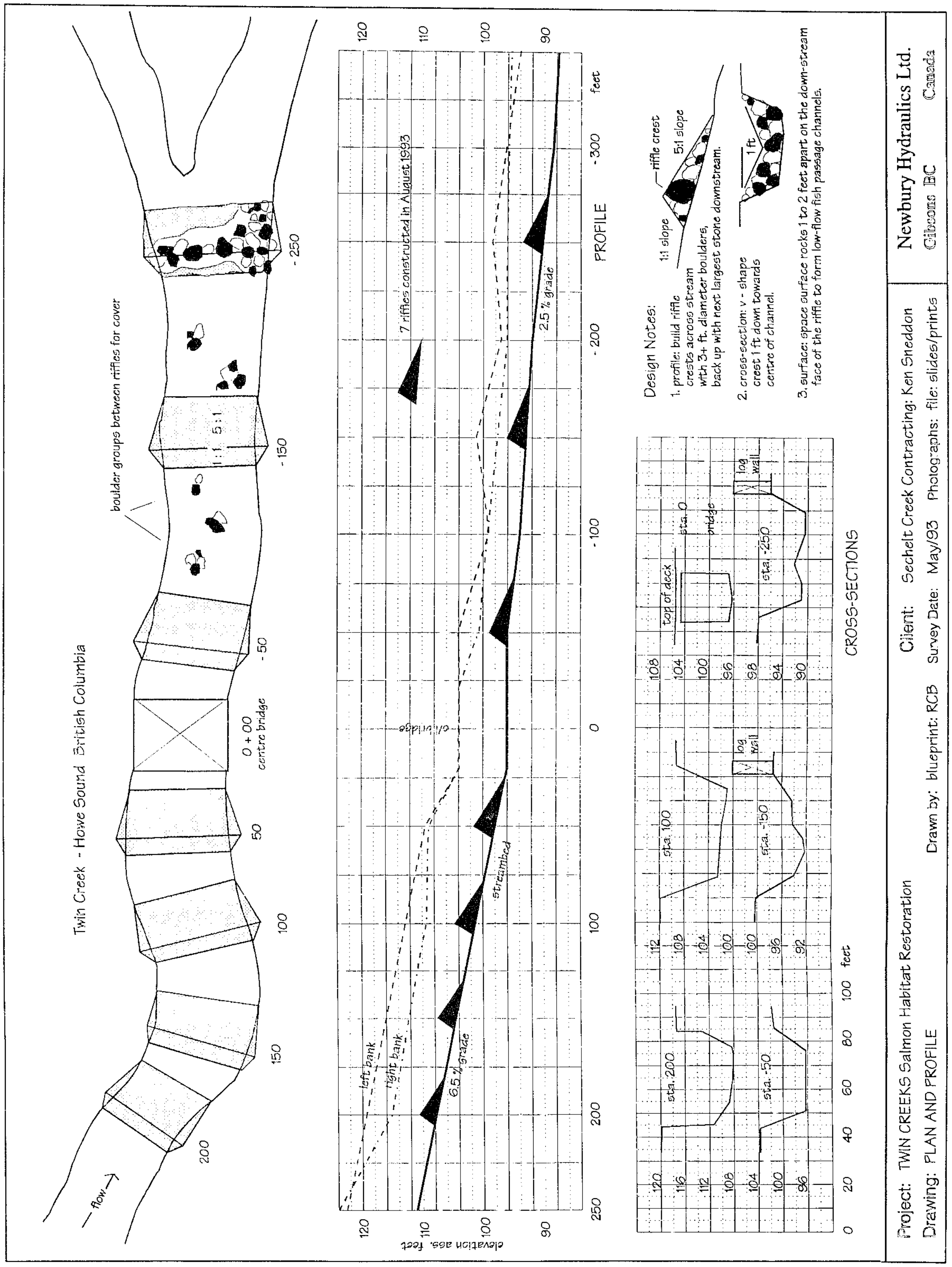


Figure F-4: *Twin Creeks, BC summary design drawing.*

Oulette Creek Project BC

In 1978, the lower 0.5 km reach of Oulette Creek was moved to the western edge of its alluvial fan. Alternating single crest log and rock drop structures constructed in the channel were undercut as the new channel degraded. In 1994, boulder rapids and pools were built at the same sites to restore pool and riffle habitats.

Table F-2: Oulette Creek project summary.

drainage area		5.6 km^2
mean annual rainfall		2590 mm
reach gradient		3 %
bankfull discharge		17 m^3/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 m^3/s
construction	surveys	10 pd
	design	2 pd
	supervision	2 pd
	backhoe and loader	25 hours
	rock hauling	15 hours

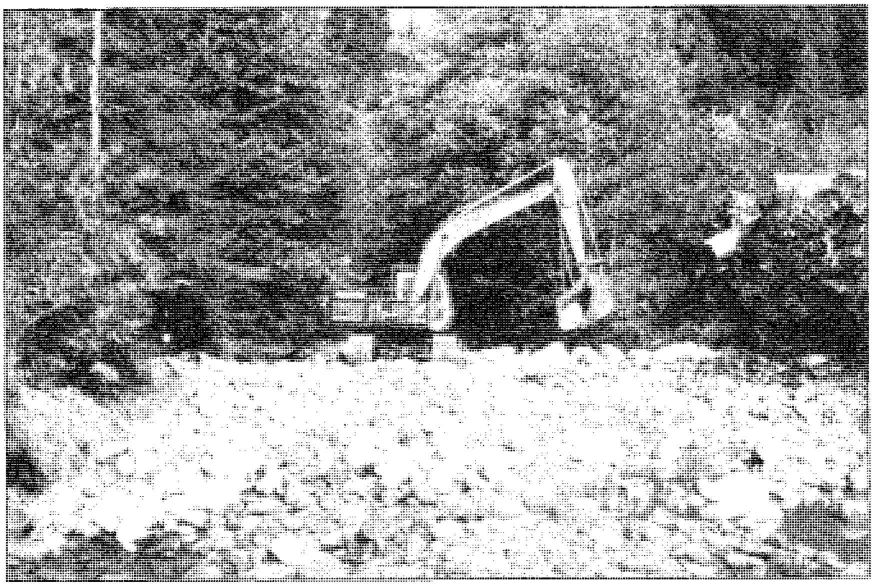
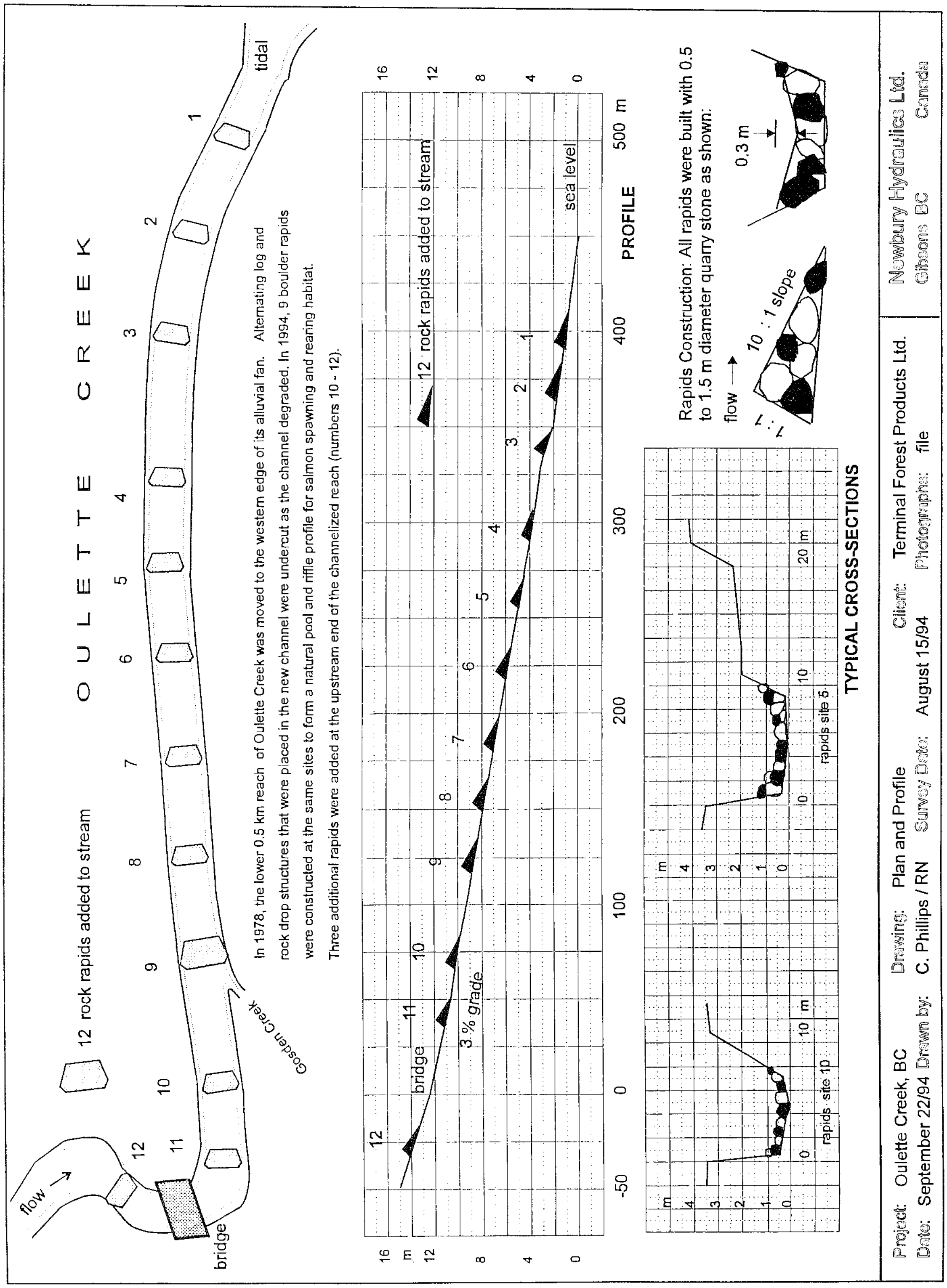


Figure F-5: *Boulders up to 1.5 m in diameter were used to construct rock rapids at intervals of 3 to 6 times the natural bankfull width of the steep gradient salmonid streams. The rapids crest and downstream off-ramp must be carefully constructed to prevent undercutting and to allow fish passage between surface rocks.*



In 1978, the lower 0.5 km reach of Oulette Creek was moved to the western edge of its alluvial fan. Alternating log and rock drop structures that were placed in the new channel were undercut as the channel degraded. In 1994, 9 boulder rapids were constructed at the same sites to form a natural pool and riffle profile for salmon spawning and rearing habitat. Three additional rapids were added at the upstream end of the channelized reach (numbers 10 - 12).

Rapids Construction: All rapids were built with 0.5 to 1.5 m diameter quarry stone as shown:

Project: Oulette Creek, BC
Date: September 22/94
Drawing: Plan and Profile
Drawn by: C. Phillips / RN
Client: Terminal Forest Products Ltd.
Survey Date: August 15/94
Photographs: file
Newbury Hydraulics Ltd.
Gibsons BC Canada

Figure F-6: Oulette Creek BC summary design drawing.

Chapman Creek Project BC

The lower 1.0 km reach of Chapman Creek was diverted away from its main estuary in the 1950's to assist in creating a log booming ground. The channel was lined with large boulders, some of which were used to construct 6 riffles and pools in an unstable section of the diversion reach.

Table F3: Chapman Creek project summary.

drainage area		72 km^2
mean annual rainfall		1270 mm
reach gradient		1.7 %
bankfull discharge		68 m^3/s
bankfull width	natural	20 m
	diverted reach	21 m
bankfull depth	natural	1.3 m
	diverted reach	1.6 m
minimum flow		0.1 m^3/s
construction	surveys	14 pd
	design	2 pd
	supervision	12 pd
	backhoe	50 hours
	materials	on site

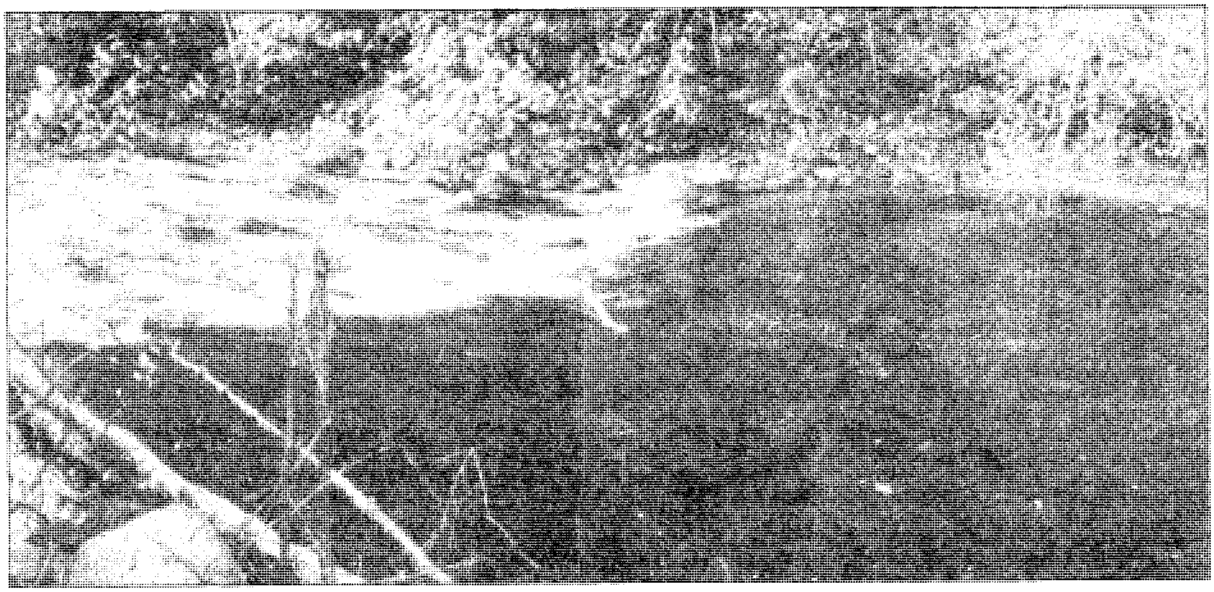


Figure F-7: Coho salmon ascending the second riffle constructed in Chapman Creek and spawning in the accumulated gravels on the margins of the upstream pool (October 1993).

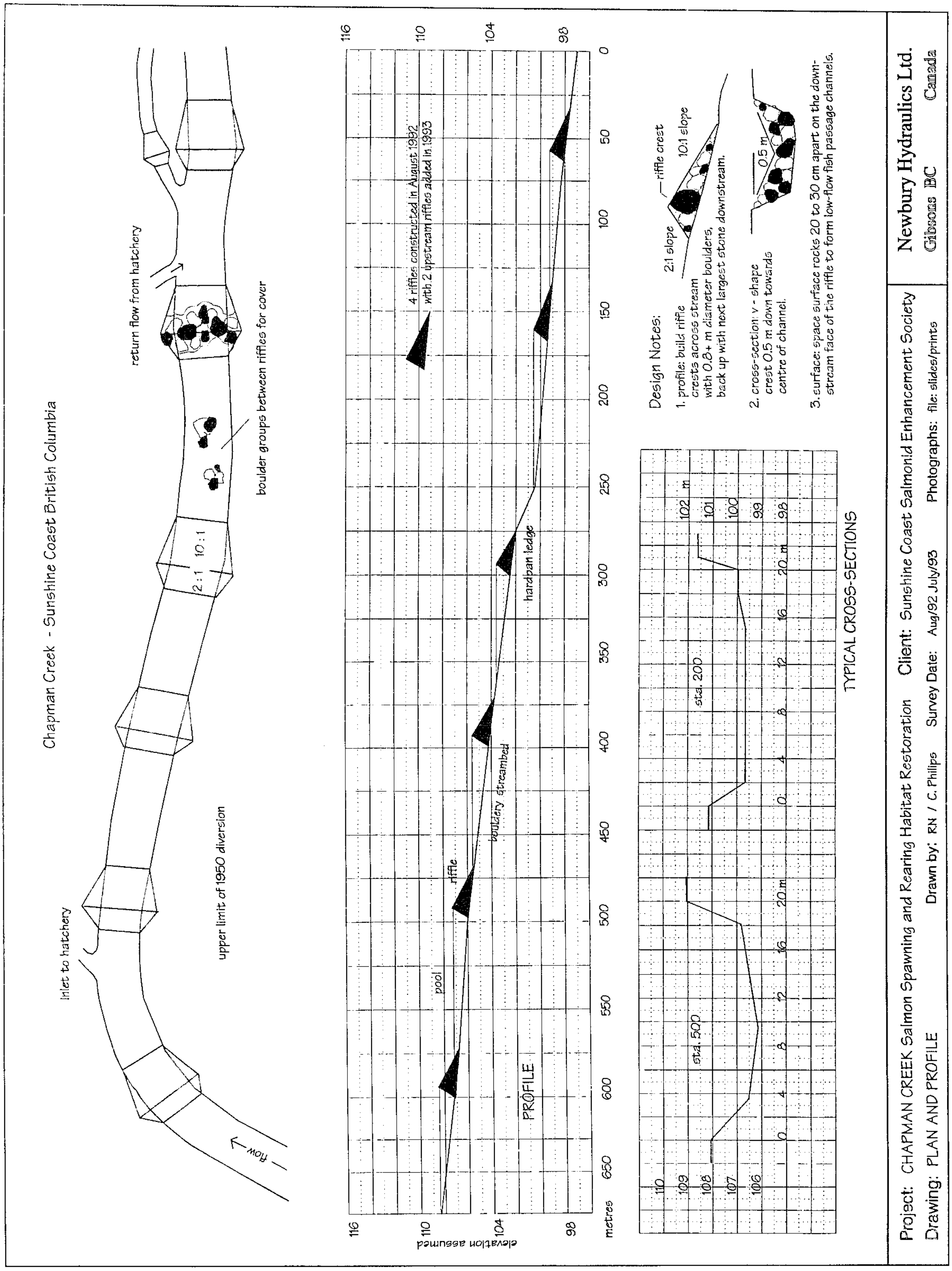


***Figure F-8:** Chapman Creek BC summary design drawing.*

Glossary

Backwater curve: the water surface profile in a section of river in which there is a gradual transition in the depth of flow upwards or downwards relative to the channel bottom. For example, if a dam or obstruction is encountered, the depth of flow will gradually increase in the reach above the dam until it reaches the pool or reservoir level. This is called the **backwater effect**. The extent of the effect depends on the frictional resistance of the upstream reach and the magnitude of the depth change. In hydraulic terms, this is **gradually-varied flow** as opposed to **rapidly-varied flow** in which frictional resistance plays a minor role.

Bankfull discharge, Q_{bf}: in a single channel stream, the discharge which just fills the channel without flowing onto the floodplains. It is also the **characteristic discharge, dominant discharge,** or **channel maintenance discharge** used in describing the central **channel geometry** (width, depth and capacity). In many North American rivers, the bankfull discharge is equalled or exceeded in two out of three years (an **annual flood frequency** of 67%). In incised channels, the characteristic discharge may occur at a lower stage, often related to the depth of regular scouring that occurs in the channel. Channel geometry relationships may be developed with either measure as long as the criteria for measurement are consistent with each sample reach.

Bed paving materials: the largest fraction of the materials on the surface of the streambed. The bed paving materials are usually deposited as the flood peak passes and remain stable during low-flow periods. If the materials are cobbles and boulders that occupy a significant portion of the flow cross-section, they will increase the hydraulic roughness of the reach (generally when the median diameter of the bed materials is greater than one-third of the depth of flow). The **unstable fraction** of bed paving materials may be determined for various discharges, giving some sense of streambed stability (see **tractive force**).

Boundary layer: the transitional region of flow immediately adjacent to all fixed surfaces where the velocity increases rapidly from zero. Stream flow is generally **turbulent**, except in this thin transitional boundary layer where viscous forces dominate and the flow is **laminar**. In a typical stream with a depth of flow of 1 m and a velocity of 1.3 m/s, the laminar boundary layer on the streambed is less than 1 mm thick.

Catchment: the topographic area which drains into a stream at a specific location as defined by all land sloping towards the channel and its tributaries. The boundary of the catchment is called the **drainage divide** or **watershed line**. Groundwater may be imported or exported between catchments.

Continuity equation: the relationship Q = v x A where Q is the discharge and v is the average velocity in the cross-sectional area of the flow, A. The flow is assumed to be "continuous" between channel cross-sections if no new inflows have occurred between the sections. This equation is often used to determine the mean velocity by measuring the cross-sectional area and dividing it into the discharge. The discharge may be measured using a velocity meter at a convenient cross-section or it may be available from a nearby gauging station.

Critical flow, v_c: the depth and velocity of the flow that occurs at a free-overflow cross-section such as the crest of a spillway or top of a boulder just below the surface where the flow continues to accelerate downstream. The critical velocity is equal to the velocity of a shallow wave caused by a disturbance in a still pool of the same depth (the **critical depth**). In both cases $v_{critical}$ = (gravity x depth)$^{1/2}$. This formula can be used to estimate the flow velocity and discharge at a free-overflow section by simply measuring the depth and cross-sectional area of the flow at the critical section. Flows that are deeper and slower than the critical flow are called **sub-critical**, and shallower and faster, **super-critical**. It is important to note that flows may accelerate smoothly from sub-critical to super-critical conditions, but they decelerate abruptly and turbulently (see **hydraulic jump**).

Cross-sectional area, A: the area of a vertical plane at right angles to the stream channel. Flow cross-section is the area of the flow at right angles to the flow direction.

Density: mass per unit volume. In the SI system, density is expressed in kilograms per cubic metre. For example, water has a density of 1000 kg/m^3 at 4^{o}C, medium-grain sand 1600 kg/m^3, and concrete and granitic rock 2600 kg/m^3.

Depth of flow, d: the vertical distance from the water surface to the streambed. This may also be determined from the stage or elevation of the flow by subtracting the elevation of the bed at the same flow cross-section.

Discharge: the volume of water passing through a cross-section of the flow for a given time period. The SI unit of measure is cubic metres per second. The discharge Q, is equal to the average velocity, **v**, times the cross sectional area, **A** (see **bankfull discharge, gauging station**).

Drainage basin: the area contributing water to a selected point along a stream channel. In some studies, the drainage basin is also called the **watershed,** although this term may be confused with the drainage divide (see **catchment**).

Duration curve: a graph with an ordered plot of all discharges for a chosen period of record expressed as a cumulative percent of all flows. For example, for a **monthly flow**

duration curve for a ten year period, the mean monthly discharges would be plotted in order of descending magnitude for a 120 months as a cumulative percentage of discharges of that magnitude or greater. The percentage is conveniently determined by dividing the rank of the discharge magnitude by the total number of flows in the period. In this case, the highest monthly discharge would be plotted at 1/120x100% = 0.8%, the second highest, 1.7% etc. Flow duration curves may be prepared for any time increment that is required to describe the range and intensities of flows for a period that is significant to the stream habitat (**hourly, daily, weekly, monthly, spawning season etc**).

Flood frequency curve (annual): a graph of annual flood peaks usually ranked in descending order and their frequency of exceedence. The graph may be interpreted as the probability of a certain discharge or greater occurring in a given year. The annual flood frequency curve describes a sample of peak annual events only and is often mis-interpreted as representing all floods (see **duration curve**). A misleading convention for describing annual floods is to interpret the frequency as a **return period**. For example, a flood of a certain magnitude or greater with a frequency of occurrence of 4% is assumed to occur in 4 years out of 100 years, or with a return period of 100/4 = 25 years. In fact, there is a 4% probability that the flood or greater will occur in every year. The plotting frequency for a given discharge is often determined using Weibull's estimate for an incomplete record where **cumulative frequency = the rank of the flood magnitude/total number of floods in sample plus 1 x 100%** plotted on **log-normal probability graph paper** to produce an approximate straight-line relationship.

Floodplain: that portion of a river valley, adjacent to the river channel, which is covered with water when the river overflows its banks during floods.

Flow: the state of flow observed in open channels is generally **turbulent**. A thin **laminar** layer of flow occurs only at fixed boundaries. Critical flow occurs at overflow crests and in steep chutes and is characterized by standing waves or a smooth undulating surface. The state of flow may be determined by calculating the **Froude Number**, a dimensionless ratio of $v / (gd)^{1/2}$. At critical flow, the Froude Number is 1. Most stream flow conditions are **sub-critical** with Froude Numbers less than 1. In rapids and steep chutes, **super-critical** or **shooting flow** may occur with Froude Numbers greater than 1. Variations in states of flow that determine local hydraulic habitats in a stream may be characterized by their Froude Number.

Gauging Station: an installation at a known stream cross-section where water levels may be observed and recorded. The relationship between the water level and discharge is determined from a **stage-discharge curve** that is derived from the overflow condition or from metering the stream velocities in the cross section.

Gravitational constant, g: the constant of acceleration due to gravity used in streamflow relationships. In SI units the constant is **9.8 m/sec^2** (32.2 ft/sec^2).

Habitat: those parts of the environment on which fish depend, directly or indirectly in order to carry out their life processes. Fish habitats include spawning grounds and nursery, rearing, food supply and migration areas. Habitat **preferences** are determined by studying fish in productive natural habitats, and measuring those characteristics of their environment which are needed for a high level of growth and production. After repeated studies on a species, a range of values or qualitative measurements for each characteristic will describe its preferred habitat. Typical stream habitat characteristics include: water velocity, depth, chemistry and temperature, channel geometry and form, substrate, and objects providing cover.

Hydraulic gradient: in streams, the slope of the energy grade line, or slope of line representing the sum of kinetic and potential energy along the channel length. It is equal to the **slope** of the water surface and streambed in steady, uniform flow.

Hydraulic habitats: the state of flow and local flow configuration in which stream biota live. The characteristics of hydraulic habitats and their locations vary with the discharge and physical characteristics of a stream reach. The physical characteristics of the channel may be surveyed under low flow but the hydraulic habitat conditions must be observed for a range of discharges (see **Froude Number**).

Hydraulic jump: the transition from super-critical flow to sub-critical flow occurs abruptly in a hydraulic jump as the thread of high velocity water turbulently decelerates into a pool or into deeper sub-critical flow downstream. Air is entrained on the surface of the high velocity flow and swept into the deeper flow to form a foaming mass of bubbles on the surface of the hydraulic jump increasing the local re-aeration efficiency in the stream. The breaking air bubbles produce the only sound made by flowing water: roaring rapids in large rivers and babbling riffles in small streams.

Hydraulic radius, R: the cross-sectional area of the flow, **A**, divided by the wetted perimeter of the flow **P**, or **R = A/P.** In wide, shallow stream cross-sections, the value of the hydraulic radius approaches the value of the average depth of flow. The term is used in the **open channel flow equation.**

Hydrograph: a graph showing stage, flow, velocity, or other properties of water with respect to time.

Longitudinal profile: a graph of elevation versus distance along the stream channel, usually measured upstream from the mouth of the stream. Segments of the profile may be plotted for isolated reaches. As most stream profiles have smoothly eroded into a concave-upward form, abrupt breaks in elevation and slope changes usually signify reaches that are bedrock-controlled, dammed, actively-eroding, or channelized.

Open channel flow equation (Manning's, Chezy's): a flow velocity equation based on an idealized rectangular channel with frictional resistance from the sides and bottom of the channel only. The relationship in SI units is $\mathbf{v = (R^{2/3}\, S^{1/2}) / n}$ where **n** is **Manning's roughness coefficient** for the channel. The original form of the equation was proposed in 1758 by Chezy for designing the canals of Paris. In this form, the roughness coefficient is **Chezy's C,** where $C = R^{1/6}/n$. For smooth regular channels, the roughness coefficient may be estimated from the bed paving material size in relationships similar to that proposed by **Strickler** where $n = .04\ (D_{50})^{1/6}$. D_{50} is the median diameter of the bed paving materials. In addition to energy losses from frictional resistance, there are also losses caused by obstructions to the flow on the bed and banks of streams that increase the roughness coefficient dramatically. Typical Manning's roughness coefficients range from 0.020 for grassed excavated channels, 0.05 for shallow streams with pools and riffles, to 0.5 for rocky cascading streams. In the latter streams, resistance decreases with increasing stage as obstacles on the bed obstruct less of the flow cross-section. Resistance factors for a known discharge may be determined by surveying the channel and solving for "n" in the open channel equation. Indirect methods include descriptive tables, photographic references and equations based on measurements in similar stream types.

Pools and riffles: the naturally undulating profile of most streams is formed by flow phenomena that accumulate coarse bed materials at intervals that are, on the average, **6 times the bankfull width.** Upstream from the accumulations, a shallow **pool** is impounded. Downstream from the crest of the accumulation, a local increase in slope causes the flow to accelerate, forming a **riffle** or rapids. Under low discharge conditions, the pool and riffle profile stores water in the channel and re-aerates the flow. The effect of the pool and riffle forms are less apparent under flood conditions, although high discharges are required to scour the pools and maintain the riffle forms.

Power, P: the rate at which the stream loses potential energy as the flow descends along the longitudinal profile. The power **P** (kilowatts) exerted by the flow in a reach may be calculated by $\mathbf{P = 10\ Q\ h}$ **where Q** is the discharge in m^3/s and **h** is the total fall in the reach in metres (length x slope).

Rapidly-varied non-uniform flow: abrupt changes in local flow conditions that occur in riffles, rapids, and chutes such as hydraulic jumps and standing waves are governed by the geometry of the streambed and bed materials. Local frictional losses are minor factors in controlling the flow.

Sinuosity: the meandering tendency of many streams may be measured by comparing the ratio of the length of the centreline of the stream to the length of a straight line connecting the same points along the channel. In general, stream **meanders** tend to complete a full sinusoidal wave from every **12 times the bankfull width** measured along the valley bottom. In profile, the meanders contain two sets of pools and riffles, with the pools occurring in the bends and riffles at the nodal points where the stream crosses from one side of the valley to the other. The average **radius of curvature** of the meander bends is **2.4 times the bankfull width**. Preferred trout habitats have been found in streams with these dimensions.

Slope, S: the change in elevation per unit distance measured along the channel. The slope is expressed as a dimensionless number in hydraulic calculations but is often recorded as a percentage i.e. a slope of .01 is a 1% slope. The streambed and low-flow water surface is composed of many local slopes. At high flow, the slope of the water surface is equal to the average bed slope under **uniform flow conditions**.

Stage: see Depth of Flow, Gauging Station

Stream Order: a method of ranking stream segments in a drainage basin in which larger segments are given higher order numbers. In the Strahler method of numbering, for a given map scale, the first marked streams are assigned order 1, where two order 1 streams combine, the next segment becomes order 2, where two order 2 segments combine, the next segment becomes an order 3, etc.

Substrate: the material forming the streambed. The streambed materials may be sampled randomly to determine a cumulative frequency curve of a median diameter size that is useful in determining the fraction of the bed materials that is erodible at a given discharge. (see **tractive force**).

Thalweg: the path traced by the flow that follows the deepest part of the channel.

Tractive force, τ : the generalized **shear stress** exerted by the flow on the streambed. The tractive force is calculated by assuming that the downslope component of the gravitational force that causes the flow is equal to the resisting shear force exerted by the fixed bed. This allows the tractive force τ in kg/m^2 to be estimated by the formula $\tau = \mathbf{1000dS}$ where **d** is the depth of flow in metres and **S** is the slope of the water surface. The tractive force has been empirically related to the size of material that can be moved along the bed. A common relationship for particles greater than 1 cm in diameter is τ (kg/m^2) is equal to the **diameter at incipient motion** in cm.

Uniform flow: occurs when the average depth of flow and velocity are constant in a reach. In this ideal case, the slope of the water surface and the average slope of the channel bed are equal. This is the condition on which the open channel flow formula is based. (see **open channel flow equation**).

Wetted perimeter: the boundary of the channel cross-section that is in contact with the flow at a given discharge (see **cross-sectional area**).

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