1992

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RIVER CHANNEL STABILITY AND THE IMPLICATIONS FOR FISH HABITAT

by

John T. Beebe

B.A., Wilfrid Laurier University, 1982.

THESIS

Submitted to the Department of Geography
in partial fulfilment of the requirements
for the Master of Arts degree
Wilfrid Laurier University
1992.

ISBN 0-315-78137-8

Abstract

The purpose of this project was to investigate various aspects of river channel stability as they relate to fish habitat. Two headwater creeks of the Credit River system, Black and Silver Creeks, and their confluent stream, the West Credit River in Southern Ontario were used in the study. Thirty-five cross-sections were established and revisited during four flow regimes, summer base flow, fall secondary peak flow, spring melt-high flow and post-spring high flow. Measurements of width, depth and temperature were taken at these times. Water samples were taken for determination of suspended sediment concentration.

Channel stability was investigated in relation to three major factors: stability of the fluid, stability of the bed, and stability of the banks. Fluid stability measurements involved measuring fluid speeds vertically and laterally through each cross-section under the four flow regimes. Individual experiments at the confluence area were conducted because of some of the earlier results from other sections of creek. Information on the rates of change of discharge were determined from secondary data provided by the Water Survey of Canada.

Bed stability was measured by looking at bed material particle size distribution, cross-sectional channel profiles and control reach topographical surveys which included particle marking and tracking. Bedload transport rates at the confluence area were determined under varying flow conditions.

Bank stability was investigated by the use of a piece of equipment developed for this thesis, the River Bank Profiler. Volumetric changes to banks consisting of cohesive as well as cohesionless material are presented for comparative purposes.

As changes in river channel stability can have a direct impact on resident fish, investigation of the biological literature was used as a framework for the geomorphological work. It became apparent that there is a direct application of fluvial geomorphology in that biologists are stating a direct need for more geomorphological work in the area of fish habitats. A conceptual framework showing the relationship between properties of fluid, bed and bank stability and the degree of interconnectedness is presented to aid both the geomorphologist and the biologist when looking at aspects of fish habitat from a geomorphological perspective.

Acknowledgements

This thesis resulted from a study of fluvial geomorphology and the health of fish habitat, funded by the Ontario Ministry of Natural Resources. I wish to extend my gratitude to a number of people who have been involved in this project. First, thanks go out to Jack Imhoff of the Ministry of Natural Resources, Maple District Office for financial support in the form of a grant. Kevin Bellamy of ORTECH International provided expertise in getting this project off the ground, and in tying the loose ends together. Field help from John Parish (ORTECH International) and Jim Dozois (Wilfrid Laurier University) was invaluable. Reg LeBlanc from the Water Survey of Canada and various members of the Credit Valley Conservation Authority provided secondary data which was used in the thesis.

I also wish to thank my Examining Committee: Dr. J. Rutherford (external examiner), Dr. E. Kott and Dr. M. C. English, whose insightful comments have made this a better thesis. Dr. English is thanked also for providing support through the Cold Regions Research Centre at W.L.U.. Dr. H. Saunderson (Advisor) deserves special thanks for sticking with me through this research, for offering timely and insightful advice as well as helping me keep a proper perspective, and for encouragement around continuing to the next level. Thank You.

The greatest support that I could have received was from my wife Cathy, who has believed in me even when she didn't understand me, and without whose support and patience I could not have succeeded.

This thesis is dedicated to my son, Spencer Thomas. I only hope that the streams and fishes are there for you to enjoy as I have.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL OVERVIEW

Fish stocking programs in spawning rivers are being carried out by the Ontario Ministry of Natural Resources (OMNR). In the last few years of record, the Maple District Office of the OMNR have stocked a total of 2,568,461 salmonids in rivers and inland bodies of water within their district alone (874,599 salmonids in 1987, 919,408 in 1988, and 774,454 in 1989). This constitutes a considerable expenditure of money, and although the dollar figures are not available, it can be considered that two dollars per fish is a reasonable estimate for staff time, cost of feed, etc. (Ontario Ministry of Natural Resources, 1991, personal communication). It is not known if the water bodies that are stocked are suitable for fish habitat. To this date no recapture information is available, so the success of these stocking programs is yet to be determined (Ontario Ministry of Natural Resources, 1991, personal communication).

Fish are stocked for two reasons. First is the attempt to reintroduce fish into areas where they were abundant in the past but have either moved out or have been extricated due to the deleterious interference of human beings. Second is the aesthetic value of fish swimming in urban and rural creeks. It could be considered important politically to show the public that their tax money is being well spent in re-establishing fishes into creeks where they have recently disappeared. Also, this gives the impression that the environment around these areas is relatively clean, whether that is the case or not.

Since spawning success is hard to predict and costly to determine, continual re-introduction of hatchery-reared fish into these streams appears to be the cost-effective method to ensure a continuing population. In order to reduce costs considerably over the long run, it is necessary to study the streams that receive introduced fish to see if they contain suitable habitat for both the seasonal and day-to-day life cycle needs of the fish and suitable spawning grounds.

Fish in the older stages of life (age 1+) are remarkably able to adapt to a range of habitat conditions, provided these conditions remain below critical thresholds for those fish. In fact, salmonids have been adapting to changes in habitat since before the Miocene, 28 million years before present (Berg, 1947 as reported in Platts, 1979). Therefore any minor modifications in habitat which are unsuitable for this age-group and older will likely result in a migration away from the modified habitat. Once fish have migrated out of an area, it is unlikely that they will return to that habitat in the near future, leaving it for future populations to determine the habitat's return to suitability. For fish younger than 1+ minor habitat modifications can have serious effects for they are not able to migrate the way mature fish are, as they are more susceptible to fluctuations in flow speeds, temperature and predation from other fish. As well, they are less able, because of their size, to compete for feeding and resting habitat with larger fish. Unhatched eggs in spawning gravel are completely under the influence of channel conditions which may affect habitat, as they are not able to migrate at all. It is this group of fish, age < 1+ and eggs, that are most important for the maintaining of fish populations in streams.

From the biological literature it can be determined that stable habitat conditions are a requirement for any fish in a river, but rivers are dynamic systems. Rivers are constantly adapting to changing conditions relating to fluctuations of input (in terms of precipitation and groundwater supply) and modifications to channel form, either by channelization due to urban construction practices or the introduction of 'foreign' substances that affect flow patterns. For example fallen bankside vegetation in the channel can cause jams or modifications to the existing bed (through the action of scouring pools) and banks (through the action of flow diversion, which can cause subsequent erosion of the banks through scouring).

There have been numerous studies undertaken (see Chapter 2 for a partial listing) which identify changes in stability in alluvial channels. The general principles of stability are well understood, as more and more microscopic studies of factors causing/affecting stability are being conducted. While it is important from a theoretical perspective to continue these in-depth studies, it is also important to apply some of the knowledge gained to real world situations.

One area where the stability of alluvial channels has a distinct and significant impact is the area of fish habitats. Fish in general, and salmonids in particular, have very specific habitat requirements depending on the age and life stage of the fish. Any changes that occur in a river channel will have an effect on the fish population, either by creating or destroying existing habitat or by changing the critical variables required for fish to be sustained in that particular habitat.

The stability of an alluvial channel is dependent on a large number of variables, some inter-related and others not. Some of the more obvious, such as discharge, substrate material, suspended sediment load, width, depth and fluid velocity are influenced by some of the more obscure, such as rate of change of inputs (precipitation, groundwater), the nature of packing, particle shape and orientation of the bed material and the types of land use activities throughout the entire drainage network.

My purpose is to examine channel stability in the context of how it relates to salmonid habitat in two headwater tributaries of the Credit River, Black and Silver Creeks, and their confluent stream, the West Credit River, located in Southern Ontario.

Any study which crosses disciplines as this one does becomes individually applicable. The work done on channel stability, which is not new to geomorphologists, is uncommon to a large extent to fisheries biologists, and the application of fish habitat studies to a geomorphological problem gives the geomorphologist an outlet for methodologies generated in the field. Also, a study such as this one requires a much more detailed investigation of both aspects of the problem--the timing, causes and magnitude of instability in alluvial channels as well as the habitat requirements of the resident fish, including what effects changes in habitat have on their physiology and behaviour and the relationship between the timing of stream events with critical stages in life history.

1.2 CHANNEL STABILITY

Any study of channel stability requires investigation of numerous properties of both the physical nature of the drainage basin and channel (slope, drainage density, constant of channel maintenance, drainage texture and so on) as well as the hydraulic properties of the movement of fluid and material.

Factors within the channel which have a direct impact on the stability of the channel are: 1) fluctuations in fluid speed; 2) changes to the width of the channel; 3) extremes of depth; 4) variation in, and rates of change of discharge; 5) the nature of the substrate, including the particle size, degree of packing or imbrication and the orientation of the bed material; 6) water temperature, which affects fluid viscosity; 7) the percentage of banks which are weak and eroding; 8) the presence or absence of vegetation, either fallen trees in the channel (which can cause vegetation jams) or underwater grasses which can act as a sediment trap; 9) the action of freeze/thaw cycles; and 10) the number of tributary inputs.

These ten factors have a number of sub-variables within each. For example, it is not only the fact that there are varying fluid speeds within the channel, but the distribution of those speeds and the direction of the flow is also important. Also, particle packing, imbrication and orientation have sub-variables such as the degree to which particles protrude into the flow, the way that they are stacked on top of one another (which influences the pivoting angle of the grains) and the relative sizes of the grains to one another on the bed (which may provide 'hiding' places for other grains, reducing the likelihood that they could be entrained into the flow).

1.3 FISH HABITAT REQUIREMENTS AND PREFERENCES

Streams are known to reflect both the hydrology and biology of their watersheds; on the other hand fish production may be related to geomorphic processes in the drainage basin (Lanka and Hubert, 1987). Studies into the habitat requirements of salmonids have been the focus of much research over the years. The problem is that research is usually very condition-specific, and that it does not relate cross-conditional susceptibility. A salmonid may be viable when water temperatures remain below 28 °C under low suspended sediment concentrations; however if the concentration of suspended sediment rises to near-critical levels, upper lethal water temperatures for the salmonid may drop to 25 °C due to the physiological stress of the sediment on the fish. Therefore, cross-sensitivity must be addressed.

This becomes important from a geomorphological perspective when one considers that suspended sediment concentration may be a result of a change in stability for the channel. In this sense, geomorphic variables need to be looked at in conjunction with physiological needs of the fish. The importance of this relationship between habitats and geomorphology has been discussed in Milner et al. (1985).

Geomorphic variables that are important in the life history of salmonids include, among others, suspended sediment concentration, the nature and mobility of the bed, depth, riffle-pool spacing (from a behavioral and territorial perspective), gradient, fluid speed and discharge. As indicated earlier in the case of stability, these variables have sub-components which can determine the suitability of a habitat for use by salmonids. For example, high suspended sediment concentrations have a physiological effect on the gill capacity of salmonids (MacDonald, 1992 personal communication), yet when the sediment filters out with decreasing fluid speed, its deposition on the bed can reduce the amount of dissolved oxygen that reaches eggs in spawning grounds. Another example deals with the nature of the bed. In a bed with a large mixture of particle sizes, spawning becomes difficult, but the larger particles provide cover for the fish from predation and provide resting places from higher flow speeds.

1.4 STUDY AREA

The study area consists of two headwater tributary streams and their confluent stream of the Credit River in Southern Ontario (Fig. 1.1). Black Creek is a first order headwater stream which runs 14.98 kilometres (km.) from Fairy Lake in Acton to its confluence with Silver Creek in Georgetown. It runs primarily through agricultural and rural lands as well as adjacent to known sand and gravel mining operations. Silver Creek is a first order headwater stream which runs for 11.2 km. from its source

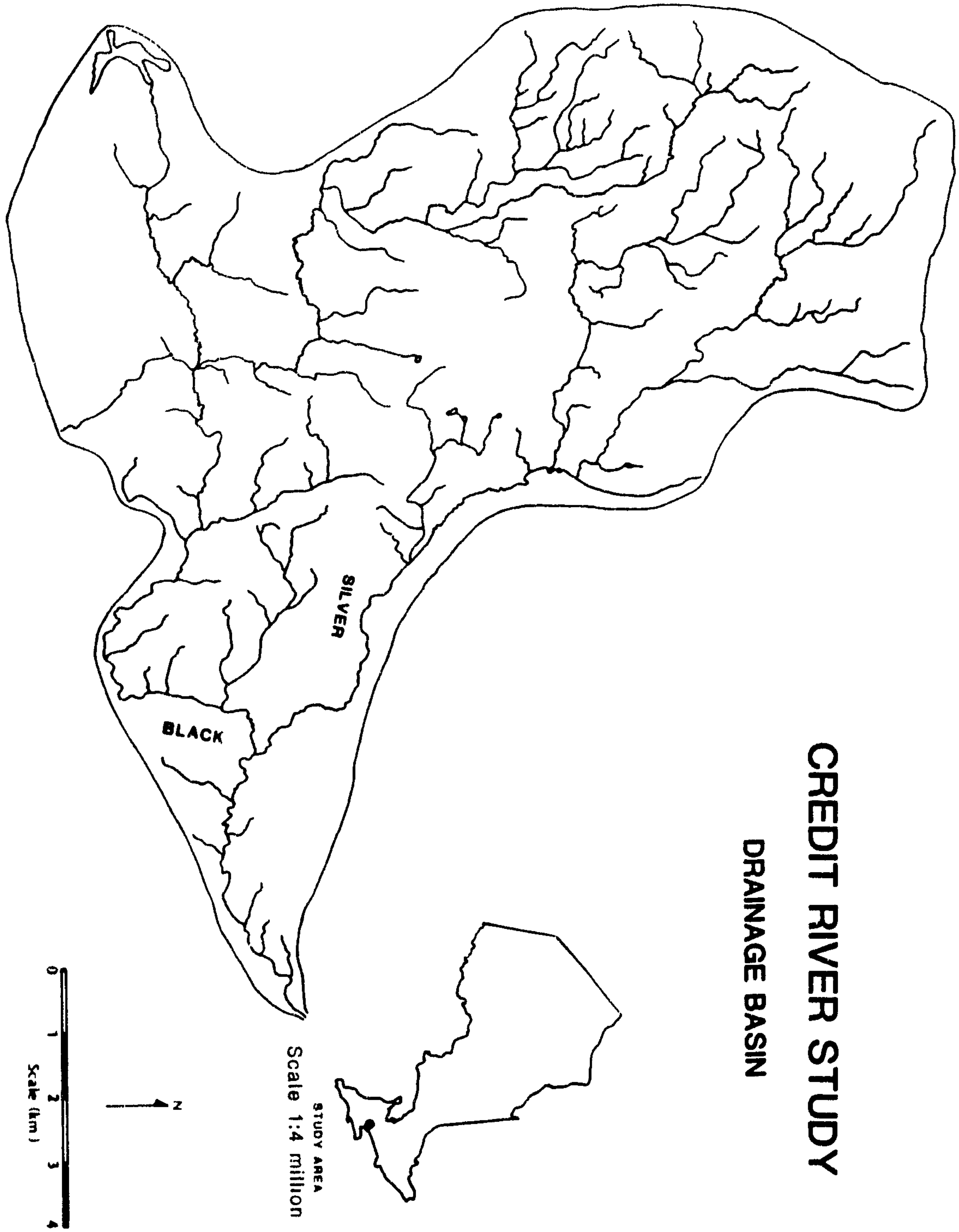


Fig. 1.1 Study area drainage basin and network

in the Niagara escarpment north of Georgetown to its confluence with Black Creek. This system runs through agricultural and rural lands as well, but also runs through the better part of Georgetown, making it a more urban stream in the downstream reaches. Their confluent stream, the West Credit River, runs primarily through urban areas for 5.54 km. and spills into the Credit river at Norval.

1.4.1 DRAINAGE NETWORK

Morphometric parameters such as drainage density, channel frequency, constant of channel maintenance, relief ratio, sinuosity and bifurcation ratio are calculated so that direct comparison to other basins can be made (Table 1.1).

Fig. 1.1 is a map of the study area drainage basin. Area of the basin is 118.87 km^2. A number of the tributary channels seen in Fig. 1.1 are intermittent, that is, they are dry during summer base flow conditions. On the other hand, during fall peak flows, they have been observed to be very active, and as such are included on the drainage basin map.

Fig. 1.2 shows that over a distance of 14.986 kilometres (km.) Black Creek drops in elevation by 115 metres (m), giving a gradient of 0.0077. Generally, the shape of the profile is consistent, except for a more rapid drop in elevation approximately 6.5 km. from the source; this is in the Limehouse area. The cause of this is not known, although it is suspected that an area of more resistant rock underlies the channel at this point.

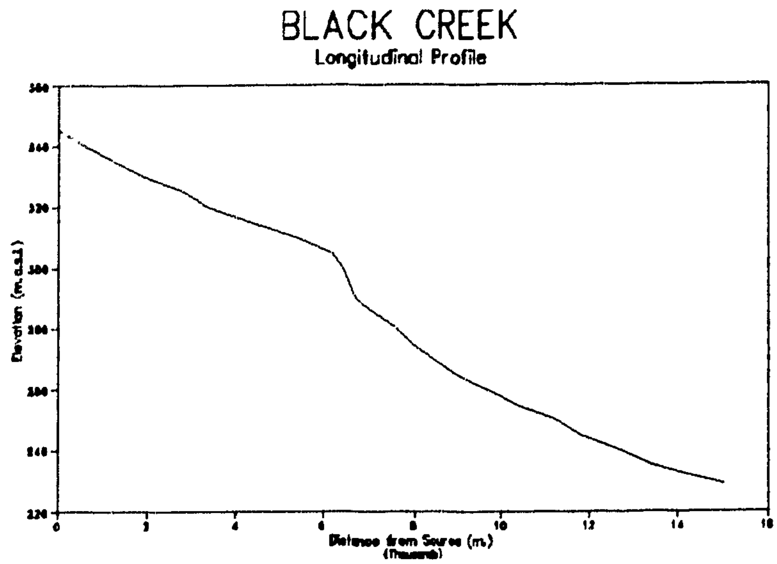


Fig. 1.2 Longitudinal profile of Black Creek

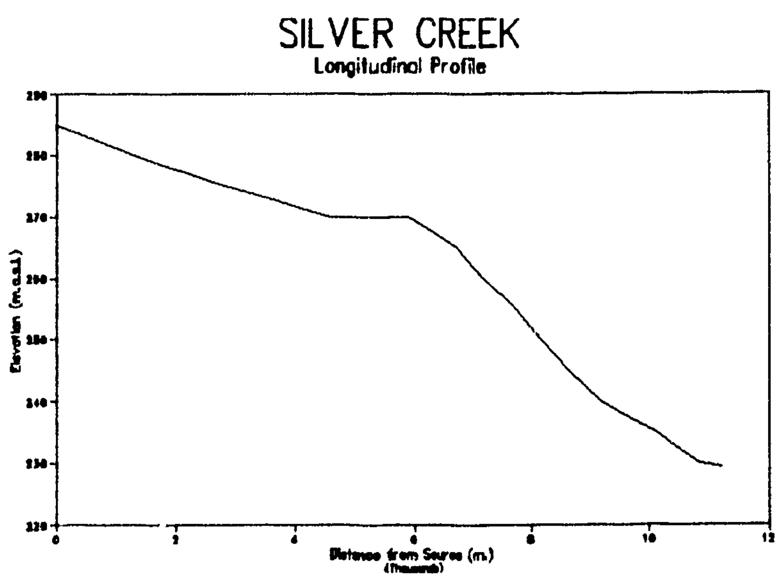


Fig. 1.3 longitudinal profile of Silver Creek

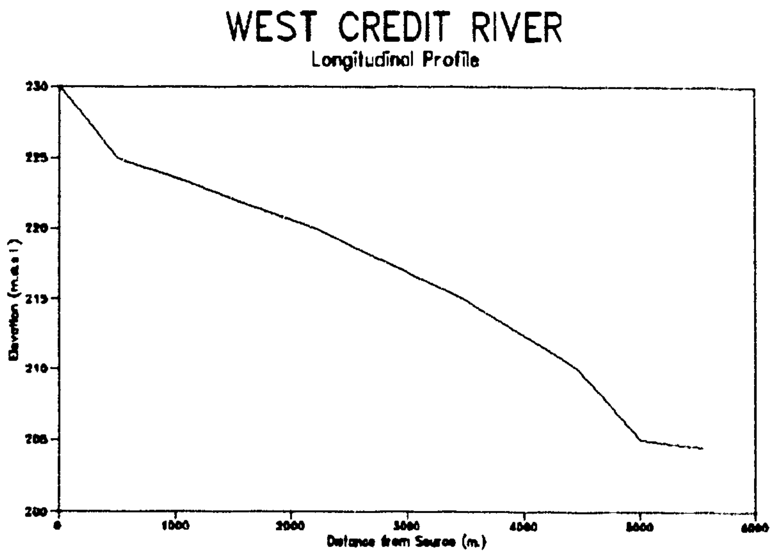


Fig. 1.3 Longitudinal profile of the West Credit River

Fig. 1.3 shows that over a distance of 11.201 km. Silver Creek drops in elevation by 50 metres, giving a gradient of 0.0045. This creek also shows a steeper gradient at about 7 km. from the source. It is anticipated that the cause of this steepening is related to that on Black Creek.

Fig. 1.4 shows that over a distance of 5.537 km. the West Credit River drops in elevation by 25 metres, with a gradient of 0.0045. The profile is relatively uniform throughout.

Table 1.1 Morphometric parameters of the study area

Drainage Density 2.72 km/km^2	Channel Frequency 0.934 $channels/km^2$		Relief Ratio 0.00966	
Constant of Channel Maintenance	Sinuosity		Bifurcation Ratio	
			Order	Ratio
	Black Ck.	1.388	1	5.4375
0.369 m/m^2	Silver Ck.	1.411	2	3.2
	West Credit R.	1.406	3	2.5
			4	2.0
			5 MEAN	3.284

1.4.2 PHYSIOGRAPHY

The physiography of a region refers to its topographical features. The landforms across this area were developed by glacial ice sheets, and the many complex interactions within and between these sheets, which are of Wisconsinan age. Their advance from Lake Ontario and Lake Erie basins, as well as from the north, and their subsequent retreat resulted in the landforms that are present today.

Ice sheets had the power to lift, carry, push and deposit large amounts of soil and rock. This deposited material remains as a heterogenous mixture of rocks, clay, and sand, scientifically referred to as till. Most of the material located in Southern Ontario was deposited by the many rivers of meltwater which flowed during the retreat of the ice sheets. This material has been sorted according to its weight, the lighter fine sand and granules being carried farther than the heavier loads.

Little information is available on this part of the Credit River Basin. Chapman and Putnam (1984) offer some information about the Credit River near Georgetown and Norval (p. 102-103):

> For about ten miles to the vicinity of Georgetown, the river flows in a narrow valley between the escarpment and the till plain. Remnants of a sand and gravel terrace mark this as the route of former ice-border drainage, but the modern valley has been cut deeply into the till and underlying shale. Numerous, (sic) small, rapid feeders enter this portion of the Credit from the face of the escarpment....At Norval it is joined by another deeply entrenched branch which drains a section of the escarpment behind Georgetown and Stewarttown.

Fig. 1.5 shows the Chapman and Putnam (1984) physiographic regions which are part of the drainage basin. Including the Niagara Escarpment, this area is characterized by till moraines, drumlinized till plains and spillways.

Fig. 1.6 shows the geology of the drainage basin. This basin is characterized by the Queenston, Cabot Head and Wiarton formations (Geological Survey of Canada, Geology Toronto-Windsor Area; 1:250000) of lower Paleozoic age. The Queenston formation consists of red shale and mudstone with minor interbeds of silty limestone and dolomite. The Cabot Head formation consists of greenish grey and red silty shale. The Wiarton formation consists of grey and blue-grey medium crystalline crinoidal dolomite, containing small bioherm reefs. There are a number of rock outcrops within the Queenston formation between Norval and Glen Williams, along Silver Creek and on Black Creek near Limehouse. There is a great deal of quarry activity in the Limehouse area.

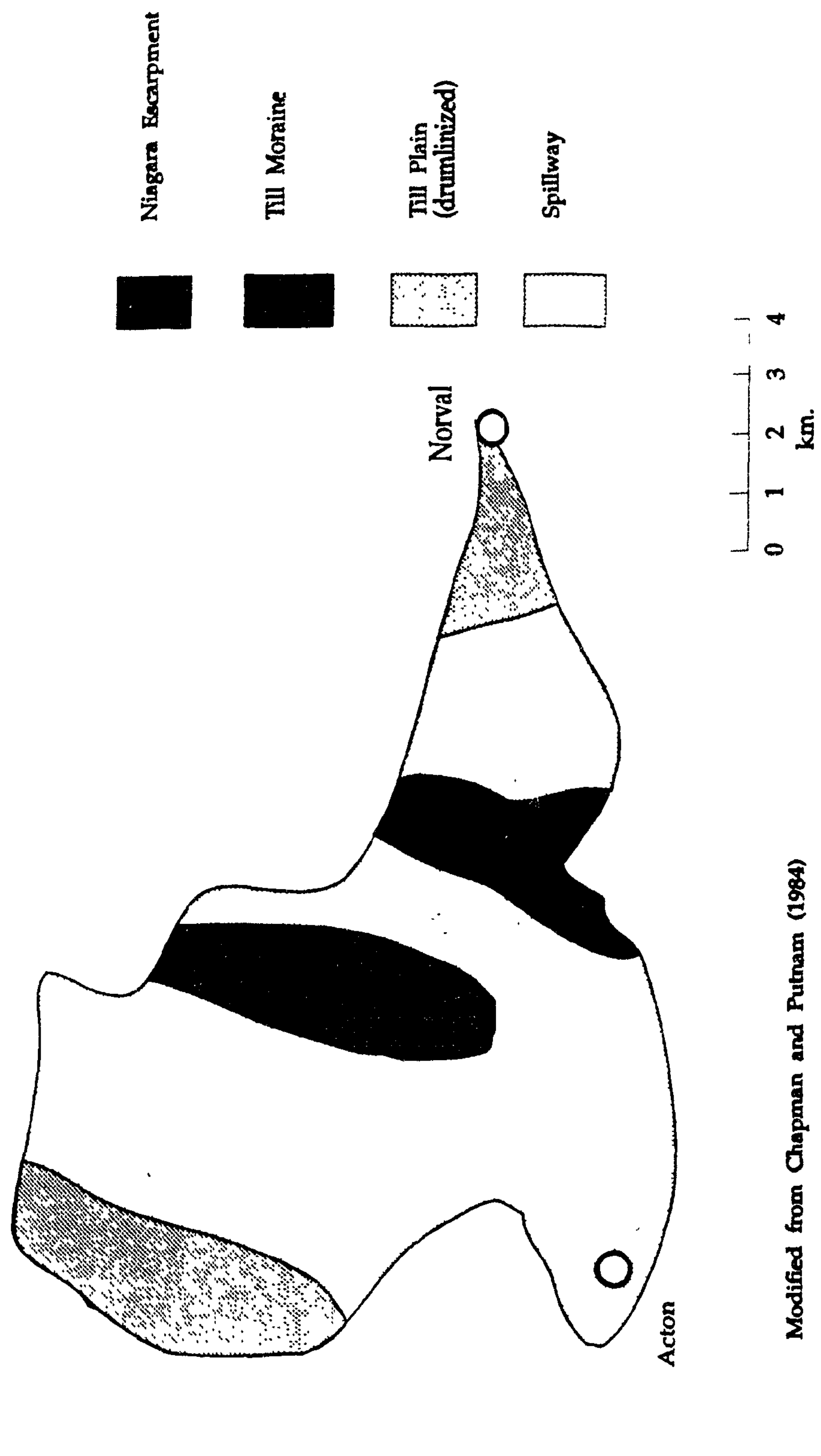


Fig. 1.5 Chapman and Putnam (1984) physiographic regions in the study area

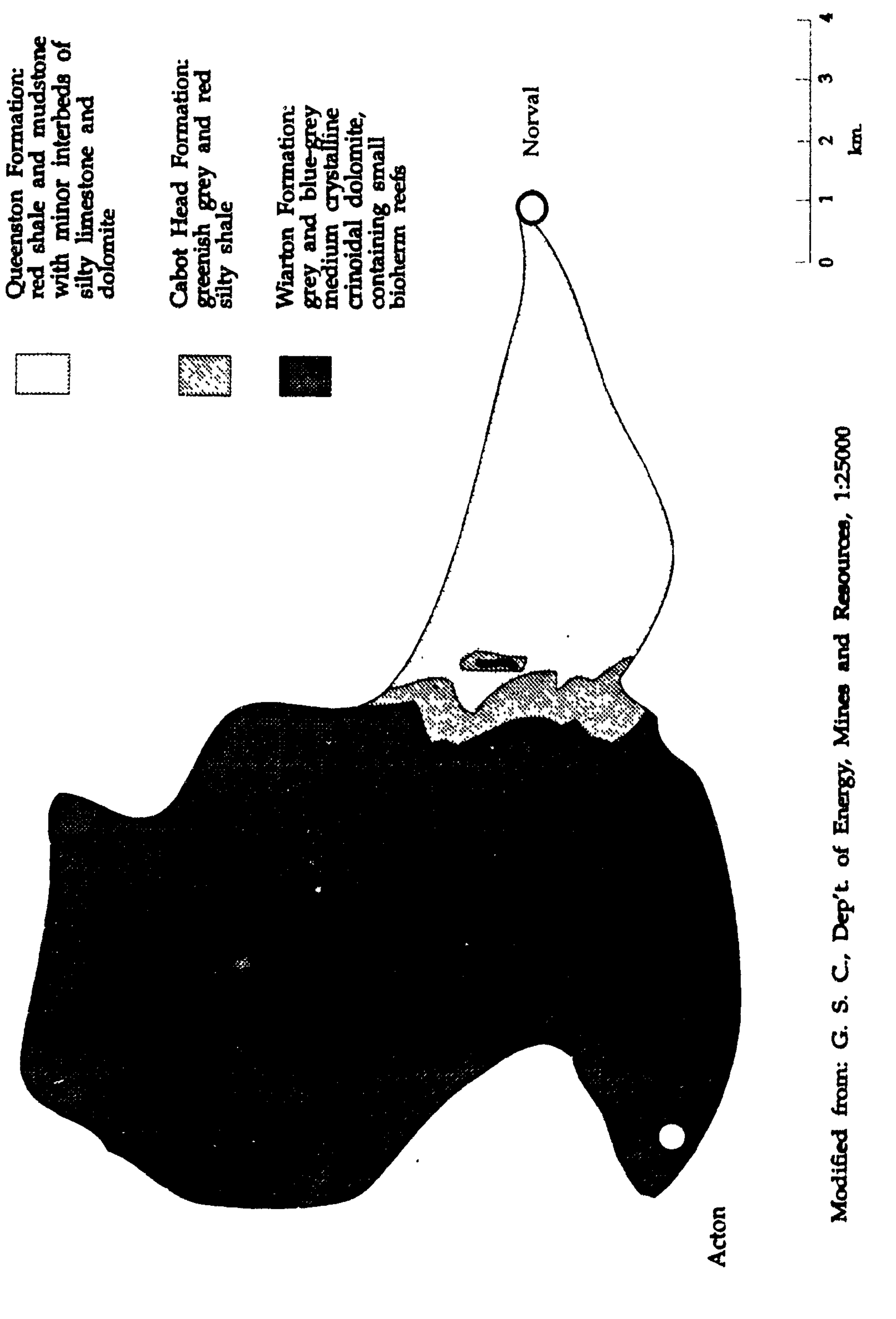


Fig. 1.6 Geology of the study area

Costello and Walker (1972) conducted a study of the Credit River area. They write (p. 389):

> Both the Wentworth and Halton outwash deposits were transported by meltwaters flowing over and parallel to the Niagara Escarpment. The meltwaters were derived from the retreating Ontario ice lobe, and also from two ice lobes to the north, one in the Lake Simcoe area 50 miles NE of Georgetown, and one in Georgian Bay 60 miles north of Georgetown. During periods of advance of the Lake Ontario ice, the Wentworth and Halton tills were deposited. The Paris-Galt moraines marked the edge of the Wentworth ice sheet. However, when Lake Ontario ice sheet melted back to a position below the Niagara Escarpment, drainage flowed between the escarpment and the ice front, down the Credit Valley, forming the Wentworth outwash deposits.

The depth of drift (or overburden) in this area ranges greatly, from <25 feet north of Norval to 101 feet at Stewarttown (Ontario Department of Mines, Map 2179, Brampton Area Drift Thickness Sheet, 1:63360; Ontario Department of Mines, Preliminary Map P.534, Guelph Sheet Drift Thickness Series, 1:50000). Thickness tends to be greater on the east side of the Escarpment and on the south side of the basin.

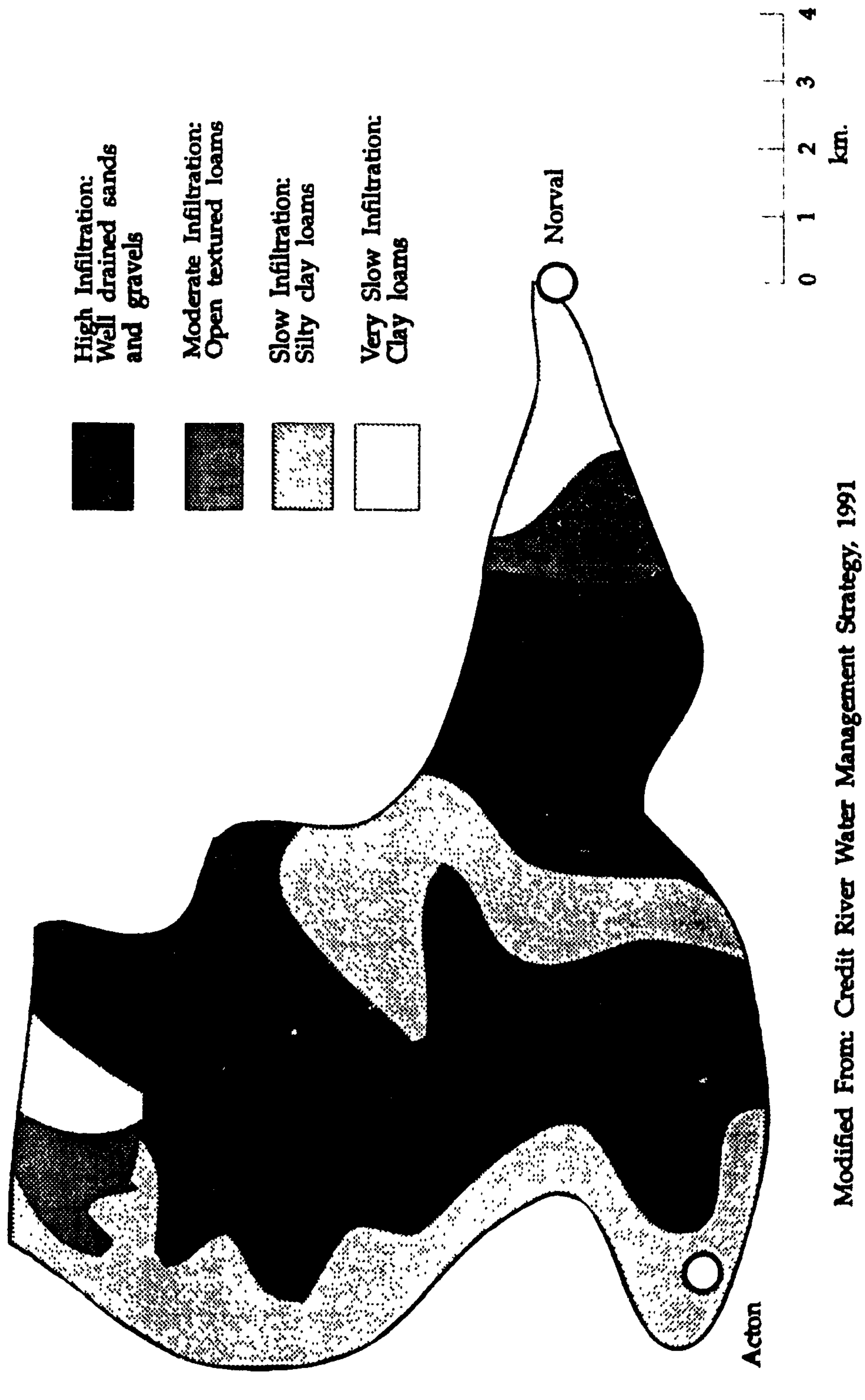


Fig. 1.7 Soils of the study area, concentrating on degree of infiltration

1.4.3 SOILS

There is little information published regarding the soils of this area. Fig. 1.7 shows the soil conditions as they relate to drainage. This area is characterized by four types of infiltration. The majority of the basin is classed as high infiltration consisting of well drained sands and gravel. There also exist open textured loams (moderate infiltration), silty clay loams (slow infiltration) and clay loams (very slow infiltration). The degree of infiltration determines the rate in which precipitation will flow overland into the channel. Due to the fact that this basin consists of well drained sands and gravels, it is expected that a large amount of the precipitation that falls in this basin will slowly make its way to the channel through groundwater flow. The implications for channel stability are such that it would take a high energy precipitation input to cause a rapid increase in flow in the channel, thus the morphology of the channel will not likely be modified except in the case of a high energy input.

1.4.4 CLIMATE

Climate is very important in any area, for it helps determine the formation of the landscape, soils, land use and type of agricultural activity. Climate is usually summarized as average temperature of the air and the average amount of precipitation. This basin is located in an area which has the necessary temperature and precipitation for agricultural land use.

The two closest precipitation recording stations are the Water Pollution Control Plant in Georgetown (lat. 43° 38' N, long. 79° 53' W, elevation: 221 metres above sea level) and the Arboretum at the University of Guelph (lat. 43° 33' N, long. 80° 13' W, elevation: 328 metres above sea level). Mean annual precipitation at Georgetown was 766.5 mm. between 1985 and 1989, and at Guelph 788 mm. for the same period. In both cases spring and fall were the most active precipitation periods.

The precipitation that falls in this area during the summer months is the result of both frontal and convective storms. Frontal storms are usually slow moving, less intense storms that generally migrate from west to east in this part of Ontario (Atmospheric Environment Service, 1991, personal communication). Convective storms, which tend to be fast moving, local, high energy events, are common in this area during the humid months of July and August. These highly localized storms can result in responses being felt in areas of the basin that received no input as direct precipitation from the storm.

1.4.5 LOCATION OF SAMPLE STATIONS

Sampling stations were set up on Black and Silver Creeks and the West Credit River; their exact locations are shown in Fig. 1.8. There were 35 sample stations chosen, 17 on Black Creek, 11 on Silver Creek, and 7 on the West Credit. These stations were chosen on the following bases: they were to be representative of the reach; they were to be as undisturbed as possible by the deleterious effects of human beings; and they were to be of approximate equal distance from each other if at all possible. Table 1.2 shows initial information regarding the sampling stations.

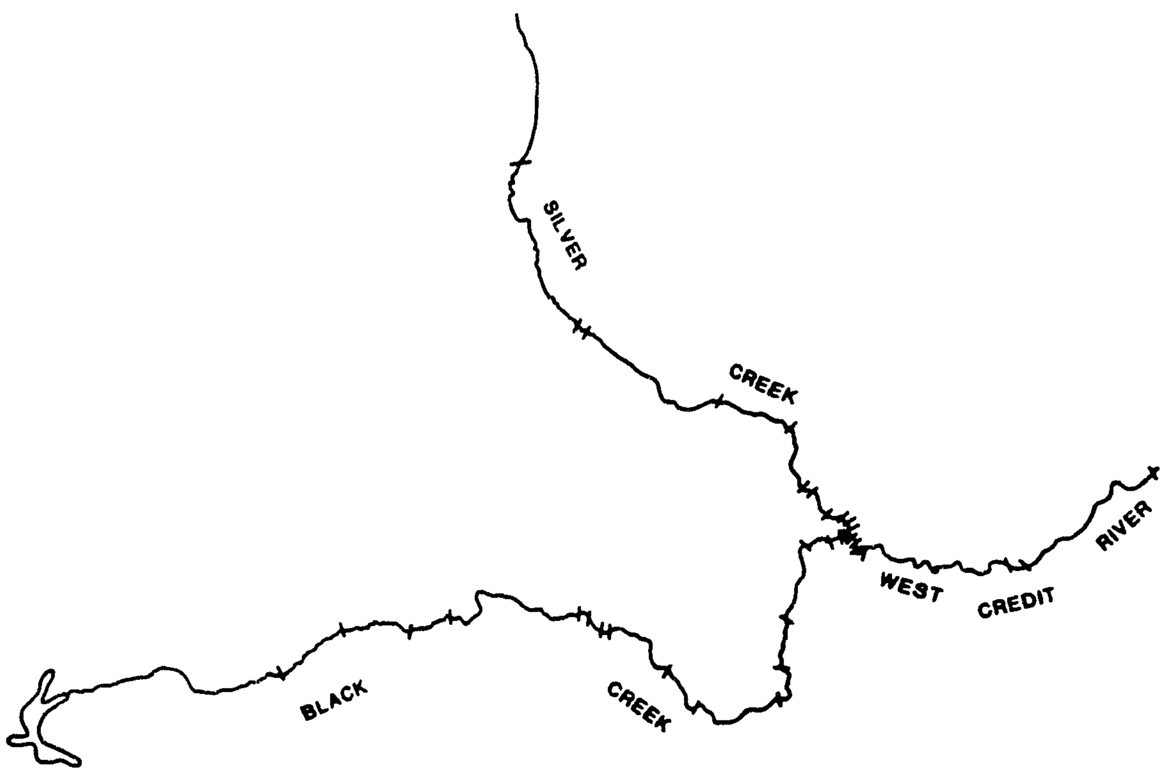


Fig 1.8 Location of sampling stations. Scale is 1:50 000.

1.5 OBJECTIVES

This study investigated river channel stability as it pertained to fish habitat, especially spawning habitat, and outlined the variables which needed to be considered when implementing plans for the alteration of river channels. Various methods were used to do this. Standard measurements of width, depth, temperature, and fluid speed through cross-sectional transects will be measured under summer base flow, fall secondary peak flow, high-input spring snowmelt conditions and post-spring melt high flows. This data will give information about how the creeks respond to different flow conditions (i.e. how easily the banks overflow, changes in channel profile). To determine the amount of suspended sediment in the creeks at different times, water samples will be collected at each cross-section and returned to the lab for analysis. The importance of these concentrations is outlined in detail in Chapter 3.

Bed material samples will be collected at each cross-section for particle size analysis. Near-bed material transport will be investigated using a Helley-Smith Sampler. This information will be compared to standard competency relationships to determine their validity for predictive purposes. The bed material particle size analysis will give information about the quality of the bed for fish spawning and other habitat use, as well as the likelihood of mobility of the bed under certain conditions, and the near-bed material transport will give an indication of the amount of transport at the bed under certain flow conditions.

In another effort to determine movement of bed material, three control reaches have been mapped with a stadia and transit under summer base flow conditions and after spring high flows. It is expected that this method will show changes in the spacing of riffles and pools as well as detecting migration of the talweg. Also, numerous particles of varying size were marked with flourescent paint, numbered, measured and recorded. These were tied into the Control Reach surveys in an effort to determine amount and direction of movement.

The manner in which particles on the bottom of channels pack against themselves and the way they orient themselves is important in two ways. Tight packing with dipping in an upstream direction indicates armouring of the bed, which prevents instability until a critical flow is reached. From a fish habitat perspective, the way particles pack and fill in with finer sediment gives an indication of the quality of that bed for spawning habitat. Two exposed (under base flow conditions) gravel bars were excavated and boxes placed in them at known intervals. These boxes were to be removed and the material in them analyzed for their packing and orientation characteristics.

A bank profiling experiment was conducted to determine the stability of banks in two reaches of Silver Creek. One reach is characterized by very loose material, and it is expected that the effects of winter frost-thaw and high spring flows in this reach will cause considerable change. The other reach is in an area characterized by more cohesive bank material. This profiling experiment quantifies the difference between these two soil types under similar flow conditions.

Table 1.2: Initial survey of the 35 sampling stations, showing width, overhanging vegetation type (O.H.V. Type), bank and bed material, phase (riffle Ri, run Ru or pool P) and adjacent land use for Black and Silver Creeks and the West Credit River (July, 1991).

Black Creek

Site	Width (m)	O.H.V. Type	Phase	Bank Mat'l	Bed Mat'l	Adj. Land Use
BC1	4.25	maple, fern	Ri	silty loam	mixed gravel	brush
BC2	4.20	willow	P	fine silt	mixed gravel	resid., brush
BC4	8.46	cedar, grape	Ri	sandy loam	fines cobbles	mature forest
BC5	5.97	maple	P	coarse sand	gravel, loam	mature brush
BC6	5.40	willow, cedar	Ru	sand, gravel	sand, cobbles	resid., golf
BC7	6.58	none	Ru	coarse sand	sand, cobbles	resid.
BC8	6.52	cedar	Ri	sand, gravel	gravel, cobbles	bush, swamp
BC9	7.31	cedar	P	soft loam	sand, gravel	bush
BC10	8.05	walnut, spruce	Ru	sandy loam	sand, cob' ' s	bush
BC11	6.28	silver maple	Ru	sandy loam	sand, boulders	resid., bush
BC12	5.42	maple	Ru	coarse loam	sand, boulders	brush
BC13	7.85	birch, maple	Ri	coarse sand	cobbles, boulders	mature brush
BC14	5.80	cedar	Ru	sand, silt	sand, cobbles	mature brush
BC17	5.23	elm, cedar	P	silty loam	sand	mature brush
BC18	4.75	aspen, beech	Ri	coarse gravel	mixed gravel	mature brush
BC19	2.61	maple, cedar	P	pebble loam	sand, gravel	mature forest
BC20	4.91	maple, cedar	Ru	sand, gravel	sand, gravel	mature forest

Table 1.2 cont'd

Silver Creek

Site	Width (m)	O.H.V. Type	Phase	Bank Mat'l	Bed Mat'l	Adj. Land Use
SC1	4.72	cedar, fern	Ru	silty loam	sand, cobbles	bush
SC2	5.61	mature elm	Ri	silt to clay	sand, gravel	bush
SC3	3.66	willow, maple	P	silty loam	clay, gravel	mature bush
SC4	3.21	mature bush	Ru	sandy silt	sand, cobbles	mature bush
SC5	6.05	maple	Ri	sandy loam	sand, cobbles	resid., bush
SC6	4.67	beech, maple	Ru	sand, gravel	silt, cobbles	school, bush
SC7	6.09	maple	P	silty clay	sandy, organics	RR track, bush
SC8	4.02	willow, grape	Ru	sand, gravel	granules, boulders	bush, road
SC9	6.97	none	Ru	sandy silt	sandy silt	farm
SC10	5.53	none	Ru	sandy silt	sandy silt	grazing
SC11	4.61	pine, spruce	P	clay to sand	clay, sand	mature bush

Table 1.2 cont'd

West Credit River

Site	Width (m)	O.H.V. Type	Phase	Bank Mat'l	Bed Mat'l	Adj. Land Use
WC1	7.26	elm, lawns	Ri	silty loam	sand, cobbles	lawn, bush
WC2	8.12	mature elm	Ri	silty loam	sand, cobbles	bush
WC3A	7.36	maple, willow	Ru	sand, gravel	gravel, cobble	mature bush
WC3B	6.32	willow	P	sand	sand, cobble	mature bush
WC4	5.91	none	Ri	sand, gravel	cobbles, boulders	resid., scrub
WC5	5.68	none	Ri	sand	cobbles, boulders	grasses, sedges
WC6	8.80	none	Ri	sand, gravel	cobbles, boulders	lawn, scrub

CHAPTER 2

BACKGROUND INFORMATION AND LITERATURE REVIEW RELATING TO FLUVIAL GEOMORPHOLOGY AND CHANNEL STABILITY

2.1 INTRODUCTION

Any review in studies such as these requires that the literature be grouped in such a manner that confusion is reduced and ease of reading is enhanced. To this end, the next two chapters are segmented into literature which deals with in-channel processes (fluvial geomorphology and channel stability) and that which deals with fish and their habitat preferences/physiological tolerance limits. A section is added to introduce the small body of literature which deals with the combination of these previous two sections (geomorphology and fish habitats).

Alluvial river channels are dynamic, constantly changing to reach some form of equilibrium through erosion and deposition processes within the basin. Equilibrium may be reached if there are no new inputs into the system, such as sediment from overland flow or bank erosion, or changes to stream direction such as those observed by the addition of a fallen tree into the channel. The way channels attempt to attain equilibrium is through movement of bed material. This movement has been the focus of a considerable amount of study over the years. Factors considered were the amount of movement, the size, shape and density of the particles being moved, the competence of the stream to move various particles of different sizes and shapes, and the hydrodynamic theories of particle entrainment.

2.2 MOVEMENT OF BED MATERIAL

2.2.1 General Theories

Probably the first extensive study into the movement of bed material by a river system was conducted by Gilbert (1914), who studied what happened to excavated mine tailings in the Southwest United States. His treatise eventually became a focal point for studies that followed, and remains to this day one of the more cited pieces of literature in North America.

Studies have concerned themselves with the amount of material that is actually moved by rivers. Middleton (1976) noted that the 'delivery ratio', or the amount of material that is moved from source to any downstream location in the system, is less than 10% for basins larger than 100 miles^2. That is, less than 10% of the material eroded and delivered to the smallest tributaries is discharged by the main stream leaving the drainage basin.

There have been a number of different theories regarding the movement of material over a river bed. Initially, it was thought that bed material moved continually, as long as there was a competent velocity present. As that velocity slowed to below competent levels, material was deposited on the bed and was re-entrained once that fluid velocity passing over the particle became competent again.

Einstein (1950) showed that the movement of material over a bed was a random phenomenon, that particles moved in a series of steps of random length separated by periods of rest which were of random duration. Bagnold (1977) found that bedload transport in natural rivers is unsteady both in time and cross-sectional distribution. He found that two-fold variations in total river transport rate can occur within a several minute period, and that "streams" of solids wander at random laterally over the bed. He concludes by saying that at any given discharge and gradient an alluvial river can transport a bed load of a given mean grain size at a greater rate the shallower the flow depth. Kuhnle and Southard (1988) showed by studying the bedload transport rate every 30 seconds in gravel bed flumes that the nature of the bed material and not simply fluid velocity determined the rate of transport, (a reaffirmation of the work of Laronne and Carson, 1976 and others). Kuhnle and Southard found that coarse bed channels had lower transport rates than smoother channels. This revised predictions of the amount of material moved in a given time for a given channel, and reinforced the fact that channels behave in different manners. Wilcock and Southard (1989) found that not only do transport rates depend on the coarseness of the channel but on the population of grain sizes available for transport on the bed surface. But, the grain size distribution of the bed surface depends on the mobility of various grains on the bed, so, the actual mobility of material on the bed depends on the grain size of the available material as well as flow velocity.

Ashmore (1991) found that bedload pulses are generated within the stream by aggradation and degradation within short reaches of the stream, and that measured pulses of bedload in the stream appear as "waves" of aggradation and are accompanied by clusters of migrating unit bars. Hoey and Sutherland (1991) postulate that transport rates are more dependent on whether or not the channel reaches in question are in equilibrium with the water flow. They suggest that the bedload equation of Bagnold (1980) overpredicts transport rates in channels that are in equilibrium or are aggrading, and underpredicts transport rates for channels that are degrading. Ashworth and Ferguson (1989) reinforced that the relative size of the grains on the bed is more important than the absolute size of the grains, particularly as it relates to the threshold shear stress for gravel entrainment, but also found that precise equal mobility of small and large particles was "approached" at higher shear stresses and transport rates.

Hassan and Church (1991) discuss the complexity of bed material movement. They identify three categories of variables that control bed movement: sedimentological characteristics of the bed (texture, packing, armouring, bed forms), hydraulic conditions of the flow (discharge, velocity, duration), and characteristics of individual moving particles (size, shape, roundness). These characteristics show that for any given flow condition over the same bed one can expect any number of different bedload transport rates.

Movement of bed material results in the formation of structures on the bed, which may be so transitory as to last for a few minutes (ripple-marks) or so stable as to last for a considerable period of time (gravel bars). Since considerable work has been done in this area, this review will touch on those studies which relate to gravel-bed channels. Laronne and Carson (1976) identified three types of structures in gravel-bed rivers. Open structures were those where particles on the bed are arranged in such a manner that they do not come in contact with one another, closed structures are those where particles are in close contact with one another, and infilled structures occur where particles fill in the voids between stationary bed fragments while rolling or sliding. These smaller particles 'seal' interparticle spaces, contributing to the strength of the bed by creating resistance to movement due to armouring. These structures are offered as proof of movement of bed material. The presence of imbricated structures further proves the notion of bedload transport. Because imbricate structures are characterized by upstream dipping of particles, their formation can only be attributed to bed movement (Laronne and Carson, 1976). Further proof of bedload transport is offered by Milne (1982), Lambert and Walling (1988) and others.

2.2.2 *Theories of Flow Competence*

The movement of bed material has been attributed to flow competence, that is, the ability of a particular flow velocity to move bed material of a particular size range. This is important in fluvial geomorphological studies because it allows the prediction of movement of material from a measurable parameter, fluid velocity.

Although investigations into the competence of a river have been carried out since before the turn of the century, it is probably the work of Gilbert (1914) that first called attention to the importance of this matter. He outlined eight factors that must be taken into consideration when dealing with the capacity of fluids to transport material: slope, discharge, fineness of the material, particle form, fluid velocity, uniformity of the material, the relationship between load and energy, and the processes of flume transportation. His work, using flumes and material of uniform sizes paved the way for further investigations into the theories of flow competence, both in flume and natural river systems and using uniform and natural materials.

Hjulstrom (1935) was the first person to graphically show the relationship between fluid velocity and the erosion, transportation and deposition of material finer than 100mm in diameter. His argument was that, all other things being equal, velocity of the fluid was the determining factor in the erosion, transportation and deposition of material within river systems. This was in spite of his recognition of the wide scatter among the data points he used and the fact that different velocities will produce different results. This work renewed interest in the problem of flow competence.

Numerous authors have looked into this problem since Hjulstrom. Nevin (1946) investigated the flows necessary to transport concrete blocks weighing 10,000 tons, a phenomenon caused by the failure of the St. Francis Dam in California. He determined that particle shape is important in the evaluation of flow competence. He also expanded on the idea of critical tractive force being a determinant of competency. Menard (1950) concurred, stating that the critical tractive force and critical tractive velocity are important parameters for the initiation of motion, and that they are applicable in both the laboratory and in the field. Lane and Carlson (1954) found in their study on the effect of particle shape on the movement of coarse sediments that, on average, disks are of the same susceptibility to movement as spheres 2.5 times their weight.

This introduced a new problem into the theories of flow competence. Menard was able to show that larger particles than were initially imagined would be able to be transported by rivers. In the past, it was assumed that larger particles were placed on the river bed by forces other than fluvial, for instance glacial. Krumbein and Lieblein (1956) were able to show, using extreme value theory, that a number of these particles were actually part of the local deposits, and that it is unnecessary to "call upon extraneous processes to account for their occurrence in the deposit".

Sundborg (1956) presented a refined competency diagram for fine sediments (<2 cm. diameter). Although his work correlated closely with Hjulstrom's, it was considered to be a starting rather than finishing point. Ljunggren and Sundborg (1968) noted that competency curves for uniform materials (such as Sundborg's 1956 curve) could not be used to determine stream competence when particles with different densities, shapes and sizes were present in the same deposit. The interaction between grains with different densities will be influential in the process, and the 'hiding effect' of larger particles is important in the process of sorting and enrichment.

Some of the first attempts to apply laboratory competence relationships in the field showed how inaccurate the process was. Birkeland (1968) found that the calculated competence required to move a boulder measuring 40x20x10 feet above ground surface would require a 40 to 80 foot deep flood moving at about 30 feet per second on a slope of 0.007. The fact that depth could range by 2x highlights how inconclusive the predictive process was during this time.

Investigators started to question the use of velocity as the determining force that entrained particles, because of the fact that near-bed velocities approached zero and that the use of mean, surface or other velocities was not indicative of the actual processes at the bed. Novak (1973) attempted to draw a relationship between critical tractive force and mean velocity using a synthesis of published works in this area. In doing so, he was able to create a situation where either measurement could be used, and then related to other works that may have used either. Novak also plotted his results against the standard Hjulstrom curve, and noted that for coarse particle transport different velocities were required than would be predicted by the Hjulstrom curve. He found that a curve of mean velocity for overturning and a curve of bottom velocity for sliding defines a zone that predicts coarse sediment transport better than the Hjulstrom-type curves (including Sundborg, 1956).

It was starting to become apparent in evaluations of competency that the nature of the boundary may play a significant role. Although Shields (1936) had worked with the condition of the boundary, most of the work in this area was just beginning in earnest. Church and Gilbert (1975) suggested that a non-cohesive bed exists in three states: normal, where materials are resting in a non-dispersed state; overloose, where materials are resting in a dispersed state, normally due to the presence of a large volume of water within the sediment; and underloose, where materials are resting in a state of close packing or imbrication. While most of the work to date has been done on normal boundaries, they argue, it is the other two states that occur most often in reality. They suggest, then, that a lower-than-experimentally-derived velocity will be needed to move a particle off an overloose boundary, and a higher-than-experimentally-derived velocity will be needed to move a particle off an underloose boundary. Church and Gilbert also noted that instantaneous velocity fluctuations can result in up to four times the fluctuation in lift and drag forces at the bed, allowing for particles up to four times in size to be moved than would be predicted.

Moving away from velocity measurements, Baker and Ritter (1975) used mean shear stresses to predict competence. Bagnold (1977) suggested that hydraulic properties of the flow need to be determined through the measurement of hydraulic gradient, flow depth, mean velocity, grain size and effective threshold values of velocity and stream power. Miller et al. (1977) state that the characteristics of the sediment are the important factors in competency. Bradley and Mears (1980), moving out of the laboratory and into the field, determined that macroturbulent or other flow conditions may entrain particles but go unrecorded in mean-value determinations of flow velocity or tractive force. Costa (1983) challenged the use of average velocity and shear stress measurements, stating that Bernoulli lift is very active in downstream transport. Brayshaw et al. (1983) showed how the arrangement of particles on the bed, and how they project into the flow, distorts the fluid stream to produce a distinctive pressure field which has significance for the entrapment or the entrainment of particles depending on their positions relative to the cluster. Andrews (1983) postulated that bed material size distribution affects the forces acting on a given particle by either hiding the particle from the flow or by the fact that the force necessary to start a large particle rolling over a smaller one is less than the force required to start a smaller particle rolling over a larger one. Other authors looked at the types of channels in a natural system (Carling, 1983), the condition of the boundary and particle size of the sediment (Carson and Griffiths, 1985; Ashworth and Ferguson, 1989; Ferguson et al., 1989), the effect of grain pivoting angles (Komar and Li, 1986; Li and Komar, 1986), particle collisions (Carling, 1990), sedimentation by river-induced turbidity currents (Chikita, 1990), and how friction angle and particle protrusion are affected by the variability of shear stresses within water-worked sediments (Kirchner et al., 1990).

For the purposes of evaluating velocities needed to carry bed material in this study, the work of Komar (1987) will be used. His attempt to formulate a competency relationship for coarse grained sediments on a mixed bed was a synthesis of previous works, re-evaluated so that all calculations would be uniform between the studies. His resulting competent velocity,

(2.1) $$U_c = 57D^{0.46}$$

where U_c = mean fluid velocity (cm sec.$^{-1}$) and D = particle diameter (cm) appears to be the best compilation of the variables needed to entrain bed material.

A distinct pattern is developing in the literature. As one tries to define the extensive number of variables necessary to start a particle in motion, the level of investigation becomes more and more intense. Komar and Carling (1991) sum up the problem of fluid and sediment hydraulics by stating that flow-competence relationships will differ from stream to stream, under different flow conditions, depending on their unique patterns of grain sorting and material sources.

2.3 SUSPENDED SEDIMENT CONCENTRATIONS

The introduction of sediment into an alluvial river channel, caused by either the failure of river banks, scouring of the bed due to either the introduction of a 'foreign' object that alters flow or a rapid increase in fluid velocity from storm events, or by overland flow can affect the stability of the channel.

Sediment yields from watershed sources are continual over time, due to the constantly changing nature of watersheds under human influence (Anderson, 1957). Despite that statement, suspended sediment concentrations are directly dependent on such factors as the base flow level (longer periods between rainstorms generally mean that more sediment is available for transport: Wood, 1977; Ongley et al., 1981). There is also a distinct seasonal component to suspended sediment concentrations, being higher (50% of the annual load) in the spring during snowmelt and lower in the summer and winter (Dickenson and Scott, 1975), although there is some disagreement on this claim (Grimshaw and Lewin, 1980).

Suspended sediment concentrations, by nature of the fact that they vary considerably over time, are difficult to extrapolate over a stream for a period of time. Because of these problems, suspended sediment rating curves have been developed to estimate suspended sediment loads from small to medium catchments (Walling, 1977). There is still a great deal of error involved in the use of these curves, and one should be careful not to use the information contained within them blindly (Walling, 1977).

Verhoff and Melfi (1978) and Verhoff et al. (1979) studied the movement of suspended sediment through a system. They found that suspended sediment moves through the system in a series of discrete steps of deposition and resuspension, rather than moving through completely in one event. This means that there is some storage of sediment within the channel at different periods of the flow, an important implication for use of the channel by fish.

Novotny (1980) suggests that the storage of sediment in the channel is of little significance due to the fact that suspended sediment only deposits under very low flow conditions or in impoundments. Lambert and Walling (1988) found that under periods of base flow and at the tail end of storm hydrographs, fine sediments settle from suspension onto the bed surface forming deposits 5-10mm thick. Depending on the proximity to flow of that layer, it may be resuspended or it may remain, where it is added to under the next depositional condition.

2.4 RIFFLE-POOL SEQUENCES

The occurrence of riffles (shallows) and pools (deeps) in a river channel is indicative of the changing stability of the channel. Wolman (1955) found that coarser materials in riffles inhibits bed erosion and thus encourages erosion of the bank. As material gets trapped in the riffle, it can become a mid-channel bar, diverting flow to the banks and encouraging more erosion. This is re-affirmed by Richards (1976) who states that channel width may oscillate along a reach in conjunction with variations in flow geometry normally associated with the riffle-pool sequence. Keller and Melhorn (1978) and Lisle (1979) found that riffle-pool sequences of gravel-bed streams are maintained by scour and fill associated with high flows, that the spacing of these riffles and pools are normally distributed, and that there is sorting of the bed material within riffles and pools.

Alternating riffles and pools have come to be recognized as a fundamental morphological characteristic of alluvial river channels (O'Neill and Abrahams, 1984). These bed forms have a major effect on flow geometry and may be a primary determinant in meandering.

2.5 OTHER FACTORS RELATING TO CHANNEL STABILITY

There are a number of other factors that play a role in the stability of alluvial river channels. Probably the most important is the amount of input into the system in the form of precipitation. Langbein and Schumm (1958) looked at sediment yield in relation to the amount of mean annual precipitation, but it is important to note that it is not only the amount of precipitation that falls over a basin, but the rate that the precipitation enters the system (Beebe et al., 1991). A fast rate of input, and subsequent fast rate-of-change of fluid velocities has been shown to remove a gravel bar consisting of particles up to 8 centimetres in intermediate diameter after one short-duration high energy summer storm in July, 1991 (present study).

The presence of in-stream and side-channel vegetation is another such factor. Mosley (1982) noted that the presence of willow trees scattered about in a river channel affected channel form, in some cases promoting bar construction immediately downstream and in others leading to deep scour of the bed. Such cases are localized, yet the influence of a newly-fallen tree can alter fluid patterns and riffle-pool sequences for a distance downstream. Vegetation at the edge of the bank may also play a more significant role in channel form. Although touched on only briefly in the literature, the type, quantity and age of vegetation roots exposed by eroding banks has a varying degree of impact, the smaller roots acting as stabilizers of the bank (Thorne, 1990), the larger tree roots acting as a rough boundary creating turbulence and subsequent erosion of the bank and bed downstream. This is observed in the present study (Bellamy et al., 1992), and will be elaborated on in Chapter 7.

Extended base flow conditions can lead to channel stabilization over a short period of time. Continued base flow conditions, such as those experienced in the summer of 1991 in this study area, can remove almost all of the fine sediment on the bed, leaving only the larger particles available for transport. The reduced flow conditions and the removal of the finer material results in a situation where shear stresses are not great enough to entrain the particles that are left on the bed (Komar, 1987). Such a dependence can lead to the formation of armoured beds, most obvious in gravel rivers. Wilcock and Southard (1989) found that the decrease in the mobility of the fine and coarse fractions as a system adjusts toward equilibrium (as happens under base flow conditions), is explained by the development of a partial static armour, which helps to decrease the mobility of finer fractions. Armoured beds probably represent the most stable a river system becomes for any length of time. They are usually eradicated once the higher secondary peak flows of the fall arrive.

As material is introduced into the headwaters of a river system, it begins to make its way along the channel towards the mouth. This process of longitudinal transport results in progressive sorting of the bed material, as the finer fractions will move farther downstream than the coarser ones (Knighton 1980, 1982). This property operates independently of any downstream increase in stream competency or capacity, provided that there is net aggradation of the channel (Middleton, 1976). Progressive downstream sorting can be broken down into two components, as Knighton (1980) writes (p. 60):

> ...the first of which concerns the lag deposition of those grain-size fractions which the stream is incompetent to transport. Regarding stream power as a suitable measure of transporting ability, a decrease in slope downstream leads to a corresponding decrease in transporting ability and an increase in the probability that coarser fractions are deposited, at least temporarily. The downstream increase in discharge partly compensates for the reduction of slope, particularly beyond the

> headwater area where the rate of slope decrease tends to exceed the rate of discharge increase. The lag deposition of coarser grains is therefore most likely in the headwater reaches. The second component is related to the transportability of different grain sizes. Of those size fractions which the stream transports, it can be argued that the velocity and distance of transport of a given size fraction may vary inversely with the modal size of the fraction. Grain size also influences the mode of transport which in turn affects the velocity of movement. This component of sorting tends to increase the proportion of finer particles in the bed material downstream, leading to changes in grain size characteristics similar to those induced by a declining slope.

Mosley (1976) and Best (1988) studied changes in channel morphology at the point where tributaries enter a river. They found that river channel confluences are characterized by complex patterns of flow and sediment transport which produce distinctive bed morphologies. The major controls on these processes are the junction angle and the ratio of discharges between the two confluent channels.

Some of these factors outlined above deal with the stability of the entire channel, while others deal with a very localized effect on bed and banks. While it is easy to minimize the potential effect of a bank root wad on the whole channel system, it is important to remember that in the instance where fish could be using that area for spawning habitat, that root wad could have devastating effects.

CHAPTER 3

BACKGROUND INFORMATION AND LITERATURE REVIEW RELATING TO FISH HABITAT PREFERENCES AND PHYSIOLOGICAL TOLERANCES

3.1 INTRODUCTION

Salmonids include the various species of trout and salmon. The three species which occur in the area of study are the brook trout, the brown trout, and the rainbow trout. Under suitable conditions of water quality the capacity of a stream to maintain salmonid populations is largely a function of the discharge and other physical structures of the channel (Milner et al., 1985; Lanka and Hubert, 1987). These recent studies show the importance that is placed on geomorphic variables within a river channel. The connection from habitat to geomorphology is summarized by Milner et al. (1985, p. 86):

> In its commonest usage, habitat refers to the local physico-chemical and biological features of a stream site that constitute the daily environment of fish, eg. channel form, dimensions, bankside and instream cover, temperature, inter- and intra-specific competition, predation and food availability. In the context of salmonids these site attributes operate by controlling territory size and availability. Impinging on these are larger-scale catchment attributes of geomorphology, topography, land use and climate (particularly rainfall). These features are inter-related but, by determining factors such as stream bank composition, gradient and discharge regime, they also directly control local site physiographic features according to the principles of stream hydraulics. Therefore, both site and catchment features must be considered in habitat evaluation, and there is a

continuum of changing habitat type along a catchment although there may be pronounced discontinuities caused by geological and topographic variation.

Other factors that determine the health of fish habitats include the amount and deposition of suspended sediment, the nature of the bed material, and channel attributes such as width, depth, velocity of flow, dissolved substances and dissolved oxygen.

3.2 SPAWNING-SITE SELECTION AND FRY EMERGENCE

The maintenance of a fish population in a river is to a large extent due to the success of spawning. The manner in which salmonids choose spawning sites is very specific, and because of this it is important to have an understanding of the selection process. Shirvell and Dungey (1983) note that the exact locations chosen by individuals appear to be related to physical characteristics such as depth, velocity and nature of the substrate. Chapman (1988) and others show that the presence of fines in the spawning bed determines the suitability of that bed for spawning (Table 3.1).

Chapman (1988) gives a good review of the process of site preparation. The female cleans an egg pocket of fines and small gravels by turning on her side and repeatedly flexing her body. The material lifted into suspension is deposited downstream by the current, leaving a "tailspill" ridge at the edge of the pocket. The female deposits her eggs into this 'centrum' and the male simultaneously fertilizes

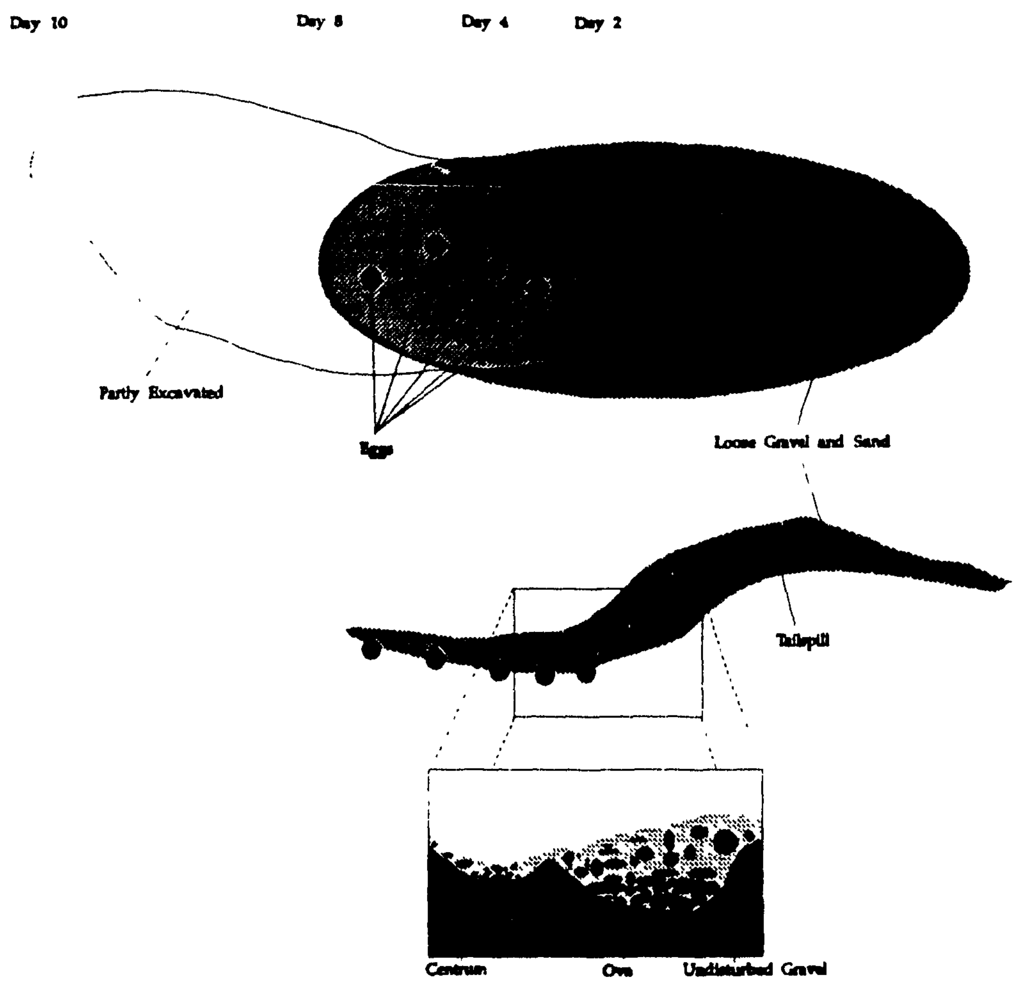
Table 3.1 Size range of particles in gravel beds selected as redds in three species of trout from Southwestern Ontario. Based on OMNR (1984).

Species	Particle size range (cm.)
rainbow trout	1.0 - 8.0
brown trout	1.0 - 4.0
brook trout	0.4 - 2.0

them, the eddying currents within the centrum helping to keep the sperm in contact with the eggs. The female then moves obliquely upstream from the first pocket and digs another. The fines again are removed by the current, but the coarser (in the relative sense) gravels are deposited over the previous pocket, covering the eggs enough to prevent predation but not enough that intra-gravel water flow is disturbed. This continues until all of the eggs are deposited. Burner (1951) described the bottom of egg pockets noting that there usually remained one or two large particles to which the eggs attached themselves. Fig. 3.1 schematically shows what a salmonid redd (area in which the eggs are deposited) would look like. The female, upon completion of the egg laying, continues to excavate obliquely upstream; it is thought that the purpose is to remove fines from a larger area than the redd.

In high density spawning areas the superimposition of redds may result (Young et al., 1990), causing disturbance to the original redd and decreasing likelihood of survival. Late spawning females may use previously constructed redds that are now free of eggs. This has been shown to have little effect on survival to emergence (Young and Hubert, 1990).

Fry emerge by swimming through the interstices of the spawning gravel to the



Modified from
Chapman (1988)

Fig. 3.1 Schematic showing a salmon redd with egg deposition surface (Chapman, 1988). Moore and Gregory (1988), noting Bams (1969) found that emerging sockeye salmon do not immediately swim to the surface to fill their air bladders (a prerequisite for swimming and feeding). Rather, they found that these fish stay near the bottom and swim laterally over short bursts, taking resting periods on the bottom. This continues until the fish reaches the side of the channel, where the flow characteristics are more suitable for young fry. Egg development of the three species of salmonids found in S. W. Ontario streams is dependent on temperature, intergravel water flow, well oxygenated water and lack of site disturbance (OMNR, 1984).

Chapman (1988) and Young et al. (1990) both address the question of spawning success. They found that because the ability to estimate the number of viable eggs in any particular redd has been ignored, and that there is not enough information to predict quantitatively the success of spawning based on physical characteristics of the stream, it is impossible to determine the success of any particular spawning event.

3.3 HABITAT PREFERENCES, SUITABILITY AND MODELLING

Lindroth (1955) noticed a vertical differentiation within the water column between trout and salmon in the same habitat; trout occupied the most suitable habitat, leaving the other localities to the salmon. Le Cren (1969) noticed that, in the absence of salmon, trout fry were found at the edge of riffles of small streams whereas larger trout were found in deeper pools. Jones (1975) found that most juvenile salmon are caught in riffles, whereas trout are most likely to be caught in deeper water. Table 3.2 shows the preferences of particular trout and salmon to flow and depth characteristics.

Table 3.2: Trout and Salmon habitat preferences (by age) to depth and fluid speed (modified from Jones, 1975).

Habitat Type	Age and Species using Habitat
Riffles	0+ Salmon
Riffles and Runs	1+ Salmon, 0+ Trout
Runs and Pools	1+ Trout
Pools	2+ and Older Trout

Jones (1975) suggests that the above information does not indicate if 0+ salmon occur in riffles by choice or because of either competition by same age trout or predation by older trout.

Others have found similar results. Saunders and Gee (1964) found that salmon parr whose homes were in riffles were only recaptured there, indicating that mobility to other habitats at this age is minimal. Elson (1967) reported that salmon parr were most numerous in rapids under 25 cm. deep, decreasing in number with increasing depth, and that they preferred cobble substrate. He suggests that these preferences may be related more to water velocity and surface turbulence than depth and substrate. Gibson and Power (1975) found salmon parr more frequently associated with riffles than pools (as long as both were present), and preferred overhead cover during the day. Symons and Heyland (1978) found that as Atlantic Salmon grew older, their habitat preferences changed, from shallower gravelly-bed riffles to much deeper riffles which included boulders. Kennedy and Strange (1982), Glova and Duncan (1985) and Bisson et al. (1988) also noted that as age changed, habitat preference also changed. In summary, trout have very different requirements at different times in their life cycle. Fingerlings live along quiet margins of riffles which have rocks, logs, or plants for concealment. As they get older they occupy swifter but shallow areas with logs or rocks to break the current, over a year old they move into deeper water and larger, older fish reside in runs or heads of pools which have considerable depth (OMNR, 1984).

It is evident that many of these same conditions (presence of pools and riffles of varying substrate type) are common across different types of streams. That does not mean, though, that all of these similar habitat types are suitable for use by fish. Mills (1971) notes that if any one of the required conditions for a particular species is altered, even though all others are acceptable, the habitat will no longer be suitable for the successful life cycle of that species. Heggenes (1988) and Bisson et al. (1988) discussed environmental variables such as depth, velocity, water quality, substrate and cover in terms of habitat suitability. Heggenes and Saltveit (1990) found that the distinct seasonal and spatial variation in habitat use suggests that fish can tolerate and adapt to a variety of habitat conditions within defined ranges, in a sense suggesting that habitat which is altered to a minor extent will be re-used at a later date by subsequent species.

An attempt to put all of these habitat qualities together in a predictive format has resulted in the generation of habitat suitability curves. These curves show the approximate amount of usage of a habitat in a certain condition (percent fines in the substrate, for example) based on the amount of fish found in areas of like habitat. The use of such curves has been cautioned by Gore and Nestler (1988) who noted that these curves display expected frequency of use by fish under equilibrium conditions, that is, curves have been generated from data taken from periods of median or base flow for a presumably stable population. The use of the curves under conditions other than those that they were developed introduces an error factor. Heggenes and Saltveit (1990) state that the considerable temporal variation in microhabitat use indicates that habitat suitability curves may only be used with caution, that snapshot studies of habitat use may give biased suitability curves, and usually curves with too narrow optimum ranges.

The next step in habitat studies is modelling. There have been many developed over the years. Fausch et al. (1988) reviewed and classified 99 such models, all are lacking in one way or another. Being based on carrying capacity of the streams and variability of habitat characteristics are part of the problem with the variability of the models themselves. Milner et al. (1985) note that due to the natural instability of streams, carrying capacity fluctuates depending on site-specific physiographic features. These fluctuations are induced by randomly changing habitat attributes, and this may explain the between- and within-site variation caused by these models. Binns and Eiserman (1979) note another problem with habitat evaluation models, that although various models have been developed, "not all have been objective, quantifiable or divorced from monetary terms".

3.4 SUSPENDED SEDIMENT TRANSPORT AND DEPOSITION

The amount, type and quality of suspended sediment has a tremendous effect on both the physiology of fish and the suitability of habitats. A very significant investigation of the effects of suspended sediment on fish physiology was done by Herbert and Merkins (1961), who found that concentrations of suspended diatomaceous earth of 270 mg L^{-1} had adverse effects on rainbow trout by thickening respiratory epithelium cells and fusing adjacent laminae, in essence suffocating the fish (Fig. 3.2, 3.3). These efforts were duplicated by Herbert et al. (1961) using china clay wastes. Even at 90 mg L^{-1}, diatomaceous earth was found to have an adverse effect as well (Herbert and Merkens, 1961).

Suspended sediment has effects other than physiological. Cooper (1965) conducted a study into the effects of transported sediment. His data (p. 26):

> ...indicate a relationship between the survival of eggs and the percentage of gravel finer than 0.336 cm. which may be caused by packing of the particles around the eggs or by the transfer of soil pressure to the eggs. These and other data indicate that gravel uniformity is a factor which can affect the survival except possibly in coarse gravel.... These results show that the deposition of sediment which would reduce the flow of water through the gravel, or which would reduce the size of the gravel, would result in reduced survival of salmon eggs in the gravel.

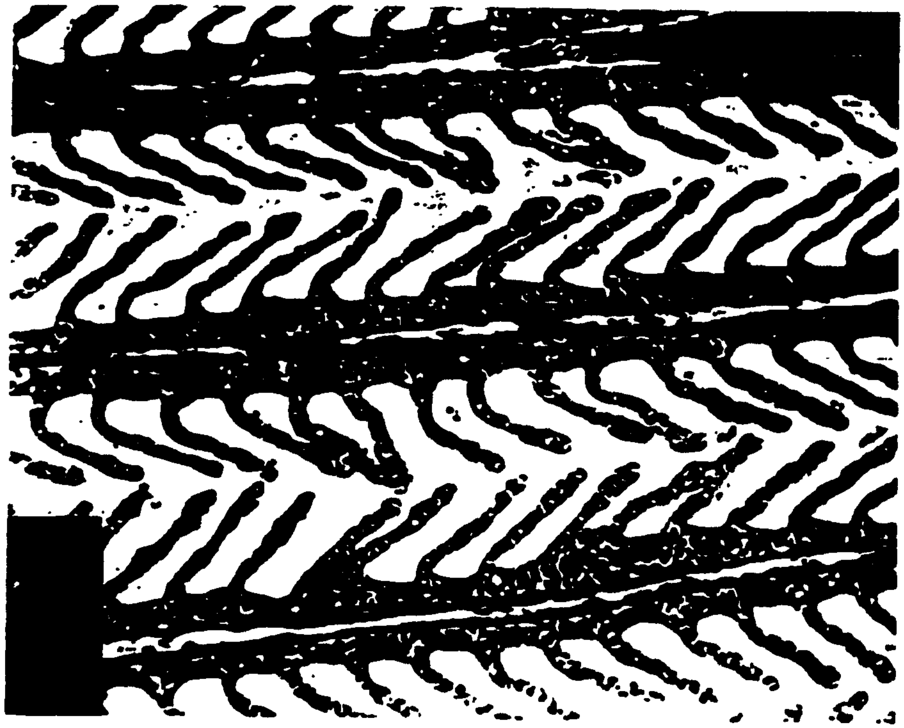


Fig. 3.2 Gill section from a healthy trout (from Herbert and Merkins, 1961)

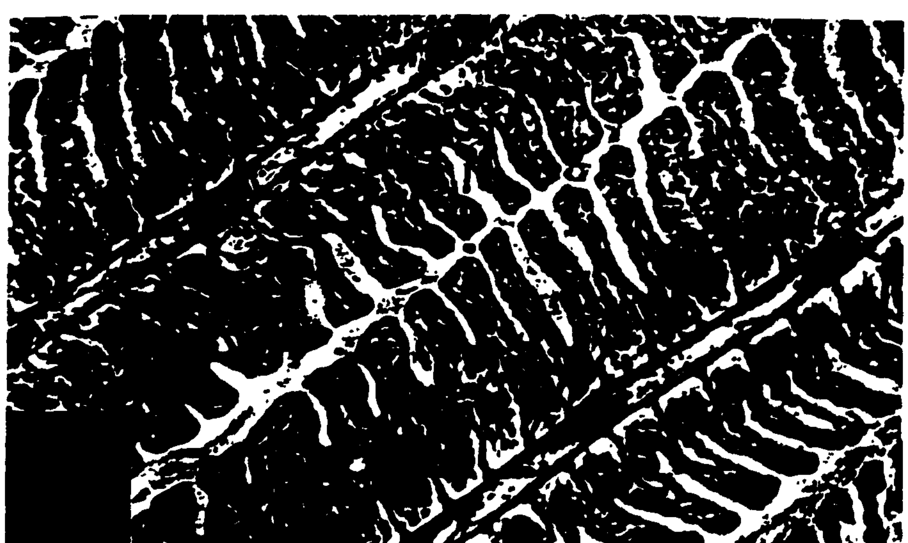


Fig. 3.3 Gill section from a trout subjected to 270 ppm. diatomaceous earth (from Herbert and Merkins, 1961)

Newcombe and MacDonald (1991) synthesized numerous other works and concluded (p. 73):

> ...salmonid fisheries can be affected by inert sediment 1) acting directly on free-living fish, either by killing them or by reducing their growth rate or resistance to disease, or both; 2) interfering with the development of eggs and larvae; 3) modifying natural movements and migrations of fish; 4) reducing the abundance of food organisms available to the fish; and 5) reducing the efficiency of methods used for catching fish.

Table 3.3 summarizes some of the findings of Newcombe and MacDonald (1991) that relate to trout. The information is presented by species type, concentration of suspended sediment, duration of exposure in hours, and the response. Newcombe and MacDonald conclude by saying that further research in this field requires investigation of the duration of exposure and response, being sure to remove the confounding effects of other variables. Redding and Schreck (1987) however feel that any stress placed on fish by increased suspended sediment concentrations is quickly adapted to by the fish, and that there are no long-term complications.

Phillips et al. (1975), Hausle and Coble (1976) and Crouse et al. (1981) found that the concentration of 1-3mm diameter sand in spawning gravel and the emergence of fry is inversely related. Hillman et al. (1987) found that increased concentration of fine sediment may reduce winter survival of anadromous salmonids by entering substrate crevasses, filling them and removing a potential habitat. Chapman (1988) and Reiser and White (1988) conclude that it is the concentration of fines that deposit in the interstices of spawning gravel that has the most adverse effect. This material creates a fine bridge between the interstices, which can close the egg pocket off from the flow of intergravel water, thus depleting the amount of dissolved oxygen that reaches the eggs. If the sediment concentration remains high, and more sediment falls out of suspension, that bridge can cement to the point where even if eggs hatch, fry cannot butt their heads through this cement to reach the current, and as a result die in the egg pocket. Cooper (1965) found that deposition of silt occurred in spawning beds even when the flow was too great to allow for deposition by being trapped by hydraulic eddies created when fluid flows around larger particles. He goes on to say that the most suitable gravel for preventing this silt deposition is larger gravel, and the worst possible gravel for this condition is actually spawning gravel. Reiser and White (1988) go on to say that improper land-use activities such as those associated with logging and road construction introduce large amounts of fines into streams, reducing the time that redds are clean or rendering the cleaning ineffective, decreasing egg survival.

Table 3.3: Effects of exposure to suspended sediment concentrations by trout and the resulting response by the fish. Conc. indicates concentration in mg L^{-1}, duration in hours (modified after Newcombe and MacDonald, 1991).

Species	Conc.	Duration	Effect on Fish
Rainbow Trout	200	24	5% mortality of fry
	7	1152	17% reduction in fry survival
	21	1152	67% reduction in fry survival
	200	168	8% mortality of fry
	90	456	5% mortality of sub-adults
	68	720	25% reduction in population size
	37	1440	46% reduction in fry survival
	47	1152	100% mortality of incubating eggs
	57	1440	23% reduction in fry survival
	270	456	10-35% mortality of sub-adults
	270	456	80% mortality of sub-adults
	101	1440	98% mortality of eggs
	100	1	Avoidance response
	100	0.25	Coughing rate increased
Brown Trout	110	1440	98% mortality of eggs
	1040	8670	85% reduction in population size
	5838	8670	85% reduction in population size
Brook Trout	12	5880	Reduction in growth rate
	100	1176	Reduction in growth rate
	24	5280	Reduction in growth rate

3.4.1 Dissolved Oxygen Concentrations

The introduction of fine sediment into redds reduces the amount of dissolved oxygen that reaches the eggs at a time when development is critical for survival. Koski (1966) found that the size of coho salmon at emergence related directly to permeability of the substrate, that gravels with high proportions of fines and low permeability tend to have low dissolved oxygen concentrations which delays embryo development. Mills (1971) reports that the minimum dose permissible for trout is 5.0 to 5.5 mg L^{-1}. The result of fish having to go a short time without this level of oxygen is lethal. Chapman (1988) found that embryos hatch earlier at larger total weight when dissolved oxygen is high, and that fry exposed to low concentrations of dissolved oxygen tended to emigrate into downstream traps after emergence because of competition during the post-emergence period. Reiser and White (1988) state that the major controlling factor influencing egg mortality is reduced dissolved oxygen caused by the reduction of intragravel velocities caused by large amounts of sediment.

3.5 NATURE OF THE BED, GEOMORPHOLOGY AND STREAM ALTERATION

Mills (1971) found that the nature of the stream bed is most important for the spawning of salmonids. Trout in streams with sandy bottoms do not reproduce, because they require fast-flowing water with a gravelly substrate. In fact, the nature of the substrate is more important than other factors such as depth. Gordon and MacCrimmon (1982) reported that the strong positive relationship between amount of gravel present and juvenile density ($r = 0.76$) and biomass ($r = 0.79$) indicates the importance of this substrate type. Sand deposition appeared to be the primary environmental factor influencing survival to emergence in their study. This is reinforced by Alexander and Hansen (1986). The nature of the substrate plays other roles as well. Kennedy and Strange (1982) note that the presence of boulders provide fish with shelter from the flow and cover from predation, and also increase the number of fish in an area by visually subdividing habitat.

Platts (1979) tried to relate geomorphological attributes of a drainage basin to the amount and type of fish found there. He noted that as stream order increased, width, depth and percentage of channel containing rubble increased, and that the number of fish species, summer water space for fish and total number of fish increased.

Alexander and Hansen (1986) treated a stream by increasing the sand load over a period of years. They found that the stream adapted by becoming wider and shallower, that pools filled, and the bottom became a uniform sand bed devoid of cover. This reduced the carrying capacity of the stream considerably. In the four years following the introduction of sand, major channel adjustments continued to be made. Water surface elevation, streambed elevation and stream width all reverted to their natural state, but water depth and 'static water volume' returned to only one-half of their original state. More important from a fish standpoint was the lack of bankside deepening and pools.

Lanka et al. (1987) found that the combined effect of watershed variables such as increased basin slope, increased channel slope, and a more dendritic drainage pattern tended to decrease response time of stream discharge to rain events. Drainage basins with these characteristics generally have greater flow variability, decreased water stored in depressions and groundwater, and lower base flows. These factors all result in poor habitat for trout. They conclude by saying that the relation between basin geomorphology and trout standing stock is the result of a link between measurable features of a drainage basin and stream habitat. This linkage may enable the use of simple measures of drainage basin geomorphology to predict potential habitat quality for trout. The difficulty with this work is that their geomorphological variables were measured from 1:24000 or 1:63360 topographical maps. Local variations in some of the variables mentioned by Lanka and Hubert are more important for trout, and these would be overlooked from this kind of study.

There are negative and positive effects of stream alterations in terms of fish habitats. Saunders and Smith (1962) created hiding places for trout by introducing stumps and rocks to a stream, finding that the year after alteration trout were found more widely distributed in their study area. Elser (1968) found that the construction of an Interstate highway altered 87% of a channel, and that the number and weight of brown and rainbow trout was about 78% greater in the unaltered sections of the stream. Moore and Gregory (1988) made a case for the consideration of the state of lateral habitats of streams, that these areas are used by emerging fry as shelter from flow.

3.6 HABITAT PREFERENCES RELATING TO OTHER VARIABLES

Numerous studies into the habitat preferences of salmonids have been undertaken. Lewis (1969) noted that salmonids are territorial and establish a social hierarchy according to habitat conditions. Moore and Gregory (1988) noted that upon emergence dispersal mechanisms result in the establishment of territories in lateral habitats.

Gorman and Karr (1978) found that seasonal changes in fish distributions and flow regimes play a major role in determining fish community structure, and that "disequilibria" may occur seasonally or throughout the year due to natural events like spring floods and human activities. Taylor (1988) also identified seasonal trends in salmonid habitat use.

Needham (1969) and Mills (1971) found that water temperature was very important in salmonid habitat use and survival. Needham noted that cold springs and spring-fed tributaries are sometimes the only source of cold water during warm summer months. Mills noted that fish adapt themselves quickly to a rise in temperature, but less quickly to a drop in temperature. Mills also noted that fish only spawn when water temperature is optimal.

Solomon and Templeton (1976) found that salmonids make five discrete movements according to their life stage. First, they move downstream from the area of hatching to nursery areas up to 6 months of age; second, they move downstream again to areas of adult growth from 6-15 months of age; third is a period of little movement by adults age 15 months to spawning age; fourth is the upstream spawning migration; and fifth is a downstream movement after spawning. Cresswell (1981) noted that stocked brown trout appear to remain nearby with little movement, and that brook and rainbow trout show greater movement in the downstream direction. Greater dispersion of all species occurs if they have overwintered prior to capture or have been stocked in cold water or in upland tributaries.

The amount of overhead cover in a habitat determines its use. McCrimmon (1954), Lewis (1969), Gibson and Power (1975), Gibson (1978) and Egglishaw and Shackley (1982) all studied the effect of cover on habitat use. General results showed that trout preferred areas of good cover, and avoided pools with minimal cover. Salmon parr were often found away from cover, but returned there quickly when startled.

Egglishaw and Shackley (1982) and Kennedy and Strange (1982) looked at the relationship between water depth and habitat use. They both found that there is considerable niche segregation according to age class, but wonder if the fish are there because of preference or as a result of predation and competition.

Water velocity has been the subject of considerable research over the years. Gibson and Power (1975) found that salmon have an advantage over trout when competing for feeding habitat in fast-flowing waters, especially when food supplies were low. Ottaway and Clarke (1981) and Egglishaw and Shackley (1982) found that vulnerability to flow was dependent on the life stage of the fish. Kennedy and Strange (1982) report that salmon are physiologically better adapted to rapid flowing water than brown trout. Cresswell and Williams (1983) found that prior acclimation to flow by hatchery-reared trout was important in reduction of involuntary migration. Irvine (1986) and Bisson et al. (1988) report strong negative relationships between habitat use and increasing water velocity. Heggenes (1988) found that a sudden change in peak flow about ten times greater than base flow had no effect on brown trout movement when that velocity is sub-critical. The fish in this case sought out low-velocity niches behind rocks in the bed. Finally, Heggenes and Traan (1988) reported that salmonid fry just entering the free-feeding stage are most vulnerable to downstream displacement by flow.

3.7 STREAM CLASSIFICATION FOR AQUATIC HABITAT EVALUATION

Although there is a wide body of literature on both channel stability and fish habitat preferences and requirements, what is most important is the relationship between the two variables. At which point does stability affect fish habitat? And what degree of habitat is affected? Some authors have attempted to quantify fluvial trout habitat in terms of geomorphic variables (Binns and Eiserman, 1979), but they are limited as to their applicability outside the stream where they were developed.

Platts (1974) was responsible for one of the more intensive investigations into this matter. He quantified geomorphic variables within the Idaho Batholith and showed how important they were to the number of salmonids in that area. Again, the problem was that this study was too location-specific, and its applicability in other areas was called into question. He recognizes this and recommends that aquatic systems should be inventoried and classified relative to all terrestrial systems.

Since that time there has been no real attempt to classify streams according to their fish habitat quality related to geomorphological features. Rosgen (1985) has been working on a stream classification system based on geomorphic variables, but has not to this point published any information on the relationship to fish habitat. He has presented an unpublished work (Rosgen and Fittante, unpublished) which utilizes his earlier classification scheme to determine the type of corrective structures needed in a stream requiring habitat reconstruction. It is likely that, as Rosgen modifies his system to make it more applicable in the field, a biologist will remedy the deficiency and establish habitat requirements along with it.

CHAPTER 4

METHODOLOGY

4.1 INTRODUCTION

A study that looks at stability in alluvial channels has a number of variables to consider, each of which requiring separate and detailed methodologies. In order to facilitate understanding, these methodologies are presented individually in Chapter 5, 6 and 7. Those things which are not pertinent to a single experiment yet are important to the overall methodology are presented here.

4.2 CROSS-SECTION IDENTIFICATION AND WALKING SURVEY

In an attempt to locate suitable representative cross-sections for study, an initial walking survey of Black and Silver Creeks was undertaken. The survey started at the confluence of these two creeks and went upstream to their headwaters. During the survey sample cross-sections were identified and staked using 12" survey pins with flagging tape for easy re-location.

Cross-sections were placed approximately equidistant from each other wherever possible. Locations were identified on Ontario Base Maps (1:10000; Ontario Ministry of Natural Resources) and cross-referenced to 1:8000 air photos (1989 flight; Credit Valley Conservation Authority). Proper location was essential for determining channel slope. Locations were coded in to the OBM for further reference.

Certain sections of Black and Silver Creeks were determined to be unsuitable for sampling as they were significantly altered by local landowners. In some instances bed materials were removed and aligned to create weirs, resulting in pool formation from which intake water could be collected. Some sections of Silver Creek were heavily polluted, especially within the City of Georgetown. Numerous tires were found on the bed, pieces of concrete and asphalt lined the channel, and articles such as refrigerator doors were pulled from the bed at various locations.

A total of 17 cross-sections, coded BC1 to BC20 (BC3, BC15 and BC16 were removed from the initial survey due to sampling problems in those areas) were identified on Black Creek. They ranged from riffle to run to pool locations and encompassed a wide variety of adjacent land uses. Some cross-sections were located above and below tributaries in an attempt to determine any changes to the system. Likewise, a total of 11 cross-sections were chosen on Silver Creek (coded SC1 to SC11), with the same range of location types and adjacent land uses. For further study, 7 cross-sections (coded WC1 to WC6--including WC3A and WC3B) were located downstream from the confluence of Black and Silver Creeks on the West Credit, ending where the West Credit flows into the Credit River at Norval. In all, 35 cross-sections were identified on these three water courses for further evaluation. During each site selection, channel width was measured and notes were taken regarding adjacent land use, overhanging vegetation type and amount, nature of the bed and bank material, and whether the site was a riffle, run or pool.

4.3 FIELD SAMPLING

Each site was visited between the period July 26, 1991 to March 31, 1992, for sampling under base flow, fall secondary peak flow, spring high flow and post-spring high flow conditions. To ensure base flow measurements were being made, sites were not visited for 48 hours after a rainfall. Attempts were made to survey the confluence area during rainstorms to obtain specific information.

At each site measurements of channel width, depth, fluid velocity, fluid temperature, suspended sediment concentration and bed material were made. Prior to any measurements, a transect line was stretched across the creek from survey stake to stake. The upstream left bank water edge was marked with tape and all measurements were taken relative to that mark.

4.4 THESIS PRODUCTION

This thesis was typed on a Samsung s550 computer using Wordperfect v.5.1, on license to Wilfrid Laurier University. Graphics were produced using Quattro Pro and Corel Draw. Map supplements 1 through 6 were hand produced and reduced using P.M.T. techniques from the Printing Department, Wilfrid Laurier University. Bank block profiles were produced using Surfer v.4.0, on license to the Cold Regions

Research Centre, Wilfrid Laurier University. Printing was done through the Computing Services Department, Wilfrid Laurier University.

CHAPTER 5

RESULTS OF FLUID STABILITY AND SUSPENDED SEDIMENT INVESTIGATIONS

5.1 HYDRAULIC GEOMETRY RELATIONSHIPS

5.1.1 Introduction and Methodology

Studies of hydraulic geometry have been conducted on a wide variety of systems, for a variety of reasons (most notably flood forecasting and hazard prediction modelling). Investigations into changes in width, depth, fluid speed and discharge are very important in the study of channel stability and the implications for fish habitat.

Changes to width in river systems are varied and numerous. Their impact on salmonids and their habitat however are not very significant. In some instances, greater channel width provides more room for fish to spawn, feed or perhaps elude predators, allowing a larger number of fish to use the same section of stream. But, for the most part, natural fluctuations in width throughout a stream are sufficient for the needs of the fish.

Certainly the more important parameters studied are mean depth and fluid speed. Variation in depth throughout a channel provides fish with areas for protection (the deeps) and areas for transport, feeding and spawning habitat (the shallows). It is very important for habitat to have a good combination of these depths to sustain fish stock. A greater need for variation is evident when considering fluid speeds. As outlined in Chapter 3, fish at different stages in their life cycle depend on different fluid speeds for their survival. Emerging fry require slow speeds in the littoral zones of the stream so that they can grow, yet older fish require faster speeds which transport food downstream and allow for a sufficient amount of dissolved oxygen to pass their gills. It also appears that salmonids subjected to a constant fluid speed are more likely to be healthier from studies of their gill capacities and electrolyte levels (MacDonald, G. personal communication, 1992). Due to the fact that fish require both still pools for safety and faster water for feeding, spawning and overall health, variability in speeds within a reach is optimal, and fish will seek out and compete for those areas.

At each site measurements of channel width, depth, fluid speed, and fluid temperature were made and recorded. Prior to any measurements, a transect line was stretched across the creek between fixed survey stakes. The upstream left bank water edge was marked with tape and all measurements were taken relative to that mark.

Width was determined by stretching a 30 metre (m.) unstretchable tape across the creek along the transect, with the 0 m. mark at the upstream left water edge. The width was read at the upstream right water edge. If there was any undercutting, that was measured as well. In cases where the upstream right water edge was not well defined, care was taken to ensure that an accurate measurement was taken. Width in centimetres (cm.) was recorded on the data sheet.

Channel depths were measured at the upstream left bank and every 20 cm. along the transect, up to and including the right bank. Measurements were made with a wooden metre stick (millimetre graduations) for two reasons: first, it was thick enough that it would not slice into the bed material and second, it was light enough that it would not depress the beds of softer material. Depths were read off to the nearest millimetre (mm.) and recorded.

In some instances fluid speeds were adequate to give higher than actual readings on the ruler, due to water butting against the stick or where standing waves were present. In these cases the high water reading and the low water reading were averaged (Fig. 5.1). When a large particle appeared on the bed directly beneath the transect, and that location was a depth measurement location, the depth to that particle was recorded. At no times were bed materials moved during sampling, in an attempt to leave the channel unaltered.

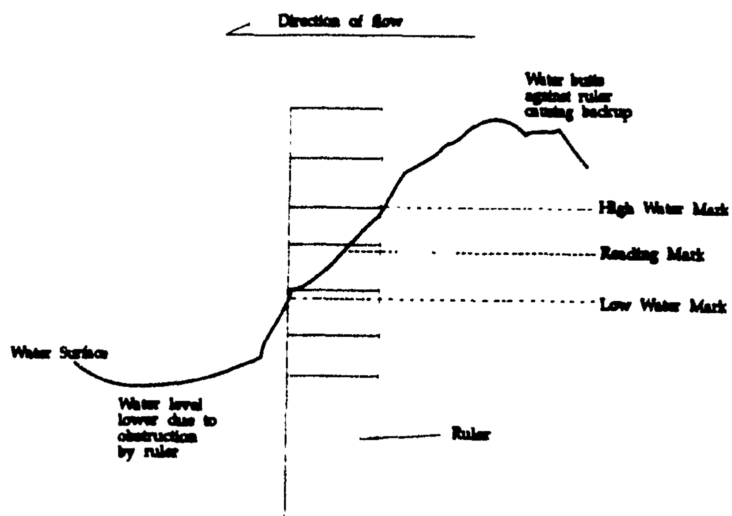


Fig. 5.1: Schematic of how depth measurements were taken in flowing water

Prior to fluid speeds being taken, the cross-section was divided up into 5 panels, using the equal-width method (Water Survey of Canada, 1986). The mid-points of these panels were determined through measurement (all measurements being taken from the upstream left side of the cross-section) and were coded P1 to P5. The exact location of the panel mid-point was marked on the transect so it could be referenced without re-measurement. Depths of all panels were recorded to the nearest mm., the same way channel profile depths were measured.

The depth of the speed measuring probe was calculated in the following manner. If the depth of the panel was less than 5 cm., one measurement was taken at D(0.5). If the depth was between 5 and 20 cm., three measurements were taken at D(0.2), D(0.4), and D(0.6). For depths greater than 20 cm., 5 measurements were taken at depths of D(0.2), D(0.4), D(0.6), D(0.8), and D(0.95). The maximum number of fluid speed sampling locations for any cross-section was 25 (5 panels * 5 depths). The measurement closest to the bed had to be at least 1 cm. off the bed so the equipment could record properly.

Fluid speeds were measured with a Marsh-McBirney 201D portable electromagnetic current meter. The meter fit around the operators neck and the probe was attached by clamp to a wooden rod, 1.83 metres in length and 2.5 cm. in diameter (Fig. 5.2). Exact distance from the bed to the electrodes of the probe were obtained from direct measurement with a tape measure.

Once depth was determined, the rod was placed onto the bed at the panel mark with the electrodes facing the flow. Once everything was in place, the unit was turned on and given time to equilibrate. Speeds were read as m. sec^{-1} at a 6 second interval, except where flow readings were less than 0.2 m. sec^{-1}. In these instances readings were taken as ft. sec^{-1} and converted. Seven readings were recorded at each location; these were averaged to get the mean fluid speed for that location.

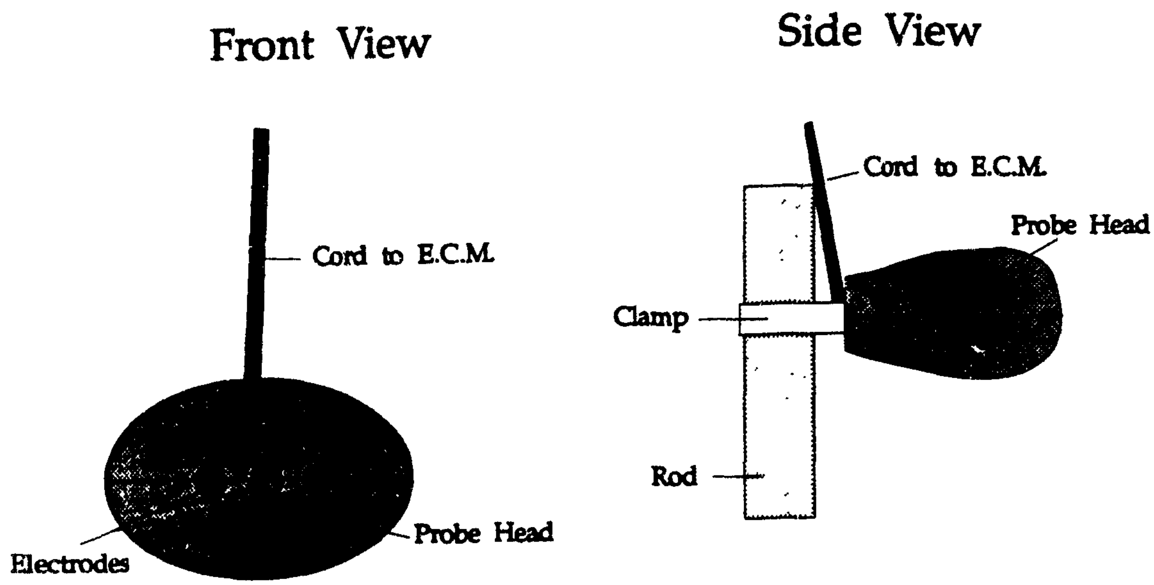


Fig. 5.2: Electromagnetic current meter probe head and assembly

In some sampling locations, negative values have been recorded. This was due to reverse circulation (flow in the upstream direction) in backwater pool areas, or in some cases was the result of an upstream obstruction in the channel (like a boulder) or an obstruction in the bank (like an exposed tree stump). Care was taken during the recording of all measurements that the water was not disturbed by movement of the operator, especially in areas where fluid speeds were very low. Extra time was allotted for probe equilibration at these locations.

5.1.2 Results

Measurements of channel width, depth, fluid speed and discharge were taken under four flow conditions. Run 1 (summer base flow conditions), run 2 (fall secondary peak flow conditions), run 3 (spring melt-high flow conditions), and run 4 (late spring post-rainfall conditions) are presented in Table 5.1 for Black Creek. Table 5.2 shows the same data for Silver Creek and Table 5.3 shows West Credit River data. Initial observation of the data shows that for each station the width, mean depth and discharge increases from run 1 to run 3, then decreases somewhat for run 4. This is not necessarily true for the fluid speed measurements. For example, Black Creek stations 1 and 2 show a mean fluid speed that is greater in run 2 than in the other peak flows (run 3 and 4). This does occur elsewhere in these creeks, but on average the mean fluid speed follows the pattern shown for mean depth and discharge.

Standard tests of the degree of association (see Leopold and Maddock, 1953) between paired attributes (width, depth, and velocity versus discharge) in the downstream direction are presented in an attempt to determine if this data fits

Table 5.1 Measurements of width, depth, width/depth ratios, velocity discharge and suspended sediment for Black Creek (Run 1= July '91, Run 2= Dec. '91, Run 3= March '92, Run 4= late March, '92).

Site	Run	Width metres	Mean Depth metres	W/D Ratio	Velocity m.p.s.	Discharge c.m.s.	Susp. Sed. mg/L
BC1	1	5.55	0.163	34	0.392	0.355	2.3
	2	5.85	0.217	31	0.47	0.597	19.3
	3	8.42	0.522	16.1	0.356	1.56	
	4	6.08	0.232	26.2	0.383	0.541	18.4
BC2	1	4.4	0.204	21.6	0.426	0.382	7.3
	2	5.6	0.208	27	0.446	0.519	19.4
	3	6.52	0.341	19.1	0.372	0.827	
	4	4.93	0.218	22.7	0.369	0.396	21.9
BC4	1	8.58	0.138	62.4	0.291	0.345	2.3
	2	8.6	0.187	46.1	0.358	0.576	19.1
	3	9.38	0.281	33.4	0.472	1.24	
	4	8.78	0.19	46.3	0.457	0.761	18.8
BC5	1	6.15	0.365	16.9	0.141	0.317	2.3
	2	6.7	0.37	18.1	0.171	0.425	19.4
	3	8.25	0.472	17.5	0.271	1.05	22.1
	4	7.4	0.355	20.9	0.192	0.504	19
BC6	1	5.5	0.226	24.6	0.218	0.271	11.4
	2	5.9	0.227	21.3	0.368	0.493	36.9
	3	5.89	0.529	11.1	0.391	1.22	89.4
	4	5.97	0.331	18.1	0.29	0.572	22.1
BC7	1	6.53	0.207	35.6	0.252	0.341	32
	2	6.75	0.288	23.5	0.355	0.691	19.2
	3	7.05	0.345	20.4	0.439	1.07	
	4	6.75	0.289	23.4	0.45	0.877	19.7
BC8	1	6.33	0.115	55	0.593	0.432	2.4
	2	6.7	0.166	40.5	0.586	0.652	19.8
	3	6.75	0.215	31.4	0.871	1.264	
	4	6.76	0.186	36.2	0.635	0.8	18.8
BC9	1	7.66	0.325	23.6	0.095	0.236	5
	2	8.05	0.363	22.2	0.11	0.322	59.4
	3	8.17	0.421	19.4	0.218	0.751	
	4	8.17	0.403	20.3	0.091	0.3	60
BC10	1	8.25	0.22	37.6	0.136	0.246	11.2
	2	8.65	0.261	33.2	0.19	0.428	19.7
	3	9.23	0.334	27.6	0.269	0.831	
	4	8.8	0.28	31.4	0.25	0.616	19.9

Table 5.1 Continued

Site	Run	Width metres	Mean Depth metres	W/D Ratio	Velocity m.p.s.	Discharge c.m.s.	Susp. Sed. mg/L
BC11	1	6.28	0.138	45.5	0.237	0.205	50.3
	2	6.8	0.203	33.6	0.432	0.584	23.5
	3	7.24	0.258	28.1	0.67	1.251	
	4	6.9	0.184	37.6	0.255	0.323	18.8
BC12	1	5	0.14	33.8	0.199	0.139	2.2
	2	6.3	0.181	34.9	0.398	0.454	21.9
	3	6.81	0.143	47.6	0.521	0.862	
	4	6.31	0.178	35.5	0.363	0.407	19.7
BC13	1	7.8	0.138	56.4	0.151	0.163	8.9
	2	8.16	0.22	37	0.222	0.399	45.9
	3	8.46	0.27	31.3	0.328	0.751	
	4	8.35	0.19	44	0.211	0.335	18.8
BC14	1	5.18	0.149	34.9	0.233	0.18	2.6
	2	5.75	0.212	27.2	0.29	0.354	22.9
	3	6.19	0.279	22.2	0.364	0.629	
	4	5.86	0.193	30.3	0.361	0.409	19.4
BC17	1	5.05	0.154	32.7	0.206	0.16	2.2
	2	5.16	0.244	21.2	0.189	0.238	68.7
	3	5.25	0.395	13.3	0.281	0.583	
	4	5.1	0.255	19.9	0.203	0.265	21.1
BC18	1	4.7	0.1	46.8	0.455	0.214	15.8
	2	4.7	0.11	42.9	0.472	0.244	20.6
	3	5.48	0.257	21.3	0.441	0.621	
	4	4.86	0.122	39.9	0.345	0.204	18.6
BC19	1	2.46	0.146	16.9	0.359	0.129	13.2
	2	3.35	0.168	19.9	0.314	0.177	100.2
	3	5.36	0.188	28.5	0.361	0.364	
	4	3.37	0.164	20.6	0.232	0.128	18.6
BC20	1	4.35	0.236	18.4	0.117	0.12	9.1
	2	4.35	0.251	17.3	0.116	0.127	38.4
	3	4.36	0.334	13.1	0.238	0.347	
	4	4.36	0.269	16.2	0.142	0.167	57.7

Table 5.2 Measurements of width, depth, width/depth ratios,velocity discharge and suspended sediment for Silver Creek

Site	Run	Width metres	Mean Depth metres	W/D Ratio	Velocity m.p.s.	Discharge c.m.s.	Susp. Sed. mg/L
SC1	1	4.61	0.254	18.2	0.133	0.156	2.5
	2	4.55	0.286	15.9	0.148	0.193	55.8
	3	5.05	0.531	9.51	0.198	0.531	
	4	4.75	0.293	16.2	0.157	0.219	23.2
SC2	1	7.05	0.056	126.3	0.339	0.134	7.1
	2	7.09	0.058	122.7	0.545	0.224	37.9
	3	7.16	0.283	25.3	0.61	1.236	
	4	7.35	0.089	82.2	0.456	0.3	22.4
SC3	1	3.54	0.698	5.1	0.057	0.141	13
	2	3.82	0.625	6.1	0.147	0.352	19.7
	3	4.14	0.852	4.9	0.268	0.945	
	4	3.65	0.668	5.5	0.07	0.172	19.2
SC4	1	3.03	0.153	19.8	0.298	0.138	2.6
	2	4.03	0.184	21.9	0.495	0.367	18.7
	3	8.29	0.322	25.7	0.46	1.23	
	4	3.36	0.229	14.7	0.359	0.277	19.1
SC5	1	6.05	0.076	80.1	0.372	0.171	37.3
	2	6.25	0.135	46.3	0.53	0.447	19.6
	3	7.09	0.347	20.4	0.562	1.38	
	4	6.3	12.1	52.1	0.468	0.356	37.4
SC6	1	4.7	0.173	27.2	0.154	0.125	2.5
	2	5.13	0.236	21.7	0.357	0.432	18.8
	3	5.89	0.407	14.5	0.33	0.791	
	4	5.16	0.234	22	0.243	0.293	19.8
SC7	1	6.4	0.429	14.9	0.05	0.143	7.3
	2	N D	N D	N D	N D	N D	N D
	3	N D	N D	N D	N D	N D	N D
	4	N D	N D	N D	N D	N D	N D
SC8	1	4.05	0.151	26.8	0.227	0.138	2.3
	2	4.6	0.256	17.9	0.346	0.407	20.6
	3	4.72	0.358	13.2	0.545	0.921	
	4	4.53	0.233	19.4	0.289	0.305	18.8
SC9	1	6.7	0.185	36.5	0.088	0.109	4.6
	2	7.1	0.366	19.4	0.134	0.347	21.6
	3	7.86	0.393	20	0.278	0.859	
	4	7.1	0.3	23.7	0.148	0.315	150.3
SC10	1	5.6	0.26	21.5	0.052	0.075	13.8
	2	5.93	0.551	10.8	0.122	0.4	19.2
	3	6.87	0.595	11.5	0.244	0.997	
	4	5.87	0.411	14.3	0.096	0.233	42
SC11	1	4.8	0.336	14.7	0.035	0.057	19
	2	6.45	0.553	11.7	0.085	0.302	20.7
	3	7.32	0.657	11.1	0.159	0.765	
	4	5.8	0.519	11.2	0.057	0.17	19

Table 5.3 Measurements of width, depth, width/depth ratios, velocity discharge and suspended sediment for the West Credit River

Site	Run	Width metres	Mean Depth metres	W/D Ratio	Velocity m.p.s.	Discharge c.m.s.	Susp. Sed. mg/L
WC1	1	6.92	0.257	26.9	0.181	0.322	5.1
	2	7.75	0.32	24.3	0.253	0.327	37.5
	3	9.18	0.629	14.6	0.338	1.95	
	4	8.77	0.3	29.2	0.291	0.767	18.8
WC2	1	8.02	0.096	88.5	0.429	0.33	4.8
	2	7.95	0.183	43.3	0.509	0.74	58.3
	3	9.17	0.38	50.1	0.58	2.02	
	4	8.16	0.194	42.1	0.551	0.87	18.8
WC3A	1	7.38	0.194	38.1	0.134	0.192	13
	2	7.75	0.256	30.3	0.262	0.52	22.1
	3	9.26	0.419	22.1	0.492	1.91	
	4	7.9	0.285	27.7	0.323	0.727	9.9
WC3B	1	6.08	0.296	20.5	0.164	0.295	26.9
	2	6.45	0.337	19.1	0.276	0.599	19.1
	3	7.73	0.546	14.2	0.51	2.15	
	4	6.54	0.364	18	0.295	0.701	21.5
WC4	1	5.85	0.12	48.8	0.604	0.424	2.3
	2	6	0.202	29.7	0.573	0.695	19.3
	3	9.12	0.392	23.3	0.681	2.43	
	4	6.28	0.203	30.9	0.614	0.784	20.7
WC5	1	5.41	0.166	32.6	0.385	0.346	37.2
	2	5.2	0.214	24.3	0.658	0.732	19.6
	3	7.42	0.376	19.7	0.642	1.79	
	4	5.79	0.269	21.6	0.657	1.02	19
WC6	1	8.47	0.149	56.7	0.323	0.408	12.5
	2	8.85	0.181	48.7	0.463	0.742	20.5
	3	10.51	0.285	36.9	0.595	1.78	
	4	9.9	0.182	54.5	0.498	0.895	9.5

previously published relationships. Fig. 5.3 shows the association between mean fluid speed (velocity in Leopold and Maddock) and discharge in the downstream direction under summer base flow conditions for all stations.

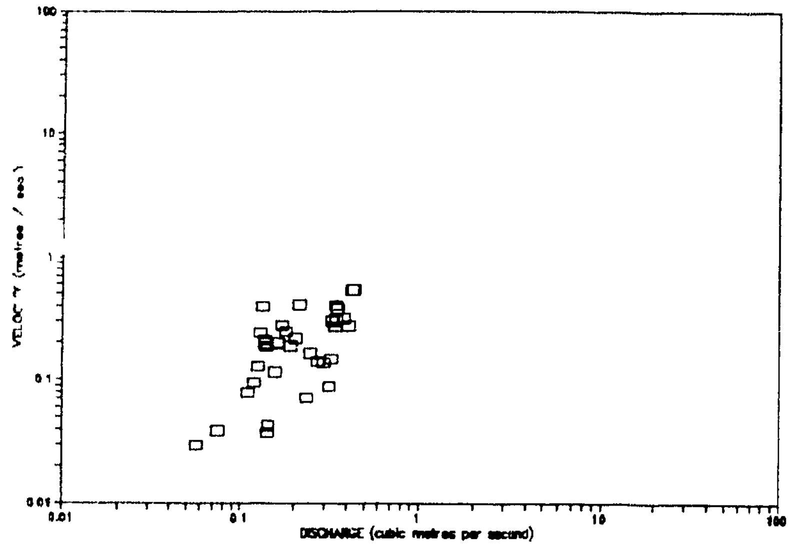


Fig. 5.3 Degree of association between speed and discharge under summer base flow conditions

From Fig. 5.3 it is seen that there is a general upward trend for velocity versus discharge, when velocity increases there appears to be a corresponding increase in discharge. There is a large amount of scatter, indicating the relationship is not as strong as ones presented by Leopold and Maddock (1953).

Fig. 5.4 shows the same degree of association for the cross-sections under spring melt-high flow conditions. Although the values for fluid speed and discharge are higher, the data points remain scattered, and it is obvious that there is not a strong relationship. The general upward trend (increasing discharge with increasing velocity) is still there.

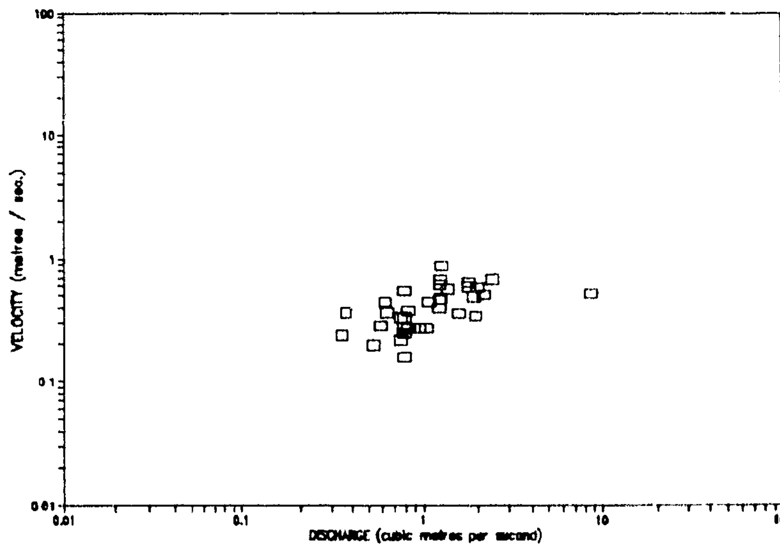


Fig. 5.4 Degree of association between fluid speed and discharge under spring high-melt flow conditions

Appendix 1 contains the remaining plots of fluid speed, and the plots of width and mean depth versus discharge under the four flow regimes in this study.

5.1.3 Interpretation of the Results

Presentation of the hydraulic geometry data in this manner presents some problems of interpretation. Leopold and Maddock (1953), in their interpretation of the relationships between width, depth and velocity versus discharge have performed a regression using variables which are in part a function of themselves. Due to the fact that discharge is the product of width, depth and velocity, any attempt at correlating w, d or v with Q will result in a good relationship because the regression is performed partly on itself. Although the intent was to produce an equation which could be used for predicting potential hazards and flood forecasting, caution should be used when interpreting results from these values. Because of this fact, another way of determining if there is a relationship between width, depth, velocity and Q in the downstream direction is necessary.

If the desired relationship is the change in these parameters as one moves downstream, the information could be determined by plotting a parameter (say discharge) against distance from the source of the river. This has been done for these creeks, and the results are found in Fig. 5.5. It is evident from Fig. 5.5 that discharge increases with distance downstream, although it appears that the amount of increase varies between flow regimes (the spring melt-high flows produced the greatest range in discharge from source to mouth, and the summer base flow conditions produced the lowest range). The large amount of fluctuation for any flow regime is shown in this figure as well as Figs. 5.3 and 5.4. The scatter suggests that for any given discharge there are a number of possible fluid speeds associated with it.

The general trend found when the Silver Creek discharges are plotted against distance downstream (Fig. 5.6) is quite different. No longer is there a definite increase in discharge in the downstream direction, indicating that this interpretation is not adequate on this small creek where discharge can vary along its length but does not vary considerably in magnitude.

Appendix 2 contains the plots of width, mean depth and velocity versus distance downstream for Black Creek/West Credit River and Silver Creek. This method does not aid in the forecasting of high-energy events the way it is presented here, there is not enough data for that. Analysis of a large data base is required before the usefulness of this method can be determined.

Although the preceding data shows the results for cross-sections as a whole, results have shown that it is necessary to look at the variation in fluid speed within a cross-section, both across the channel and throughout the depth (Fig. 5.7). This data will give a better indication of the changes in stability that are apparent at-a-station, and would be missed through the use of mean values for fluid speed.

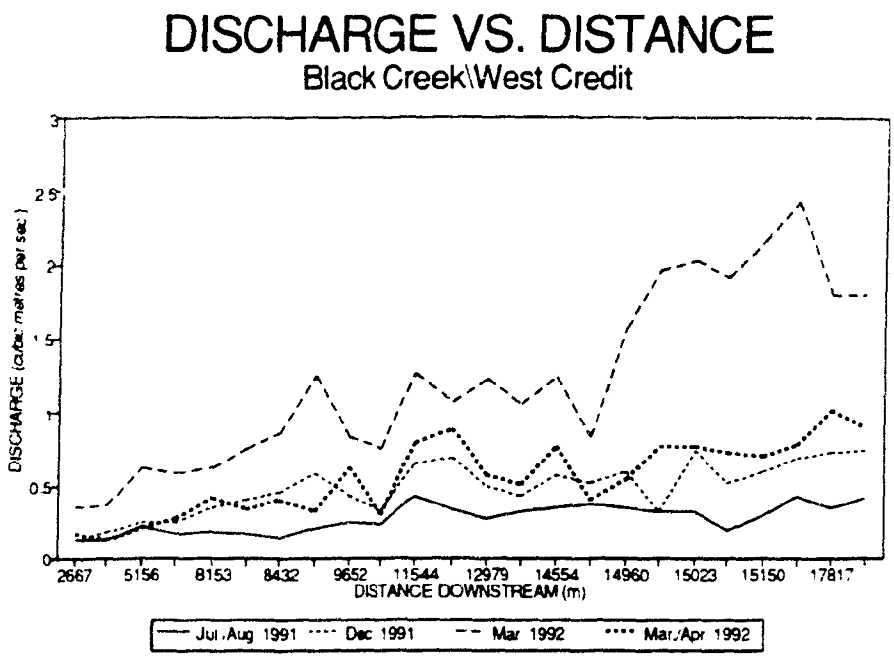


Fig. 5.5 Discharge plotted against distance from source for Black Creek and the West Credit River

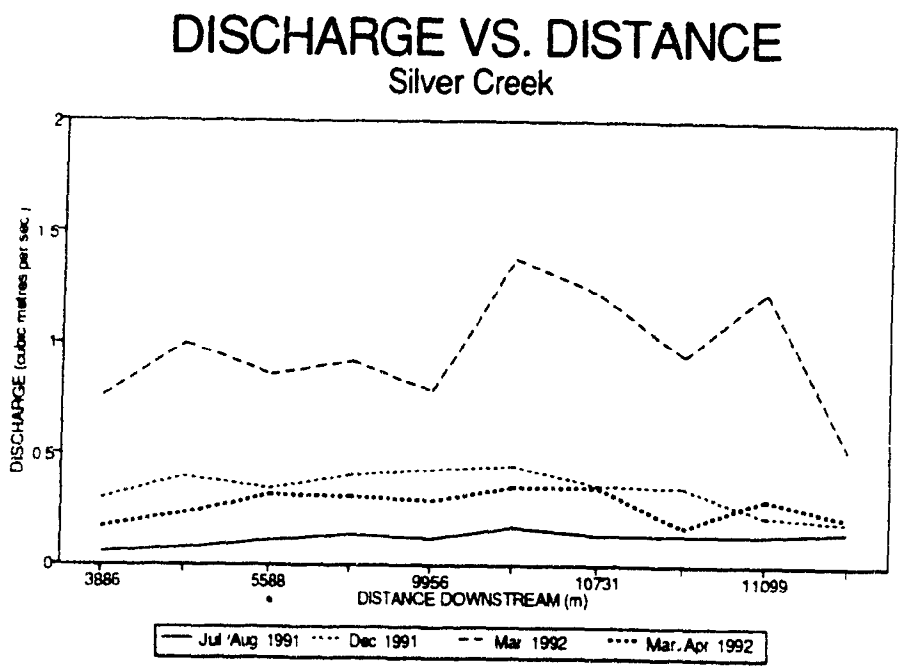


Fig. 5.6 Discharge versus distance downstream for Silver Creek data

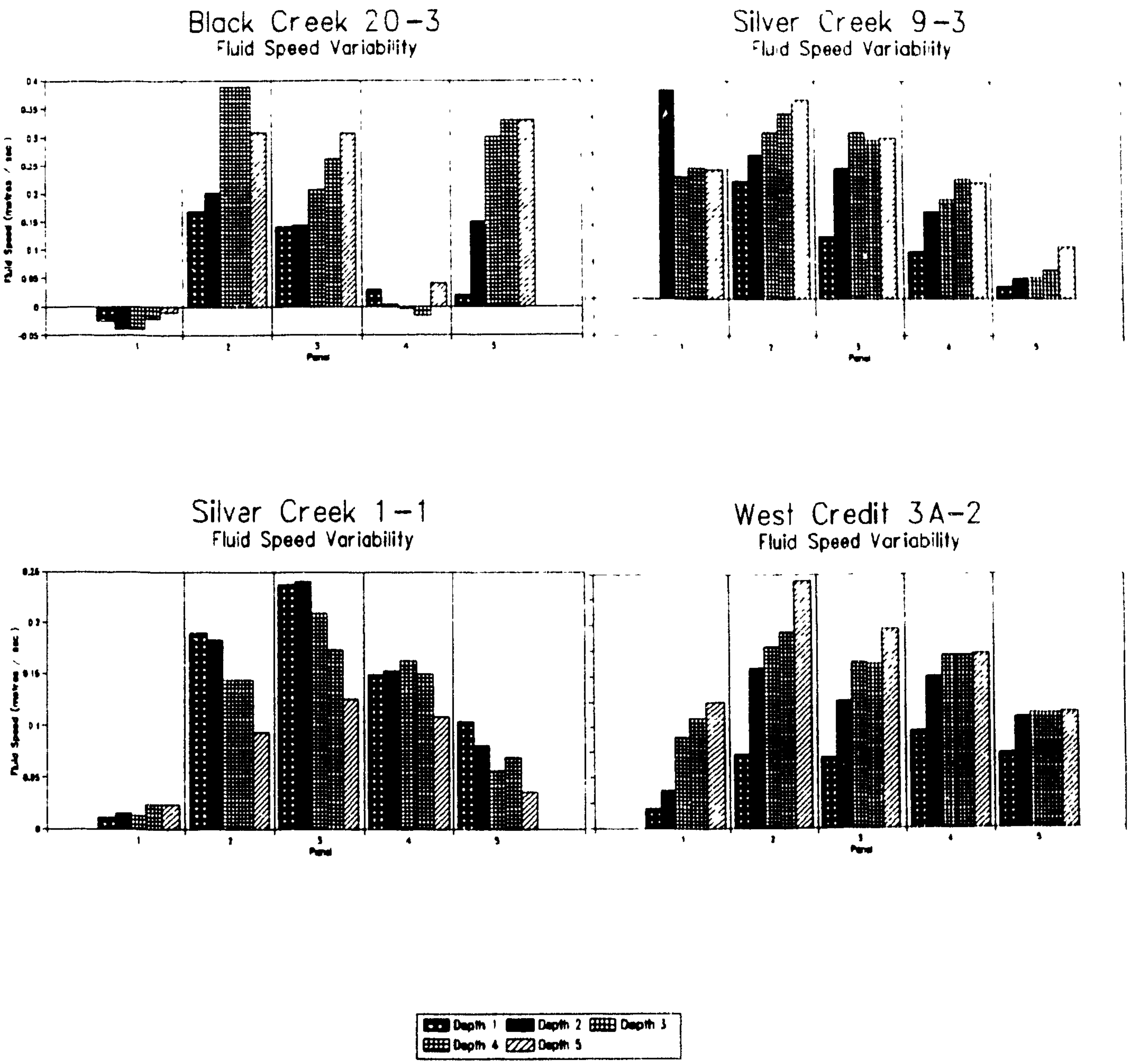


Fig. 5.7 Variation in fluid speed laterally and vertically through four selected cross-sections under different flow regimes.

From Fig. 5.7 it is apparent that fluid speeds do not always act according to theory. Black Creek 20-3 shows that there is a decrease in fluid speed at D(0.4) in panel 4. What is interesting in that particular cross-section is that fluid speeds at the D(0.4) plane are moving very fast in panels 3 and 5. In this particular instance the diversion of flow at panel 4 is caused by an obstruction in the stream immediately upstream of the cross-section. Another obstruction at the bank is causing the reverse flows seen in panel 1.

Another flow anomaly is seen in the Silver Creek 9-3 chart. Panel 1 shows very little flow at the bed (depth 1) yet at the next plane closest to the bed the highest flows in the cross-section are recorded. This is even more interesting when one considers that those flows are greater than the maximum flows at any other panel at all depths. Brooks (1985) and Saunderson (1992) have shown that in a meander of the Nottawasaga River points of maximum flow speed can be achieved at or near the bed in some instances.

Flow profiles for Silver Creek 1-1 and West Credit 3A-2 show more of the theoretical distribution of fluid speeds through a cross-section. The reduced flows at panel 1 in Silver Creek 1-1 are caused by an obstruction in the bank.

5.2 CONFLUENCE SURVEY

5.2.1 Introduction and methodology

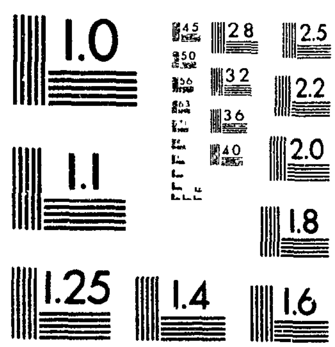
Field measurements of fluid speed have shown that there can be considerable variability over a short period of time. This may be important in studies of stability if during variable flow fluid speeds at the bed surpass the critical speed for particle entrainment. Because of this a study of the variability in fluid speed on the three sections of stream in the confluence area was undertaken.

Two electromagnetic current meters were set up to take concurrent fluid speed measurements at one minute intervals. Sites were selected on Black and Silver Creeks and the West Credit River which corresponded with hydraulic geometry survey locations. A fourth site was selected upstream on Silver Creek where flow was constricted by a side-channel gravel bar and where a change in bed elevation caused the flow to move quickly through the area (called Silver Chute). Silver Creek was chosen as the site which remained constant in all measurements because it could be correlated with the Silver Chute location.

The probe of the current meter was attached to a rod that had been driven into the bed. Depth was recorded at the probe site and the probe head was located at the theoretical point of maximum velocity. Several depth measurements as well as a width measurement were recorded.

2

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT



PRECISION℠ RESOLUTION TARGETS

5.2.2 Results

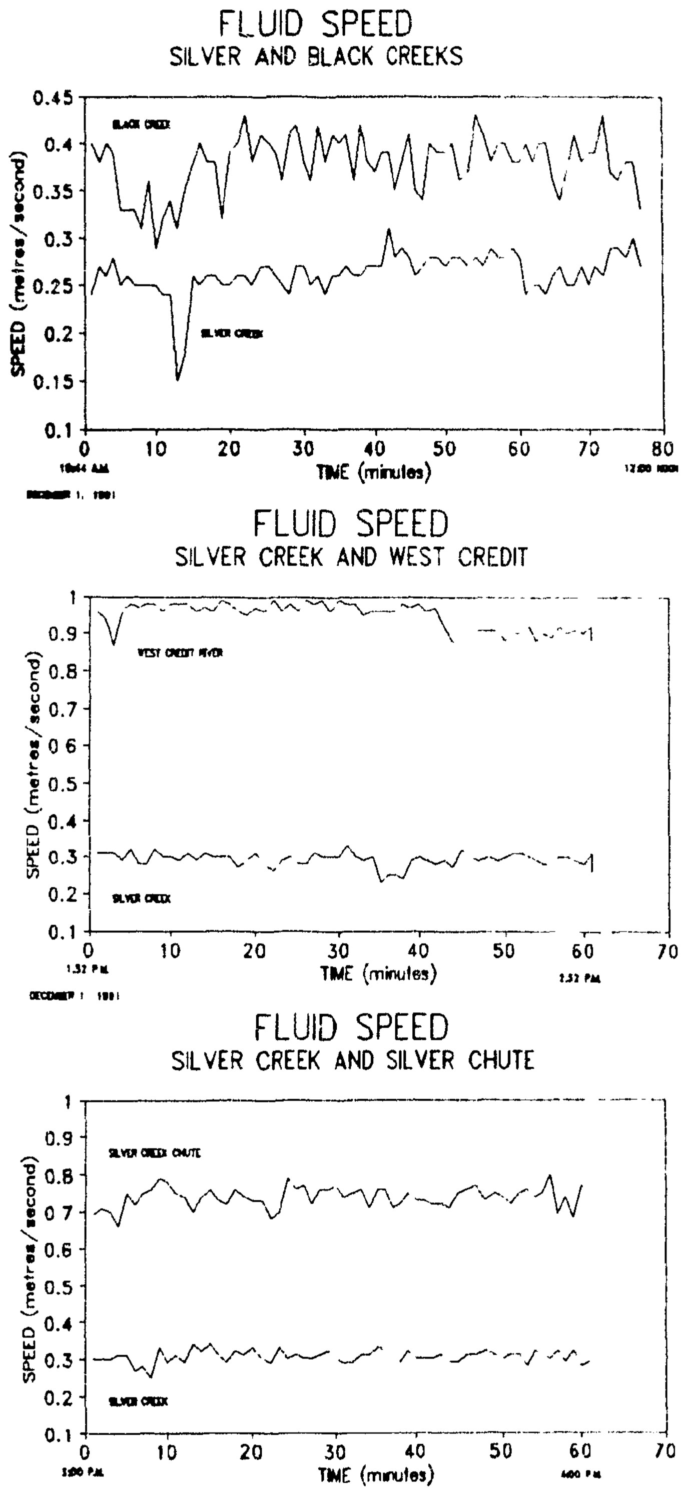


Fig. 5.8 Concurrent fluid speed measurements for Silver Creek, Black Creek, the West Credit River and the Silver Chute site.

Fig. 5.8 shows the concurrent fluid speed measurements for Black and Silver Creeks (A), for Silver Creek and the West Credit River (B), and for Silver Creek and the Silver Chute (C). Summary statistics are presented in Table 5.4.

Table 5.4 Summary statistics for the Confluence Survey. Silver Creek 1 refers to the concurrent survey with Black Creek, Silver Creek 2 with the West Credit River and Silver Creek 3 with the Silver Chute.

	Black Creek	West Credit	Silver Chute	Silver Ck. 1	Silver Ck. 2	Silver Ck. 3
Mean Speed ($m\ sec^{-1}$)	0.379	0.944	0.738	0.262	0.292	0.305
Stand. Dev'n.	0.030	0.038	0.029	0.022	0.019	0.016
Min.	0.29	0.87	0.66	0.15	0.23	0.25
Coeff. of Variation (%)	7.92	4.03	3.93	8.40	6.51	5.25
Max.	0.43	0.99	0.80	0.31	0.33	0.34
Number	77	64	61	77	64	61
Disch. ($m^3\ sec^{-1}$)	0.899	1.67	0.995	0.427	0.476	0.497

5.2.3 Interpretation of the Results

Note that there are periodic fluctuations in fluid speeds on Black Creek; they are not as pronounced on Silver Creek (Fig. 5.8 A). The periodicity could be caused by the higher fluid speeds on Black Creek, resulting in more turbulent fluid flow. It may also be caused by temporary storage and sudden release of fluid. This is a question for further research. There is a marked decrease in fluid speed on Silver Creek at 13 minutes. This is caused by a leaf coming in contact with the electrodes of the Marsh-McBirney current meter. Another observation is that at 58 minutes there is a definite drop in fluid speed on Silver Creek, and there appears to be a lag before speeds return to average. This is different than the fluctuations that are usually found on these creeks. The general slope of the line from 60 minutes onward is considerably steeper than the rest of the record, indicating a more rapid rise in fluid speeds. The cause of this is not known at this time, although changes in wind direction may have been a contributing factor.

Fig. 5.8 B shows fluid speeds taken concurrently on the West Credit River and Silver Creek. Of note is that at 40 minutes on the West Credit there is a definite drop in speed, yet unlike the dip on Silver Creek mentioned above, speeds do not appear to return to average. These subtle changes in flow dynamics can have implications on the morphology of the channel, either by changing local conditions for suspended sediment transport or by increasing boundary shear stresses necessary for the transport of bed material. Also of note is a dip at 4 minutes on the West Credit, caused by a leaf obstructing the electrodes of the current meter. The West Credit, along with having the highest mean fluid speed, also has the greatest variability about the mean, as shown by the higher standard deviation (Table 5.4). Discharges are also higher on the West Credit.

Fig. 5.8 C shows fluid speeds taken concurrently on Silver Creek above the confluence and at the Chute site. There is higher variability in the flow at the Chute site; this is anticipated with faster fluid speeds flowing over a rough boundary. Interesting to note is the decrease in variability in fluid speeds at the Silver Creek site as time goes on. Table 5.4 shows that the standard deviation is decreasing, yet mean fluid speed is increasing over the same time period. It was expected that as speeds increased so did variability, yet this does not seem to be the case in this instance. Another interesting item of note is that the periodicity of flow at the Silver Creek Chute site is less regular than at the Black Creek site.

5.3 FLUID RESPONSE TO INPUT FROM PRECIPITATION

5.3.1 Introduction and Methodology

The manner in which creeks respond to inputs from precipitation will have a direct impact on the stability of the channel. If a high-energy, short-duration rainstorm were to pass through a basin, the creeks may respond with a rapid rate of change of discharge (usually associated with urban areas or under extremely wet or dry conditions) or may respond with a lower rate of change of discharge (usually under conditions of high infiltration capacity of the soil). A rapid rate of change will more likely result in greater instability by nature of the forces involved on the bed, banks and in the fluid. Because the study creeks have some urban surroundings, this response rate was studied.

Secondary data was provided by the Water Survey of Canada in Guelph, Ontario (hourly discharge data for the West Credit River at Norval and Black Creek below Acton) and the Atmospheric Environment Service in Toronto, Ontario (precipitation data twice daily for the Georgetown Water Treatment Plant). The West Credit River at Norval is approximately 200 metres upstream of site WC6 and Black Creek below Acton is approximately 240 metres downstream from site BC20. Hourly discharge and total precipitation were plotted against time for these two sites.

5.3.2 Results

Fig 5.9 shows the response of discharge to input from precipitation under three different conditions. Fig. 5.9 A shows response after a long period of hot dry weather (minimum 12 days without precipitation), Fig. 5.9 B shows response to input at a time when base flow had not been attained due to previous precipitation, and Fig. 5.9 C shows response to two separate events within a 24 hour period.

5.3.3 Interpretation of the Results

Fig. 5.9 shows a relatively fast response time for the creeks under all conditions. Normally after a period of dry weather there is an initial flushing into the creeks followed by a period of infiltration of surface water into the soil. When that soil becomes saturated overland flow then directs precipitation into the creeks at a faster rate. Fig. 5.9 (A) may be showing such a response. The double peak in discharge after one rain event lasting a few hours in duration suggests that there was some process (?infiltration) that prevented the creek from continuing to rise.

Table 5.5 Rate of change of discharge for the periods between rainfall and peak flow and between peak flow and end of period under three different precipitation conditions.

Period of Precipitation	Station	Rate of Change to Peak ($m^3 sec^{-1} hr^{-1}$)	Falling Rate of Change ($m^3 sec^{-1} hr^{-1}$)
July 29 0100-	West Credit	0.411	0.023
Aug 3 0000	Black Creek	0.137	0.009
Aug 3 0100-	West Credit	1.748	0.099
Aug 6 0000	Black Creek	0.202	0.014
Nov 29 0100-	West Credit	0.216	0.091
Dec 3 0000	Black Creek	0.218	0.013
Same period	West Credit	0.192	0.024
Second Peak	Black Creek	0.036	0.004

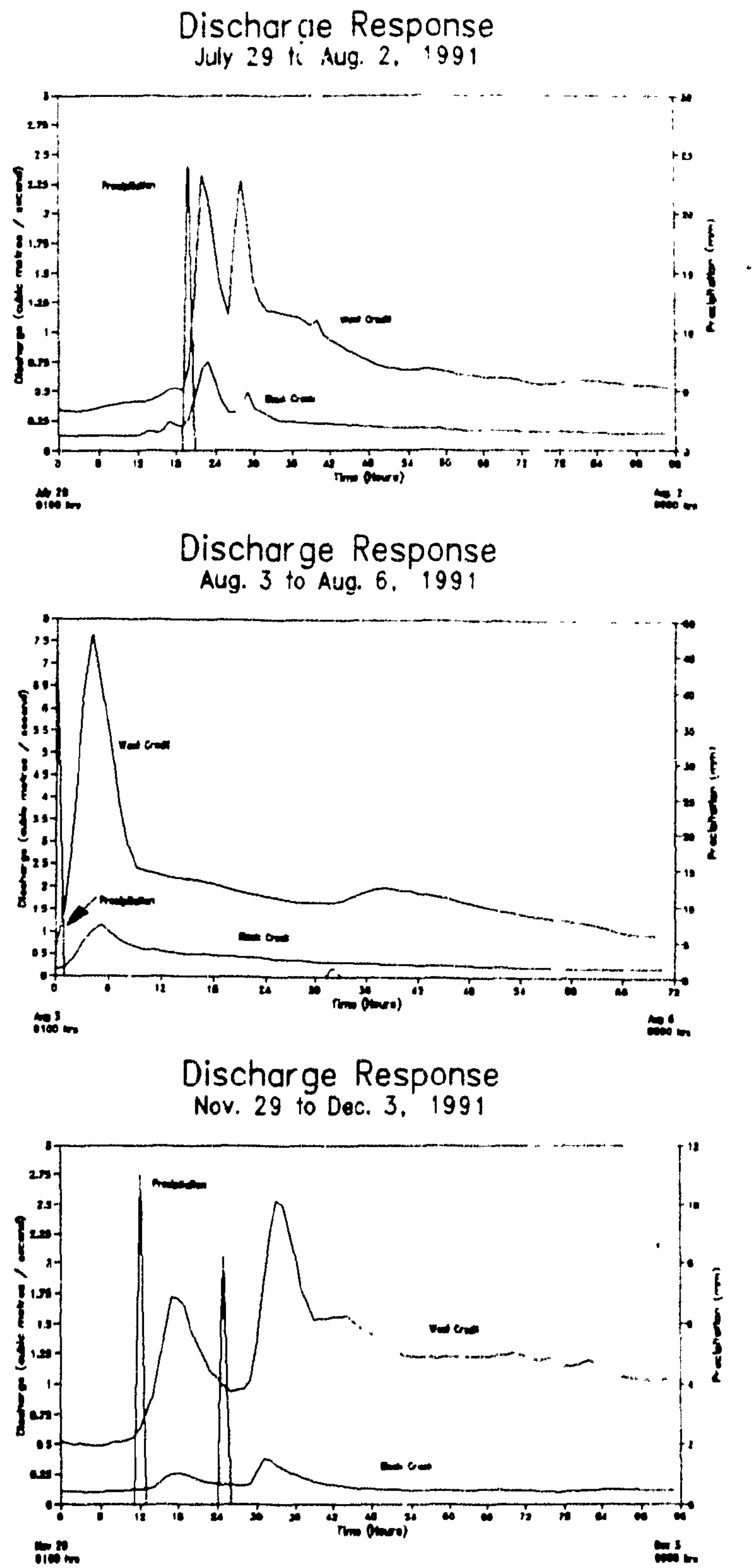


Fig. 5.9 Discharge response under dry (A), wet (B) and fall (C) precipitation conditions.

Fig. 5.9 (B) shows that a precipitation event which occurred before base levels were reattained resulted in a greater discharge response (in terms of volume of discharge and rate of increase of discharge). Although the amount of precipitation was greater than the previous event the amount of increase of discharge was large enough that it may have included some water from the previous event. Fig. 5.9 (C) reinforces this fact. A secondary precipitation event of smaller volume has resulted in a much greater increase in discharge than a previous event.

As much as the amount of change in discharge caused by precipitation is important, from both a geomorphological and biological perspective it is the rate of change (which is indicated by basin conditions) that is of greater importance. Geomorphologically, slow rates of increase in fluid speed (as associated with increases in discharge) have a lesser effect on bed instability than faster rates of change. In fact, a slow rate of change may selectively remove some of the finer particles on the bed, allowing the larger particles to flip or rotate in such a manner as to armour the bed, enhancing stability for a period of time. Faster rates of change could have the effect of removing the entire contents of the bed, replacing it with material from upstream. In fact, during one high-energy storm in the summer of 1991 a gravel bar at the site of WC3B was entirely removed and deposited downstream. This bar consisted of particles up to 8 cm. in intermediate diameter.

Biologically, the effect of faster rates of change on fish is dramatic. Current research at McMaster University in Hamilton is finding that increases in fluid speed of only 5 cm. sec^{-1} over a one hour period are sufficient to reduce yearling salmonids' capacity to swim against the current, resulting in either the fish being swept downstream or the fish dying from exhaustion (MacDonald, G. 1992, personal communication). Table 5.5 shows that rates of increase in discharge vary from 0.192 to 1.75 $m^3 sec^{-1} hr^{-1}$ on the West Credit and from 0.036 to 0.202 $m^3 sec^{-1} hr^{-1}$ on Black Creek. This of course does not mean that fluid speeds increased at that rate, because certainly depth (and possibly width) increases with input from precipitation. Barring that, it could be safely assumed that increases of 5 cm. sec^{-1} occur during these three examples on both creeks, which would result in certain changes to fish populations in these areas.

5.4 SUSPENDED SEDIMENT CONCENTRATIONS AND SUSPENDED LOAD

5.4.1 Introduction and Methodology

The concentration of suspended sediment has been shown to be very important in the health of fish habitats. Highly stable concentrations that are below critical levels for fish health are the optimal conditions that can be achieved. Unfortunately stable conditions are not attainable for any considerable period of time. Spring runoff conditions are responsible for up to 80% of the total suspended load carried by streams in Ontario (Walling, 1977). The greatest amount of the remainder is carried by increased flows from storm events the rest of the year.

Suspended sediment samples were collected at all cross-sections using a DH-

48 sampler with large bore nozzle. In instances where depth was too shallow or fluid speed too slow to allow for equal transit of the DH-48, a surface to bed grab sample was taken using DH-48 bottles and equal transit (Smith, B. D. 1991, personal communication).

The location of these samples was determined as either 1) mid-channel, where the channel was of approximate equal depth through the cross-section, or 2) at the talweg when the channel cross-section depth was varied. Once obtained the bottle was capped with parafilm (to reduce spilling or evaporative loss), transported back to the lab and analyzed.

In the lab the sediment/water mixtures were weighed, then vacuum filtered through pre-weighed and oven dried Whatman filter paper. The filter containing the water/sediment mixture was oven dried for 24 hours at 100° Celsius (to burn off any organic matter), and then filter and sediment were re-weighed. Subtraction of the initial filter weight left the weight of sediment in grams. This value was converted to give the weight of sediment in milligrams per litre of water.

5.4.2 Results

The results of 102 suspended sediment sample collections under three different flow regimes are contained in Tables 5.1 to 5.3. There were no collections for the spring melt-high flows because conditions were unsafe on the creeks for accurate sample collection. Figure 5.10 shows the relationship between discharge and suspended load under all sample conditions. Sediment load for each site is determined for the 24 hour period during which the sample was collected (assuming no change in suspended sediment over that period).

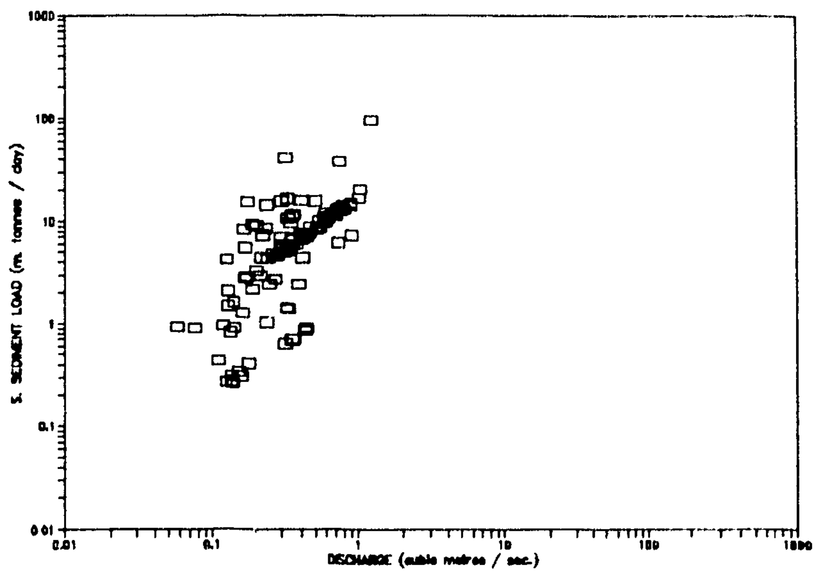


Fig. 5.10 Suspended load versus discharge under all sampling conditions.

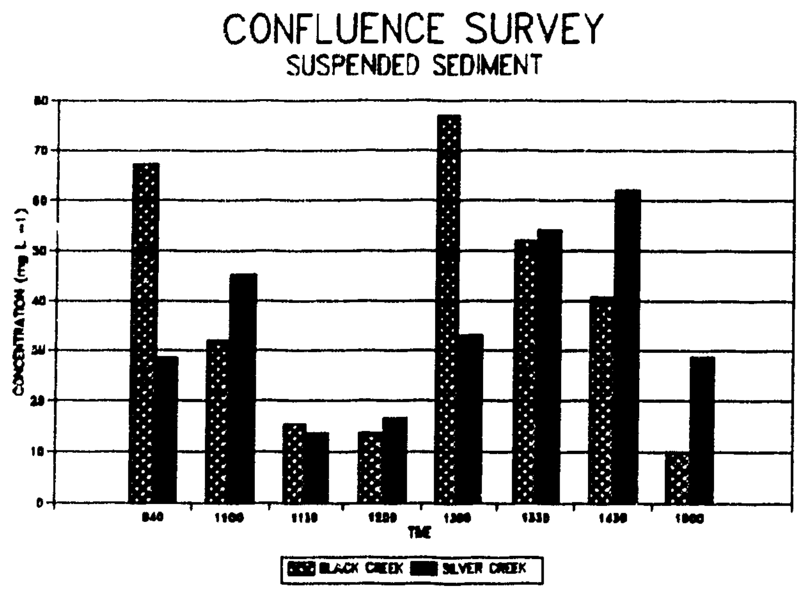


Fig. 5.11 Variation in suspended sediment concentrations between Black and Silver Creeks under simultaneous sampling conditions. Both distributions are periodic but out-of-phase.

Visual observations of differences in turbidity suggest suspended sediment concentrations may be different between Black and Silver Creeks. This has led to a further experiment which examines the variability of suspended sediment concentrations over a short time period. During fluid studies of the confluence area, suspended sediment samples were taken concurrently on both Black and Silver Creeks to determine if there was any actual difference in the concentrations of suspended sediment transported. Figure 5.11 shows the simultaneous concentrations in suspended sediment over a four hour period. Concentrations from this study (Dec. 1, 1991) and a further study conducted April 15, 1992 are presented in Table 5.6.

5.4.3 Interpretation of the Results

Fig. 5.10 shows a general increasing trend of suspended sediment load with increasing discharge, but the relationship is not a definite one. Departures from the straight-line relationship are likely caused by changes in sediment availability. Very low increases in discharge may result in high suspended sediment load if there has not been any flushing of suspendable sediment from the system in a considerable period of time. Conversely, high discharges associated with low suspended load are likely the result of a recent removal of the suspendable sediment from the area.

Concentrations of suspended sediment vary considerably between the sampling stations for every flow regime (Table 5.1). Considering the effects of various concentrations of suspended sediment on salmonids (Table 3.2), concentrations found in these creeks are sufficient to have harmful effects even at the summer base flow level. What is probably most important in terms of this study are the durations of exposure, because little can be done about the actual concentrations considering the material transported as suspended sediment has its origin in the channel or on the surrounding flood plain. Urban construction practices will increase the suspended load near creeks (sampling of a drainage culvert from a construction site on the West Credit River showed concentrations of 167 mg L^{-1} flowing directly into the river during a misty autumn rain), but apart from the construction of sediment traps there appears to be little that can be done. Higher concentrations in these creeks generally do not last for a period greater than 2 weeks (504 hours), with the exception of spring periods when there is considerable precipitation and melting snow over a long period of time.

Table 5.6: Variation in suspended sediment concentrations during two confluence surveys.

Date	Creek	Time	Suspended Sediment (mg L^{-1})
Dec. 1, 1991	Black Silver	0940	67.14 28.62
	Black Silver	1100	32.15 45.22
	Black Silver	1130	15.43 13.65
	Black Silver	1200	13.66 16.73
	Black Silver	1300	76.88 33.14
	Black Silver	1330	51.92 54.12
	Black Silver	1430	40.71 61.95
	Black Silver	1500	9.80 28.93
Apr. 15, 1992	Black Silver	1000	39.1 59.2
	Black Silver	1200	20.1 43.4
	Black Silver	1400	21.7 19.2

It is clear from the results in variation of suspended sediment concentrations that the time of sampling could determine the concentration value obtained. Fig. 5.11 shows that sampling during different times of the day could result in either an overestimation or underestimation of the actual suspended sediment concentration. This should be an important consideration when sampling creeks for their suspended sediment concentrations.

5.5 OVER-WINTER STORAGE OF SEDIMENT IN ICE

5.5.1 Introduction and Methodology

Field investigations from this study have shown that under ice-up conditions there is a considerable amount of sediment which can be trapped in the ice. This sediment appears to have three sources: that which has settled out during low flow periods and has become trapped in crevasses, that which is picked up when the ice comes in contact with the bed, and that which is introduced by bank slumping. All of this material becomes available for transport when the ice melts.

To determine the amount of sediment that is stored in the ice it was necessary to collect ice samples from different areas. These chunks of ice were measured to determine their volume and then placed in sealed containers for transport back to the lab. In the lab the ice was allowed to melt and the excess water was drained off. The filtered sediment sample was oven-dried at 100 °C for 24 hours and the sediment was weighed. The result is a mass of sediment per unit volume ice.

Areas where the ice was in contact with the bed required that a piece of ice be pried from the bed and measured as to areal extent. Sediment was scraped off the bottom and stored for transport. In areas where bank slumping occurred, an area of 10x10 centimetres was marked off and all sediment that was contained in that area was collected and transported to the lab.

5.5.2 Results

Table 5.7 Results of sampling for sediment content trapped in channel ice

Sample Number	Size/Volume of Ice Sample (cm^2)or(cm^3)	Weight of Sediment (g)	Mass per cm^2 or cm^3 Ice (g)
1	100 cm^2	495.7	4.96
2	686.4 cm^3	2.1	0.0031
3	348.1 cm^3	2.3	0.007
4	206.98 cm^3	6.9	0.0332
5	504.2 cm^3	8.5	0.0168
6	12230.4 cm^3	67.9	0.0056
7	526.9 cm^2	458.7	0.8705

Note: Samples 1 and 7 are scrape samples, therefore ice size is in cm^2

5.5.3 Interpretation of the Results

One of a number of conditions must prevail before this sediment trapping can happen. One, there must be ice contact with the bed, in which sediment becomes frozen to the ice and is picked off the bed when that ice separates from the bed. Two, there must be a period of ice or snow melt which results in both flowing water over the surface of the ice and transport of sediment from the land surface onto the ice. Three, there must be some form of bank collapse either through the process of frost action or natural failure due to saturated conditions which provides sediment to the channel. Any one of these three factors, all of which have been observed in the field, must be present for the trapping and storage of sediment in ice.

There is one other possible cause for the trapping and storage of sediment in ice, the presence of anchor ice (ice that forms on the bottom of the channel before any other fluid freezes) being that possibility. Speculation regarding the formation of this ice states that particles of sand or silt at the bottom of the channel are colder than the surrounding fluid, and as fluid temperatures hover around $+1^{\circ}C$ the thin film of water that surrounds the particle freezes because of contact with that colder particle. When a large number of particles are found together (a natural occurrence in river beds) that frozen particle binds with other like particles to create a slushy form of ice at the bed. When water temperatures drop, that slush rises toward the surface and is transported downstream with the current until it lodges against an obstruction. It then remains as a continually growing clump, exposed to much colder air temperatures, and freezes with the initial sediment particles still intact. Considering the great number of particles available for this type of action, a large amount of sediment may be stored in ice.

That amount of sediment could be staggering. Consider a theoretical piece of ice from Silver Creek which is 1000 cm. long, 800 cm. wide and 10 cm. thick (for a volume of $8x10^6$ cm^3). Using the mean value for sediment trapped within one cm^3 of ice from Table 5.7 (0.01314 grams), and assuming that the density is constant over the entire ice chunk, this theoretically results in the storage of 105,120 grams of sediment in that chunk alone. Extrapolated over the entire creek that value would be astronomical (although this ice was not found over the entire creek at one time).

The implications for fish are obvious. Melting of sediment-rich ice in the spring during periods when there is a lot of sediment introduced into the channel through snowmelt and overland flow will result in high concentrations of suspended sediment, the effects of which have been already discussed. Noting that not only the concentration of suspended sediment but the duration of that concentration is important (Table 3.2), the contribution of sediment from ice into the channel becomes more hazardous to fish. Ice generally melts slowly in the spring, resulting in a continuous introduction of sediment into the channel which may last (with overnight re-freezing) for more than two weeks. All of this may result in extremely high concentrations of suspended sediment for an extended period of time in the spring.

CHAPTER 6

RESULTS OF BED STABILITY INVESTIGATIONS

6.1 BED MATERIAL PARTICLE SIZE DISTRIBUTION

6.1.1 Introduction and Methodology

The importance of particle size distributions on the bed of channels is very important from a fish habitat perspective. If a fish is to use an area of the bed for spawning, that bed must have a specific and particular particle size distribution (Table 3.1). Feeding habitat requires a different type of bed, consisting predominantly of larger particles that serve to provide shelter and to physically subdivide the habitat.

In order to determine what sections of the study creeks were suitable for which fish activity, bed material samples were collected to determine particle size distributions. These were compared to each other by grouping them according to the physiographic location in the streams where the sample was taken and then compared to a particle size distribution curve from a known spawning area.

Bed material samples were collected for each hydraulic geometry sampling cross-section. If the bed appeared uniform, one sample was taken, if the bed showed varied characteristics more than one sample was taken. When extremely large particles were present on the bed, 5 were chosen from below the transect line and their long, intermediate and short axes were recorded. Bed material was collected using a scoop sampler, which was dragged along the bed in an upstream direction across the transect line. Once collected, whatever liquid was in the scoop was poured into a Nalgene bottle and marked "bed fines", as this liquid contained the finest particles that were thrown into suspension by the scooping action. The rest of the material from the scoop was put in a bag and sealed for transport to the laboratory. The scoop was then thoroughly cleaned so subsequent samples would not be contaminated.

In the laboratory the bed material/water mixture was allowed to dry. Once dry the sample was mechanically sieved with a Ro-tap sieve shaker. Sieve sizes started at -6 phi, decreasing by 1 phi intervals until the sand range, then decreasing by one-half phi intervals. The last pan represented material finer than +4 phi. Each sieve was weighed and the total weight recorded, and this weight was compared to the total weight of the sample prior to sieving.

6.1.2 Results

Bed material particle size distributions have been classified according to the particular stretch of the creeks from which they were obtained. Fig. 6.1 shows the curves for the sites that are within the confluence area. These have been grouped together because they share a common physiographic region which has unique fluid patterns that would not be found elsewhere. Fig. 6.2 shows the remainder of the West Credit River sites, including a sample from the bank at WC6 for comparative purposes.

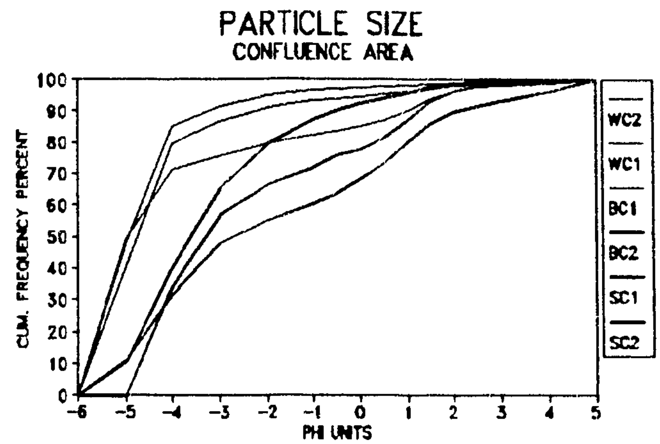


Fig. 6.1 Bed material particle size curves for sites in the confluence area.

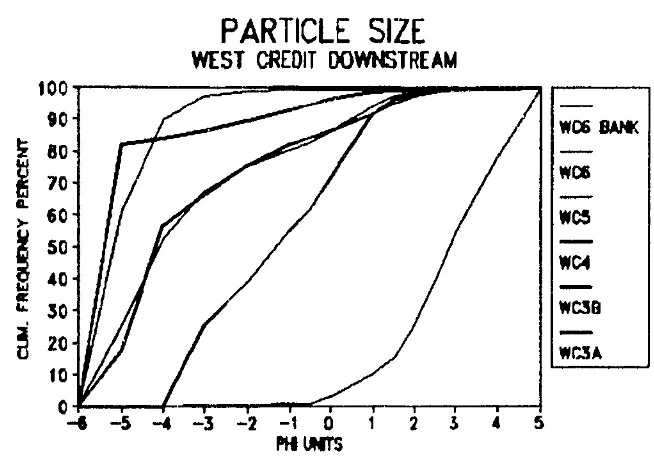
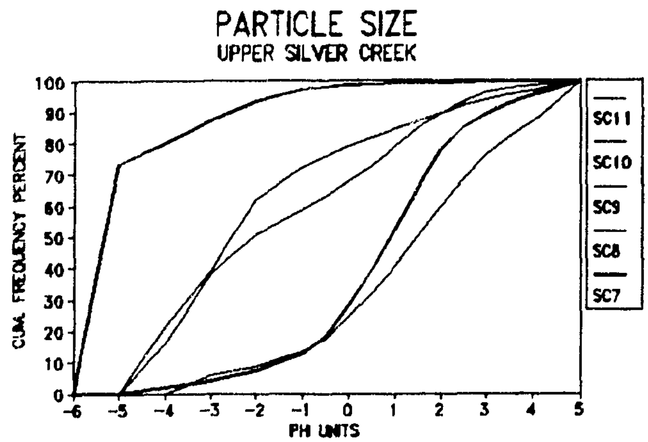


Fig. 6.2 Bed material particle size curves for the West Credit River sites.



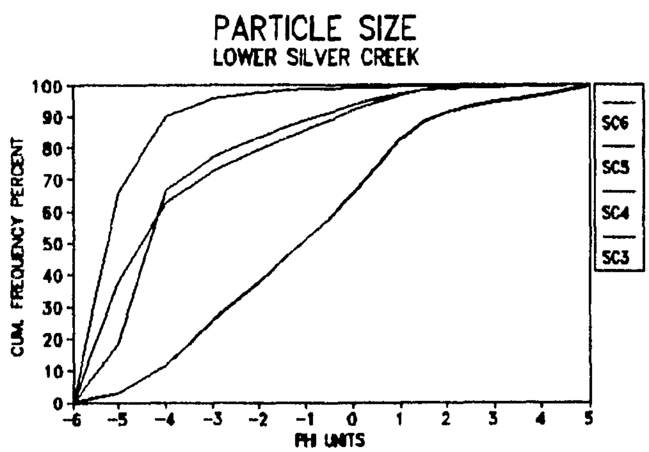
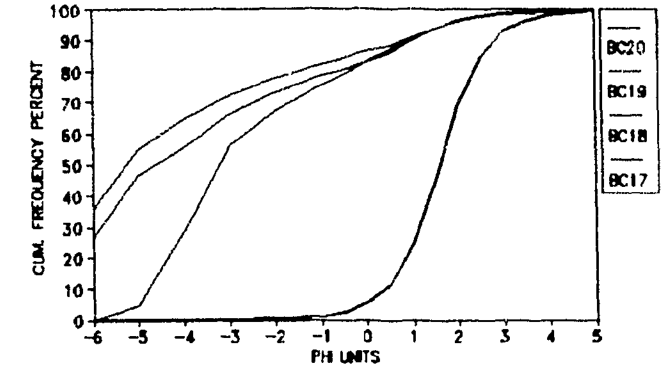
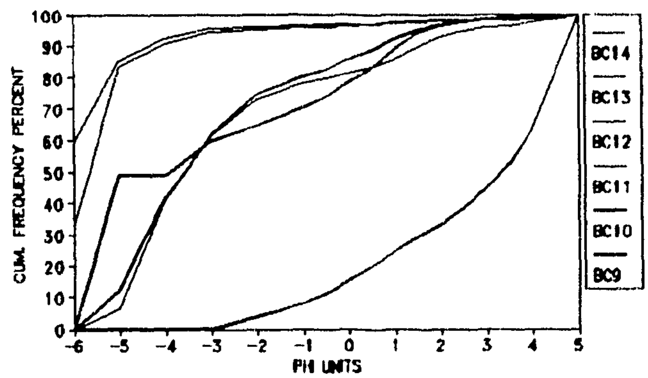


Fig. 6.3 Bed material particle size curves for Silver Creek sites.

PARTICLE SIZE
UPPER BLACK CREEK



PARTICLE SIZE
MIDDLE BLACK CREEK



PARTICLE SIZE
LOWER BLACK CREEK

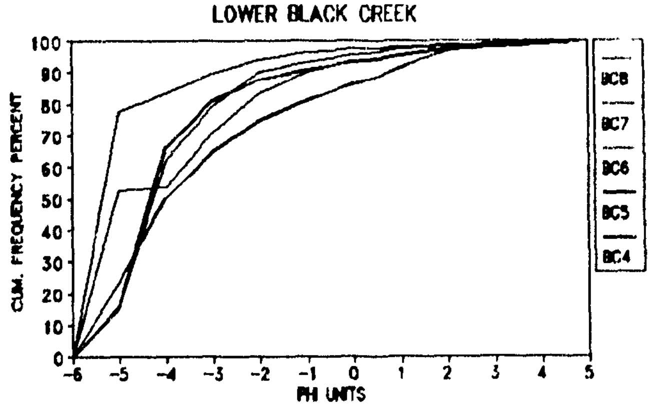


Fig. 6.4 Bed material particle size curves for Black Creek sites.

Fig. 6.3 shows the bed material particle size distributions for the Silver Creek sites. These have been separated into upper and lower sites, as field evidence showed a difference in the material on the bed as distance from the source increased. Fig. 6.4 shows the same information for Black Creek. These have been divided into upper, middle and lower sites for similar reasons to Silver Creek, the difference between middle and lower sites on Black Creek being the presence of the Stewarttown Dam just upstream of BC7. This appears as a natural break to flow and may have an influence on the presence or absence of particular bed material.

There are differences in the distribution of particular bed material within cross-sections. The presence of large obstructions, which act as flow deflectors, may cause a change in the bed material to the point that the bed becomes suitable for fish use. Fig. 6.5 shows one such instance.

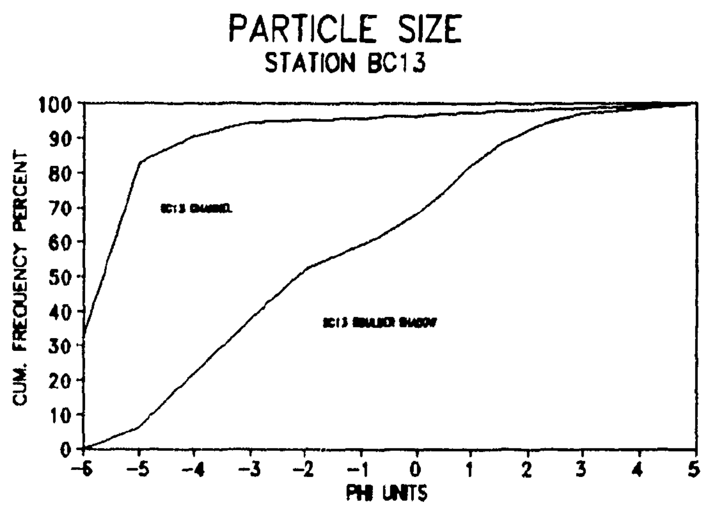


Fig. 6.5 Changes in bed material particle size distribution caused by the presence of a large obstruction in the channel.

Differences in bed material have other root causes. In an area where there is considerable undercutting of the bank, particle size distributions are quite different at the undercut from the rest of the channel. This is seen in Fig. 6.6.

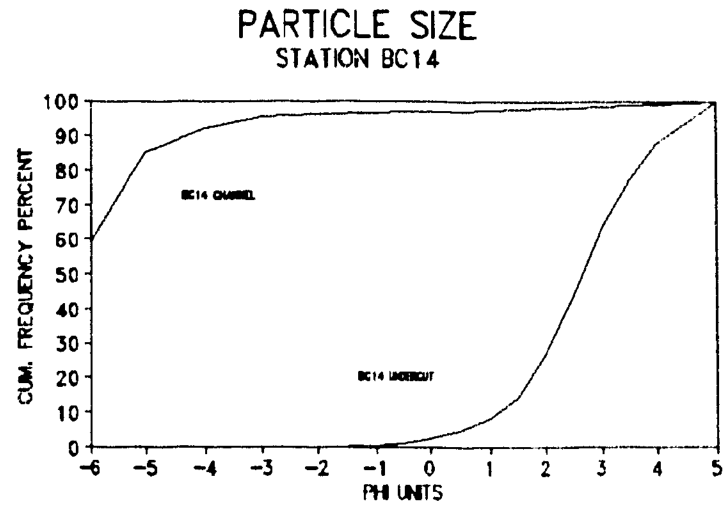


Fig. 6.6 Difference in bed material particle size distribution between a mid-channel sample and from under a bank undercut.

6.1.3 Interpretation of the Results

The bed material particle size distributions show fair relationship to one another when grouped into similar physiographic areas in most instances, yet there are cases where the distributions both match very well or differ greatly within the same region. An example where this differing occurs is BC9 in Middle Black Creek region. Bed material is finer in this reach than the rest, the reason for this being that the site is located in a large pool area, where fluid speeds decrease rapidly and there is subsequent settling of finer material onto the bed.

Some sites that are close together show similar particle size distributions. In upper Silver Creek, sites SC7 and SC10 mirror each other closely, yet on the West Credit River, sites WC4 and WC5 show much different particle size distributions. Probably the best visual match occurs between BC7 and BC4 in the Lower Black Creek region, (sites which are more than 2000 metres apart), which is reinforced by the summary statistics (Table 6.1).

A bed sample from a known spawning area was collected and analyzed as to its particle size distribution for comparative purposes (Fig. 6.7). If comparison is made to the other curves, it becomes apparent that very few sites on the creeks match the distribution. Chapman (1988) reports that salmonids will spawn in a large range of particle sizes (2 to 256mm in diameter). The fact that other beds do not match this particular spawning area distribution may not be significant due to the wide range in suitable spawning particle size. However table 3.1 indicates that for the trout that may be present in this system there is a definite preference for gravel of a certain size. In fact, there was little evidence of spawning activity other than at the lower reaches of SC1, indicating that optimal spawning gravel may be more specific than is reported in some literature.

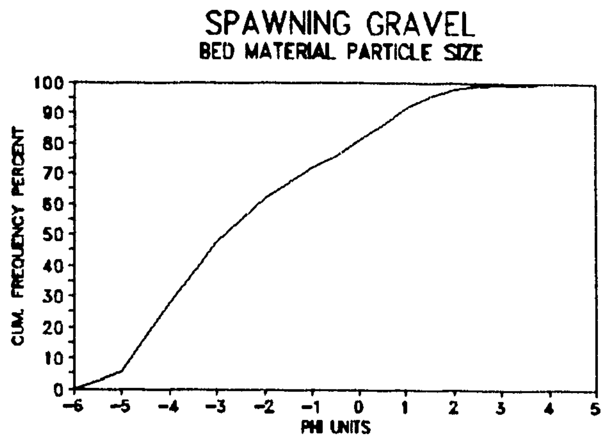


Fig. 6.7 Bed material particle size distribution of a sample of known spawning gravel from the West Credit River

Further statistical analysis of the bed material particle size distributions is presented (Table 6.1) for comparative purposes. Comparison with spawning gravel shows that only 6 sites share similar values for graphic mean (a measure used to determine the overall size of the sample). Of those six only one shows a similar match to inclusive graphic skewness (a measure which aids in the determination of the effect of the tails of the curve on the distribution), and that one sample does not match very well with the spawning gravel in inclusive graphic standard deviation (a measure of the degree of sorting of the material). That particular site (SC1) which most closely matches the spawning gravel is just upstream of a location where spawning did occur in the fall of 1991 (as evidenced by the visual observation of spawning redds).

SITE	Graphic Mean	Inclusive Graphic Skewness	Inclusive Graphic Standard Deviation
SPAWNING GRAVEL	-2.25	0.28	2.27
WC1	-3.67	0.75	2.54
WC2	-4.92	0.34	1.03
WC3A	-3.25	0.63	2.22
WC3B	-5.21	0.68	1.24
WC4	-1.50	0.05	1.63
WC5	-3.33	0.57	2.21
WC6	-5.08	0.07	0.56
WC6 BANK	2.87	0.02	1.34
BC1	-4.50	0.50	1.61
BC2	-2.37	0.50	2.35
BC4	-4.17	0.53	1.63
BC5	-3.25	0.48	2.45
BC6	-4.25	0.67	1.98
BC7	-4.17	0.50	1.47
BC8	-5.00	0.56	1.07
BC9	2.75	-0.56	2.01
BC10	-2.92	0.42	2.12
BC11	-3.08	0.47	2.72
BC12	-2.58	0.56	2.45
BC13	-5.67	0.35	0.77
BC13 BOULD SHADO	-1.75	0.17	2.45
BC14	-6.37	0.01	1.23
BC14 UNDERCUT	2.67	0.19	1.11
BC17	1.58	0.15	0.89
BC18	-3.58	0.42	3.01
BC19	-2.50	0.48	2.21
BC19 UPSTREAM BAR	-1.83	0.48	2.07
BC19 DSTREAM BAR	-1.08	0.03	2.41
BC20	-4.25	0.51	2.90
SC1	-3.25	0.43	1.82
SC2	-2.08	0.37	2.90
SC3	-1.25	-0.06	2.36
SC4	-3.83	0.62	1.62
SC5	-5.17	0.68	0.78
SC6	-3.92	0.50	2.07
SC7	0.83	-0.12	1.73
SC8	-4.83	0.63	1.23
SC9	-2.08	0.44	2.63
SC10	1.58	-0.07	2.32
SC11	-2.08	0.44	2.63

Table 6.1 Summary statistics for bed material samples

Other observations can be made from Table 6.1. A full 60% of the bed samples appear as very poorly sorted, and there are implications for fish habitat. Poorly sorted spawning beds indicate the possibility that material lies outside of the desired optimal spawning gravel. If this material is in the fines range, clogging of the redds is a likely result. If the material is in the boulder range, this would be disadvantageous for spawning but could be advantageous for resting, feeding and territorial habitat.

There is a considerable difference between the particle size distributions (both graphically and statistically) between BC13 and the BC13 boulder shadow (Fig 6.5) and between BC14 and the BC14 undercut (Fig. 6.6). The differences within the BC19 site and upstream and downstream gravel bar are the basis for the gravel bar packing experiment described in section 6.5.

6.2 BEDLOAD TRANSPORT SAMPLING

6.2.1 Introduction and Methodology

Bed stability is determined in part by the amount of bed load transport under differing conditions. Given the particle size distributions in these creeks, the amount of that material which is being transported by the flow along the bed is of great importance to fish habitat use. Movement of the bed at times when it is critical that the bed remain stable could have devastating results, for instance the movement of part of the bed under conditions that would be found after a high energy summer storm when that bed has just been used for spawning would likely result in the mortality of the spawn.

The amount of near-bed material being transported by the flow was determined using a Helley-Smith Sampler. This apparatus, which contains an opening of known size on one end and a catching bag on the other, was placed on the bed of the creek and allowed to remain there for a period of time not exceeding 2.5 hours (depending on the flow). If the flow was fast the sampler was left on the bottom for shorter periods of time than if the flow was slower. By returning the bags to the lab and extracting the material that was trapped, it was possible to determine the weight of material moved per unit time per unit width of channel. It was important to place the sampler at locations in the channel where it could rest entirely on the bed, for if there were an opening between the bottom of the sampler and the bed, material could pass through the sample area without being trapped.

In the laboratory the bag was allowed to dry and the contents carefully removed. Any large organics were removed by hand, and the remaining part of the sample was oven-dried over a 24 hour period at 100 °C to remove any smaller organic material. The sample was then weighed and the total weight per unit width per unit time was determined.

6.2.2 Results

Table 6.2 shows the results of nine bed material transport samples taken at varying dates at the confluence area. It was determined that the confluence was the best place to take the samples because all three systems could be sampled easily and the results compared against one another for analysis. Visual observation has shown that there is a marked difference in the transport rates across the cross-section (this is reinforced by the difference in fluid velocities across the channel at the bed as outlined in the previous chapter). As a result daily and annual transport rates are presented for one metre widths of the channel rather than being extrapolated for the entire channel width.

Table 6.2 Results of bedload transport sampling over three flow events

Date Location	Duration (hours)	Weight Sample (g)	Wt. per m. of bed (g)	Daily Amt. per m. of bed (g)	Annual Amt. per m. of bed (kg)
Dec. 1 '91					
SC1	2	4.56	60.79	729.59	266.304
BC1	2	3.48	46.39	556.79	203.231
WC1	2.5	11.02	146.93	1410.52	514.842
Ap. 6 '92					
SC1	1	2.05	27.33	655.99	239.459
BC1	1	2.14	28.53	684.79	249.952
WC1	1	49.52	660.26	15846.39	5783.935
Ap. 11 '92					
SC1	1	100.47	1339.59	32150.39	11734.895
BC1	1	86.0	1146.46	27519.99	10044.799
WC1	1	21.33	284.39	6825.59	2491.343

6.2.3 Interpretation of the Results

There are some interesting observations that can be made from the results. First is that, during the Dec. 1, 1991 sample, Silver Creek had a greater transport rate than did Black Creek. This is interesting because fluid speed measurements made at the time of sampling indicated a greater fluid speed at the location of the Black Creek sample. This difference, 66 kilograms over a year, is likely caused by the fact that Silver Creek may have more material in the transportable range than Black Creek does (that is there is more fine material in Silver Creek than Black Creek at the sampling sites).

Spring high flow transport rates were not significantly higher than the fall rates at the Black and Silver Creek levels, but the West Credit River sample is greater by more than an order of magnitude. Again, availability could be part of the reason, but included here of note is that the fluid speeds were significantly higher at the bed (35 cm. sec^{-1}) than on Black (14 cm. sec^{-1}) or Silver (12 cm. sec^{-1}) Creeks.

Spring rain sampling has provided a complete reversal from the spring high flow sample. The April 11, 1992 sample shows that greater transport occurs on Black and Silver Creeks, with the West Credit River falling far behind. Fluid speeds at the bed on Black Creek were 38 cm. sec^{-1} and on Silver Creek 65 cm. sec^{-1}, while on the West Credit River they were 58 cm. sec^{-1}. Fluid speeds indicate that there should be greater transport in the West Credit than on Black Creek. The fact that there is not could be the result of limited availability or that there is an obstruction on the bed somewhere upstream which could cause material to be stored or redirected away from the talweg.

6.3 TOPOGRAPHICAL CHANGE: CONTROL REACH SURVEYING

6.3.1 Introduction and Methodology

Given that there is a certain amount of near-bed transport within these creeks, it was necessary to determine at the reach scale what changes were occurring over a period of time. One method to determine change was to survey entire reaches and compare summer baseline to spring post-high flow surveys. This would give direct information regarding riffle-pool sequences as well as investigating whether movement is continuous or step-like. Painting selected particles and tying the particles in to the survey would help determine distance and direction of movement of particles of measured diameter. This information could then be compared to standard competency relationships in the literature.

Three reaches were chosen for an intensive survey of bed planimetry and topography. The reaches chosen (Silver Creeks 2-3 and 5-6, and the confluence area) were selected as they appeared to be either representative of the creeks as a whole (SC5-6), or because they displayed some unique features (SC2-3, confluence area).

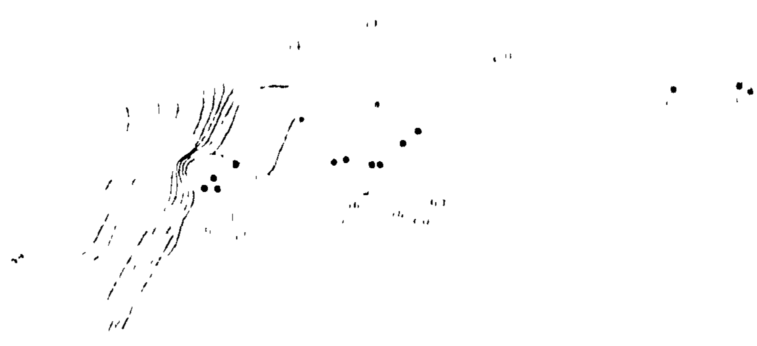
Initial surveying was completed in late August for base flow conditions according to standard procedures using a K&E Stadia and Transit. From a command position, outlines of the left and right water edges (to outline the creek form), the centre line of the creek (to outline riffle-pool sequencing), and a series (> 200) of random points along the creek were taken. Stadia locations were marked so that they could be re-occupied in the spring. Spring re-surveying results were compared to August maps to determine the amount of change in the creeks over the winter and peak flow periods.

During the initial survey numerous particles were marked with fluorescent paint, measured as to their long, intermediate and short axes, numbered and recorded. Paint was applied on the upstream edge of the particles, so that any rotation or flipping of the particle could be determined. These particles, which ranged from cobble to boulder size and from rounded to platy shape, were located in the creek (on the bottom or on mid-channel bars) or at the sides of the creek (on side channel bars or on banks). Where possible, measurements of the particle were taken without disturbing the resting position of the particle. This was done to ensure that the critical factors of orientation, packing and imbrication were not altered, so that any movement of the particle would be entirely caused by the flow.

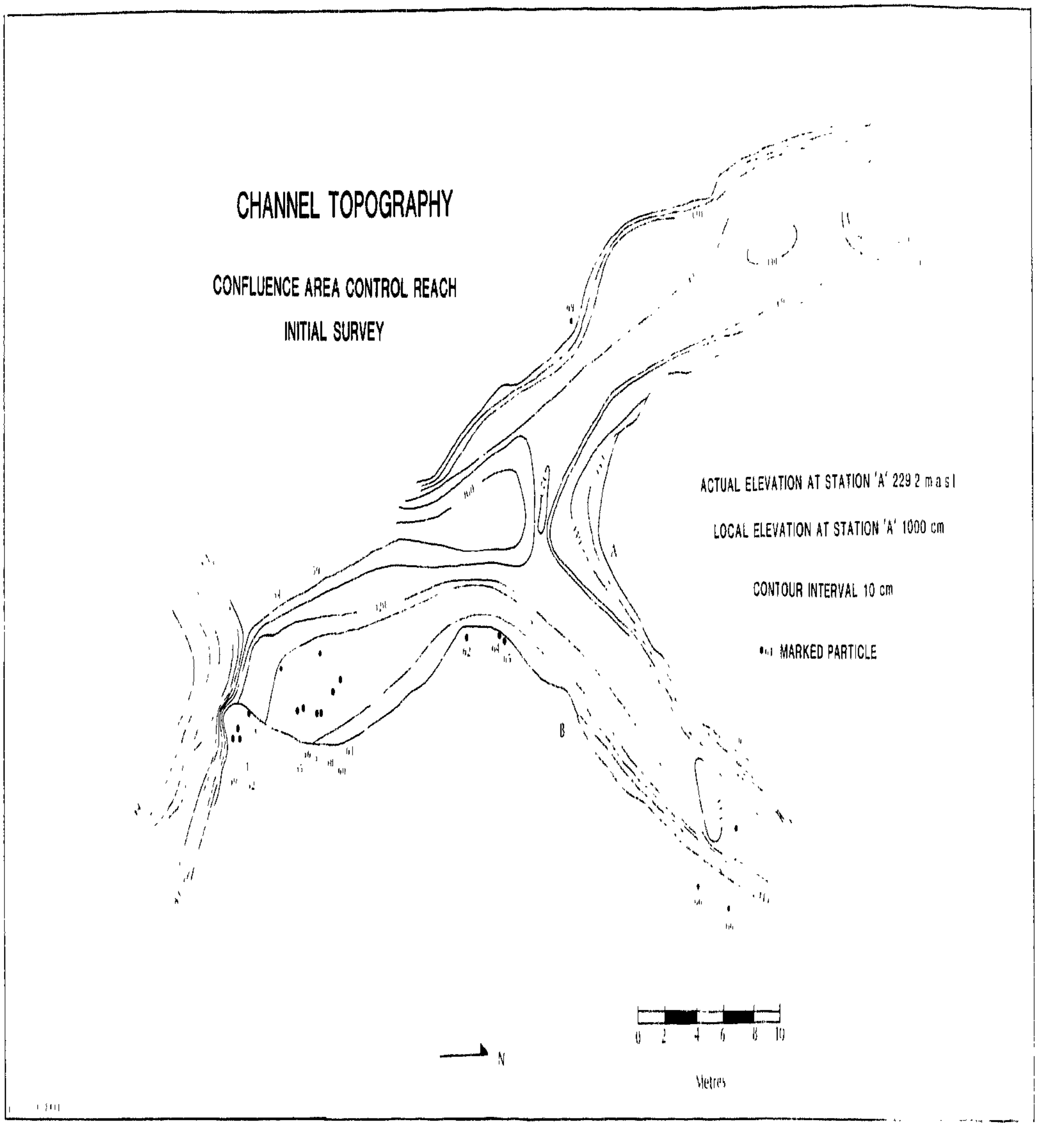
Sixty-four particles were marked over the three reaches, with a minimum of 20 particles for any particular reach. The spring survey attempted to locate as many of these particles as possible and tie them into the survey to determine amount of movement.

CHANNEL TOPOGRAPHY

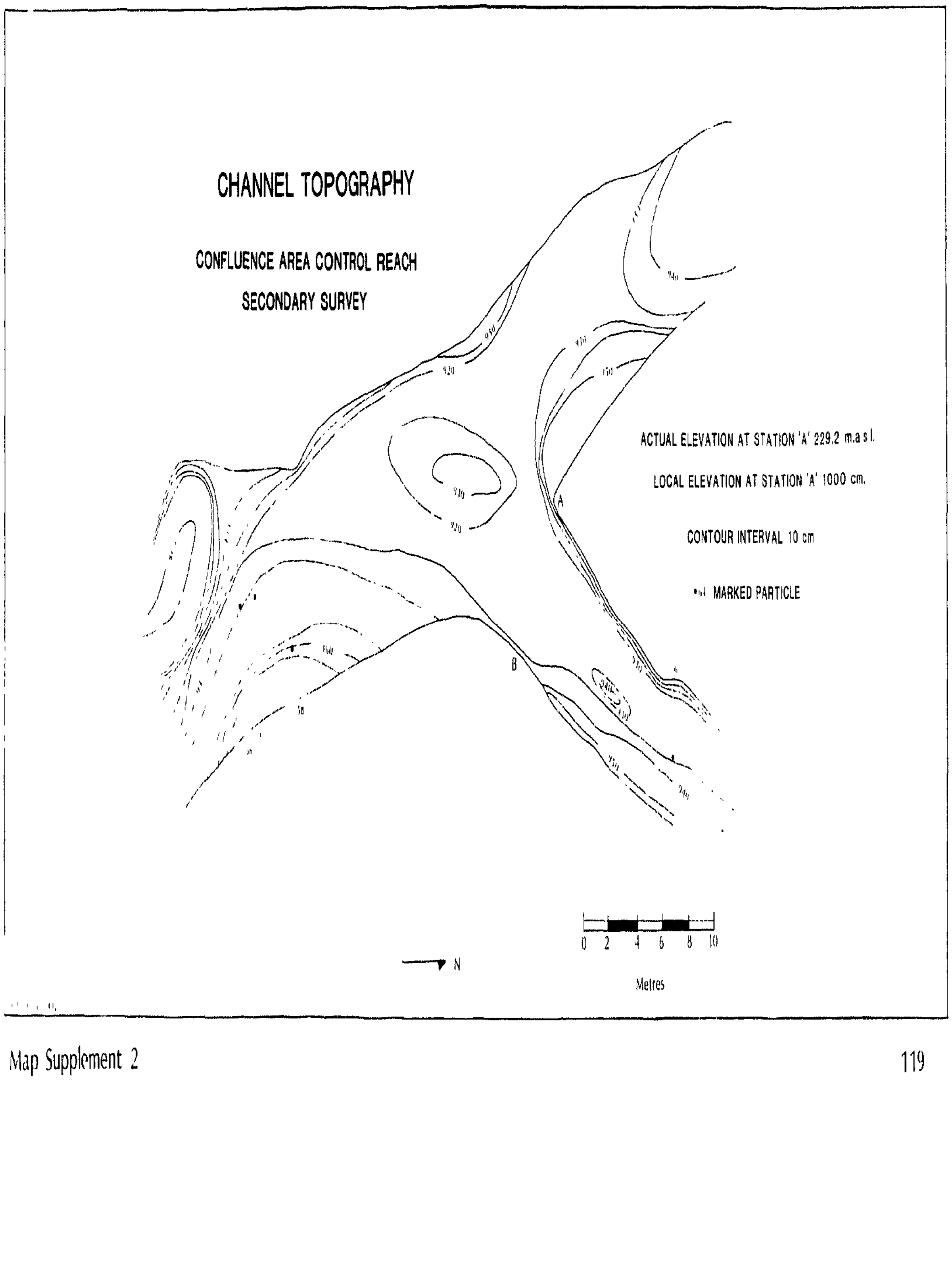
CONFLUENCE AREA CONTROL REACH
INITIAL SURVEY

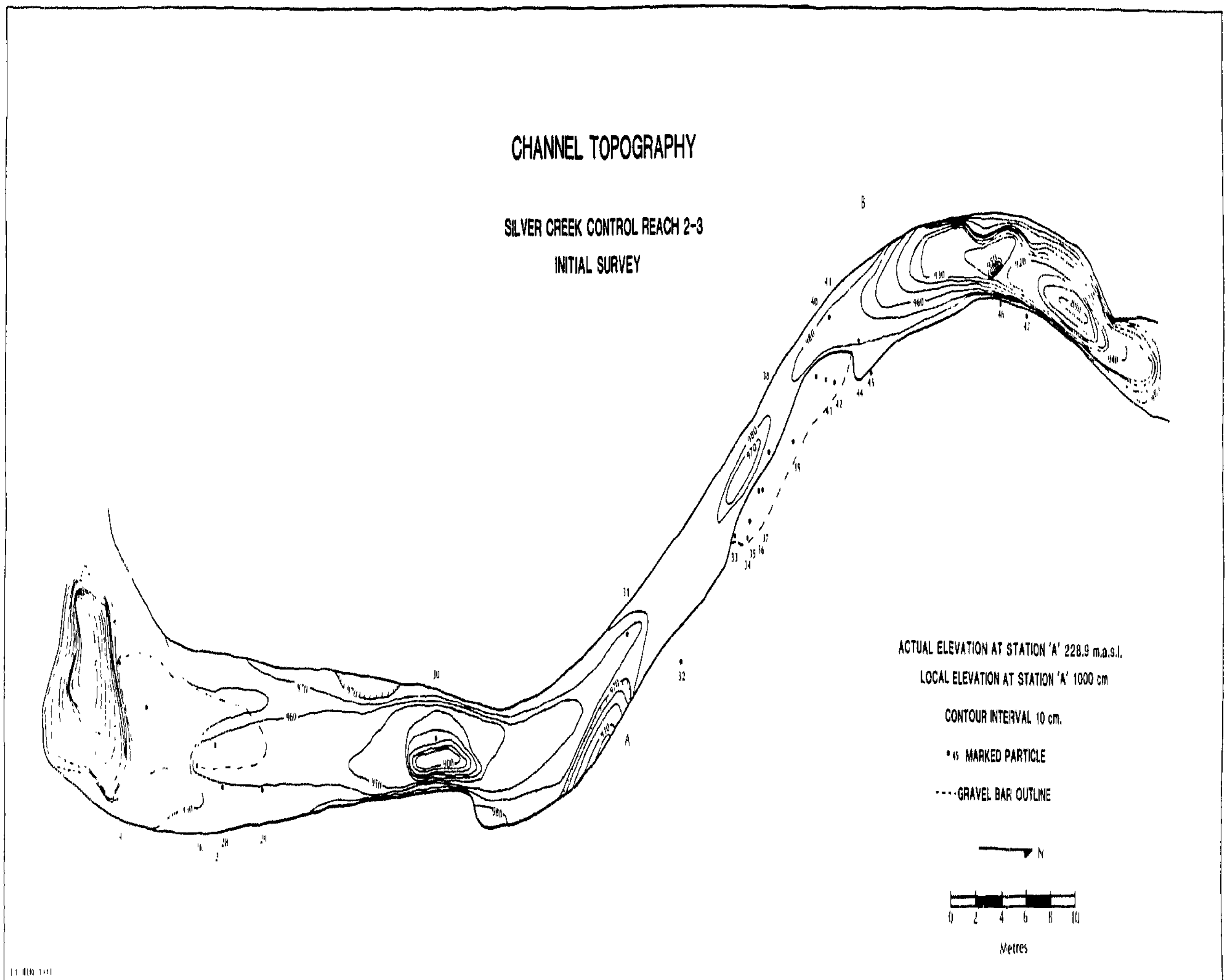


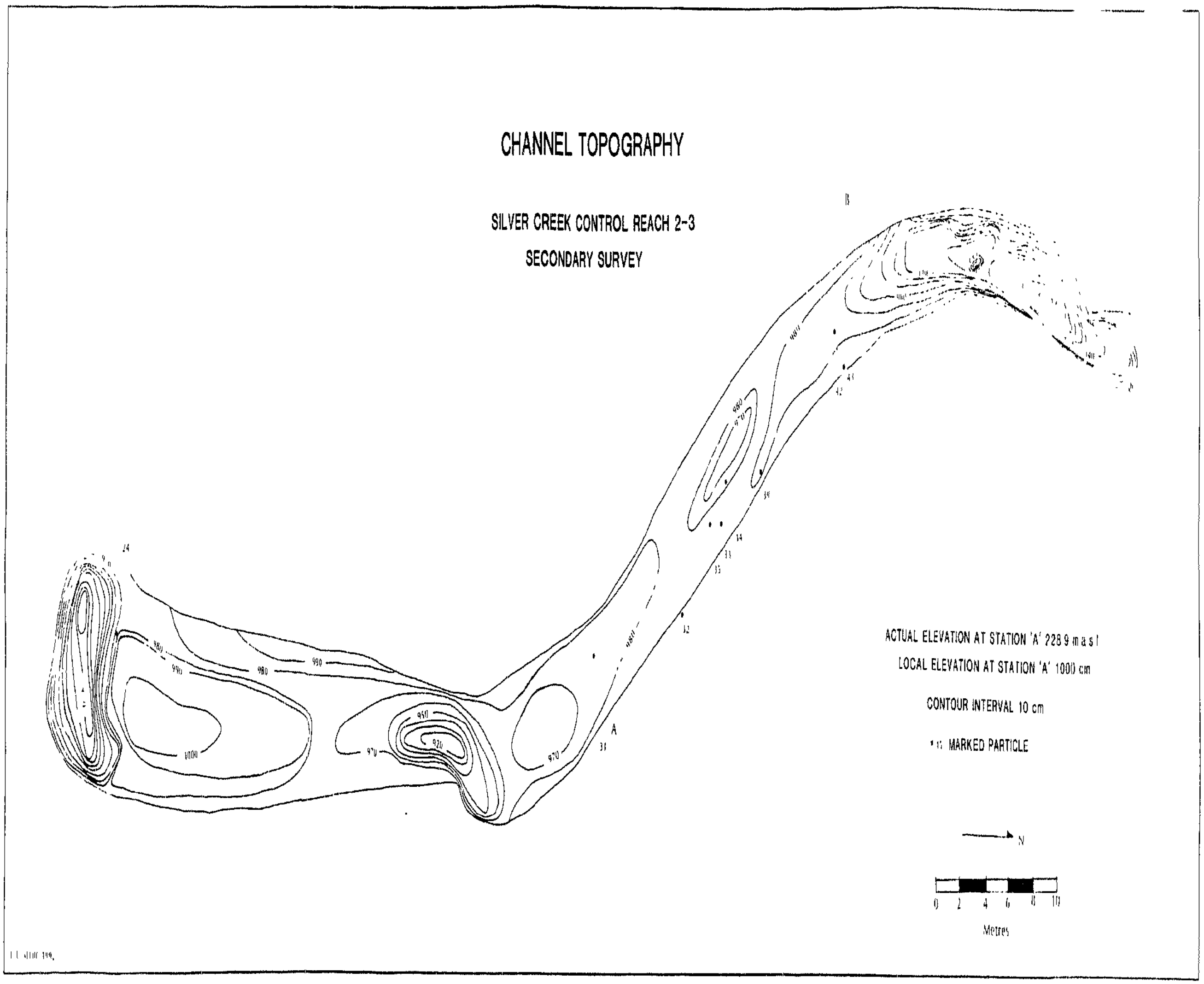
Map Supplement 1

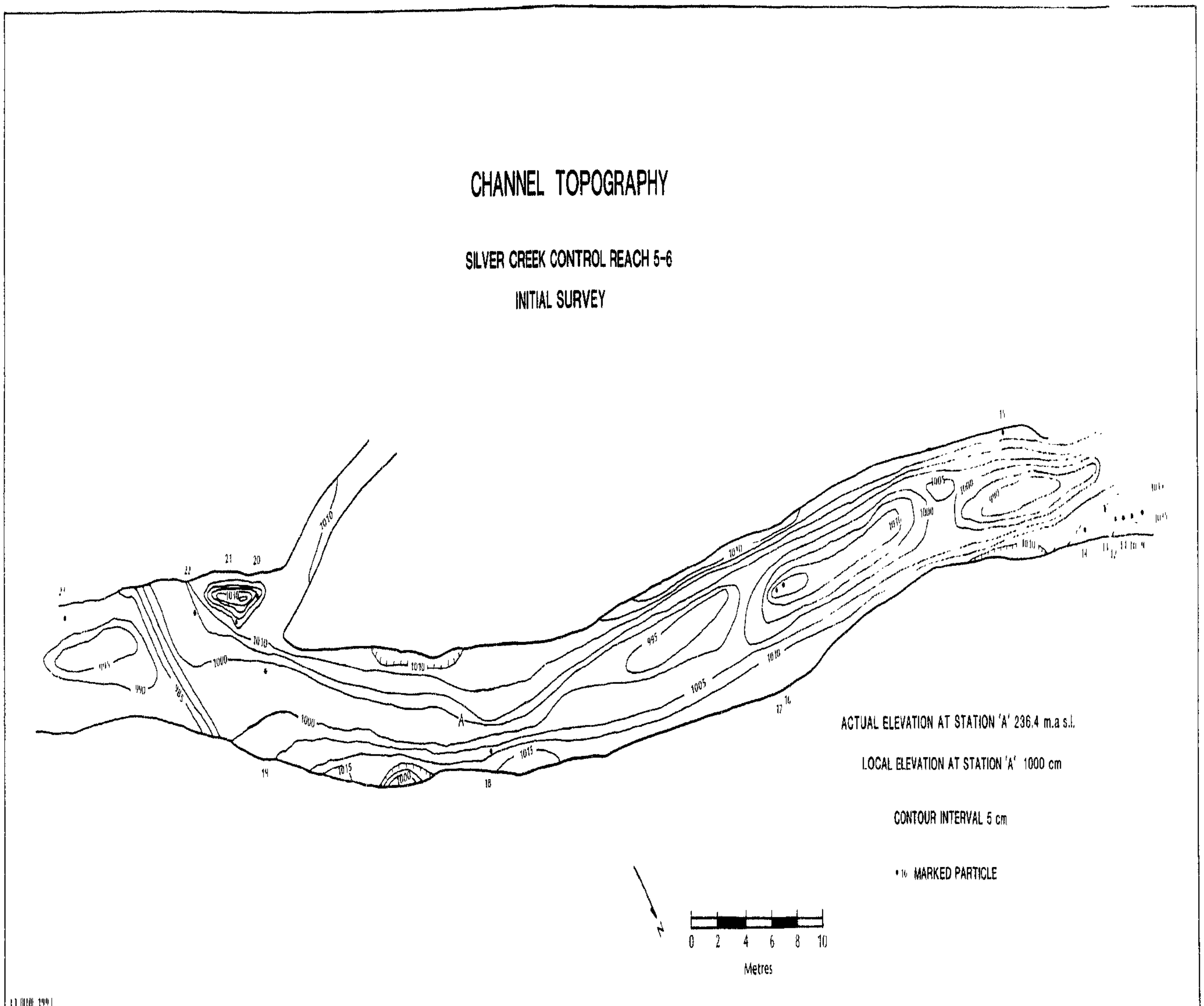


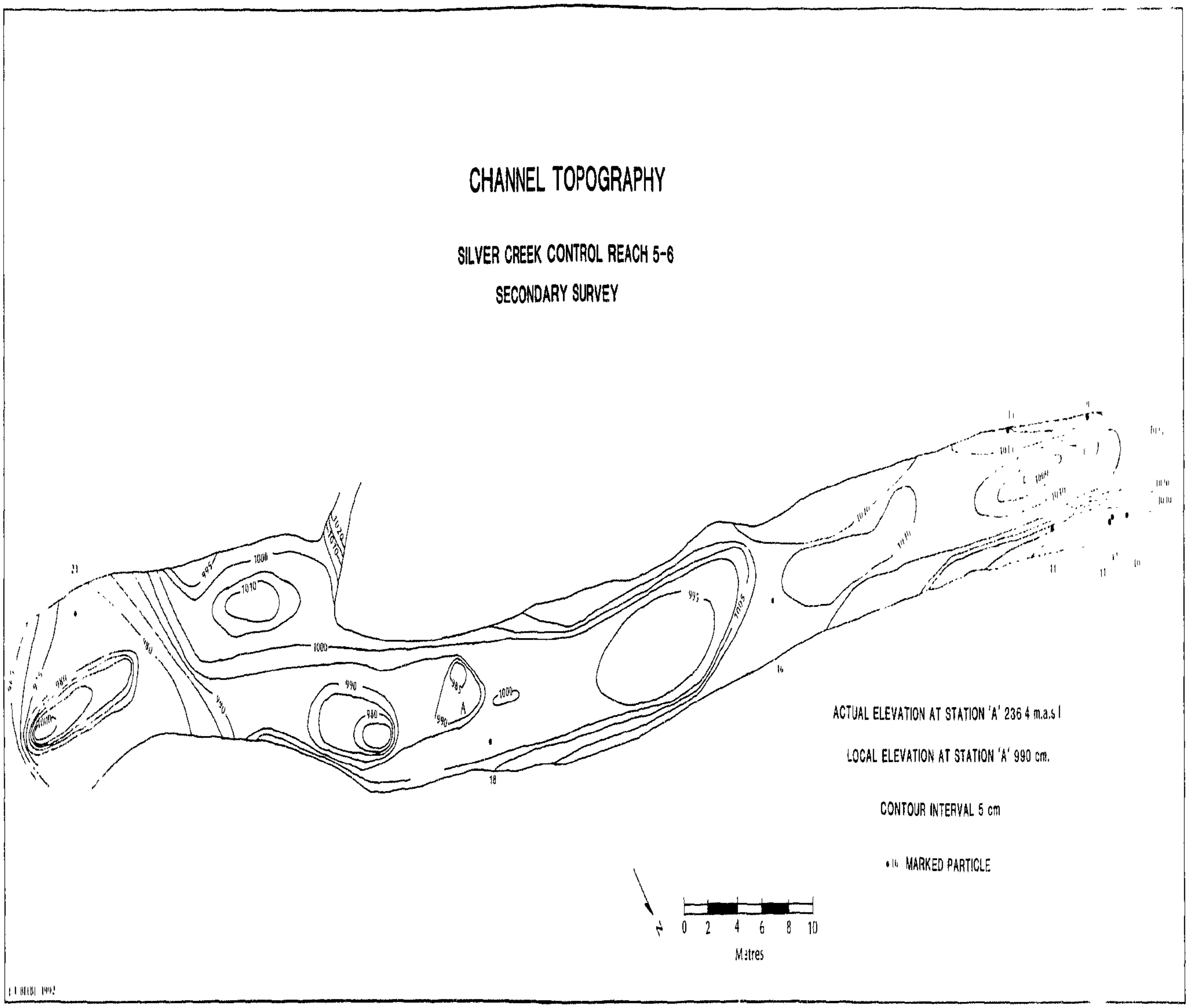
CHANNEL TOPOGRAPHY
CONFLUENCE AREA CONTROL REACH
INITIAL SURVEY
ACTUAL ELEVATION AT STATION 'A' 229 2 m a s l
LOCAL ELEVATION AT STATION 'A' 1000 cm
CONTOUR INTERVAL 10 cm
MARKED PARTICLE
A
B
N
Metres


CHANNEL TOPOGRAPHY
CONFLUENCE AREA CONTROL REACH
SECONDARY SURVEY
ACTUAL ELEVATION AT STATION 'A' 229.2 m.a.s.l.
LOCAL ELEVATION AT STATION 'A' 1000 cm.
CONTOUR INTERVAL 10 cm
MARKED PARTICLE
A
B
N
0 2 4 6 8 10
Metres


CHANNEL TOPOGRAPHY
SILVER CREEK CONTROL REACH 2-3
INITIAL SURVEY
ACTUAL ELEVATION AT STATION 'A' 228.9 m.a.s.l.
LOCAL ELEVATION AT STATION 'A' 1000 cm
CONTOUR INTERVAL 10 cm.
•45 MARKED PARTICLE
----GRAVEL BAR OUTLINE
N
0 2 4 6 8 10
Metres


CHANNEL TOPOGRAPHY
SILVER CREEK CONTROL REACH 2-3
SECONDARY SURVEY
ACTUAL ELEVATION AT STATION 'A' 228.9 m a s l
LOCAL ELEVATION AT STATION 'A' 1000 cm
CONTOUR INTERVAL 10 cm
MARKED PARTICLE
N
Metres


CHANNEL TOPOGRAPHY
SILVER CREEK CONTROL REACH 5-6
INITIAL SURVEY
ACTUAL ELEVATION AT STATION 'A' 236.4 m.a s.l.
LOCAL ELEVATION AT STATION 'A' 1000 cm
CONTOUR INTERVAL 5 cm
MARKED PARTICLE
N
0 2 4 6 8 10
Metres


CHANNEL TOPOGRAPHY
SILVER CREEK CONTROL REACH 5-6
SECONDARY SURVEY
ACTUAL ELEVATION AT STATION 'A' 236 4 m.a.s l
LOCAL ELEVATION AT STATION 'A' 990 cm.
CONTOUR INTERVAL 5 cm
MARKED PARTICLE
0 2 4 6 8 10
Metres

6.3.2 Results

Map supplements one through six represent the topographic maps determined from the initial (August, 1991) and secondary (March, 1992) surveys. Map supplements one and two represent the confluence area, supplements three and four represent the Silver Creek 2-3 area and supplements five and six represent the Silver Creek 5-6 area. The initial surveys in all cases show the location and numbers of the marked particles for that reach, and the secondary surveys show the locations and numbers of the particles that were located upon re-survey. Table 6.3, 6.4 and 6.5 show the particle numbers and measurements of the long, intermediate and short dimensions (where possible) of the Silver Creek 5-6, Silver Creek 2-3 and Confluence area respectively.

Fig. 6.8 shows the difference in longitudinal profile along a talweg transect for the initial and secondary survey of the Confluence area reach. The same information for Silver Creek 2-3 and Silver Creek 5-6 is contained in Figs. 6.9 and 6.10 respectively. Table 6.6 shows the number of found particles that have moved, the amount of movement and the resulting speed necessary to move a particle of that size from Komar's (1987) determination of flow competency.

Table 6.3 Marked particle measurements for Silver Creek 5-6 Control reach.

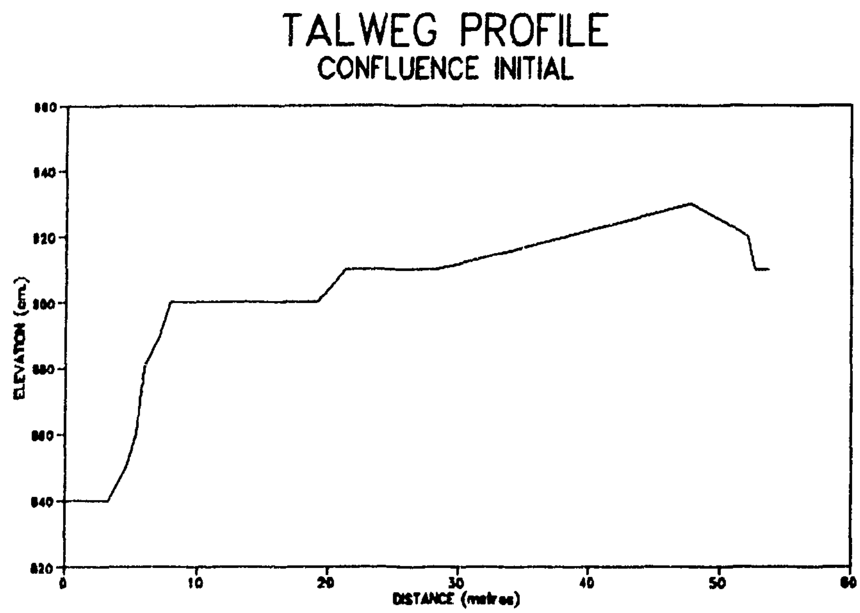
Control Reach	Clast Number	Clast Dimensions (cm.) Long	Intermediate	Short
Silver Ck. 5-6	1	12.7	9	5.8
	2	18.7	11	2.1
	3	18.9	16.7	9.2
	4	13.5	11.1	9
	5	22.4	14	2.5
	6	5.9	4.4	2
	7	Large Boulder in Stream		
	8	11.5	8	3.8
	9	8	5.1	1.8
	10	11	8.3	2.8
	11	8.3	5.2	1.6
	12	16.2	12	7.8
	13	13	8	4.5
	14	9	7.2	0.6
	15	16.8	15	6
	16	16.8	13.5	4.5
	17	15.5	9.9	0.7
	18	74	56	N/A
	19	58	53	N/A
	20	20	11.5	2
	21	10.2	9.9	4
	22	13	11.5	1.5
	23	20	20	20

Table 6.4 Marked particle measurements for Silver Creek 2-3 Control reach.

Control Reach	Clast Number	Clast Dimensions (cm.)		
		Long	Intermediate	Short
Silver	24	Large Oil Drum at Gravel Bar		
Ck. 2-3	25	12.4	11.9	0.5
	26	10.9	8.5	N/A
	27	12.8	10.9	2.9
	28	17.5	9.7	N/A
	29	28.1	19.2	4.2
	30	28.6	23.3	6.7
	31	11.5	11.5	11.5
	32	Oil Drum on Bank		
	33	17	6.6	4
	34	16	14.2	0.7
	35	12.1	8.3	4.2
	36	17.2	10.8	1.5
	37	11.9	6.3	3.4
	38	11.9	9.4	4.8
	39	14.4	9.8	5.6
	40	11.8	9.9	6.6
	41	21.6	19.1	3.2
	42	18.1	10.4	5.2
	43	12.4	9.1	N/A
	44	52.8	36.1	N/A

Table 6.5 Marked particle measurements for the Confluence Area Control reach.

Control Reach	Clast Number	Clast Dimensions (cm.)		
		Long	Intermediate	Short
Confluence	50	5.9	5.4	N/A
Area	51	11.3	7.8	N/A
	52	16.9	9.6	N/A
	53	8.6	7.2	N/A
	54	15.8	14.6	N/A
	55	12.3	6.9	N/A
	56	9.7	6.2	N/A
	57	8.8	6.4	N/A
	58	16.6	13.7	N/A
	59	17.9	9.3	N/A
	60	13.8	8.3	7.4
	61	8.7	8.2	N/A
	62	10.5	5.3	N/A
	63	13.2	9.8	N/A
	64	9.2	7	N/A
	65	66	30	N/A
	66	66	33.5	N/A
	67	103	87	N/A
	68	23.4	13.9	N/A
	69	Log in Bank		



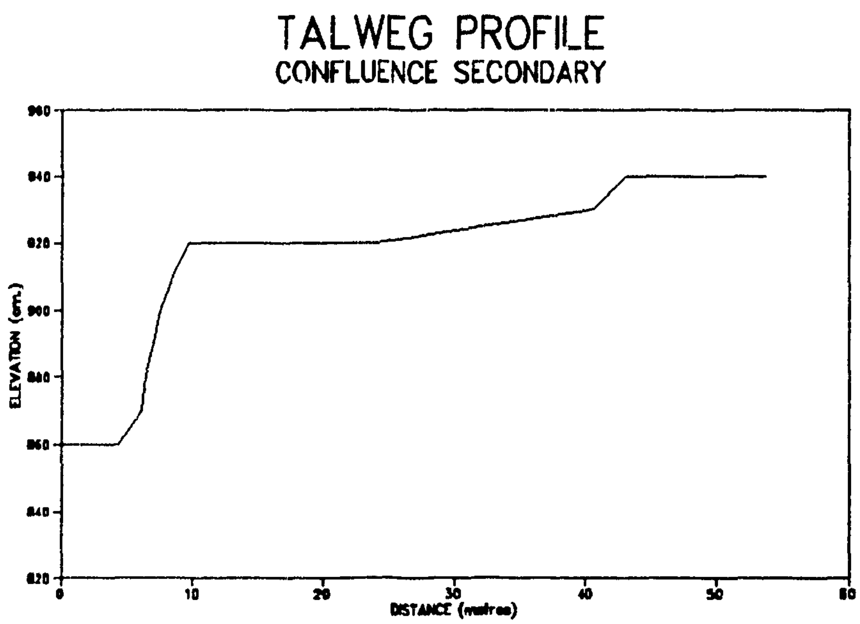
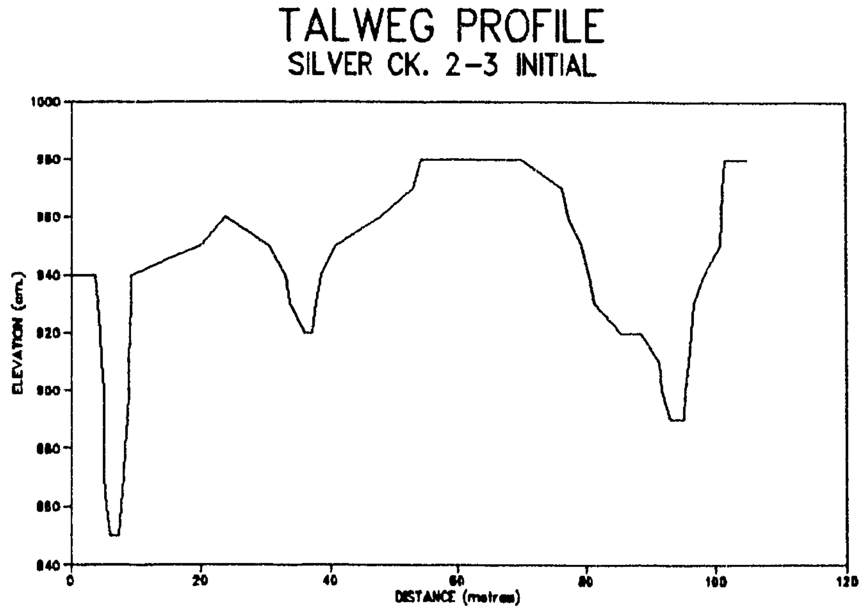


Fig. 6.8 Talweg profiles for the Confluence Area initial and secondary surveys (Black Creek section). Vertical exaggeration = 4.



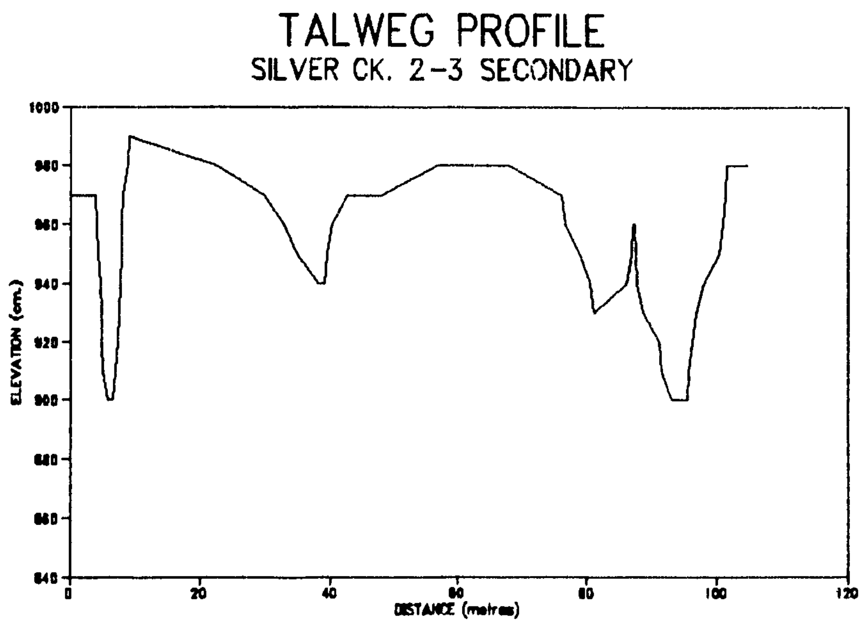
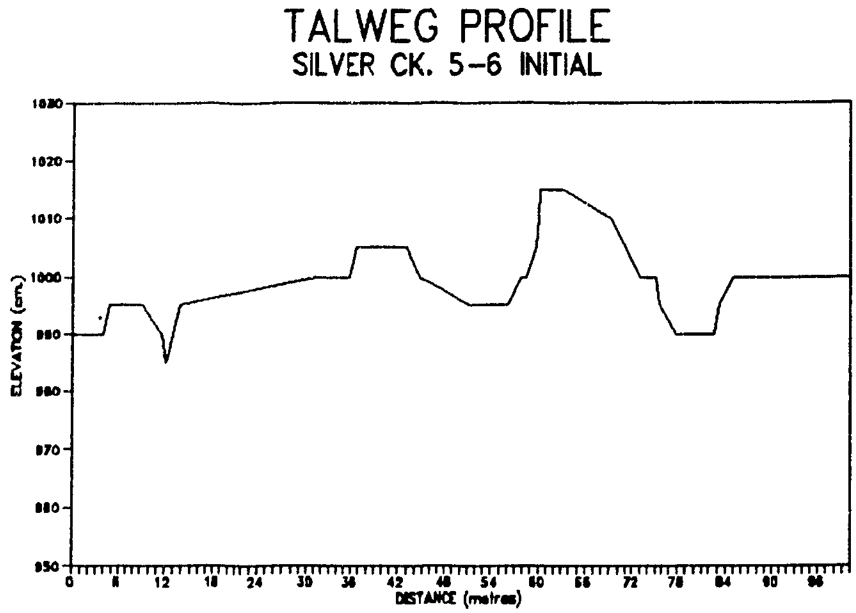


Fig. 6.9 Talweg profiles for Silver Creek 2-3 initial and secondary surveys. Vertical exaggeration = 4.



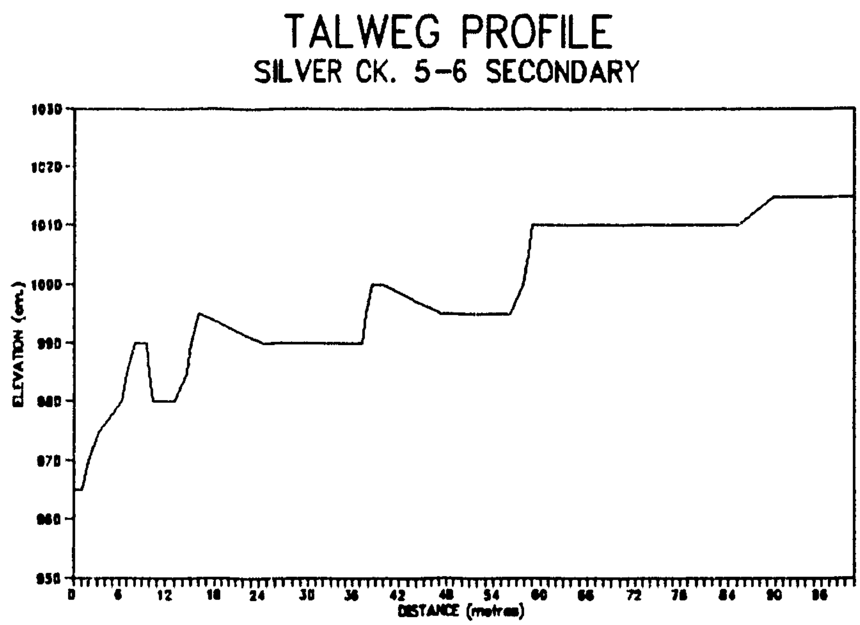


Fig. 6.10 Talweg profiles for Silver Creek 5-6 initial and secondary surveys. Vertical exaggeration = 4.

6.3.3 Interpretation of the Results

Map supplements 1 and 2 (from the Confluence area) show adjustment in the orientation of riffles and pools. During the initial survey a pool located above the scale on the map appears to be oriented cross-ways across the channel, yet the same pool is oriented in an upstream-downstream direction in the secondary survey. The secondary survey also shows that the topography of the bed is much less complicated after spring flows than after a summer of base flow. What is happening between spring and fall is that the creeks are working toward some form of equilibrium; the result of these processes makes a more complicated topography. The orientation of the scour pool at the junction of the two creeks during the initial survey indicates that greater flow comes from Black Creek (which is located at the top of the map), but that orientation changes after the secondary survey to indicate flow strength was greater coming from Silver Creek. Considering the size of the two creeks this would seem to go against what instinct would dictate.

Some of the same properties that were found in the Confluence area were also found in the Silver Creek 2-3 study reach. The topography of the bed during the initial survey was considerably more complicated than the secondary survey. But there were other interesting things occurring. The area at the upstream edge of the reach (the right side of the map) changed very little during the study period. This is the area which is bounded by very cohesive bank material, and little change would be expected. The other end of the reach, which is bounded by more cohesionless material, has undergone considerable change. The gravel bar which was not well outlined in the initial survey is quite well outlined at the 10 cm. contour interval. Also of note is the fact that the scour pool at the end of the gravel bar has filled in, with depths decreasing by 40 cm. at the deepest part and the general shape of the pool changing to a more gently sloping one. This is reinforced by the profile in Fig. 6.8.

Differences in the topography of the bed in the Silver Creek 5-6 study reach are more difficult to identify, because the stadia location is in the channel itself. Care was taken to ensure that control spot heights were used to document the change in the bed at the stadia location; it was determined that the general elevation of the bed dropped by 10 cm. The bed is more complicated in the initial survey (consistent with the other two reaches) and the orientation of the pools is generally in the upstream-downstream direction. The pools are more compressed in the initial survey, indicating that exposure to base flow conditions has some impact on the shape and size of these pools. Changes in slope are evident in Fig. 6.9, which shows that initially the bed has a small change in slope across the study reach, yet the secondary survey shows a definite downstream drop in elevation over the entire reach.

Twelve of 22 marked particles found had moved, for a total of 54.4%. The remaining particles that were not found may have moved, or they may have been buried so that they could not be found. In any case, because they were not found they could not be used in the results.

Table 6.6 Relationship between found particles that had moved, distance moved and the fluid speed necessary to transport that particle according to Komar (1987).

Particle Number	Size (cm)	Distance Moved (cm)	Speed (cm sec^{-1})
9	8.0x5.1x1.8	500	120.60
10	11.0x8.3x2.8	30	150.88
11	8.3x5.2x1.6	95	121.68
12	16.2x12.0x7.8	37.5	178.77
14	9.0x7.2x0.6	87.5	141.33
16	16.8x13.5x4.5	263	188.72
31	11.5x11.5x11.5	225	175.31
34	16.0x14.2x0.7	200	193.16
35	12.1x8.3x4.2	100	150.88
39	14.4x9.8x5.6	206	162.87
56	9.7x6.2xN/A	325	131.94
57	8.8x6.4xN/A	350	133.88

Note: the time interval between surveys was 7 months.

Even under the highest flow conditions that could be measured safely, fluid speeds rarely attained some of the higher speeds noted here for transport (Table 6.6). Fluid speeds may have been reached at times other than those sampled. What may be the cause of particle movement in this case could be the rate of change of fluid speeds. If fluid speeds increased slowly to the critical velocity, that particle may be moved at the competent speed reported by Komar (1987). However that same particle could be moved at a much slower speed if that fluid speed increased at a rapid rate, essentially changing the hydrodynamic properties of flow around the particle. This is a question for further research. If the speed for transport of spawning-sized gravel is known, creeks could be regulated during the critical spawning period to ensure that such speeds are not achieved. But it is also necessary to determine the effect of differing rates of change of fluid speeds that are necessary for the transport of those spawning gravels before any flow regulation may be effective.

Entrainment of particles on the bed appears to be a selective process, that is, not all particles of a given size range (or smaller) will be set in motion by a fluid speed which is determined to be competent for that size range. For example, the speed needed to move a particle with a mean diameter of 13.5 cm is 188.72 cm. sec^{-1} (like particle #16 found in the Silver Creek 5-6 control reach), yet an adjacent particle with a smaller diameter (particle #17 in the same reach) requiring a fluid speed of approximately 163 cm. sec^{-1} was not moved. The causes of this selective entrainment may relate to the position of the particle in relation to the flow (does the point of maximum flow at the bed pass over one particle and not another), its protrusion into the flow, the effects of upstream particles in terms of hiding the particle from the flow, and the differences in hydrodynamic properties (forces of lift, drag, pivoting angle and so on) of the flow around the two particles.

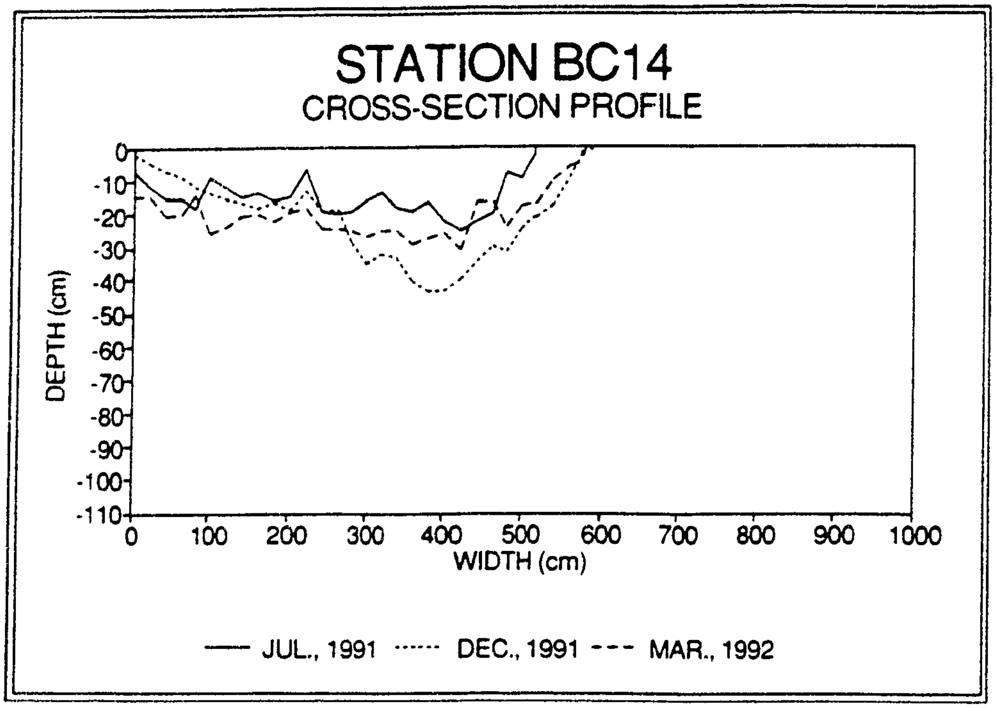
6.4 CROSS-SECTIONAL CHANNEL PROFILES

6.4.1 Introduction and Methodology

Further investigation of bed movement is available at the cross-section scale. Under three of the four flow regimes a cross-sectional profile along a consistent transect was determined. These profiles should be able to show local changes to the bed along that transect. While this is a very site-specific investigation, it helps to show that under some conditions bed movement is more pronounced than others.

6.4.2 Results

Cross-sectional profiles are shown in Fig. 6.11 which display considerable bed movement along the transect. Profiles which do not show much change are shown in Fig. 6.12. Differences in bed profile in Fig. 6.12 are attributed to the use of water level as the datum from which measurements were taken. All 35 cross-sectional profiles are presented in Appendix 3.



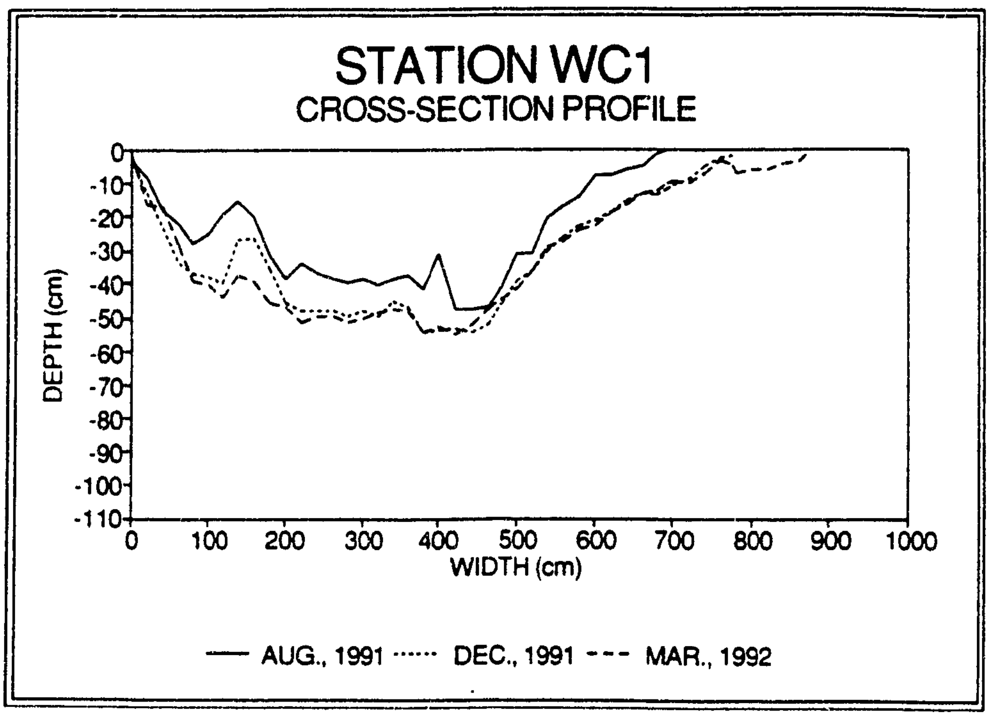
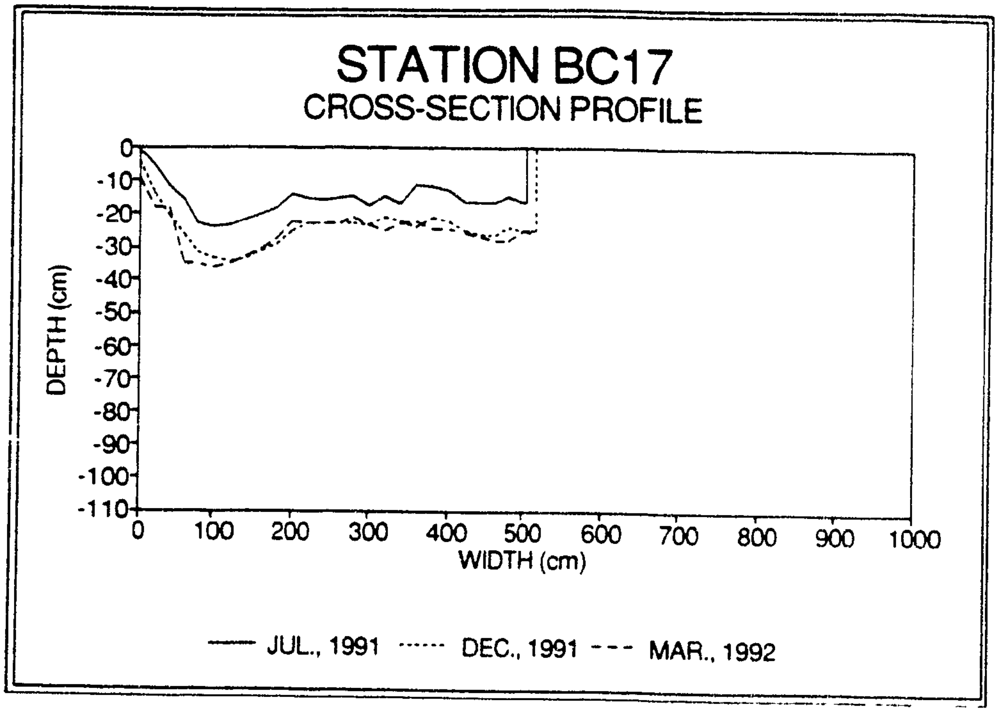


Fig. 6.11 Cross-sectional profiles from 2 sites showing considerable change in the bed over the sampling period



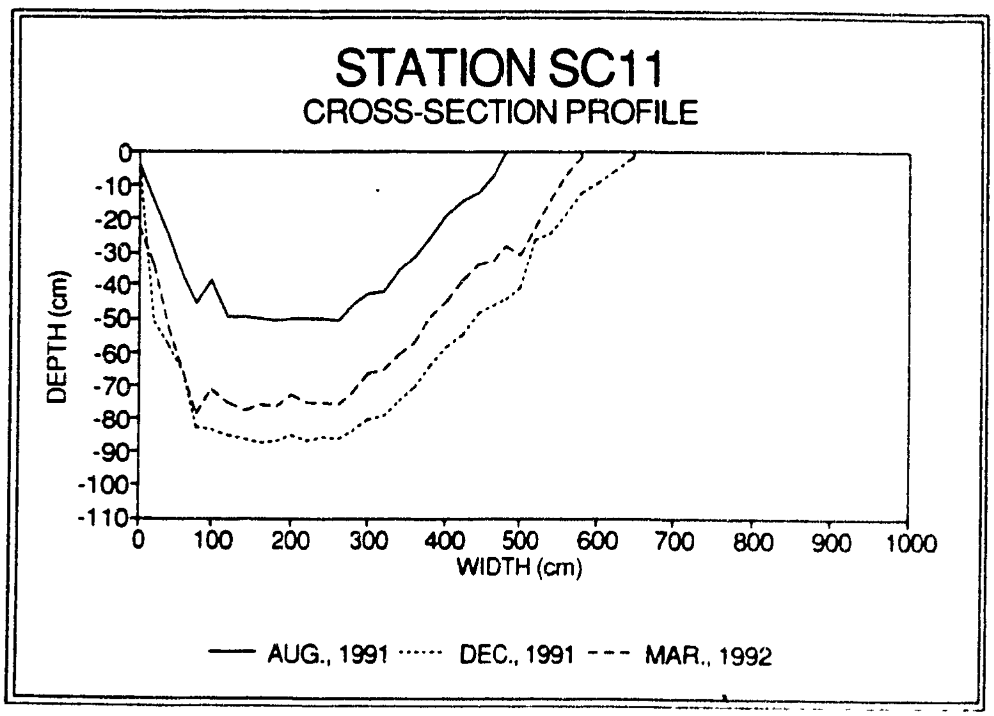


Fig. 6.12 Cross-sectional profiles from 2 sites showing little chang in the bed during the sample period

6.4.3 Interpretation of the Results

Close inspection of the cross-section profile for WC1 indicates movement over time of a large particle located at approximately 420 cm. from the upstream left bank. This particle was at least 20 cm. in height, which means that flows exceeding 200 cm. sec^{-1} would be needed to move the particle. It is likely that the particle moved by rolling, given the local topography of the bed, and that such rolling of a distance of only 10 cm. would be sufficient to get it away from being under the transect line. The BC14 profile shows a shifting of the talweg between July and December, 1991. In this cross-section there is deposition on the left side of the channel and scour on the right side during this period. It appears that in the period between December 1991 and March 1992 the channel is re-adjusting back towards a more uniform cross-sectional profile.

Both BC17 and SC11 show little change in cross-sectional profile. The bed at BC17 is comprised entirely of sand which appears to come from tributary channels draining local sand and gravel mining operations, and there are a number of fallen trees across the cross-section which act as flow dissipators. These trees prevent flows from getting fast enough to do any significant readjusting of the bed. The bed at SC11 consists of larger particles overlain by fine sands and silts, as this is a large pool area and transported sediments will settle out here as flows diminish. This is not to say that there is no bed load transport in these areas, just that bed topography does not change significantly.

The relative stability of the beds in these cross-sections would be of great benefit to salmonids if the beds were comprised of material that the fish could use; however the material on the surface of the bed is too fine for spawning. These areas could be used for feeding or resting habitat, uses which do not rely on stable bed conditions.

6.5 GRAVEL BAR PACKING EXPERIMENT

6.5.1 Introduction and Methodology

Two gravel bars which were exposed under base flow conditions were chosen as sites to investigate the packing and orientation of particles under the influence of flowing water. The first gravel bar, located at site BC19, was chosen because it was noticed that there was a definite difference in particle size from the upstream to the downstream end (Fig. 6.13). It was expected that there would be different packing arrangements between these two ends of the bar. The second gravel bar, just downstream from SC2, was chosen because it had been identified as a known spawning area.

For this experiment, eight boxes were constructed of 3/4 inch pine material, measuring 12x24x4 inches. Tops for each box were constructed which had dowel holes and pins, so they could be attached to the bottom pieces in the field and secured. Once the spacing of the boxes was determined, holes were dug in the gravel bars and the boxes buried so that the top edge of the box was even with the undisturbed bar surface. Excavated bar material was then placed back in the boxes and levelled.

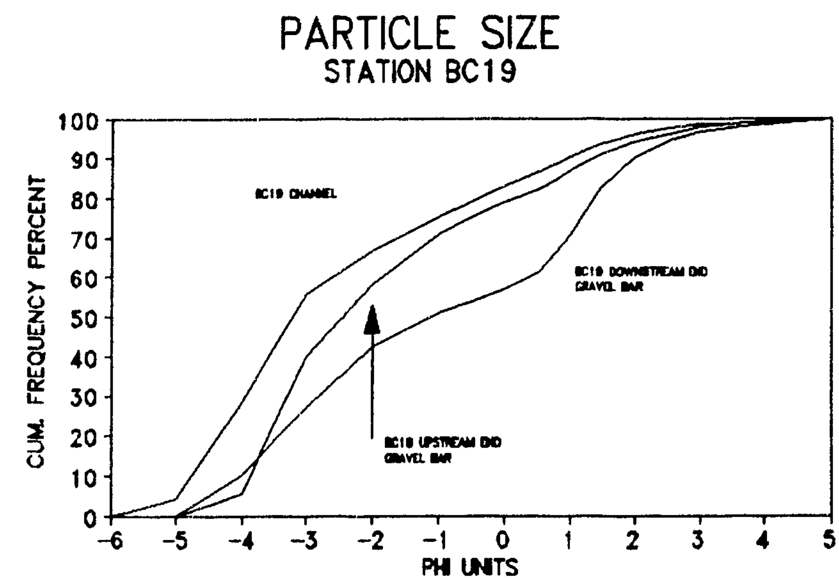


Fig. 6.13 Differences in particle size distributions between the upstream and downstream ends of the BC19 gravel bar relative to the mid-channel distribution.

Each box was measured relative to a known point as well as to each other, so that they would be easy to locate if aggradation of the bar occurred. As well, the orientation of the long edges of the box was recorded relative to 0 degrees north, so that all material in the box would be of known orientation. Boxes will be extracted after a solidifying resin is applied *in situ*, which will prevent movement of the particles from their natural state. In the laboratory, sections will be sliced from the blocks and polished for analysis.

6.5.2 Results

These boxes have not been removed from the gravel bars at the time of this writing because they remain under water and removal at this stage would result in contamination of the sample. Continuous investigation has revealed that the orientation and packing is continually changing, and these boxes are giving information about the movement of material over a gravel bar.

Fig 6.14 is a photograph of an exposed part of a gravel bar which was uncovered in early spring. One week later, this box was covered by fast-flowing water and will likely have different packing and orientation characteristics.

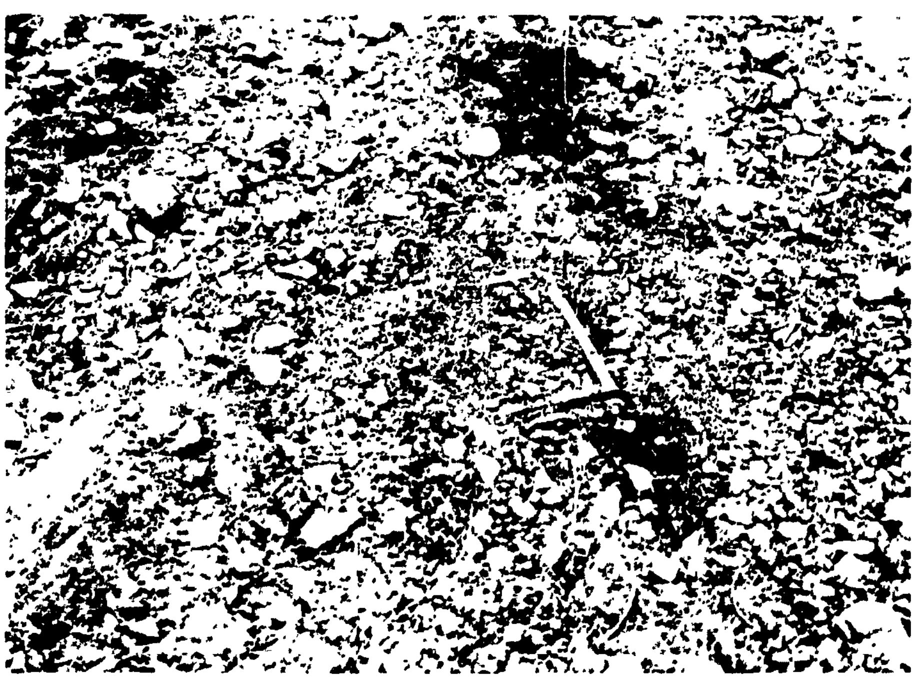


Fig. 6.14 Exposed portion of a gravel bar packing box. This box has since been covered with water.

CHAPTER 7

RESULTS OF BANK STABILITY INVESTIGATIONS

7.1 BANK PROFILING EXPERIMENT

7.1.1 Introduction and Methodology

The effect of winter frost heaving and spring high flows on banks can be significant. If slumping of banks occurs, an introduction of sediment into the channel is the result. This bank instability is important from a fish habitat perspective, and therefore should be considered in stability assessments.

Surveys of Black and Silver Creeks have shown a distinct difference in the cohesiveness of bank material. These differences may have an affect on the amount of material that is contributed to the channel under erosional conditions (frost-thaw or exposure to flowing water). Because of these differences, two specific sites were studied to determine the amount of contribution--a cohesive area of bank (Bank Profiling Site 1) and a more cohesionless area (Bank Profiling Site 2). Each site was visited in the fall of 1991 and again in the spring of 1992 in an attempt to document change.

In an attempt to quantify the volumetric change to a bank over these periods, a river bank profiler has been developed to take measurements of a bank profile

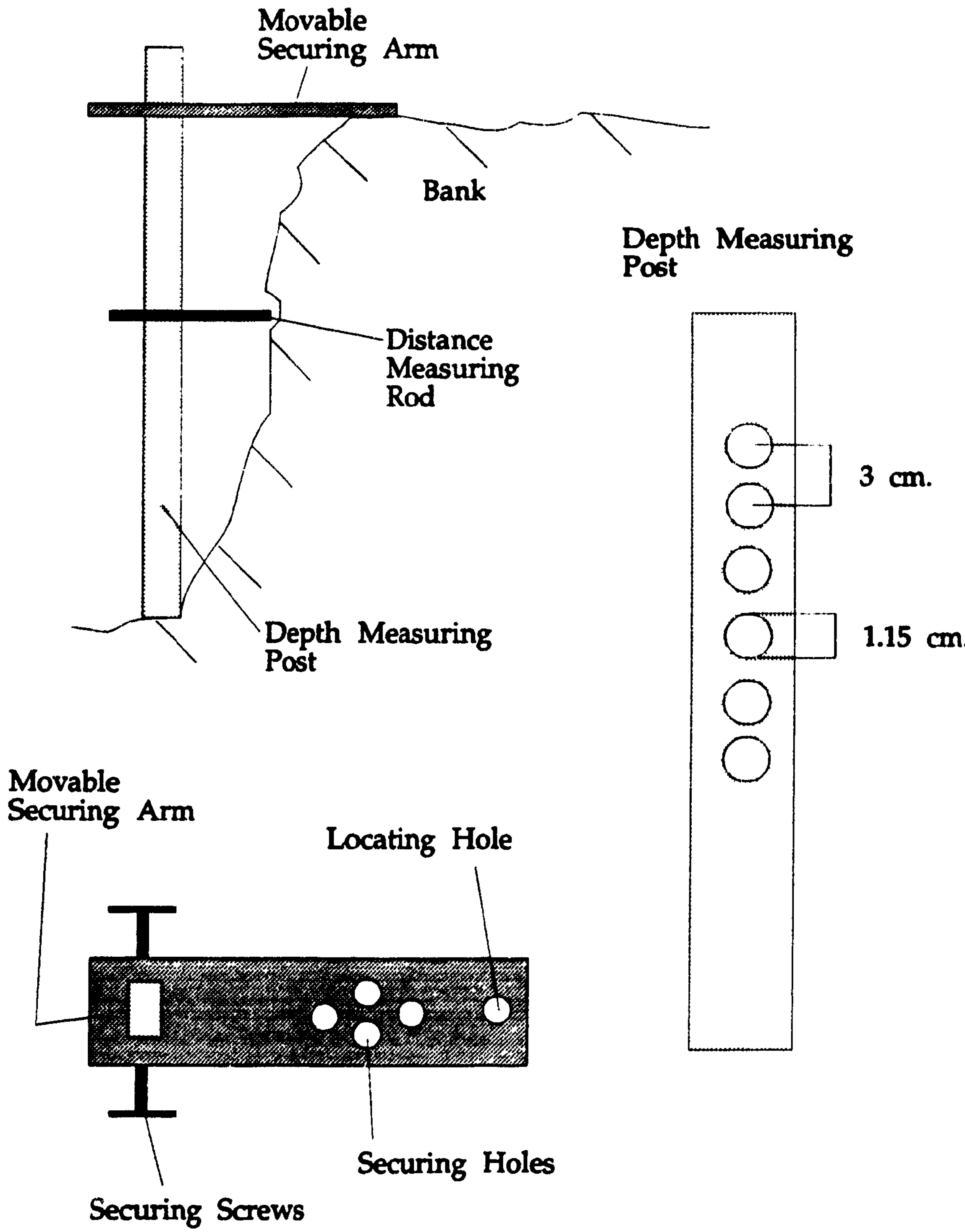


Fig. 7.1 Schematic of the River Bank Profiler and its component parts (not to scale)

(Fig. 7.1). The mobile securing arm is lowered onto the bank so that the locating hole is directly above a locating stake. Spikes are driven through the securing holes on the arm to ensure that the profiler does not move. A line level is used to make sure that the securing arm is level, and a block of wood is used to ensure that the depth measuring post is perpendicular to the securing arm. The stabilizing screws are then tightened so the apparatus does not move.

At this point measurements are taken. The distance measuring rod is inserted into the holes in the depth measuring post (which are centred at 3 cm. distance apart from each other) and distance to the bank is then recorded. Once the entire bank profile is measured, the apparatus is moved to the next locating spike and the process repeated. By having the locating spikes a known distance apart, and by having them run along a straight line transect, the total volume of the measured block can be determined (provided the spikes are not located too far apart). The x (distance along the transect), y (height of bank in 3 cm. intervals) and z (distance from depth measuring post to bank) values are entered into a software program, Surfer (V. 4.0), which then calculates the profile of the bank along the transects measured. Surfer interpolates intermediate values between measured ones through a series of user-directed steps, producing a block profile. Surfer can then calculate the volume of the block profile (Surfer V. 4.0 Reference Manual, 1989).

These sites were re-visited in the spring of 1992. Using the locating spikes that were left in the ground from the initial set of measurements, the area was re-surveyed. This information was entered into a Surfer file and block profiles and volumes were calculated. Any change in the bank will be evident visually by the block profile, and mathematically by the volumetric calculation. The difference between volume calculation 1 and 2 is the amount of bank material that has been lost (or gained).

7.1.2 Results

Fig. 7.2 shows the initial bank profile from the cohesive bank (A) and the bank profile after winter frost-thaw mechanisms have been at work (B). Although there does not appear to be a considerable difference in the bank over the two sampling periods, in actual fact there has been a volumetric change of 0.0721 metric tonnes over the entire length of the bank. Clearly the stability of the material has been a factor in the amount of slumping.

Fig. 7.3 shows the initial bank profile from the cohesionless bank (A) and the bank profile after winter processes (B). This bank has undergone a considerable change between the sampling periods. It has been determined that a loss of 0.6179 metric tonnes was introduced into the channel from this site. Table 7.1 shows the actual achieved values for the bank changes.

Other than attempting to determine volumetric change to the banks, specific transects can be studied to determine local changes in a specific area. Fig. 7.4 (A) shows the change to a transect along the cohesive bank, Fig. 7.4 (B) shows the same information along a transect in the cohesionless bank.

Fig 7.2 Initial (A) and secondary (B) block profiles from a cohesive bank. Bank length is 14 metres.

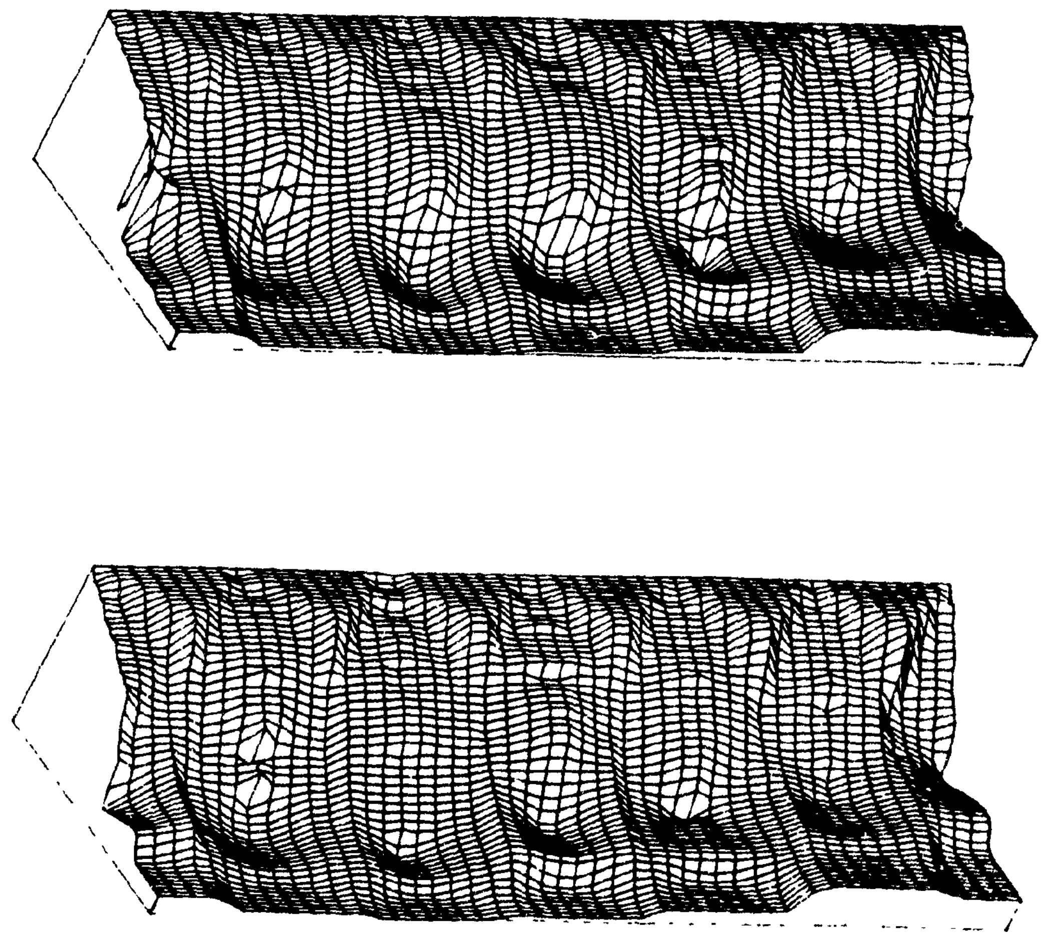


Fig. 7.3 Initial (A) and secondary (B) block profiles from a cohesionless bank. Bank length is 8 metres.

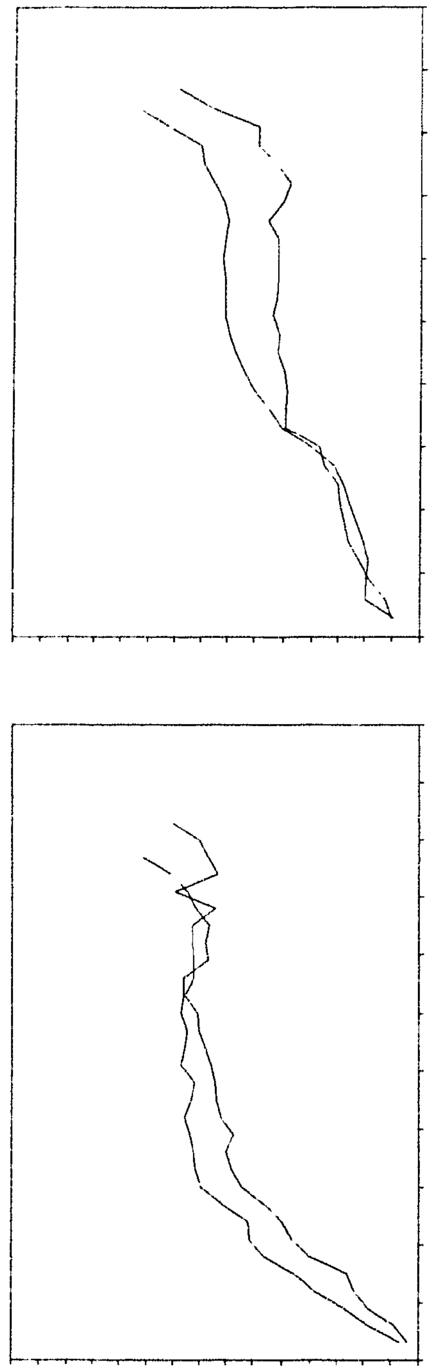


Fig 7.4 Transect profiles from a cohesive (A) and cohesionless (B) bank. Notches are 10 cm. intervals.

Table 7.1 Volumetric changes to bank profiles for a cohesive and cohesionless bank

Site	Volume pre (cm^3)	Net Volume (cm^3)	Volume post (cm^3)	Net Volume (cm^3)	Bank Loss (tonnes)
Cohesive Bank	10.313 $x10^6$	10.310 $x10^6$ +/- 3600	10.285 $x10^6$	10.277 $x10^6$ +/- 21900	0.0721
Cohesionless Bank	5.245 $x10^6$	5.244 $x10^6$ +/- 1890	5.012 $x10^6$	5.011 $x10^6$ +/- 1750	0.6179

Note: net volume is the term given the volumetric block profile calculated by the Surfer program.

7.1.3 Interpretation of the Results

Table 7.1 shows that there appears to be a large difference in the amount of material lost from the cohesionless bank compared to the cohesive bank. Although it appears from Fig. 7.4 that the cohesive (A) bank has lost more material than the cohesionless (B) bank, that has not been the case over the entire profile. The transects presented in Fig. 7.4 indicate that there may be areas of either bank which undergo more change than others.

The results show that areas of cohesionless bank material contribute significantly more material to the channel than cohesive banks do. It is not known if the contribution is the result of frost-thaw processes or erosion from flowing water; that is a question for further research. In terms of bank stability, the cohesionless material is much more unstable. Large quantities of material introduced into the channel become available for bed and suspended load transport. Increases in bed load transport can result in the burying of spawning gravels (rendering them useless for that purpose), whereas increases in suspended sediment also has a drastic effect on adult fish physiology.

The degree to which the difference in bank material affects the channel is greater than just the contribution of material for transport. The nature of bank material has a profound effect on the width/depth relationships as well.

7.2 THE ROLE OF COHESIVE AND COHESIONLESS BANK MATERIAL

7.2.1 Introduction and methodology

Channel width and mean depth can be altered by the nature of the bank material at a location. On Silver Creek an outcrop of cohesive clay in the bank had the dramatic effect of decreasing channel width and increasing depth, yet less than 100 metres downstream that cohesive material was not present, and the channel returned to a broader profile.

Shallow streams attempt to dissipate energy along their length through divergent flow, that is flow moves away from the talweg towards the banks. Where bank material is cohesionless, divergent flow causes erosion of the bank and a widening of the channel. When the bank material is cohesive enough to prevent erosion (at the scale of the force of the natural flow in the channel) convergent flow is the result, where the stream must readjust its attempts to dissipate energy in another manner. Convergent flow causes increased tractive force and scour under high flow conditions, creating pools (Keller and Melhorn, 1973). This fluctuation between divergent and convergent flow, partly caused by the nature of the bank material, is one process in the creation of riffles and pools.

Fig 7.5 shows the adjustment of an area of stream which is bounded by very cohesive clay bank material. Width to depth ratios in this cross-section vary slightly within the 4.9 to 6.1 range under all flow conditions. In contrast to this is Fig. 7.6, an area of stream less than 100 metres downstream which is bounded by more cohesionless bank material. The channel adjusts its width to depth ratios to between 25.3 to 126.3 under all flow conditions.

7.2.2 Results

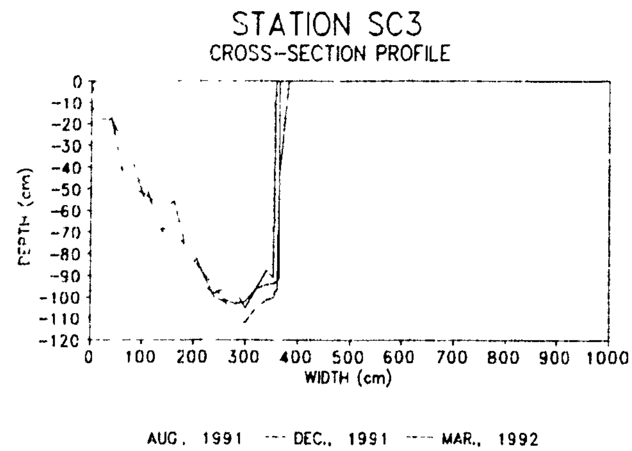


Fig. 7.5 Channel profile from a section with cohesive bank material

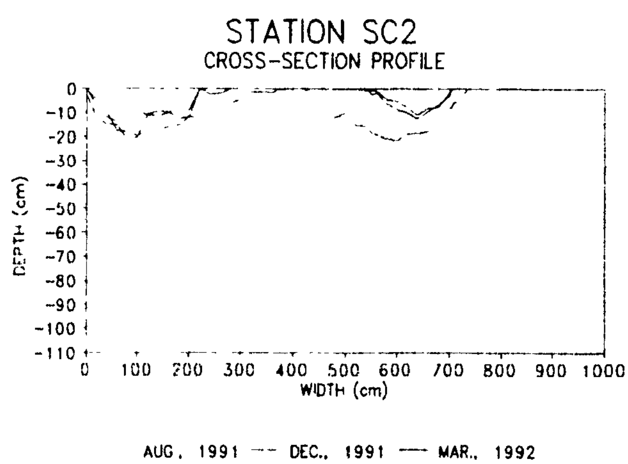


Fig. 7.6 Channel profile from a section with cohesionless bank material

7.2.3 Interpretation of the Results

There are numerous changes in width/depth ratios within the study creeks, yet very few are the direct result of a change in the nature of the bank material. Areas which have marked changes in depth are usually accompanied by some form of obstruction to the flow; areas which seem to have constrictions on channel width are usually accompanied by an object which resists erosion. One such obstruction which contributes to increases in depth and limits expansion in width is the presence of bankside and fallen vegetation.

7.3 THE ROLE OF VEGETATION IN BANK STABILITY

7.3.1 Introduction and methodology

Visual observation has shown that areas of stream bank that are made of the same material are subject to different patterns of erosion or stability. The one variable that appears to have a direct effect on these areas is bankside vegetation. It is known that thin spindly roots can help bind soil against erosion (Thorne, 1990), and there are great quantities of those roots throughout the study area. Observation in this study has shown that there may be a critical root size which determines the interface between protecting the soil and causing erosion through increased turbulence. As thicker diameter roots are exposed into the flow, they become an obstruction to that flow. An analogy would be a large particle sitting on a bed of fine sand. That large particle becomes an obstruction to flow as water must move around it, resulting in scour and deposition processes that commonly occur on channel beds. The same processes are at work with these larger roots. As flow past the root becomes redirected, some of it gets pushed toward the bank. If that bank consists of cohesionless material, or if the flow has a strong enough erosional capacity, the bank is going to be re-shaped around those root systems. If the roots protrude down far enough into the flow then fluid redirection also affects the bed by creating scour holes.

7.3.2 Results

Fig. 7.7 shows a typical area of bank (625 cm^2) along Black Creek which consists of numerous spindly roots from bankside ferns. Although this bank looks as if it would be unstable, attempts to remove material by hand were met with considerable resistance. Fig. 7.8 shows what happens when a bank is comprised of these roots. Flow past the bank is able to erode the bank under the root line, causing undercutting. When the undercut is large enough, the entire bank will slump under its own weight into the channel.

Fig. 7.9 shows a typical area of bank along Silver Creek where exposed tree roots have had an erosional impact on the bank. It is difficult to get a look at the bank material in this area, as distance from the roots to the bank exceeds 25 cm.

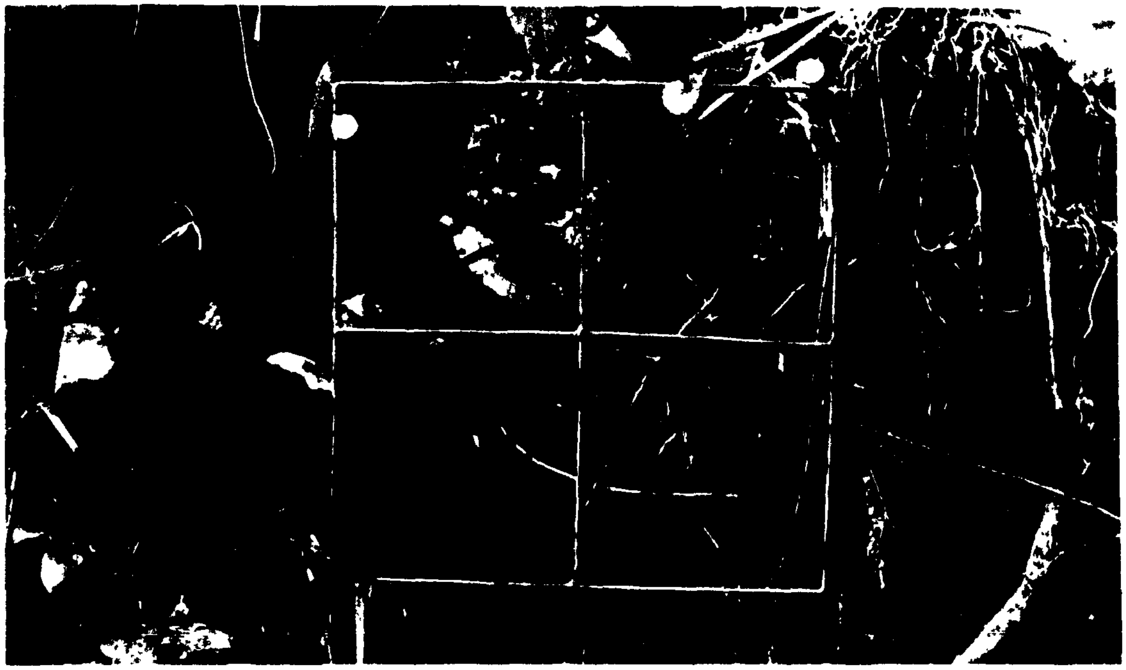


Fig. 7.7 Example of thin fern-like roots which act to stabilize bank material

Fig 7.8 Bank undercutting where thin roots act as temporary bank stabilizers

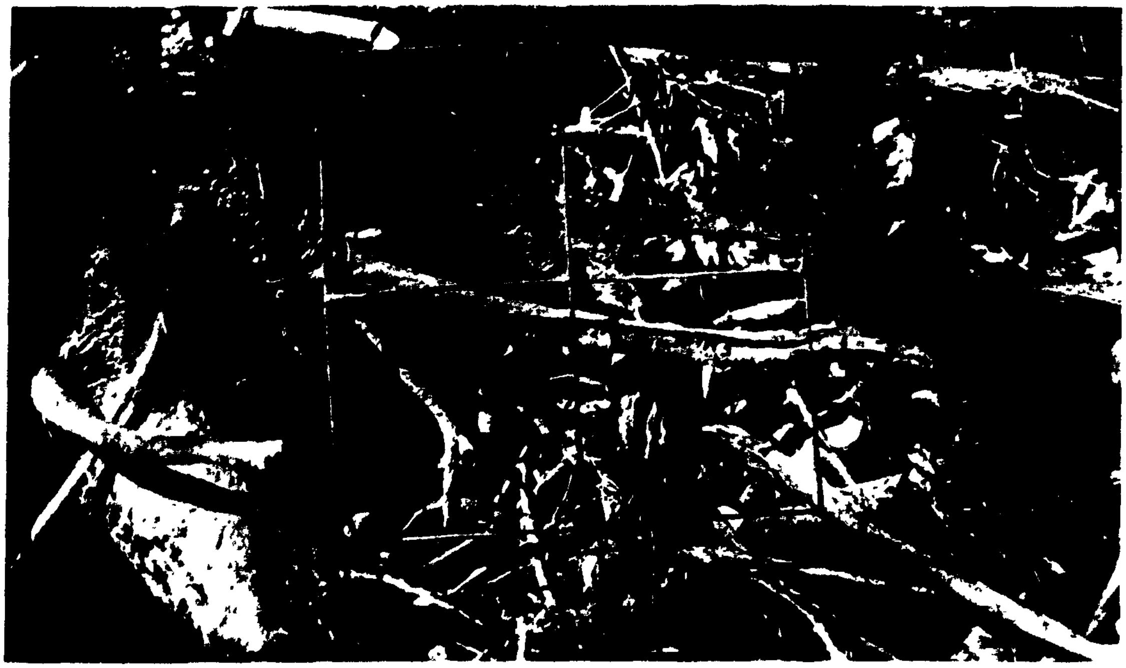


Fig 7.9 Thick exposed tree roots which act as flow deflectors enhancing bank erosion

7.3.3 Interpretation of the Results

The differences between Fig. 7.7 and 7.9 are visually quite obvious. The thin roots from the ferns have a greater density as there are more roots per unit area. The tree roots represent a smaller number of roots per unit area. Because of this the effects of these different types of roots can be seen. Naturally the larger number of roots per unit area will stabilize the bank by binding the soil together. When there is a small number of roots and the roots are quite large the growing root causes the soil to become less stable, and water flowing past the root and hitting the unstable soil will result in erosion.

Sometimes the force of flowing water against the bank is too great for the smaller roots to act as stabilizing agents. Fig. 7.10 shows a section of bank on the West Credit River which has grasses and ferns as vegetative cover. During the spring melt period a section of the bank collapsed entirely (Fig. 7.11) and was washed away. The fracture planes within the bank (Fig. 7.12) indicate a major slumping of the material. The slumped section was approximately 10 metres long in a section of bank that was over 200 metres, and was located closer to the downstream end of the bank section but not at the end of the bank. From a fish habitat perspective, this area is a major transport route between the Credit River and the tributaries where spawning usually occurs. The slumped material which became suspended sediment would have an effect on the physiology of fish downstream of the section, and bedload transport of the material could cover natural spawning grounds.

Fig. 7.10 Vegetated bank on the West Credit River

Fig. 7.11 Area of bank erosion on the West Credit River

Fig. 7.12 Close-up of the fracture planes at the West Credit River bank erosion site

CHAPTER 8

DISCUSSION

8.1 INTRODUCTION

Studies of channel stability which relate to fish habitat require a number of individual investigations which on the surface appear to be independent and in fact have been treated so in the literature. However all of these individual investigations presented here are connected through a complex network of interrelationships. This chapter shows one such interrelationship in detail and outlines another. There is discussion of the methodology applied to this study, a discussion of previous attempts at quantifying habitat from a geomorphological perspective, and a conceptual diagram showing the relationship between fluid, bed and bank stability investigations and their relevance to fish habitat will be presented.

8.2 THE RELATIONSHIP BETWEEN FLUID SPEED, SEDIMENT AND SPAWNING GRAVEL

One of the more complicated interrelationships in channel stability is the one between fluid speed, the transport and settling of sediment and the effects on spawning gravel. Fluid flowing at a particular speed has the ability, as long as there is an available supply, to transport sediment of a given particle size, either in suspension or as traction load. Naturally, when the speed of the fluid slows down, that particular particle will be deposited. This can have significant implications for spawning habitat.

The biological literature shows that optimal spawning gravel ranges between 2 and 256 mm. in diameter for salmonid species although individual species may have more restrictive requirements (Table 3.1). It is assumed, then, that particles less than 2 mm. that are introduced into spawning gravel will aid in the clogging of that gravel. The geomorphological literature shows that depositional speeds for material ranging from 2.0 mm. to 0.06 mm. vary from 52 cm. sec^{-1} to about 24 cm. sec^{-1} (Table 8.1). To determine whether sediment finer than 2 mm. diameter is settling out simply requires finding the ratio of recorded fluid speed versus settling velocity. If that ratio is below 1.0, that particular sediment size will settle out at the recorded speed. Mean fluid speeds recorded in this study show that 33.6% of the time mean fluid speed is lower than 52 cm. $sec.^{-1}$, indicating that particles less than 2 mm. are being deposited throughout these creeks.

For a particle to be deposited it has to have been entrained in the first place. If speeds are not competent to entrain that particle then it is impossible for it to settle into spawning gravel, for it likely was not in motion. That 2 mm. particle requires an erosional velocity of between 90 cm. $sec.^{-1}$ (according to Sundborg, 1956) and 75 cm. $sec.^{-1}$ (according to Komar, 1987). Mean fluid speeds rarely got above the erosional velocity for that 2 mm. particle for the study sections (0.7% of the measured flows at 75 cm. $sec.^{-1}$ and 0% of the measured flows at 90 cm. $sec.^{-1}$).

Table 8.1 Eroding and depositional velocities for particular sediment diameters (interpreted from Sundborg, 1956).

Particle Diameter (mm.)	Eroding Velocity (cm. sec.$^{-1}$)	Depositional Velocity (cm. sec.$^{-1}$)
2.0	90.0	52.0
1.5	70.0	42.0
1.0	50.0	36.0
0.6	49.0	30.0
0.4	41.0	28.0
0.2	39.0	25.0
0.1	37.0	24.0
0.06	36.0	24.0

Inherent in this discussion is the fact that use of mean values for fluid speed disregards extremes of high speed that may be present in the flow but are masked by extremes of low speed. Therefore, assumptions made on the strength of mean speeds may be erroneous to the extent that habitat that may appear to be suitable for spawning actually is not.

To illustrate this, speeds required to entrain and deposit material finer than 0.85 mm. will be used. This size fraction has been identified by Chapman (1988) as being significant for the survival of salmonid embryos.

The erosional velocity for this particular size fraction is between 49 and 50 cm. sec.$^{-1}$, and the settling velocity for that same size particle is on the order of 32 cm. sec.$^{-1}$ (interpreted from Sundborg, 1956). Using mean fluid speeds from the sampling stations, we see that the erosional velocity is exceeded 15.0% of the time under measured flow conditions. This indicates that material of this size and finer is being transported within these creeks at various times of the year (assuming availability). The settling velocity is the important one for consideration here. Mean fluid speeds for the sampling stations show that the settling velocity is exceeded 67.9% of the time on the West Credit River, 48.5% of the time on Black Creek, and 36.6% of the time on Silver Creek, giving an overall average of 47.9%.

If we were to analyze the fluid speeds for a particular cross-section by means of absolute values for fluid speed across the cross-section rather than using average values, we would see a difference. For example, station BC1 shows mean fluid speeds under all measured flow conditions which are higher than the settling velocity of the 0.85 mm. particles. Table 8.2 shows the actual recorded speeds for three of the four sampling events by panel and depth for station BC1 (spring high flows were recorded differently and therefore that data is not in the same detail). Notice that there are many instances where speeds are far below the settling velocity for the 0.85 mm. particles, indicating that there could be material of that size and smaller settling out in this cross-section. Of more importance is the fact that 60% of the speeds at or nearest the bed (D*0.8 and D*0.95) are below 32 cm. $sec.^{-1}$.

Table 8.2 Measured fluid speeds vertically and cross-sectionally for station BC1 under three of the four measured flow conditions. BC1-1 values are shown in normal font, BC1-2 are shown underlined and BC1-4 values are in bold face. Speeds are in cm. sec.$^{-1}$. Blanks indicate that no measurement was taken, usually because flow depth was below 20 cm.

	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5
D(0.2) SURFACE	13.3 40.9 **34.0**	39.6 67.9 **73.7**	73.7 76.7 **73.1**	78.0 60.0 **60.6**	23.1 4.7 **15.7**
D(0.4)	15.6 35.7 **17.1**	39.4 58.7 **71.4**	69.0 75.6 **80.6**	70.0 57.7 **54.9**	19.7 3.1 **12.3**
D(0.6) MIDDLE	 27.9 **12.4**	37.4 47.9 **59.3**	63.0 66.6 **73.0**	 51.0 **56.0**	
D(0.8)	12.3 13.9 **6.4**	31.3 31.0 **47.1**	44.1 54.7 **59.3**	53.6 54.7 **42.7**	12.6 3.3 **10.3**
D(0.95) BED	 11.9 **-0.4**	23.1 25.1 **27.9**	30.3 37.9 **37.3**	 37.9 **25.0**	

Given this information bed samples should hold a greater percentage of fines in areas where the depositional velocity is not exceeded. Using this example, and looking only at summer base flow conditions (BC1-1 in Table 8.2), panel three represents the point in the cross-section where fluid speeds are the highest throughout the entire column of water. Panel five represents a point in the cross-section where deposition of this finer material should occur on a large scale given the fluid speeds. Bed material samples taken for those two panels under base flow conditions show that this is indeed the result. The percentage of bed material finer than and including 1.0 mm. (the closest size range for sieving in this study to 0.85 mm.) for panel three was 5.53%, for panel 5 the percentage of bed material finer than and including 1.0 mm. was 100%. It can safely be assumed that there is not a great difference in the underlying material of the bed. Given that the panels are 2.22 metres apart, the difference then could be attributed to the deposition of fine material in panel five and the erosion of fine material in panel three.

This illustrates how varying fluid speeds along with bed and suspended material can alter the particle size distribution of the bed at a site in a known spawning area. But these are not the only variables at work here. What has not been mentioned to this point is the cause of the slowing of fluid speeds near the panel five location. Just upstream from panel five a tree has fallen over onto the bank and some of the branches protrude into the water. These branches act to redirect flow away from that side of the channel, to the point where the fluid beyond the tree actually is flowing upstream at times due to the eddy effect caused by the flow obstruction.

In conclusion, at the BC1 site, bed material particle size distribution cross-sectionally is influenced by lateral and vertical variation in fluid speed, suspended sediment transport, bed load transport, the presence of bankside vegetation that has collapsed into the channel, and bank erosion (causing the tree to fall and also potentially providing material available for transport from an upstream collapse). In other words, bed material particle size distribution, and subsequent spawning habitat, at this site is directly influenced by fluid, bed and bank instability. In terms of spawning habitat bed particle size distribution may be more important than range of particle size (Fig. 6.7 and discussion p. 109).

Another example of the interrelatedness of these variables is the movement of large particles along the bed. Briefly, bed movement is related primarily to the speed of the surrounding fluid, but there are other significant variables as well. Micro turbulent fluctuations in fluid speed near the bed (exemplified in mean fluid speed seen in Fig. 5.8) which fluctuate above and below the critical erosion velocity for a particular particle may be enough to entrain that particle even though mean speeds are much lower. Once entrained, transporting velocities are slower and the particle is moved.

Slope of the channel is also important, not only in the downstream (transporting) direction, but cross-sectionally as well. If a large particle rests on a side slope which is near the angle of repose for that size particle (as has been found in the study area, especially near large pools), a small fluctuation in fluid speed may be enough to start that particle rolling down the side slope. Once moving, fluid speeds which may never approach erosional velocity may transport that particle downstream.

Fast rates of change of fluid speed (such as those found during high-energy summer storms) can also result in a larger particle being entrained than the flow competence equations would predict. A fast rise in fluid speed could be likened to a 'wall' of water flowing downstream (this has been reported in urban hydrology literature). When that 'wall' strikes a particle it is more likely to move that particle at slower mean speeds than predicted because of the greater momentum of the 'wall'.

Other variables include saltating particles in the flow, which could act through abrasion by changing the pivoting angle of grains, the transport of logs or other material that could strike the bed, and the scouring action of ice during spring thaw. All of these, which have been investigated in the literature individually, are complexly intertwined, and they all have the potential for great impact on spawning habitat.

8.3 DISCUSSION OF THE METHODOLOGY USED IN THIS STUDY

8.3.1 Fluid Stability and Suspended Sediment Investigations

The manner to which fluid speed measurements were taken could have been more detailed. Measurements taken with a Marsh-McBirney Model 201D Electromagnetic Current Meter are limited to fluid speed only; it would have been useful to get directional information as well. That way, better investigation of flow around large particles on the bed as well as flow around bank obstructions (primarily vegetation) could be undertaken.

The number and locations of fluid speed measurements taken at each cross-section may seem at first to be overly detailed for this type of study, but further analysis of the results has shown that details about the variability of fluid speeds at the bed would have been missed using more conventional methodologies. Also, the use of five panels across the cross-section has been necessary to determine how differences in flow contribute to the nature of the bed material (see 8.2).

The collection of suspended sediment samples requires mention. Although field evidence showed that there was little difference in concentrations collected with a pump sampler or a standard DH-48 sampler, in creeks where the flow is slow and water depth is limited the DH-48 was ineffective. For the sake of consistency a pump sampler should be used. Although cross-sectional variability of suspended sediment may be important (given the importance of suspended sediment on fish and habitat), this issue was not addressed in this study due to limitations of time and manpower.

Analysis of the particle size distributions of suspended sediment is important when considering settling velocities over spawning areas. The samples that were collected in this study were both too limited in amount and too fine in size to be properly and accurately analyzed.

8.3.2 Bed Stability Investigations

Investigations of bed material particle size distribution in active spawning rivers should concentrate on the percentage of material finer than 0.85 mm. and the distribution of that material throughout the channel. Efforts should be made to identify source material for this sediment to determine if the amount that reaches the channel could be curtailed. As well, laboratory analysis of these bed samples should concentrate on those particles smaller than 2.0 mm., as that is the theoretical lower limit of spawning gravel.

Bedload transport samples used in this study were restricted to the confluence area primarily because of the difficulty in reaching other sites with heavy equipment. The samples were also restricted to one location through the cross-section, usually because the bed was so rough that the equipment could not sit flat on the surface of the bed in more than one place. Because fluid speeds are varied cross-sectionally, results of the sampling were not extrapolated for the entire width of the channel. Future sampling through spawning areas should entail full cross-section sampling to determine the actual effects of varied flows on transport.

Cross-sectional channel profiles yielded good results, despite difficulties when measurements were made in areas where standing waves were present. Future measurements of this type should be taken from a fixed datum above the transect that could be re-occupied with accuracy. That would take away the error inherent when water surface is used as the datum. Other depth measurements should then be substituted for water depth.

The control reach surveys were able to show considerable differences in the topography of the channel reaches in areas where change might be expected, and showed very well little change to channel topography in Control Reach Silver Creek 2-3, upstream area, where very cohesive material characterizes the bed and banks.

The particle marking and re-surveying experiment was more successful than initially anticipated. Success rates in these experiments usually range from 10-15% of marked particles being found, in this study 34.4% of the marked particles were found and resurveyed in the spring. This success may be related to the fact that larger particles were marked, meaning that greater flows would be needed to move them, and those greater flows may not have occurred. Future particle marking experiments should ensure that the entire particle be painted, numbered and then coated with a protecting sealant which would prevent the paint being removed by abrasion from saltating and suspended particles moving downstream. Of course, this veneering of the particle may change the intricate hydrodynamic properties of fluid flow past the particle, possibly hindering or enhancing entrainment.

8.3.3 Bank Stability Investigations

The river bank profiler developed for this study has shown that there is a change in bank profile in both cohesive and cohesionless bank areas, with the greater change occurring in areas where the bank consists primarily of cohesionless material. The causes of this instability were not determined in the course of this study; that is a question for further research. Certainly more detailed sampling would help identify the rate of change to the bank, and could give an indication of the seasonality of that change. This would be important if bank collapse occurred at spawning time, introducing large amounts of sediment into the channel for transport.

Computer plots of the block profiles are not accurately representative of the entire bank (as evidenced from field observations). This could be due to the wide spacing of the profiling transects or the algorithm used by the software package to interpolate intermediate values. This in turn invalidates the actual volumetric loss computed for the profiles, but because the same calculative steps were used for all blocks, relative losses would be comparable.

Both the roles that cohesive bank materials and bankside vegetation play in the determination of channel shape require further investigation. This study has shown that these variables are important and have a significant impact; the degree of that impact and the effects on fish habitat are yet to be determined.

8.4 PREVIOUS ATTEMPTS AT STREAM CLASSIFICATION FOR AQUATIC HABITAT

There have been many instances where researchers have attempted to classify streams according to their capacity to sustain fish populations from a geomorphological perspective (Fausch, et al. 1988). Most authors have attempted to create classifications based on a limited geomorphological criteria, and some of their results are encouraging, yet they continue to fall short of what is required.

Platts (1974) was one of the first to study the relationship between geomorphic variables and salmonids with an attempt at stream classification. That classification system was specific to streams of the Idaho Batholith, and as such is not applicable elsewhere. Platts was able to quantify the number of fish found in each of his geomorphic groups, but like other studies that followed there was no attempt to determine cross-susceptibility between geomorphic groups.

Platts recognizes the limitations of his study, as he writes (p. 95):

> The methods used to quantify the aquatic environmental conditions failed to describe adequately pool quality, stream-bank environment, and aquatic vegetation. Where sample size was sufficient, the methods used were reliable for quantifying and making comparisons among stream depths, and widths, composition of stream channel materials, percent of pool and percent of riffle ratings, and channel elevations. The inventory techniques demonstrated that even though considerable data may be collected, valid information is elusive.

This study was useful because it showed that there were differences in the number of fish of different species found in areas of different geomorphic type (or subtype). For example, he found that in areas where fine sediment in the bed was between 15 and 19%, there were on average 4.8 total fish in that area, with an average of 2.2 rainbow trout, 0.2 brook trout, 0.03 cutthroat trout, and so on. This information showed that there were indeed geomorphologic reasons for differences in fish stock, and that these should be investigated further.

Binns and Eiserman (1979) attempted to quantify trout habitat according to a limited number of geomorphic variables (for instance late summer stream flows, eroding stream banks, and stream substrate). By rating each variable on a scale of 0 (worst) to 4 (best) and correlating that rating with fish standing crop (determined by sampling reaches for the number of fish per hectare) they were able to show that as stream rating increased so did trout standing crop. They did not determine the relationship for geomorphic variables and standing stock alone; their results included the presence of fish food abundance, fish food diversity, and so on. Their results are skewed from a geomorphological perspective by the fact that if there was sufficient and diverse food available there was likely to be trout there as well. This is a problem to which there appears to be a simple solution. Because there must be food available for fish to occupy an area, researchers should remove the influence of that variable by ensuring that there is an equal amount of food under each geomorphological condition and then determine where the fish are located.

The Binns and Eiserman Habitat Quality Index also shows that there is a distinct influence on fish habitat selection based on geomorphological variables. Again, because the biologists are not schooled in fluvial geomorphology there appears to be satisfaction in stating that there is a geomorphological component to fish habitat selection with little follow-up research.

The reason that there is little follow-up to stream classification is probably because it is a monumental task, one that fluvial geomorphologists have been working on for decades. The first classification of streams was likely provided by William Morris Davis, who classed streams according to their 'age', with three classes called Youth, Maturity and Old Age. This was the standard for many years until the desire for more detailed information took over. Since then, attempts at finding relationships between width, depth and fluid velocity versus discharge (like Leopold and Maddock, 1953) and others have been attempts to classify streams in one way or another.

One attempt to classify streams according to their morphological characteristics has been developed by Rosgen (1985). This is without doubt the most detailed attempt at stream classification to date. Rosgen uses variables such as gradient, width/depth ratios, substrate materials and so on, each variable having a number of sub-classes attached to each (for instance, sinuosity is classed as 1.0-1.1, 1.1-1.2,1.2-1.4, and so on). Each sub-class relates to a specific stream type, classed by Rosgen and illustrated in the paper. It is easy to see that this type of classification system would work very well on large rivers, where there is a transformation from high-gradient steep-sided valleys in the source area to low gradient floodplain valleys at the mouth of the same river. The difficulty when using this classification scheme on the study creeks is that they usually end up being classed the same from source to mouth. This is the case for Black Creek, which is classed as C2 throughout the creek. Silver Creek has two classifications based solely on the fact that the headwaters are in the Niagara Escarpment.

This broad classification in small streams seems to have little use when applied to fish habitat studies. Rosgen and Fittante (unpublished) applied the classification scheme of Rosgen (1985) to streams where habitat reconstruction was needed, and found that under certain circumstances they were able to achieve success. This encouraging note should be taken in future research efforts, as more work is needed in this area.

Although the Rosgen (1985) classification system is the most detailed to date, it still is not all-encompassing. The system is difficult to use in the field, and there should be more attention paid to the variables described in the biological literature, such as percent of bed fines less than 0.85 mm. and suspended sediment concentrations.

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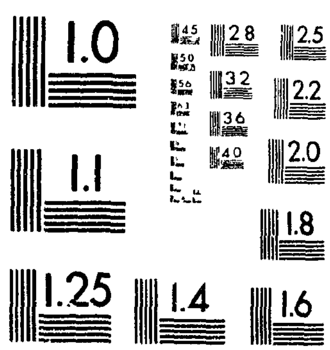

PRECISION℠ RESOLUTION TARGETS

8.5 CONCEPTUALIZING RIVER CHANNEL STABILITY: A FRAMEWORK FOR RESEARCH IN THIS AREA

It is possible while doing research on river channel stability and the implications for fish habitat that the individual focus precludes the overall perspective. Certainly any one of the studies undertaken in this thesis could have become the primary focus for research. Important to the entire scope of this research is the applicability to real world situations.

Each sub-experiment in this study is related in some manner to each other, either through direct or indirect degrees of association. Bringing them together in a conceptual framework may enable future researchers to focus their special abilities in such a manner that they mesh with work done in other fields.

Figure 8.1 is an attempt at conceptualizing the interrelated features of fish habitat studies from a geomorphological perspective. Central to the framework is the concept of habitat studies, being the application to which all other research is focused. Fluid, bed and bank stability 'nodes' are directly related to habitat studies through clearly defined lines outlined in this thesis. Other variables, such as hydraulic geometry relationships (which have been studied here) and physico-chemical processes (which have not) are also directly related to habitat studies. Each of these nodes of research are interconnected through a series of potential relationships. These relationships may also be direct (i.e. rate of change of discharge affects bedload transport) or less direct (i.e. fluid speed plus cohesiveness of bank material affects particle size distribution of the bed). The term potential indicates that relationships may or may not always be present.

Each node is then central to all investigations that directly relate to that node. Such component parts are the basis for individual research which can then be carried out. Each of these component parts has a sub-level which better defines the physical properties inherent in them. This diagram does not revert to that level of identification in an attempt to reduce complexity.

It is important when looking at Fig. 8.1 that although the component parts are not visually connected by lines they may be interrelated on the basis of the degree of association between nodes. Therefore, all parts of the diagram are in some way connected to all others.

Fig. 8.1 may assist fisheries biologists by providing an overall picture of some of the components of fluvial geomorphology that relate to fish habitat. That is clearly one of the benefits of this work. Fluvial geomorphologists may also be aided by this work, for it gives a focus to their research that may not have been identified in the past.

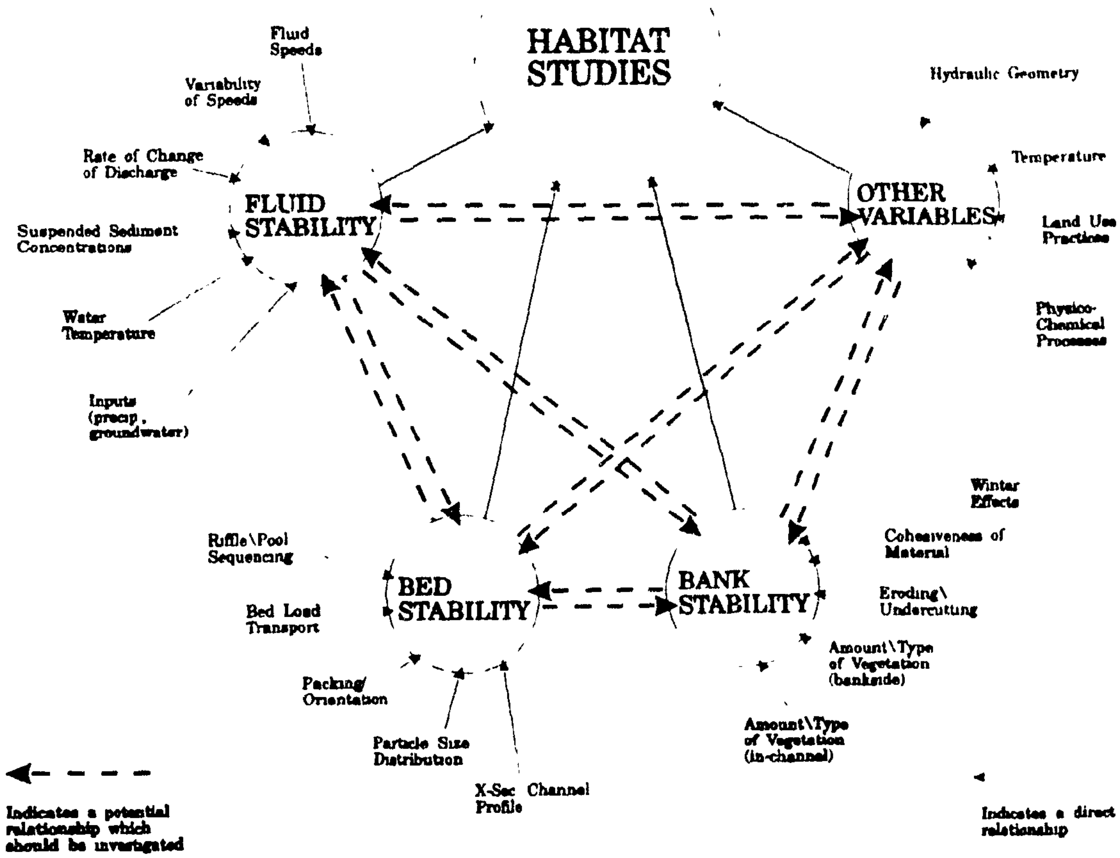

Fig. 8.1 Conceptual framework for the relationship between fluvial geomorphology and fish habitat

CHAPTER 9

CONCLUSIONS

9.1 SUMMARY

9.1.1 Objective and Results

The objective of this thesis was to investigate river channel stability as it pertains to fish habitat, outlining the variables needed for consideration when planning alterations to channel form. By meshing studies common to fluvial geomorphology with investigations of interest to fisheries biologists, this objective has been realized. The thesis was able to identify a number of variables which, through a complex network of interrelationships, all require study when considering channel alterations. Results have shown the importance of using more detailed sampling schemes when dealing with fluid speed and discharge measurements, for standard measurement of the mid-channel fluid speed along with a few depth measurements across the channel are simply inadequate to define the ongoing processes in the channel. Results have also stressed the importance of bankside and in-channel vegetation in the alteration of channel form.

A river bank profiler was developed for use in this study, the purpose of which was to document change to river banks consisting of different types of material (cohesive versus cohesionless). Although there is an error factor inherent in the use of the profiler and subsequent interpolation of data by software programs which are not designed specifically for that purpose, results are encouraging.

The use of standard surveying techniques to document topographical change to river beds was quite successful. Differences in summer and post-spring beds may shed light into the ability of summer base flow conditions to complicate the topography of the bed over relatively long periods of time. Certainly more intensive surveying would aid in this research.

A conceptual framework has been developed to assist both fluvial geomorphologists and fisheries biologists in their research. The lines of interconnectivity between properties of fluid, bed and bank stability should be the focal point of research in this area. In conclusion it can be said that stability of fluid, bed and banks are related at even the primary level, and that they are directly related to fish habitat in rivers in Southern Ontario.

9.1.2 Stability in River Channels

Does stability occur in river channels? It is evident from the results that there may be minor periods of stability that are both fleeting and random. In terms of fluid stability, measurements have shown that everywhere through the cross-section (lateral and vertical) of the creek fluid speeds fluctuate by as much as 0.05 $m. sec.^{-1}$ within a 2 second time span. So, although fluid speeds can remain stable, that stability lasts only for a very brief period of time.

Bed stability occurs for longer periods of time than fluid stability. Under summer base flow conditions certain areas of bed where particles are large enough to do so become armoured, enhancing stability until a critical fluid speed is attained which undermines that stability. This period of stability may last for brief periods of time, and in areas of the channel it may not occur at all.

In terms of degree of stability, banks are the most stable of the three. Changes to banks may occur over winter and into the spring, but the processes that cause changes to banks may be less active in the summer months. The term 'most stable' should not to any degree indicate that banks are to be considered stable, for even at the microscopic level there is activity in banks from the settling of particles to the growing of roots.

Although streams can be considered stable on a drainage basin scale for periods of time, it can be stated that there is no condition under which fluid, beds and banks are stable in a natural channel at the level where there is no impact for fish and their habitat.

9.2 FUTURE RESEARCH

Work in the area of river channel stability and the relationship to fish habitat is a relatively new area, so there is a considerable amount of research that needs to be undertaken. Within the bounds of this study, though, the results indicate a few areas which require direct investigation.

While the role of vegetation has been identified in this study, the effects of bankside vegetation in the modification of bed and banks requires detailed study. As well, the difference between small roots (i.e. ferns) and larger roots (i.e. trees) exposed at the bank/water interface and how they relate to 1) the generation of erosive turbulence at that interface and 2) bank stabilization due to the clinging effect must be determined.

Coupled with this is the role that vegetation which has fallen into the channel plays in the modification of channel form. Visual observation has shown that fallen trees can be the starting point for the formation of gravel bars, and they can also cause complete redirection of flow, resulting in channel migration. While fallen trees provide suitable cover for feeding and resting habitat, they may change the properties of the bed and fluid flows in such a manner that habitat is lost. Measurements indicate an increase in talweg sinuosity when a fallen tree is present in the channel. At the Silver Creek Control Reach (where there is no tree in the channel), talweg sinuosity was determined to be 1.46. Near the confluence on Black Creek talweg sinuosity downstream from a fallen tree was determined to be 2.57.

The role that the formation of anchor ice plays in the separation of sediment from the bed, and the subsequent over-winter storage of sediment in ice requires further study. Results have indicated that a considerable amount of sediment can be stored in a small area of channel, and the release of that sediment during periods of increased suspended sediment concentrations may have drastic effects on fish physiology.

The fluctuation of suspended sediment concentrations found in the confluence survey has direct impact on the way suspended sediment is sampled. Results indicate that timing of the sample collection may influence an over- or under-estimation of concentration which has direct management implications. A new methodology must be developed which requires continued sampling for the overall mean concentration of suspended sediment before any management decisions are made. Research into this area may show that suspended sediment pulses may be periodic, and this relationship may be dependent on the fluctuations in fluid speed found during the confluence survey.

The investigation of packing and particle orientation that was begun in this study, and is ongoing at this point, should be investigated further. The relationship between packing and suitability for spawning is not found in the literature, yet it may be of importance.

Although attempts have been made to quantify fish habitat from a geomorphological perspective, they are to this point ineffective. Part of the problem stems from the fact that only the biologists are doing the work. There needs to be collaborative works done in this area if a suitable classification scheme, which is applicable to a wide variety of streams and geomorphological conditions, is to be developed. A part of the problem may be that each stream is unique and therefore a universal model is unlikely to be found.

The role that water quality plays in the determination of suitable habitat is an important factor that was not considered here, but should certainly be contained in future studies of this nature.

Most of all the timing of events is of paramount importance. All of the factors which have been identified as crucial may be entirely harmless if they occur at times when fish are not occupying the particular part of the river. Research should look into the role that timing plays in the determination of suitable fish habitat.

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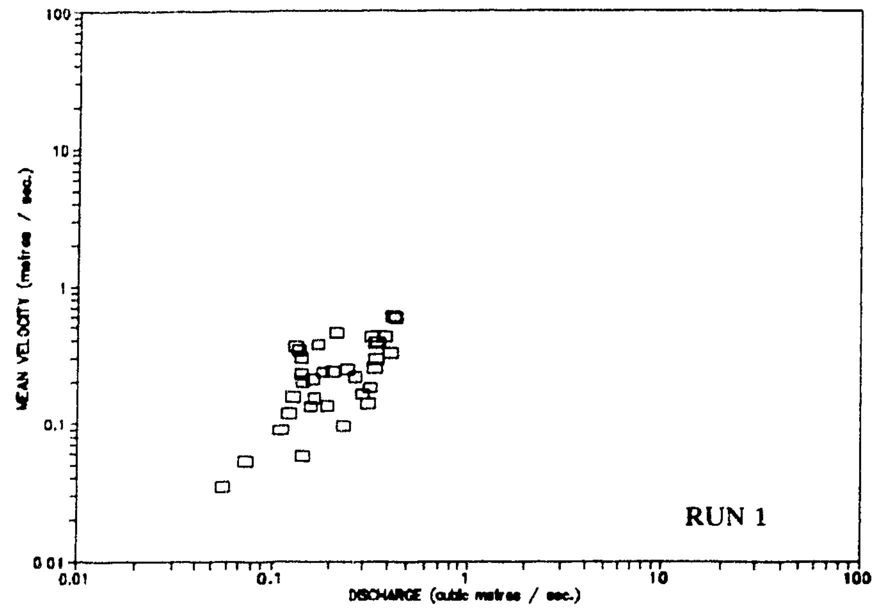
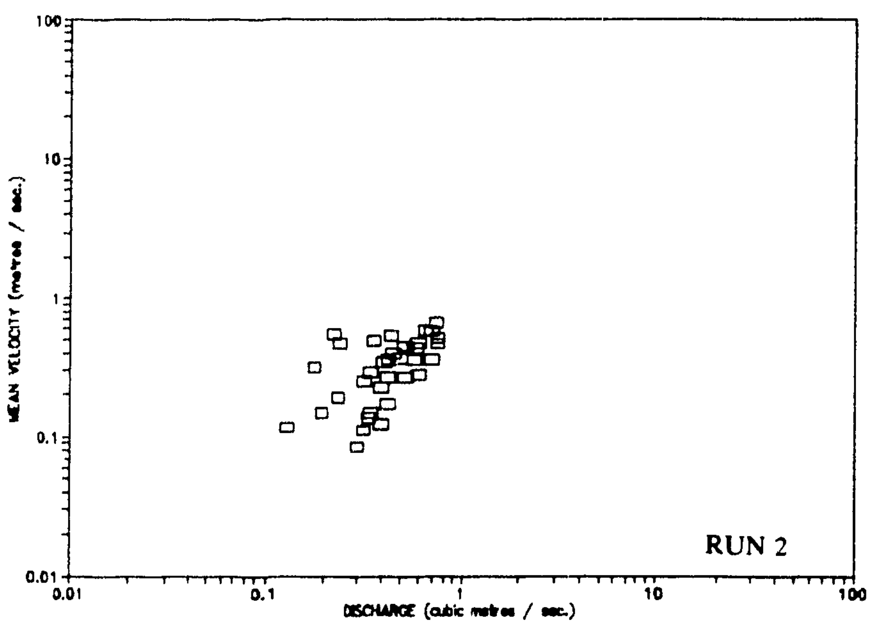
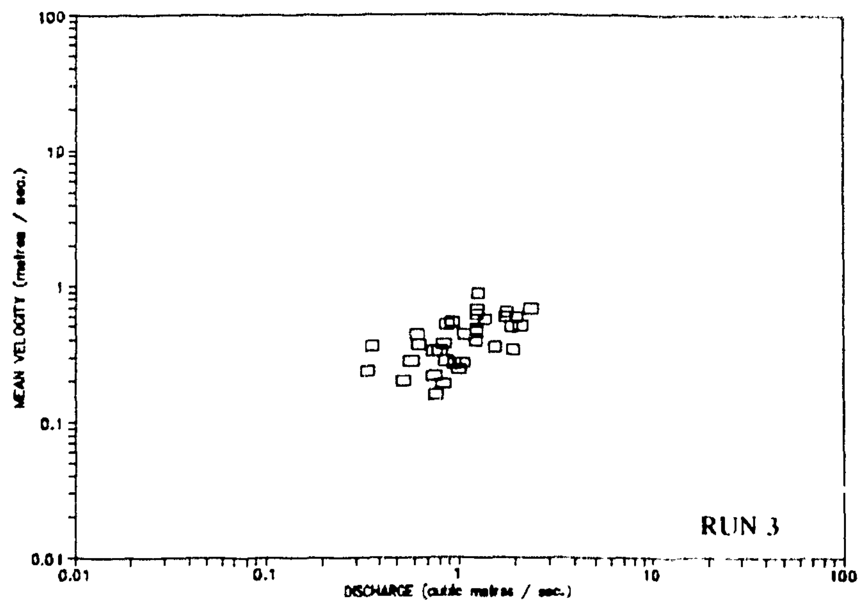
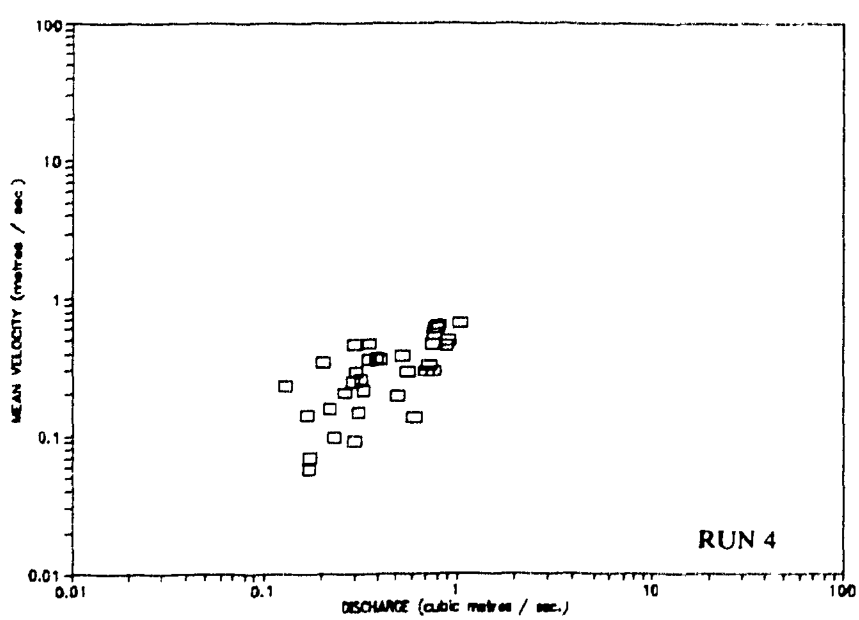
Appendix 1

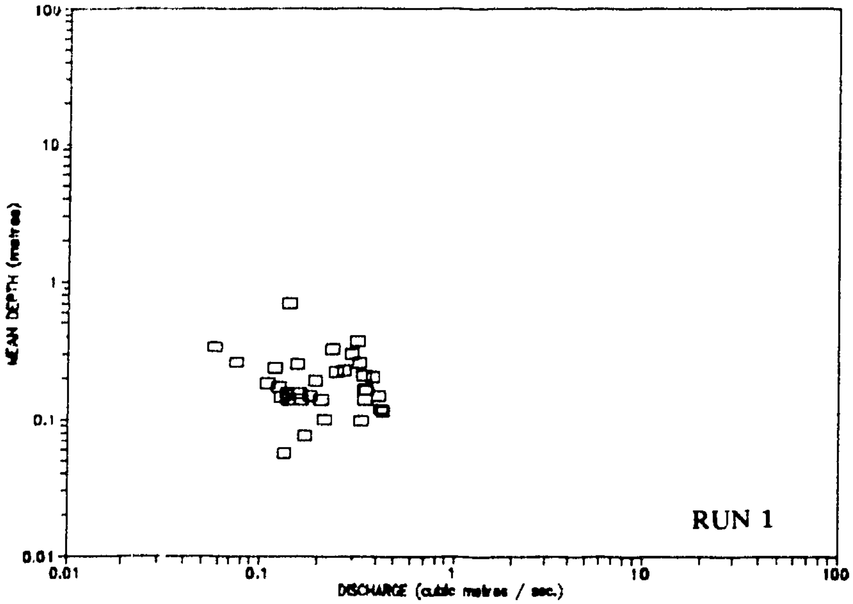
PLOTS OF VELOCITY, WIDTH AND DEPTH VERSUS DISCHARGE UNDER FOUR FLOW REGIMES


MEAN VELOCITY (metres / sec.)
DISCHARGE (cubic metres / sec.)
RUN 1


MEAN VELOCITY (metres / sec.)
DISCHARGE (cubic metres / sec.)
RUN 2


MEAN VELOCITY (metres / sec.)
DISCHARGE (cubic metres / sec.)
RUN 3


MEAN VELOCITY (metres / sec.)
DISCHARGE (cubic metres / sec.)
RUN 4



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MEAN DEPTH (metres)
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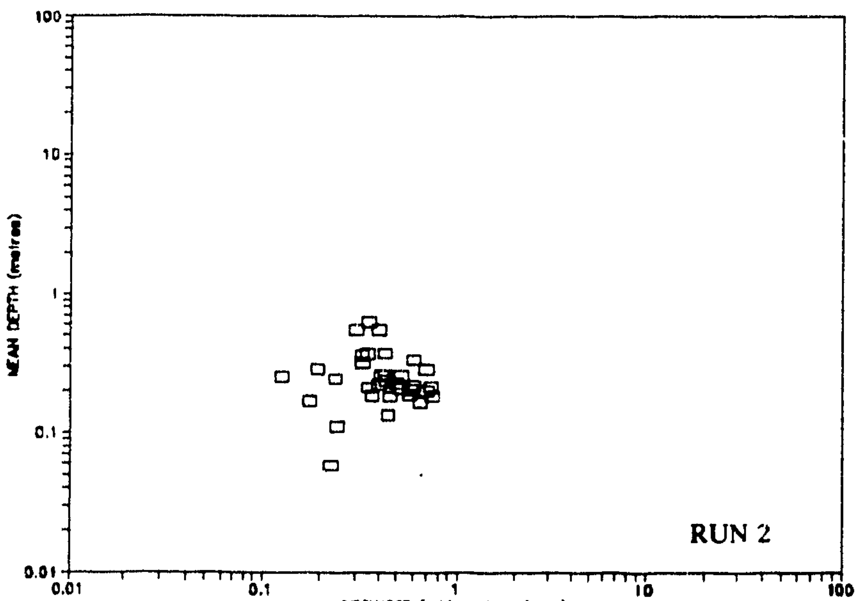
DISCHARGE (cubic metres / sec.)
RUN 1



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DISCHARGE (cubic metres / sec.)
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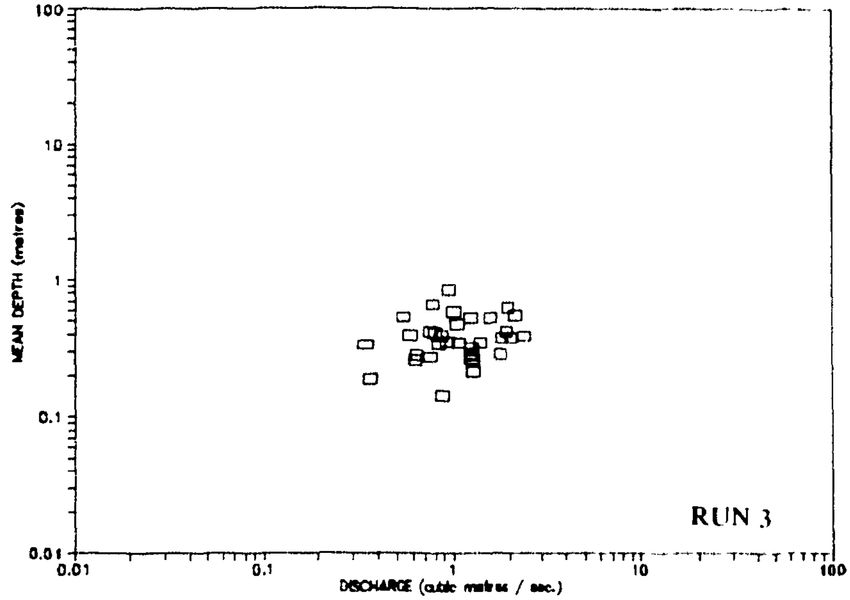

MEAN DEPTH (metres)
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DISCHARGE (cubic metres / sec.)
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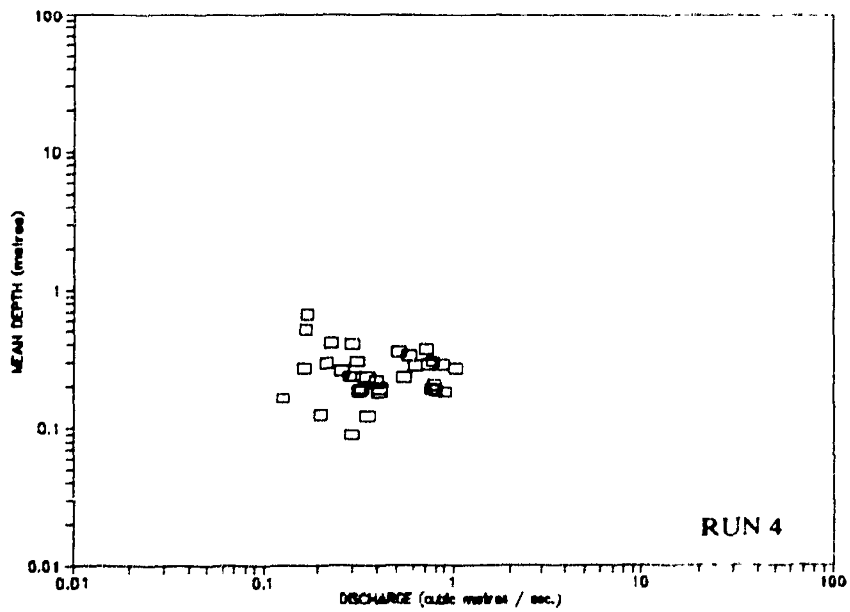

MEAN DEPTH (metres)
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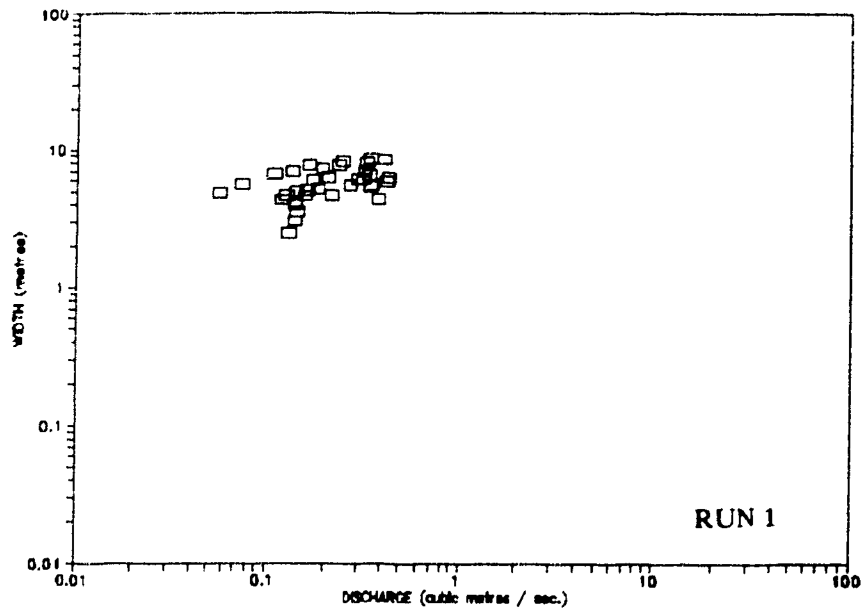
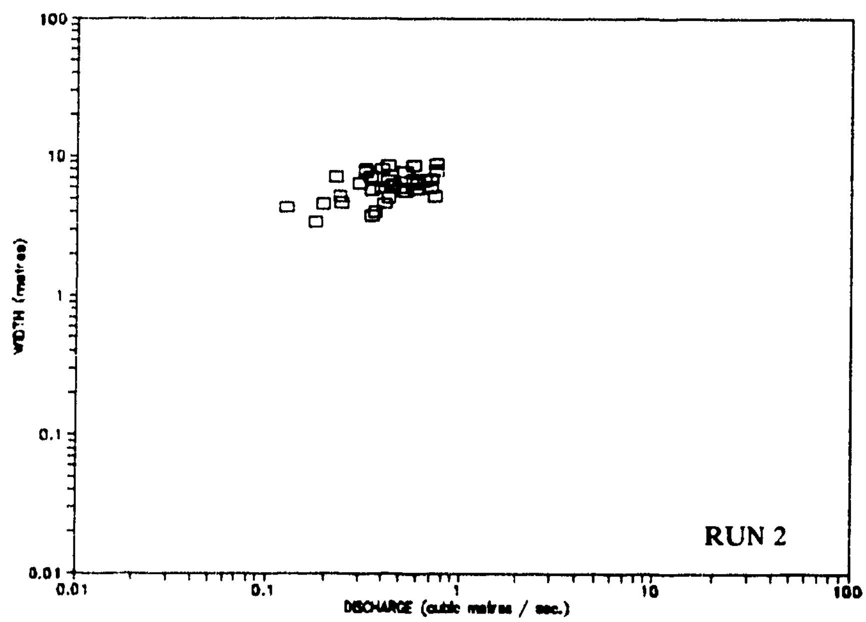
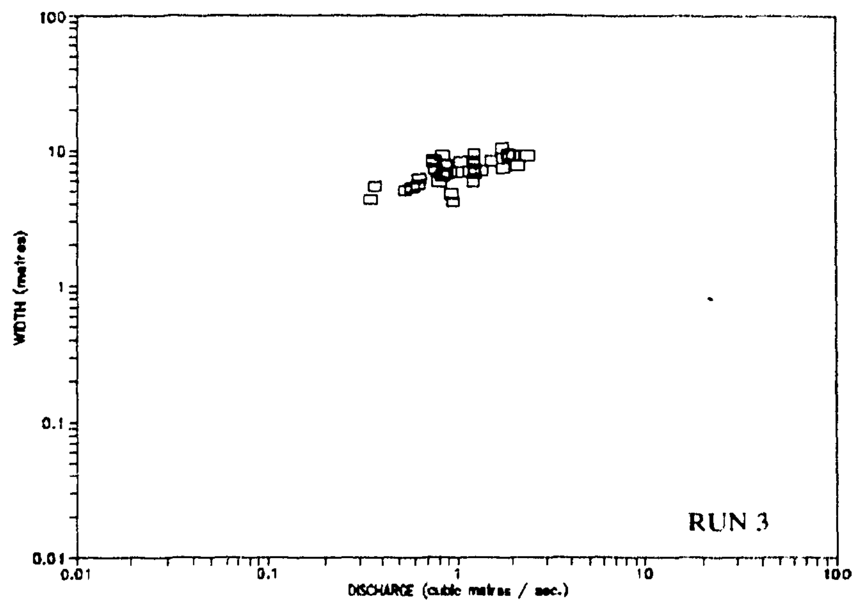
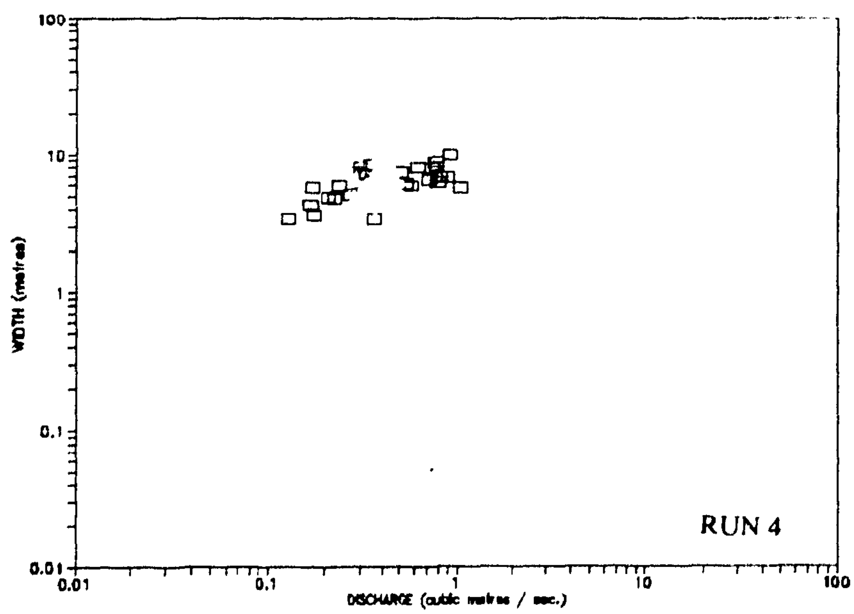
0.01
0.01
0.1
1
10
100
DISCHARGE (cubic metres / sec.)
RUN 4


100
10
1
0.1
0.01
WIDTH (metres)
0.01
0.1
1
10
100
DISCHARGE (cubic metres / sec.)
RUN 1


100
10
1
0.1
0.01
WIDTH (metres)
0.01
0.1
1
10
100
DISCHARGE (cubic metres / sec.)
RUN 2



100
10
1
0.1
0.01
WIDTH (metres)
RUN 3
0.01
0.1
1
10
100
DISCHARGE (cubic metres / sec.)



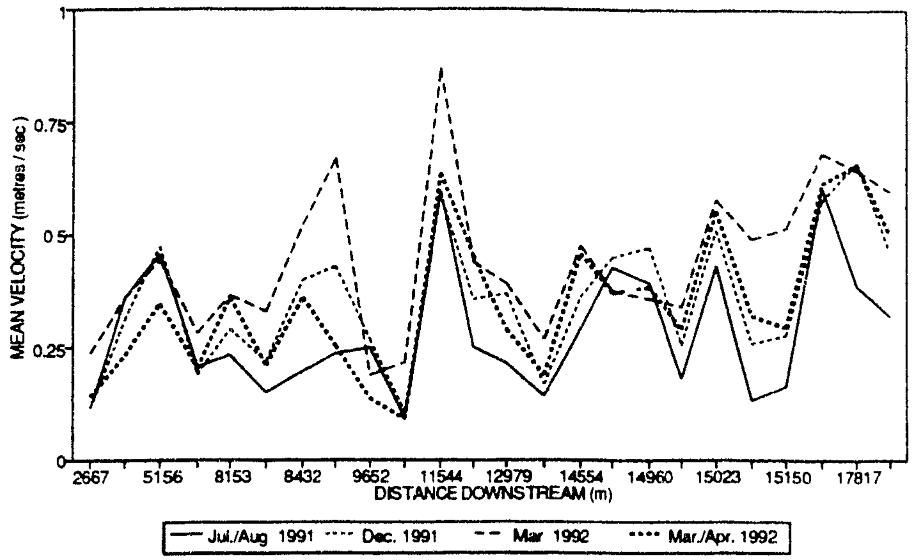
100
10
1
0.1
0.01
WIDTH (metres)
RUN 4
0.01
0.1
1
10
100
DISCHARGE (cubic metres / sec.)

Appendix 2

PLOTS OF FLUID SPEED, WIDTH, DEPTH AND DISCHARGE VERSUS DISTANCE DOWNSTREAM FOR BLACK CREEK/WEST CREDIT RIVER AND SILVER CREEK SITES

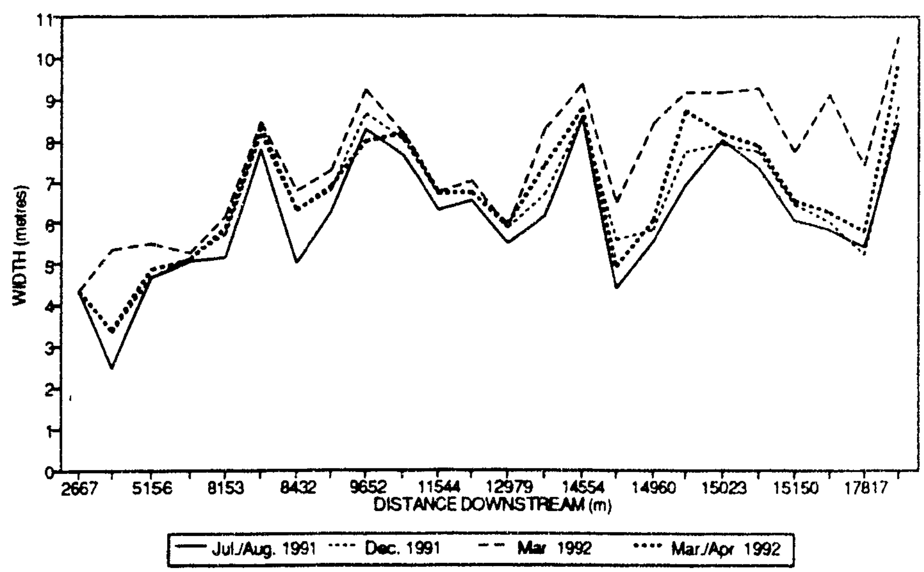
MEAN VELOCITY VS. DISTANCE

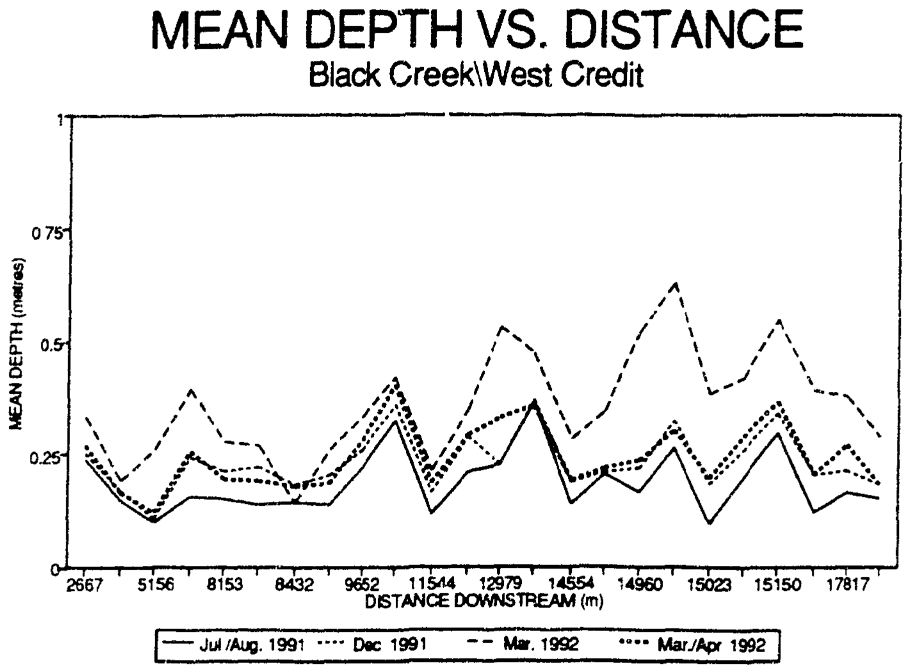
Black Creek\West Credit

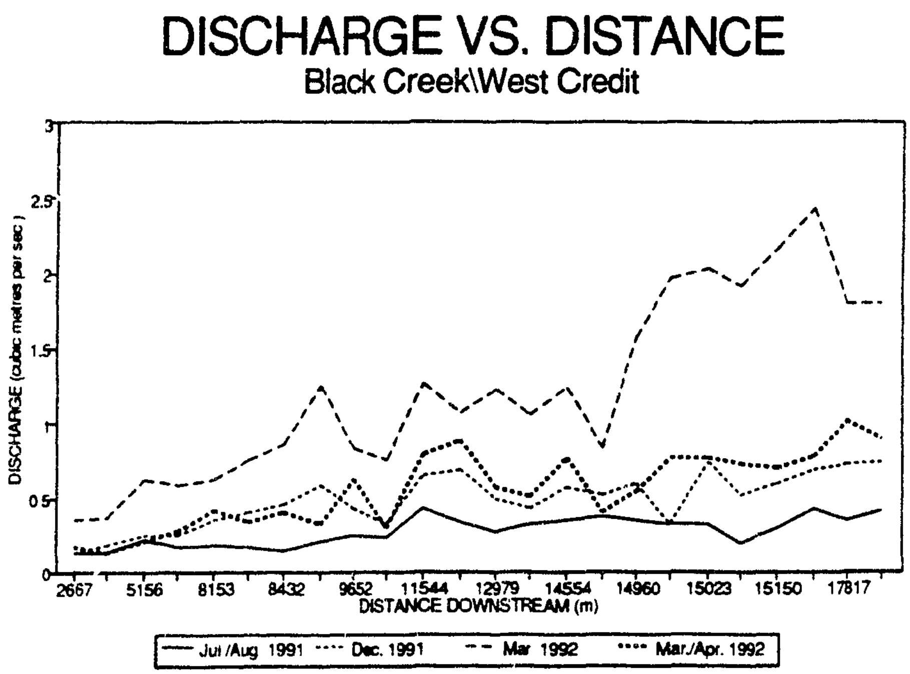


WIDTH VS. DISTANCE

Black Creek\West Credit

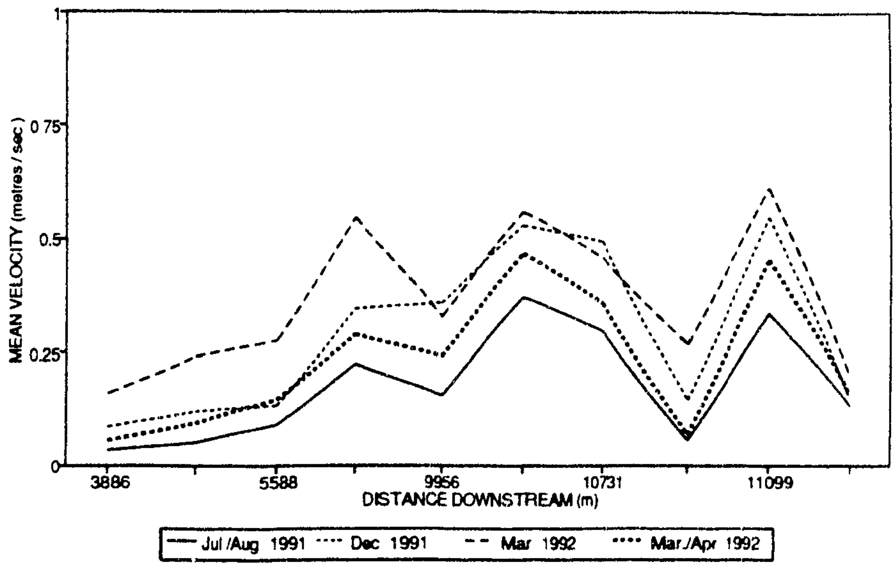



MEAN DEPTH VS. DISTANCE
Black Creek\West Credit
MEAN DEPTH (metres)
1
0.75
0.5
0.25
0
2667
5156
8153
8432
9652
11544
12979
14554
14960
15023
15150
17817
DISTANCE DOWNSTREAM (m)
Jul/Aug. 1991
Dec 1991
Mar. 1992
Mar./Apr 1992

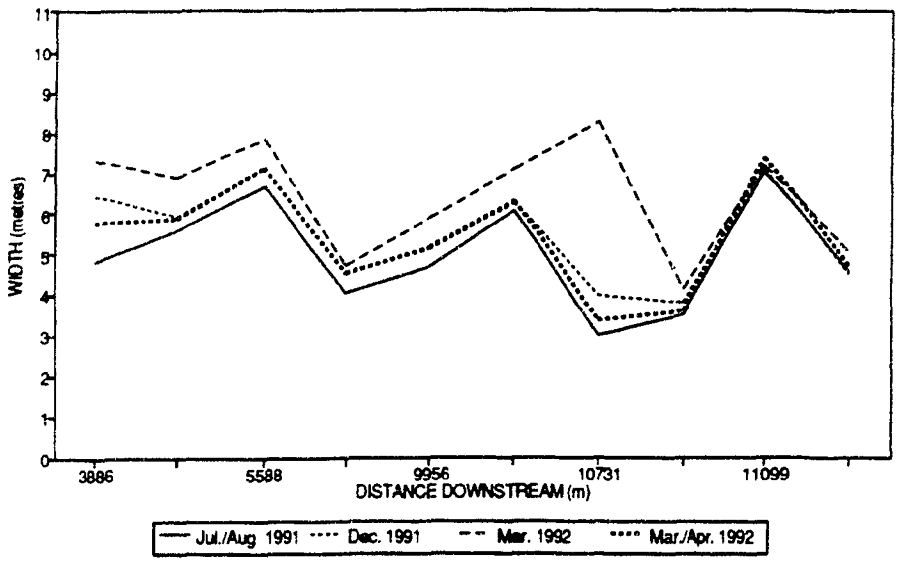

DISCHARGE VS. DISTANCE
Black Creek\West Credit
DISCHARGE (cubic metres per sec.)
3
2.5
2
1.5
1
0.5
0
2667
5156
8153
8432
9652
11544
12979
14554
14960
15023
15150
17817
DISTANCE DOWNSTREAM (m)
Jul/Aug 1991
Dec. 1991
Mar 1992
Mar./Apr. 1992

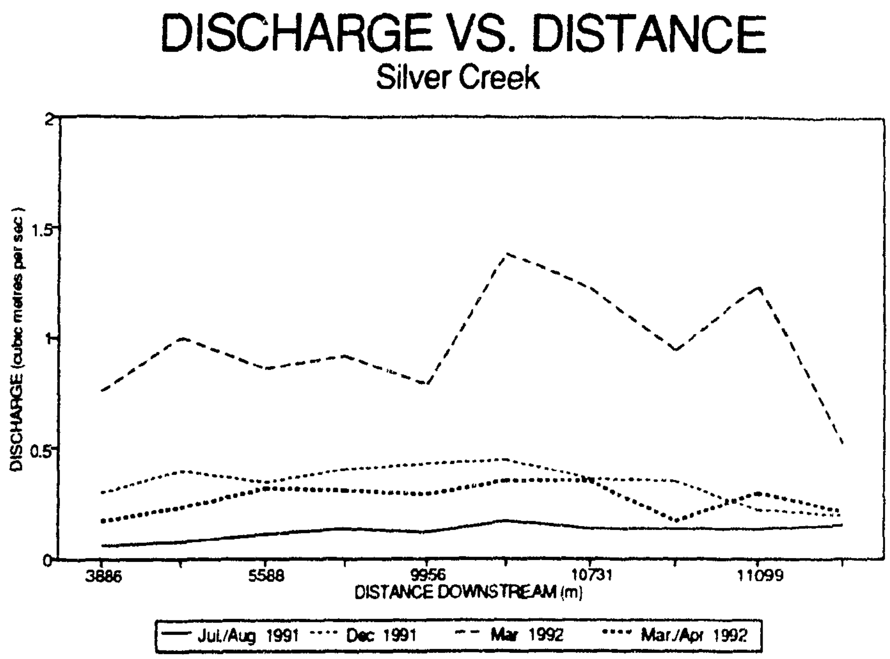
MEAN VELOCITY VS. DISTANCE

Silver Creek

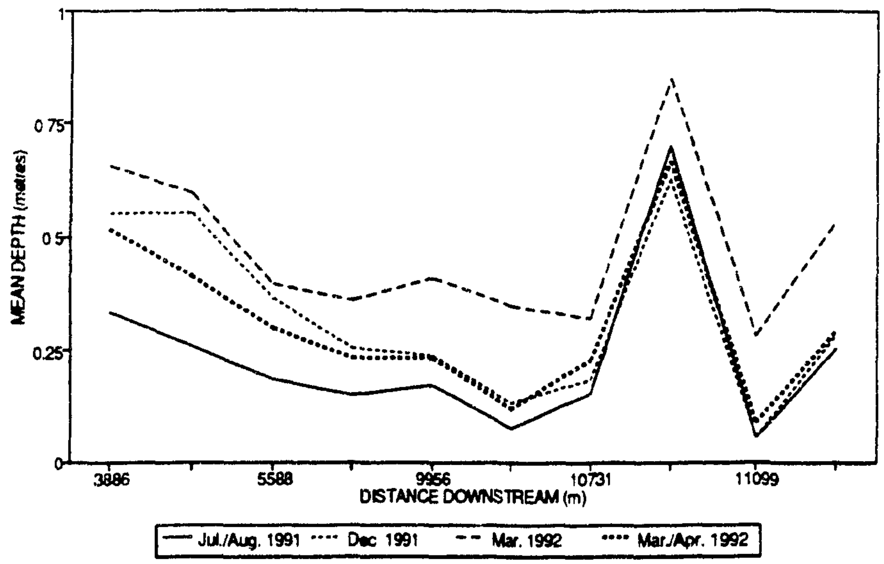


WIDTH VS. DISTANCE
Silver Creek



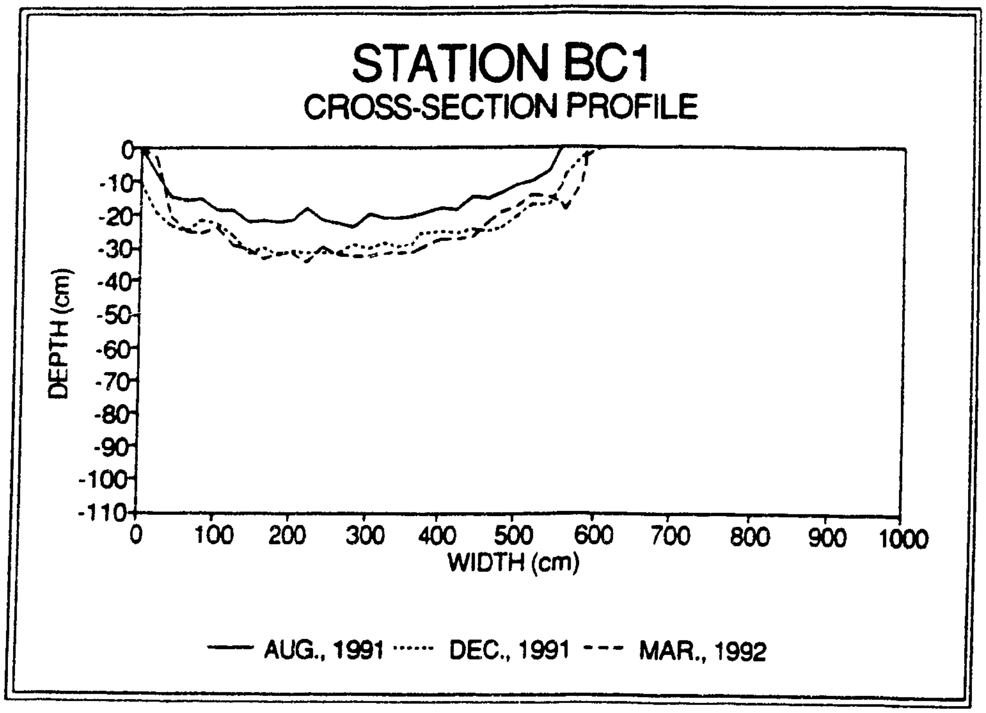

DISCHARGE VS. DISTANCE
Silver Creek
DISCHARGE (cubic metres per sec.)
2
1.5
1
0.5
0
3886
5588
9956
10731
11099
DISTANCE DOWNSTREAM (m)
Jul/Aug 1991
Dec 1991
Mar 1992
Mar./Apr 1992

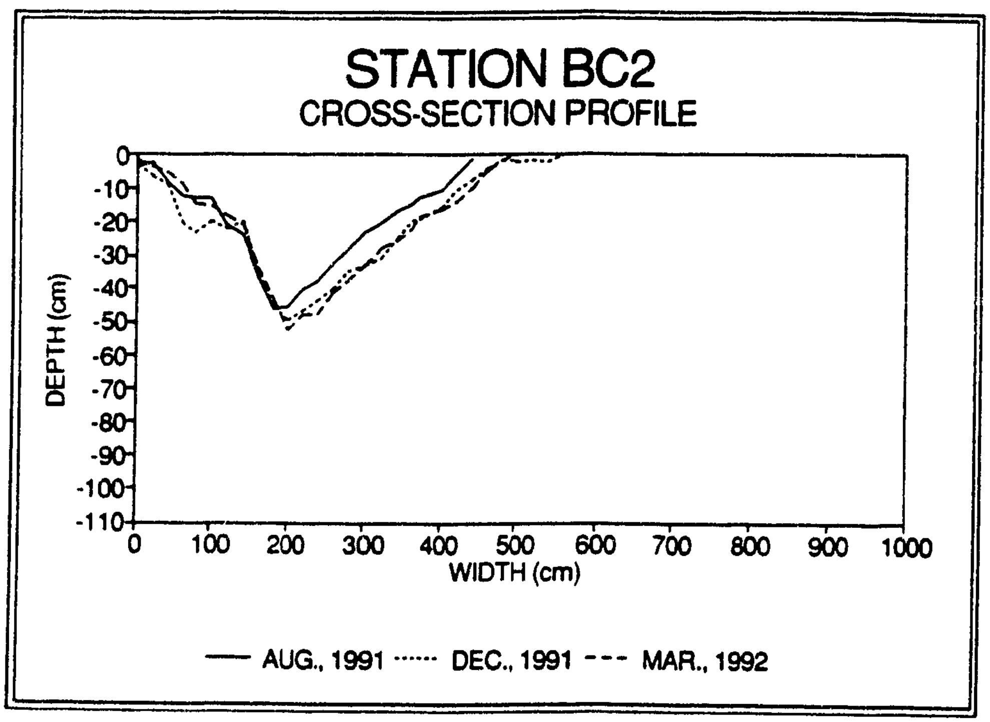
MEAN DEPTH VS. DISTANCE
Silver Creek

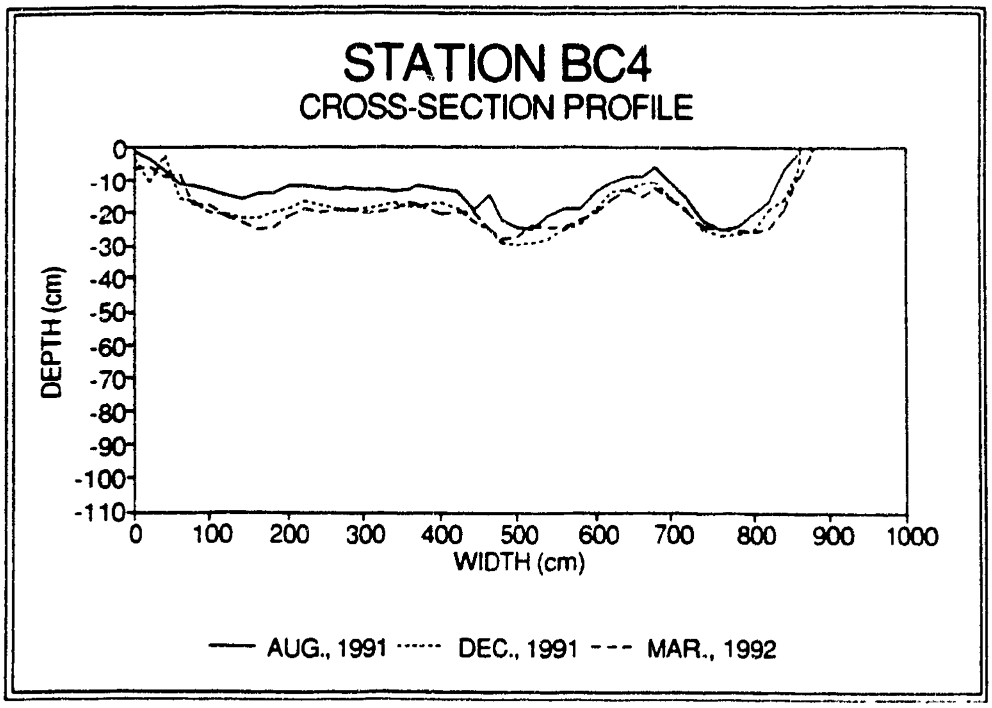


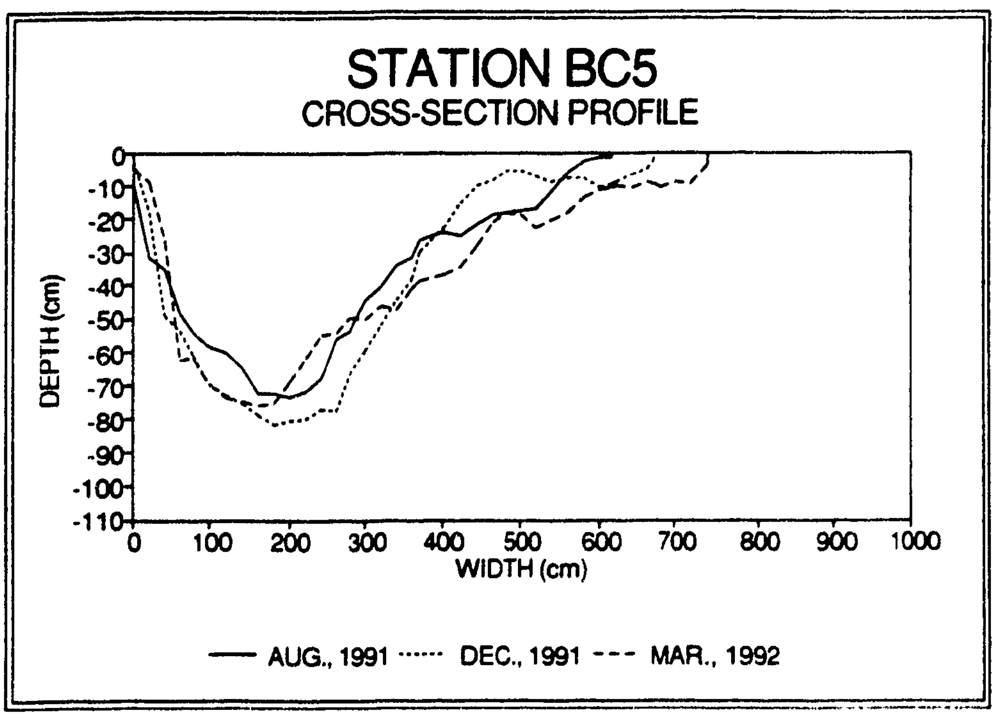
Appendix 3

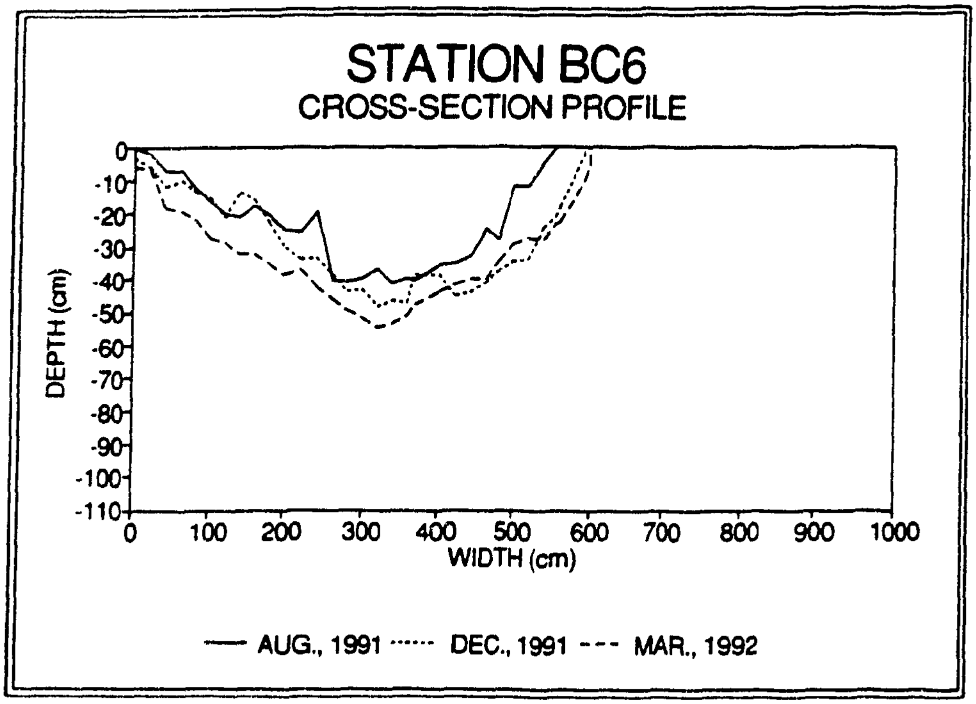
CROSS-SECTIONAL CHANNEL PROFILES FOR EACH SAMPLING STATION UNDER THREE SAMPLING REGIMES

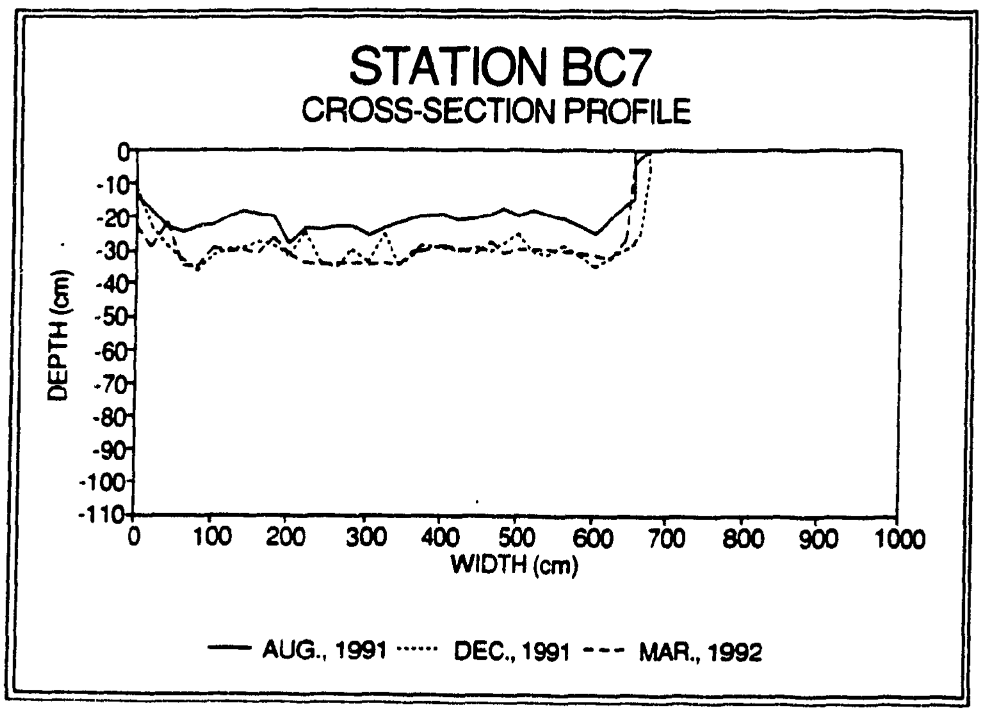

STATION BC1
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

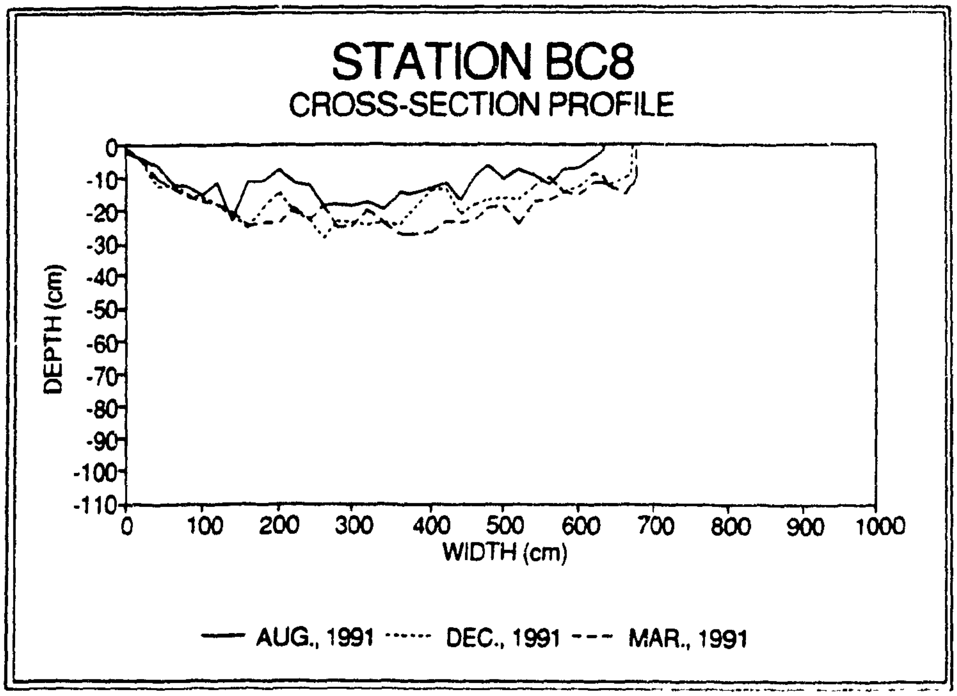

STATION BC2
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

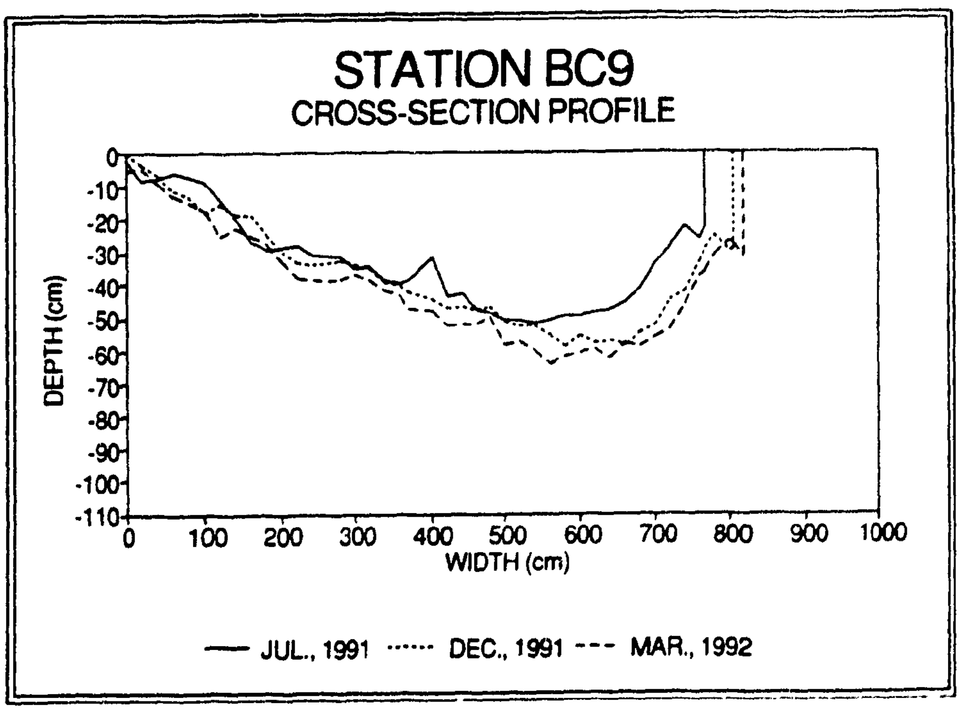

STATION BC4
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0 100 200 300 400 500 600 700 800 900 1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

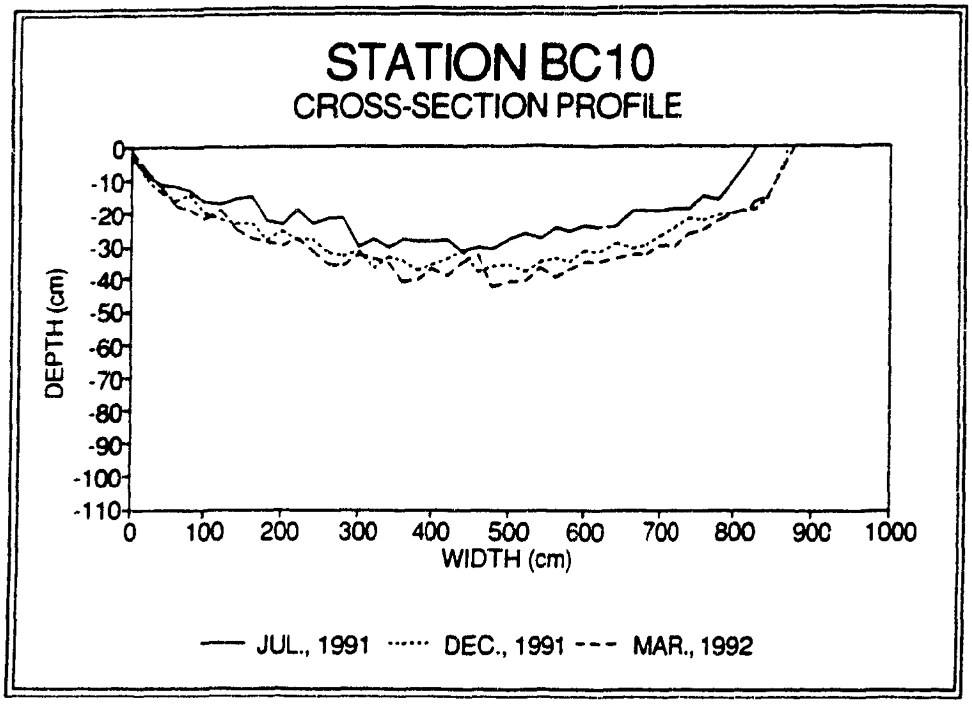

STATION BC5
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0 100 200 300 400 500 600 700 800 900 1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

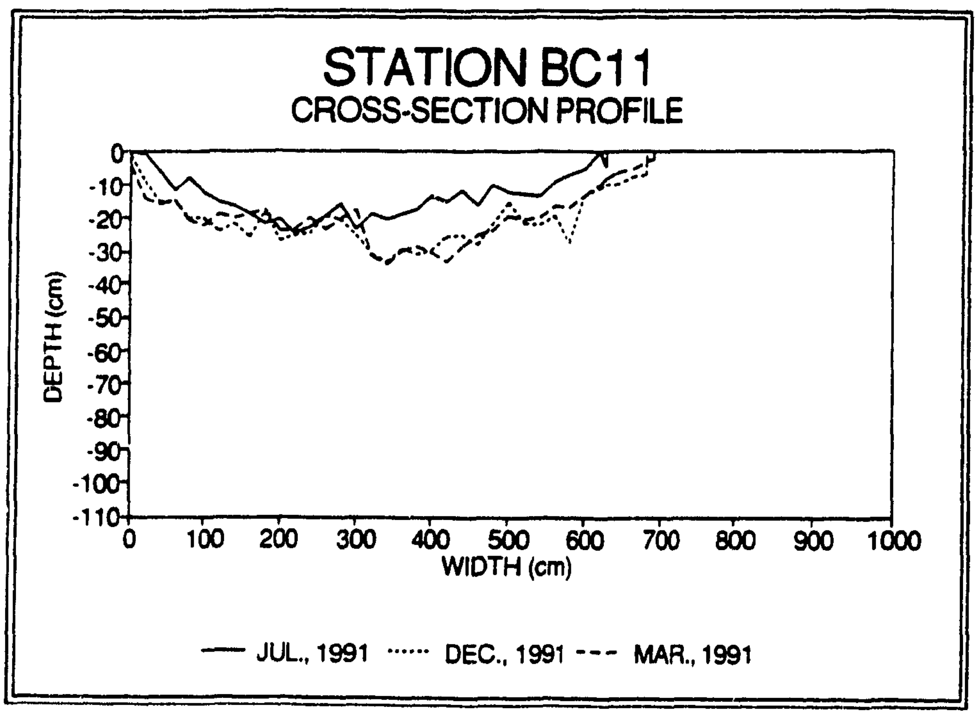

STATION BC6
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

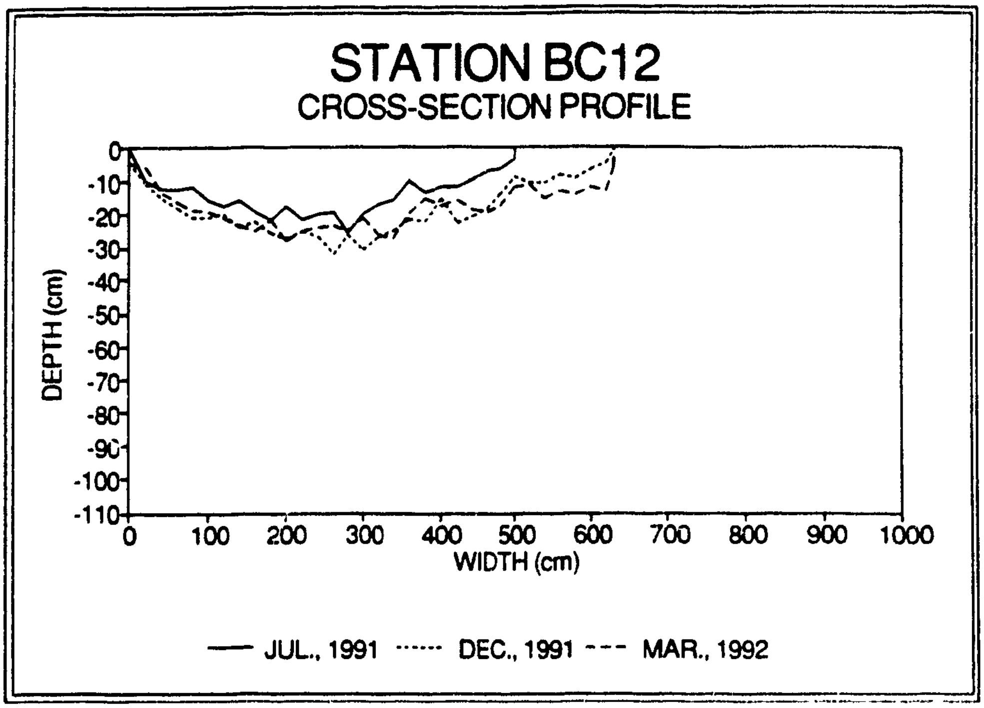

STATION BC7
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

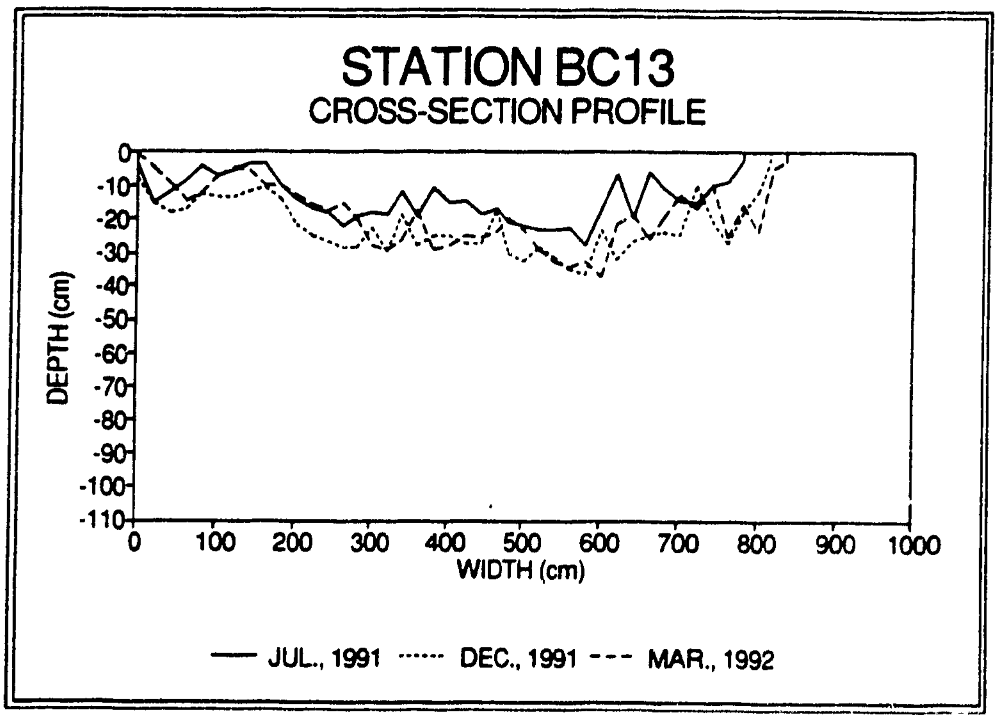

STATION BC8
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1991

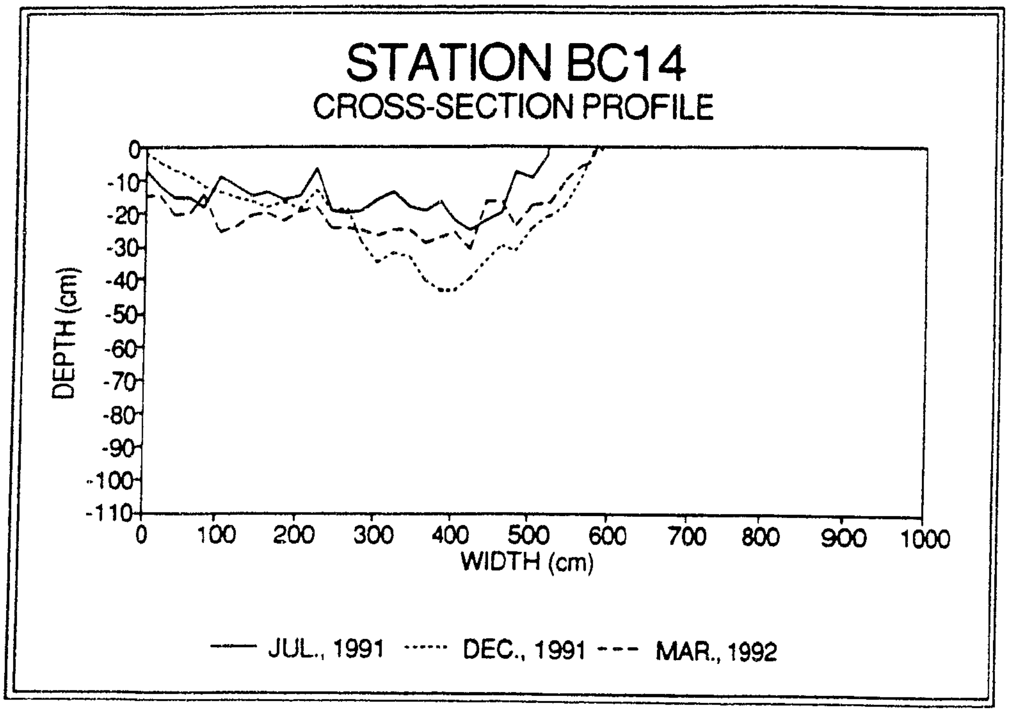

STATION BC9
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
JUL., 1991
DEC., 1991
MAR., 1992

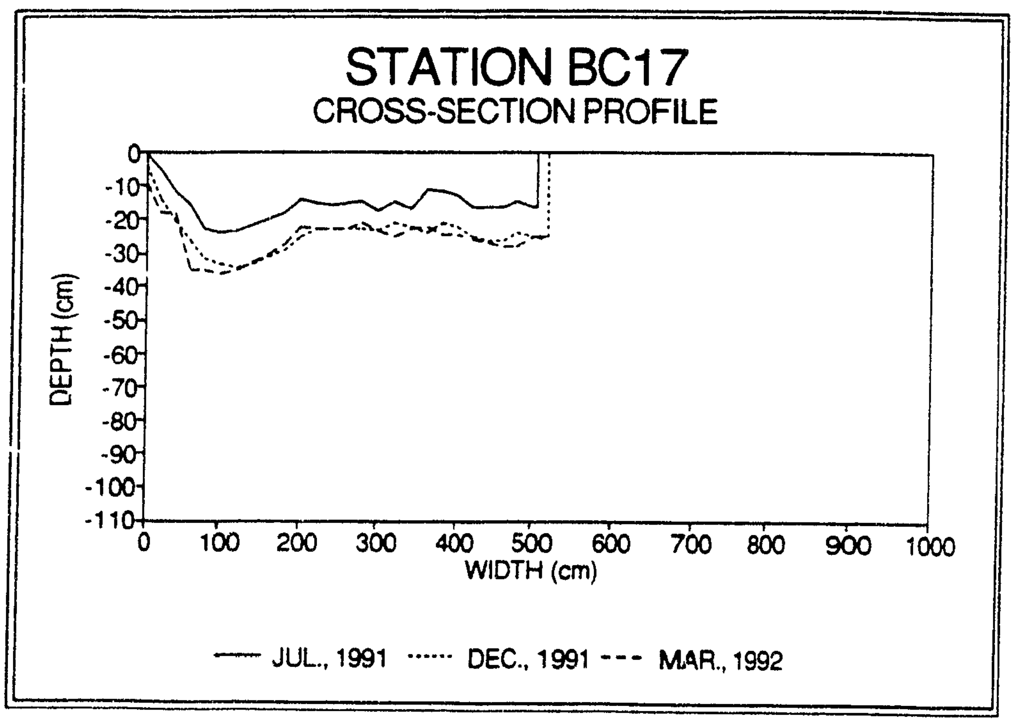

STATION BC10
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
JUL., 1991
DEC., 1991
MAR., 1992

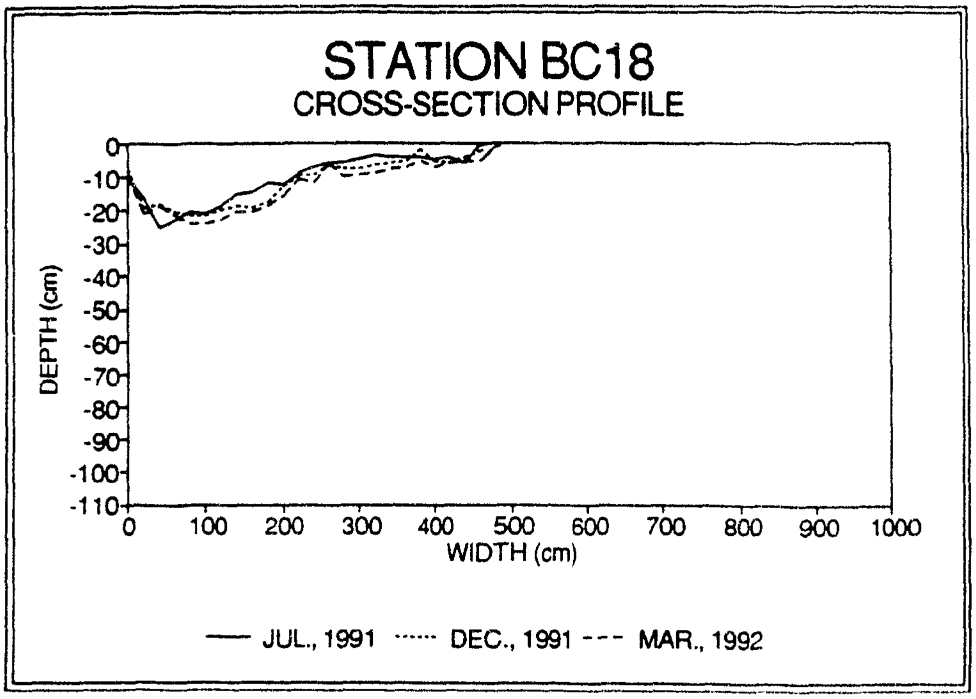

STATION BC11
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
JUL., 1991
DEC., 1991
MAR., 1991

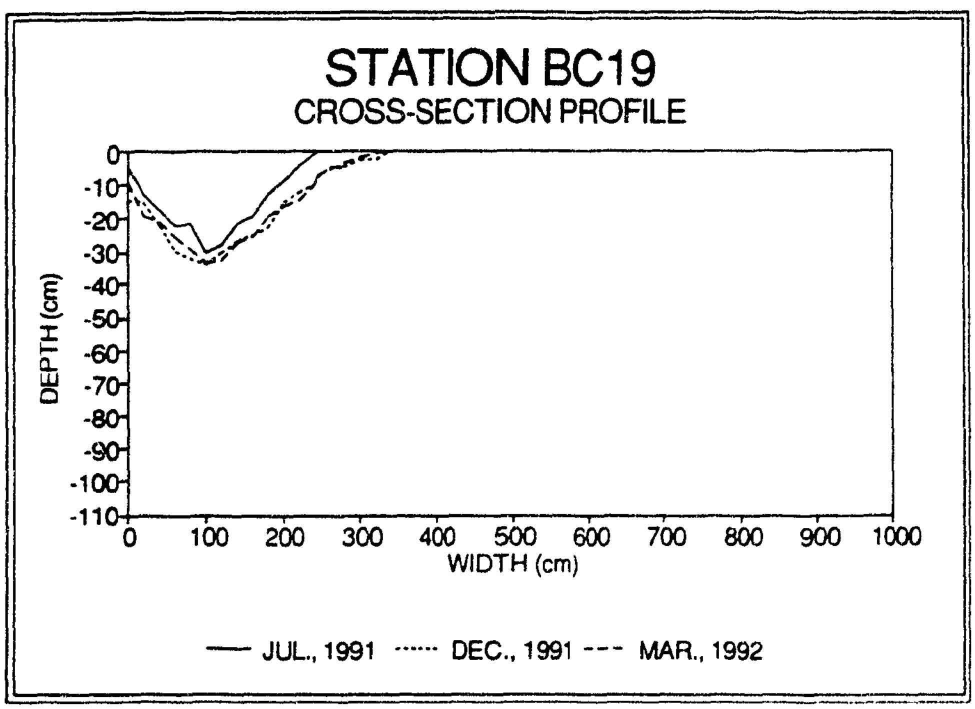

STATION BC12
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
JUL., 1991
DEC., 1991
MAR., 1992

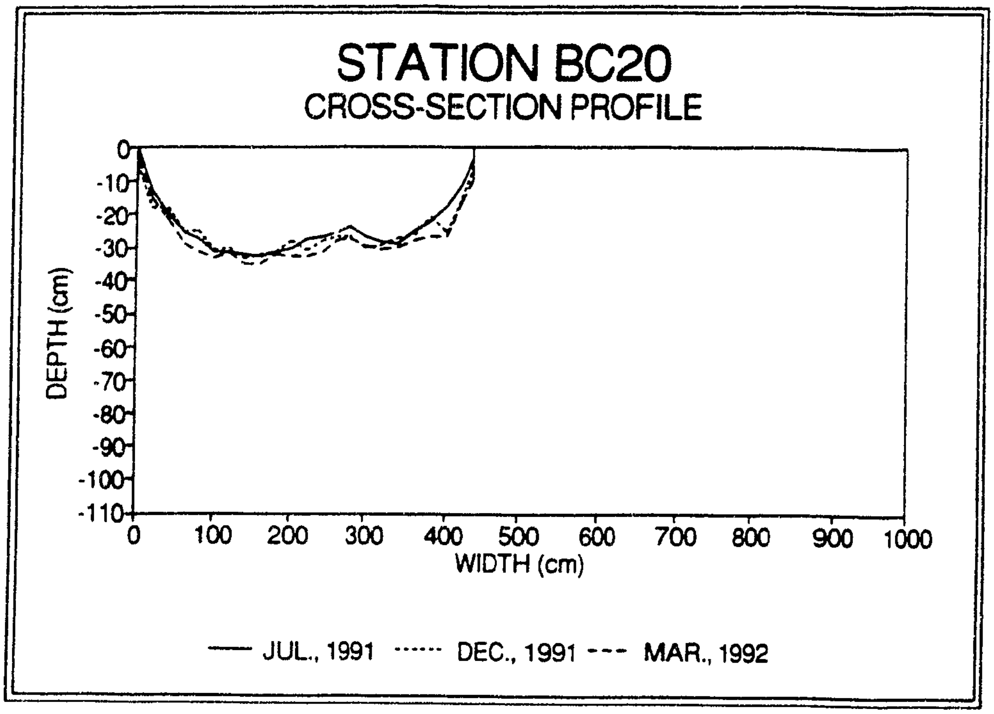

STATION BC13
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
JUL., 1991
DEC., 1991
MAR., 1992

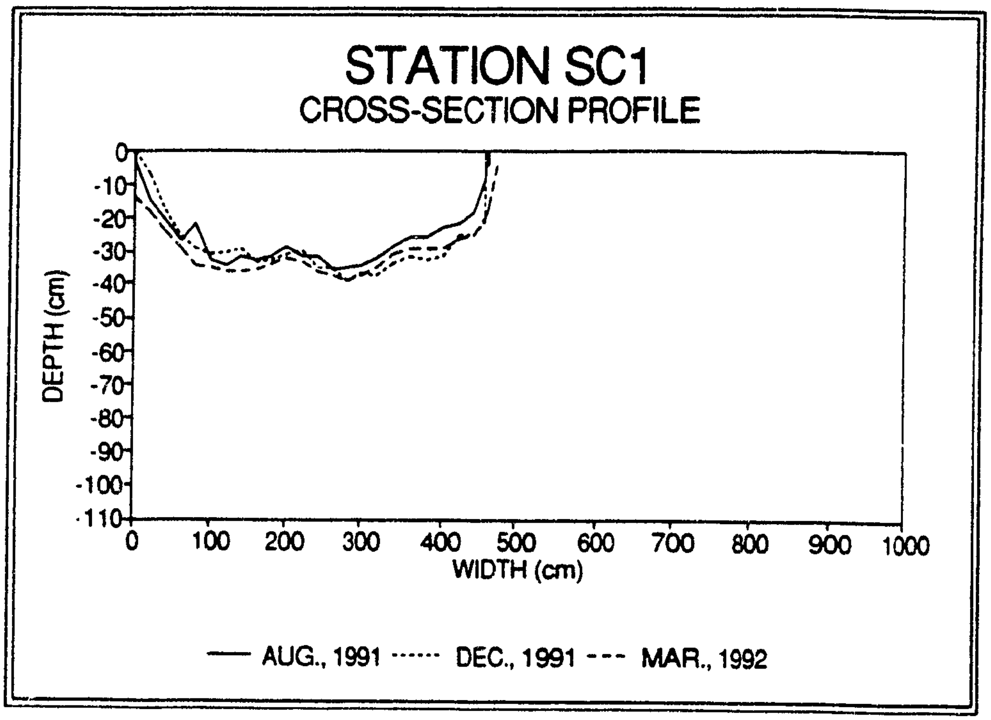

STATION BC14
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
JUL., 1991
DEC., 1991
MAR., 1992

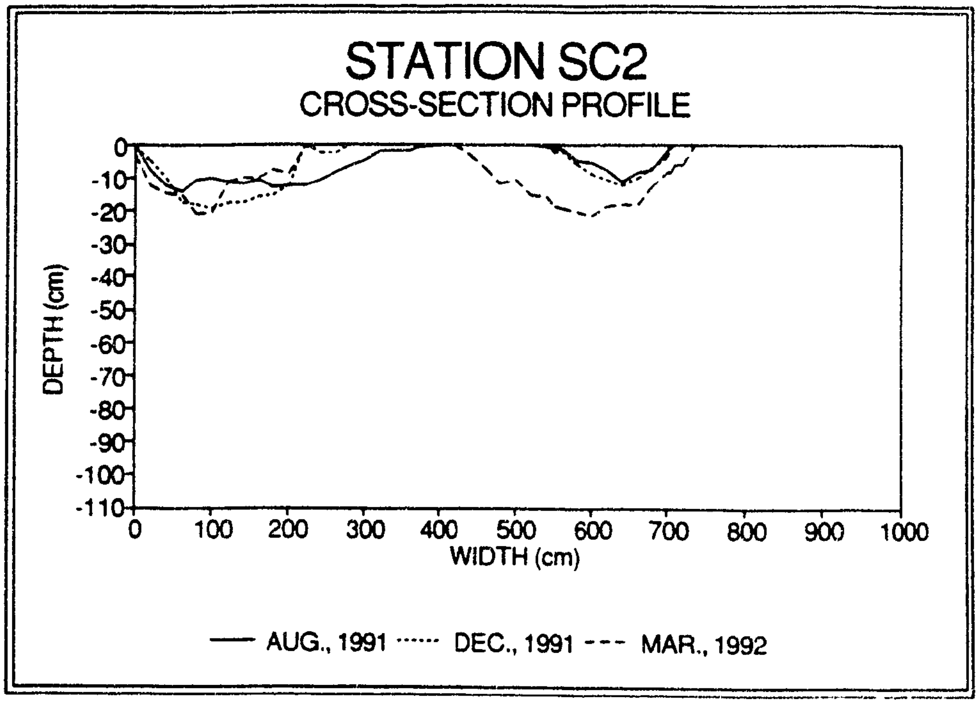

STATION BC17
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
JUL., 1991
DEC., 1991
MAR., 1992

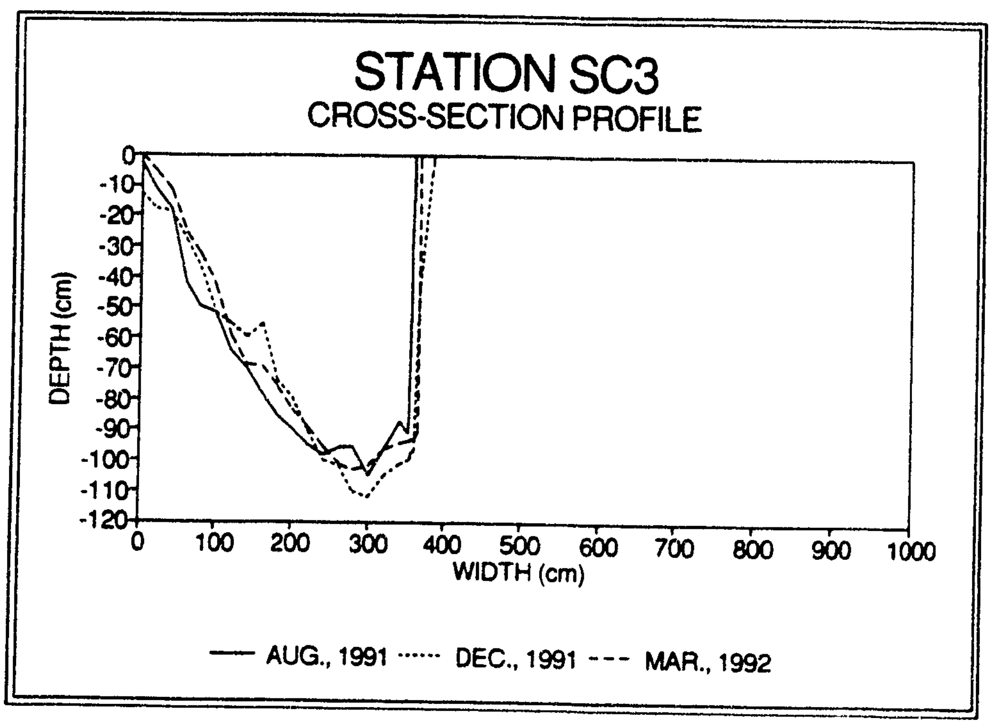

STATION BC18
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
JUL., 1991
DEC., 1991
MAR., 1992

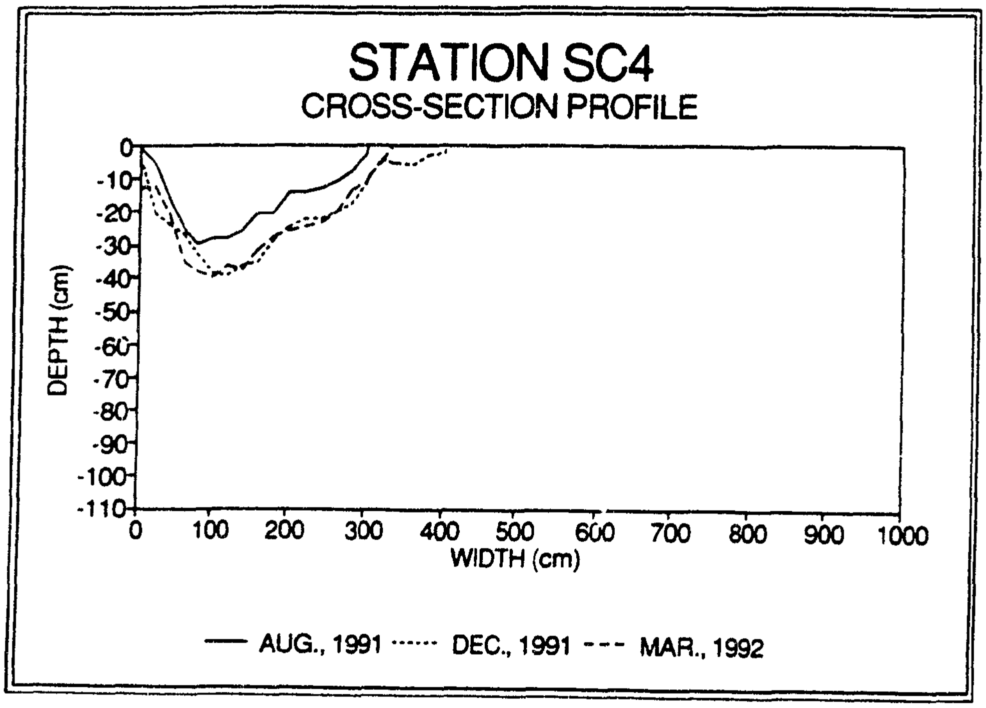

STATION BC19
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
JUL., 1991
DEC., 1991
MAR., 1992

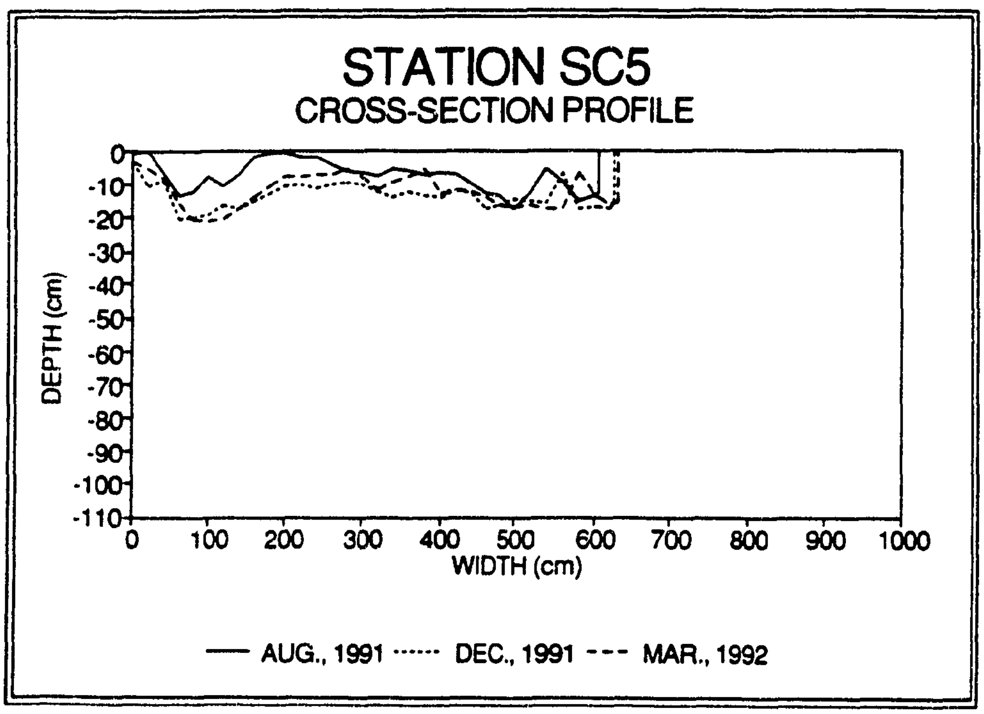

STATION BC20
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
JUL., 1991
DEC., 1991
MAR., 1992

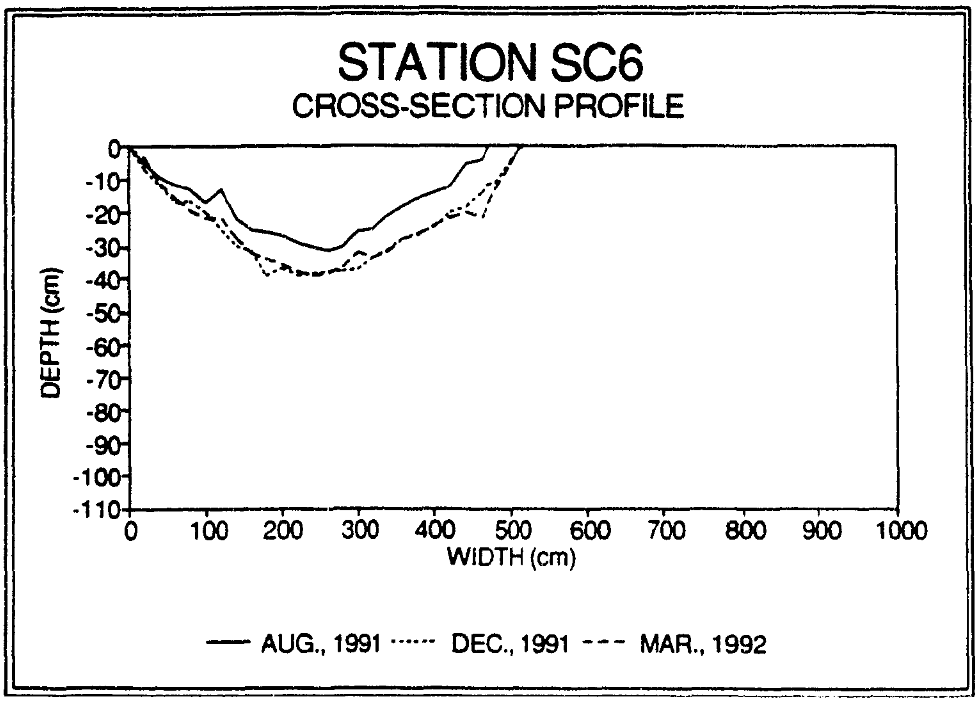

STATION SC1
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

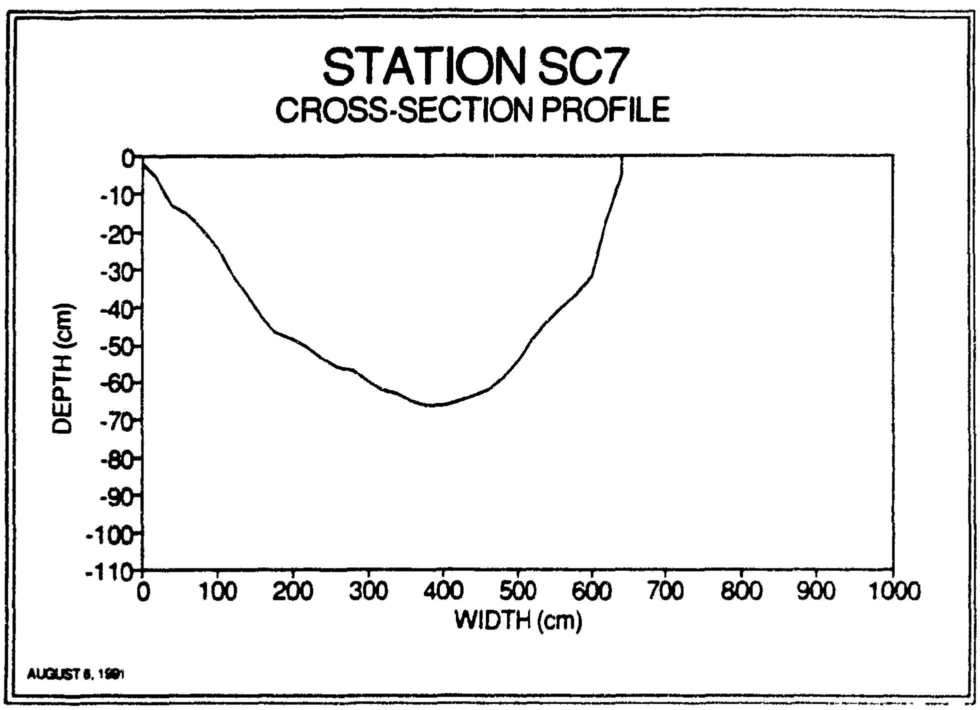

STATION SC2
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0 100 200 300 400 500 600 700 800 900 1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

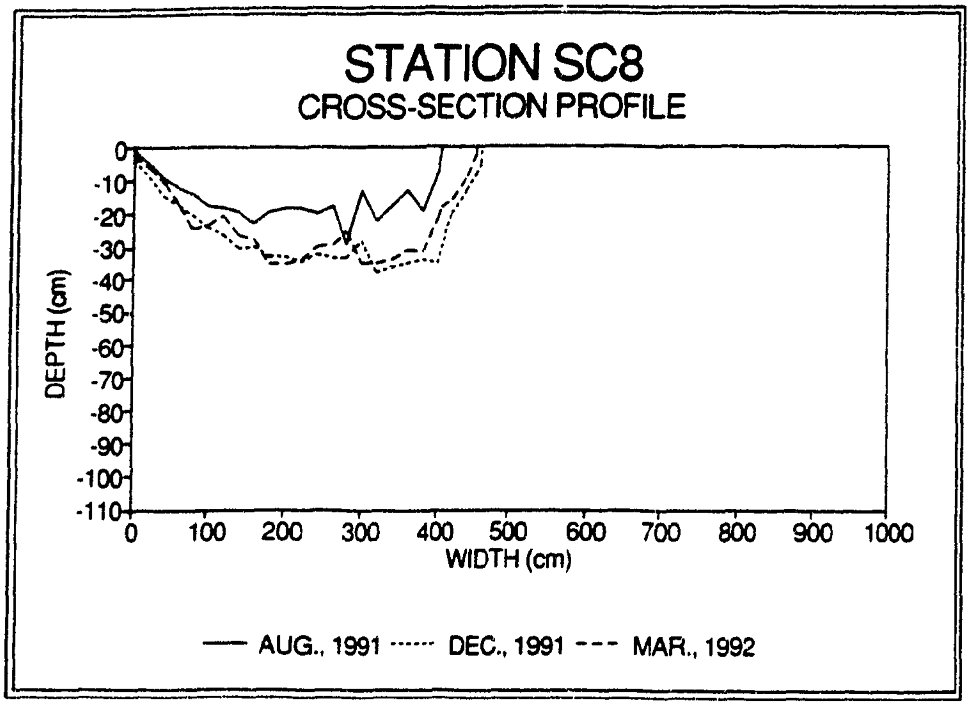

STATION SC3
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
0 100 200 300 400 500 600 700 800 900 1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

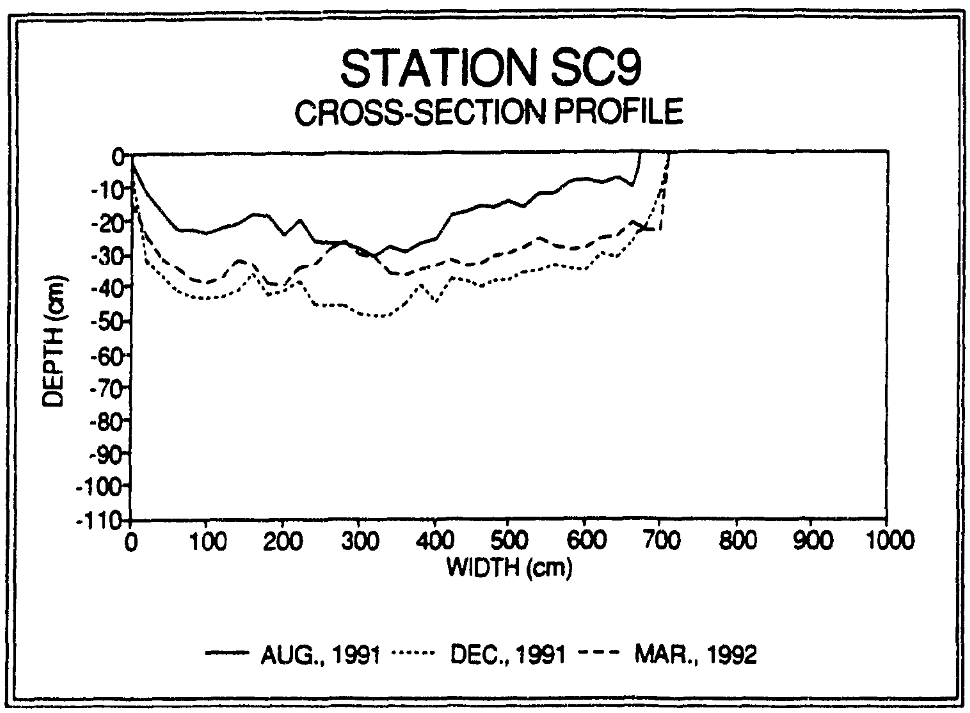

STATION SC4
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

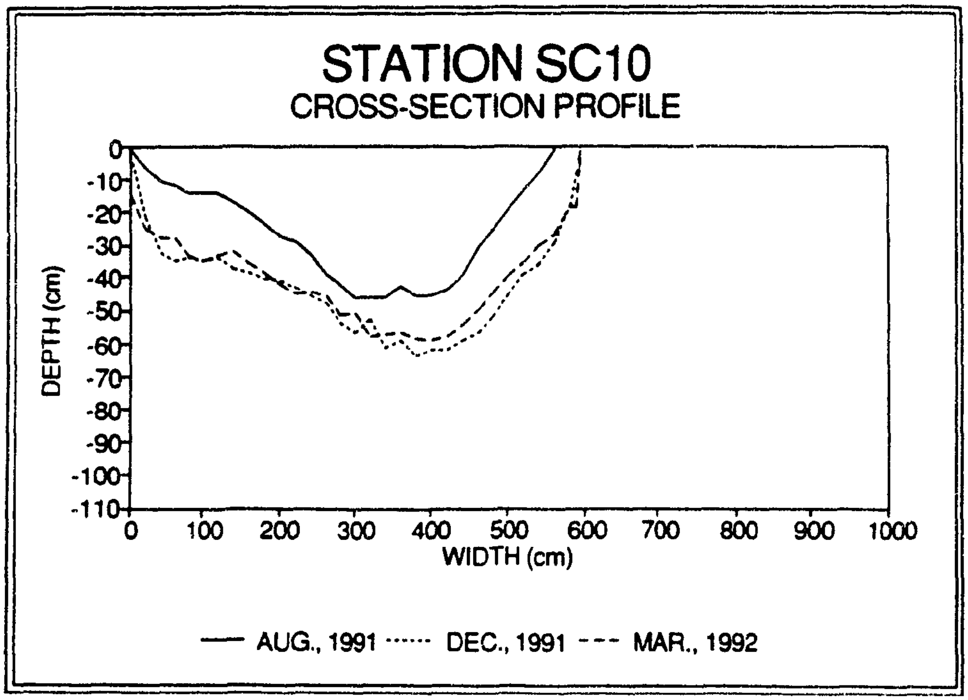

STATION SC5
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

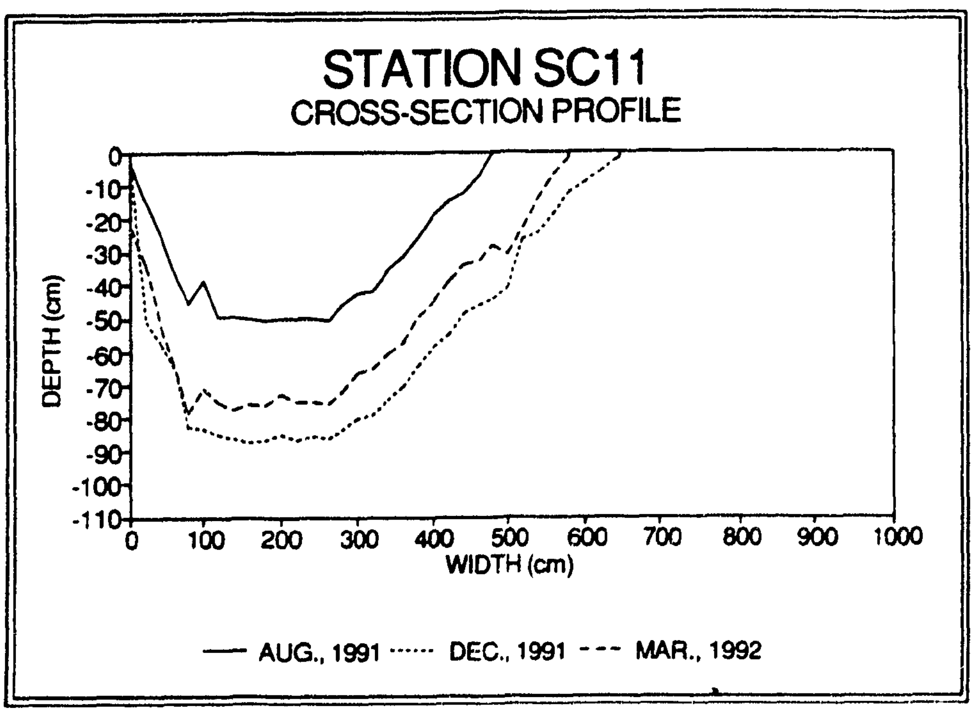

STATION SC6
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

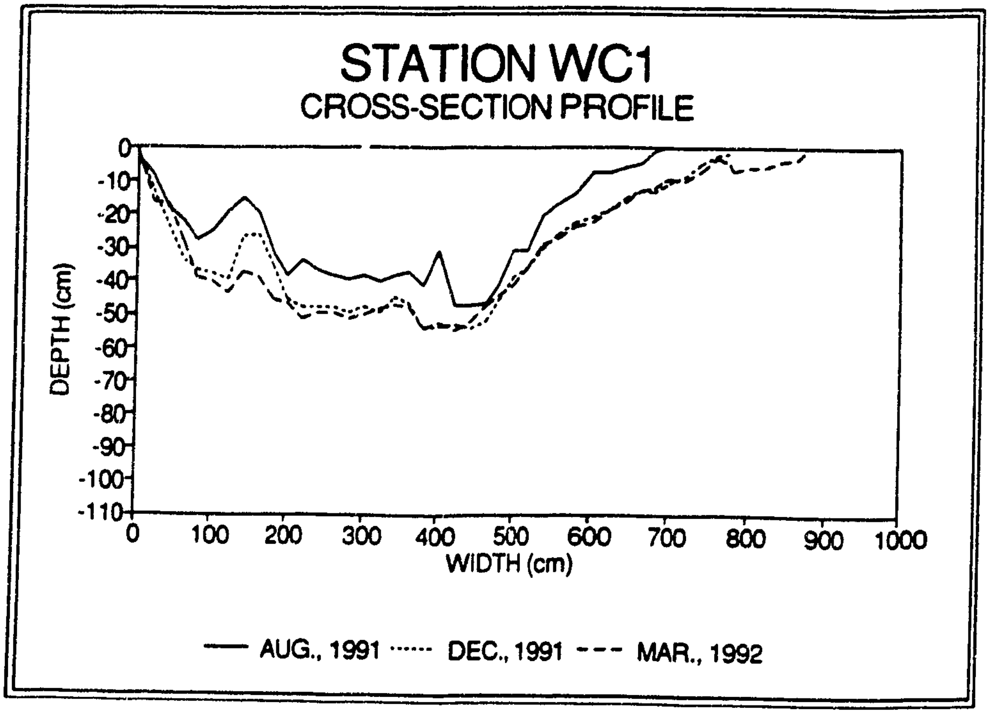

STATION SC7
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)

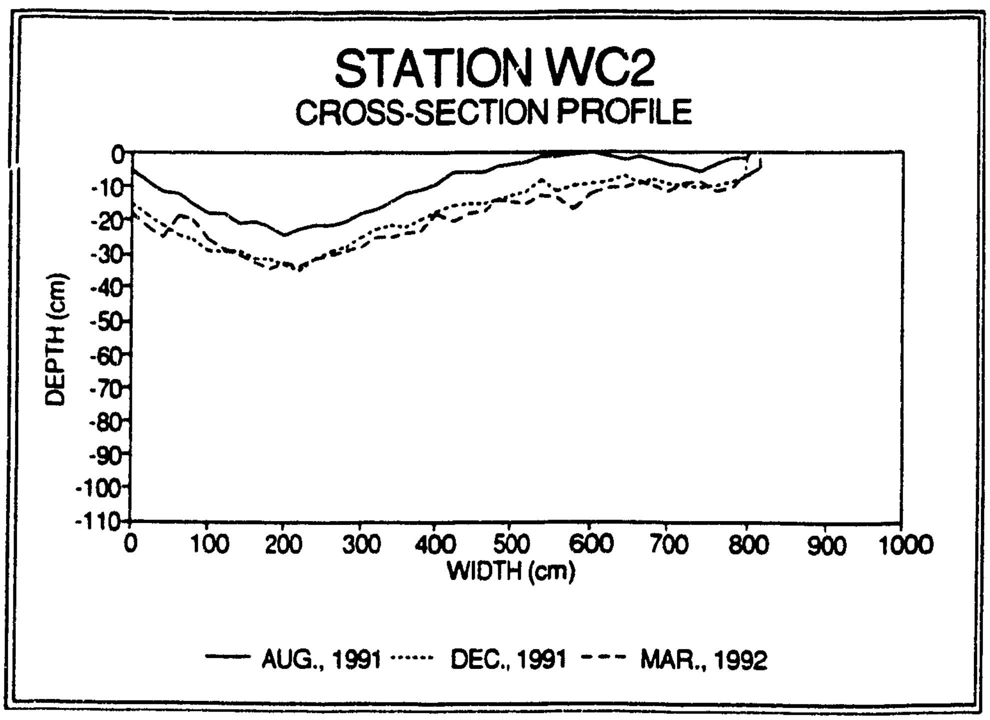

STATION SC8
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

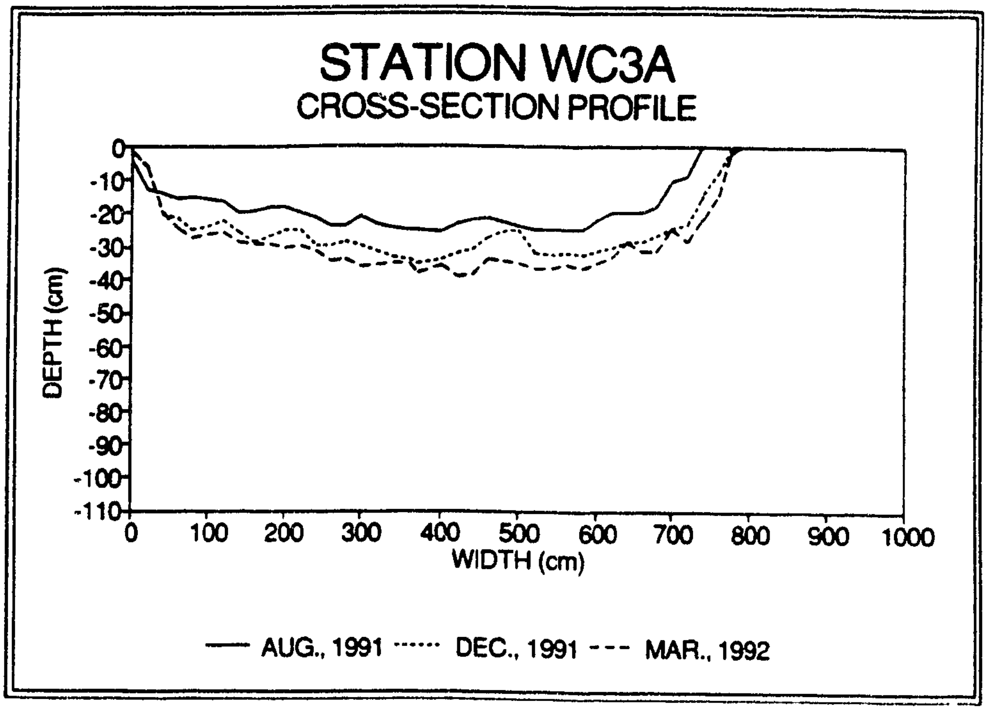

STATION SC9
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

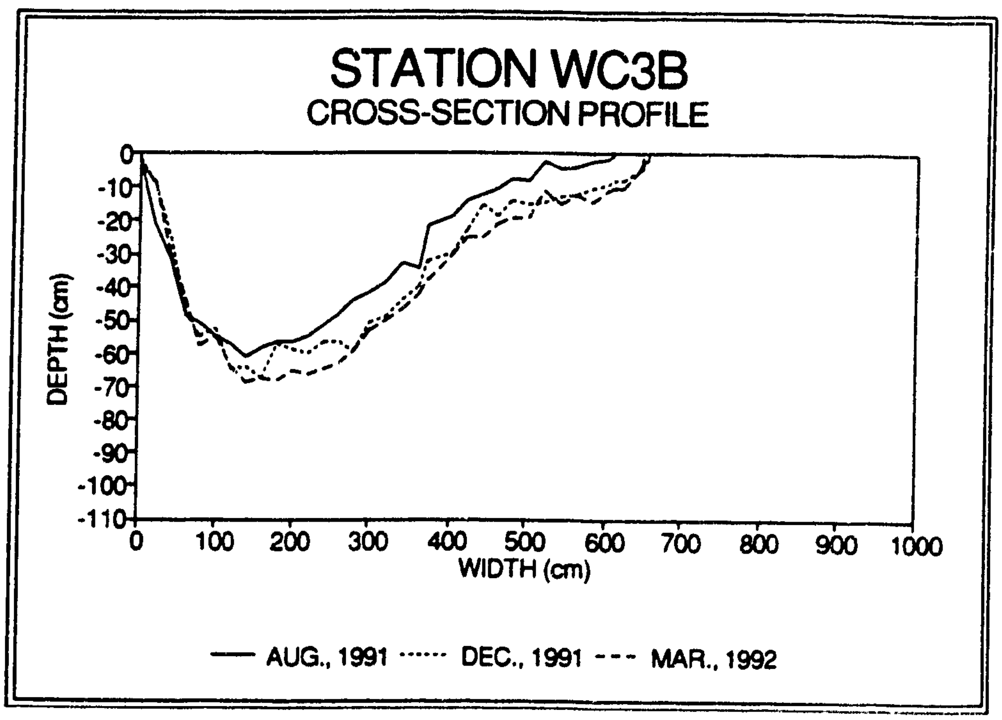

STATION SC10
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

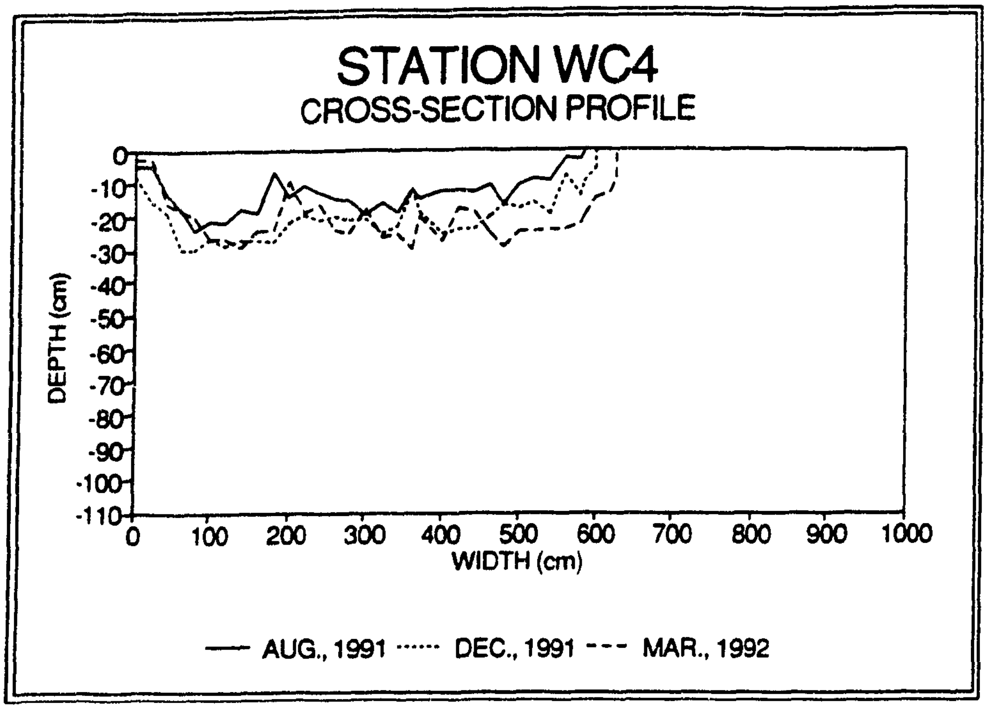

STATION SC11
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

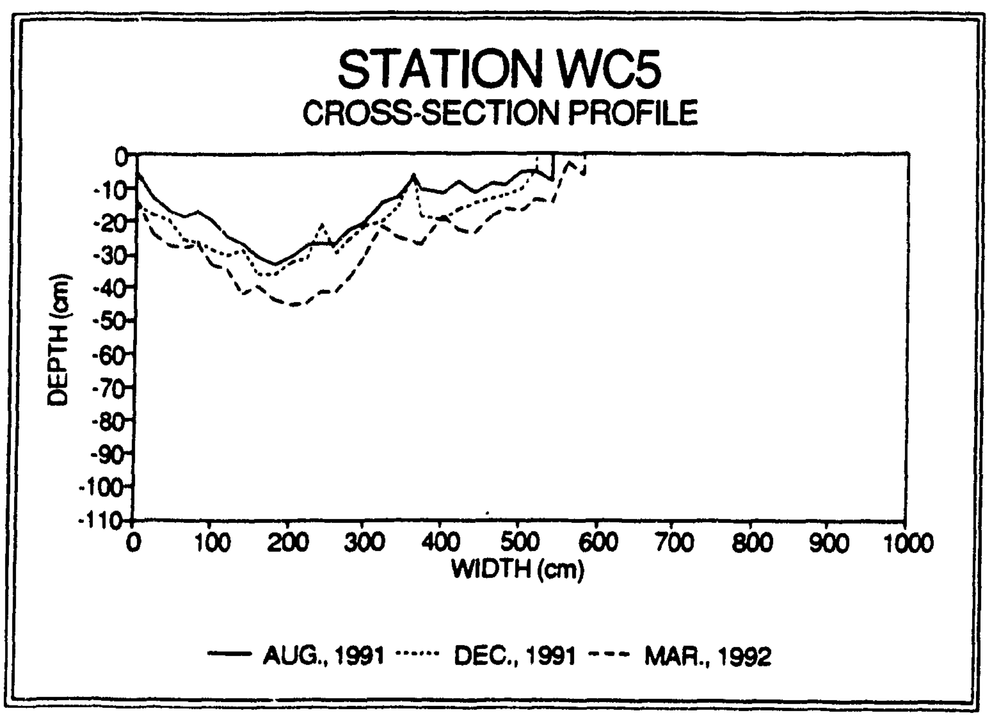

STATION WC1
CROSS-SECTION PROFILE
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
DEPTH (cm)
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992

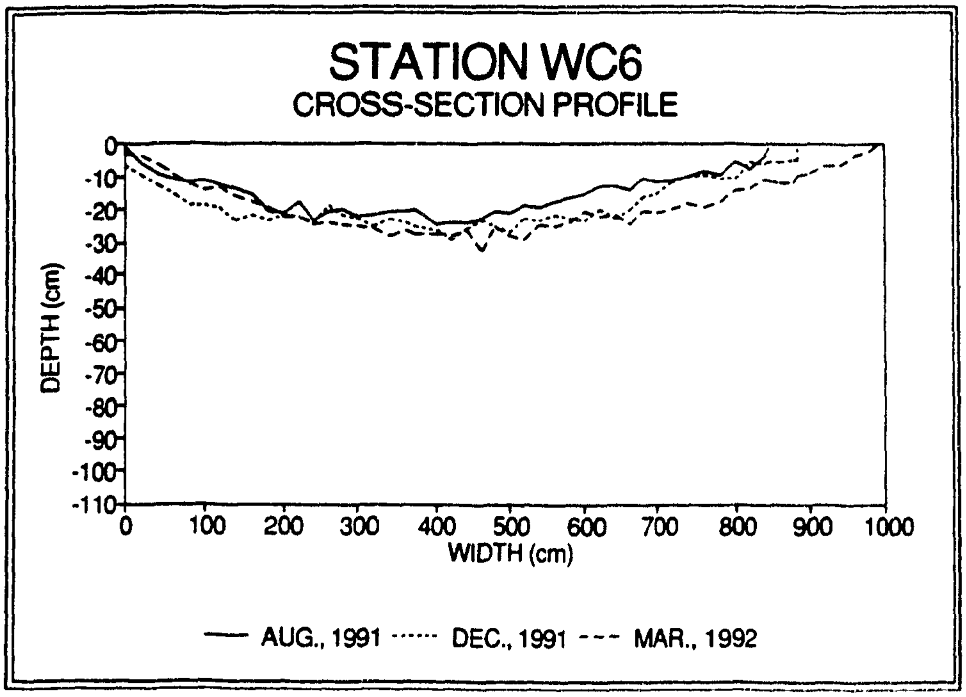

STATION WC2
CROSS-SECTION PROFILE
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
DEPTH (cm)
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992


STATION WC3A
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992


STATION WC3B
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992


STATION WC4
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992


STATION WC5
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992


STATION WC6
CROSS-SECTION PROFILE
DEPTH (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
0
100
200
300
400
500
600
700
800
900
1000
WIDTH (cm)
AUG., 1991
DEC., 1991
MAR., 1992