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Sediment Intrusion and Deposition Near Road Crossings In Small Foothill Streams in West Central Alberta

by

Liane C. Spillios ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Master of Science

in

Water and Land Resources.

Department of Renewable Resources

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Sediment Intrusion and Deposition Near Road Crossings in Small Foothill Streams in West Central Alberta submitted by Liane Celine Spillios in partial fulfilment of the requirement for the degree of Master of Science in Water and Land Resources.

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Date August 30, 1999

In memory of my mother, Ann.

Abstract

The objective of this study was to determine the effect of road crossings on fine sediment < 2 mm in diameter in stream substrates downstream of crossings in first to third order streams. Streambed material from upstream and downstream of 15 crossings in foothill streams of west central Alberta were sampled over two years using freeze core sampling techniques modified for the study area. Paired t-tests indicated more fine sediment downstream of narrow stream crossings (streams < 2.5 m wide) than upstream in both study years (P=0.11 and P=.03). Fine sediment differences were larger, and P-values smaller in the second year because greater sample volumes were taken closer to crossings than in the previous year. Increased sand downstream of crossings in narrow streams is large (up to 30 %) compared to silt and clay in many streams (up to 8 %). Five out of 8 narrow study streams warrant further investigation.

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Introduction

Salmonids, members of the Salmonidae family including char, trout, grayling, whitefish, and salmon are important for recreational and commercial fisheries in North America (Meehan 1991). In Alberta, the provincial government has identified bull trout (*Salvelinus confluentus* (Suckley)) as a species of special concern (Alberta Environmental Protection 1994a) and protected it by setting sport fishing harvest limits to zero (Alberta Environmental Protection 1997). It is believed by some that salmonid habitat in Alberta has declined over the last several decades. It is possible that the extensive network of resource extraction roads in the foothills could be a factor in such a decline. Road stream crossings are a primary source of erosion and associated sedimentation in streams (MacDonald *et al.* 1991). During rainfall and snowmelt, suspended sediment concentrations downstream of crossings can be high (Rothwell 1983) and can be harmful to fish (MacDonald *et al.* 1991). Such concentrations can be short-lived, which makes monitoring logistically difficult and often expensive. Following high flows, suspended sediment settles on and into streambed gravels, which can impair aquatic habitat and result in the mortality of incubating fish (Sterling 1992). Sediment intrusion into streambed gravel can affect fish populations by suffocating fish eggs, hindering the removal of metabolic wastes and preventing newly hatched fish from emerging (Waters 1995, Sterling 1992, Chapman 1988, Lisle and Eads 1991). It can also disturb benthic macro-invertebrate populations, which inhabit the interstitial spaces of streambed gravel (MacDonald *et al.* 1991, Crouse *et al.*1981, Bjornn *et al.* 1977, Cordone and Kelly 1961).

Sediment intrusion and deposition are the foci of this study. They can result in long term habitat alteration and may have more permanent effects on fish habitat and community structure than suspended sediment. An examination of the literature revealed many studies and reviews pertaining to methods of streambed sampling (McNeil and Ahnell 1964, Walkotten 1976, Everest *et al.* 1980, Platts and Penton 1980, Carling and Reader 1982, Platts *et al.* 1989, Grost and Hubert 1991, Lisle and Eads 1991, Rood and Church 1994, Waters 1995). Freeze core sampling is one technique where streambed substrate is frozen to a probe and then extracted for analysis. Studies using freeze core sampling techniques to study streambed material have tended to publish information on the intricacies of sampling itself, but have rarely reported the results of analysis. Very few studies discuss streambed composition in relation to road crossings or other point sources. Two exceptions are Duncan and Ward (1985) and Bilby (1985). Some studies also relate change in substrate composition over time to management activities (e.g. Platts *et al.* 1989).

Resource industries of Alberta, such as forestry and petroleum, must follow operating rules designed to minimise erosion and stream sedimentation from roads and road crossings (Alberta Environmental Protection 1994b, Canadian Association of Petroleum Producers 1993). The effectiveness of these guidelines has seldom, if ever, been evaluated. One reason for this may be the lack of reliable evaluation methods and the high cost of testing guidelines and monitoring compliance.

More information about the effects of road crossings on sediment intrusion in streambeds is needed. There is a lack or shortage of published literature regarding:

- the results of freeze core sampling studies,
- streambed sampling in Alberta streams,
- sediment intrusion and deposition in streambed material from road crossings.

Reliable and consistent methods to appraise guidelines and to perform environmental audits in Alberta are needed, particularly given current provincial government policies to downsize and transfer management responsibilities to resource industries. Local studies to determine appropriate sampling techniques are necessary to establish the effects of roads and road crossings on streambed substrate.

Background

Numerous processes affect the amount of sediment transported into and within a stream. Levels of rainfall and snowmelt influence the amount of water available to carry sediment from the land into a stream. Increased flow in the stream channel gives the stream itself greater erosive power and greater ability to carry sediment. Cut and fill sections in roads and other vegetation disturbances can increase the amount of sediment available for sedimentation, particularly on steep slopes.

Sediment and Stream Dynamics

Sediment transport over land and its deposition into streams can result from overland flow. Clay and gravel sized particles are more resistant to erosion than sand (Morisawa 1968). Clay resists detachment because of its strong cohesive forces, and gravel resists movement because of its size and weight (Morisawa 1968). Although it takes high-energy flow to detach silt and clay, their transportation once in motion can be maintained with very little energy (Morisawa 1968).

Kinetic energy, or energy of motion, works to first detach particles and then transport them by overland flow. This energy of motion can be described mathematically as follows (Hewlett 1982):

Energy of Motion (Kinetic Energy) $KE = \frac{1}{2} M V^2$ (equation 1)

Where:

Mass M = (volume of water) * (density of water)

Velocity V = velocity of raindrops or flowing water

Velocity is a more important variable controlling detachment than flow volume. If the velocity of water is doubled, then the kinetic energy is quadrupled. If the volume of water is doubled, the kinetic energy is doubled.

These principles are also applicable to open flow in channels. Sediment within the stream moves both on the bed (bedload movement) and in suspension. Streambed particles can be moved by saltation, sliding, or rolling whereby grains are temporarily lifted or moved a short distance forward when energy and turbulence conditions allow (Knighton 1984). Bedload is very difficult to measure or even closely estimate (Morisawa 1968, MacDonald *et al.* 1991) because sampling devices affect the flow and bedload movement, and they must be calibrated (MacDonald *et al.* 1991).

Higher above the streambed, water flow is characterised by turbulent flow (Leopold *et al.* 1964) and sediment is carried primarily in suspension. Even large particles or rocks, or particles with high cohesion can be picked up or entrained by turbulent water flow when energy is high. Suspended sediment is easily measured at any given time, but sampling requirements to detect small sediment increases are large and expensive because of high variability (Brown 1980).

Total stream energy is most influenced by velocity, and in turn, velocity is affected by the stream gradient, water volume, water viscosity, and channel and bed characteristics (Morisawa 1968). The Chezy formula is one equation that describes this relationship (Morisawa 1968):

$$\mathrm{Vel} = C\sqrt{(R\ S)} \qquad \text{(Equation 2)}$$

The equation describes the mean velocity (Vel) of a stream as function of hydraulic radius (R), which is the cross sectional area over the wetted perimeter of the stream, and slope (S). Friction is represented by the constant (C) which incorporates gravity, roughness, straightness, and cross sectional form (Morisawa 1968). The formula follows the definition of uniform flow which states that no acceleration of flow occurs. This is because local momentum gains and losses are balanced, as are boundary resistance losses and kinetic energy renewal (Richards 1982).

So far the discussion has centred on the detachment and transportation of sediment. Once particles are in motion they can be moved long distances before they fall out of suspension, or in the case of larger particles, they may be re-deposited quite quickly. Stokes' law of settling velocity, which applies to small spherical grains and equates the upward and downward forces affecting a suspended grain (Morisawa 1968), describes these factors. The grain size and density are the primary factors in the rate of settling for small particles since gravity, viscosity, and water density are constant at a given time and place (Morisawa 1968). However, the settling velocity for larger grains must take inertia into account. A particle is deposited from suspension when the settling velocity for that grain size exceeds the upward frictional forces from the water.

The processes of detachment, transportation, and deposition constantly affect a streambed, its banks and the way water flows downstream. Theoretically streams are in a state of dynamic equilibrium (Morisawa 1968). In other words, on a local physical or temporal scale, streams may be aggrading or degrading while remaining relatively stable overall or over the long-term. Constant, small-scale changes in a stream occur both laterally in cross sections and longitudinally from headwaters to its outlet.

Longitudinal Stream Profile

Longitudinal stream profiles are generally concave (Morisawa 1968) at the watershed scale. This concavity results from interaction between a stream's capacity and competence with the amount and type of load (Morisawa 1968).

The stream adjusts its gradient in order to transport its load. If stream energy decreases sufficiently, some of the stream's load is deposited (Morisawa 1968). The deposition causes the slope below that point to increase, thereby increasing the stream's transport ability (Morisawa 1968). Conversely, scour is the result when a stream has excess ability to transport material, and this decreases slope below that point. On a watershed scale, near the headwaters of a stream, scouring is generally more predominant and the overall slope is higher, whereas further downstream deposition predominates and the overall slope is lower (Morisawa 1968).

At a local scale, the longitudinal profile channel undulates between pools and riffles (Richards 1982). Pools are defined as sections of the stream channel that have a concave profile along the longitudinal axis of the stream, or as areas of the stream channel that would contain water even if there were no flow (MacDonald *et al.* 1991). Riffles are those sections of the stream channel which have a convex profile along the longitudinal axis of the stream. They can generally be described as shallow rapids, and the water over them is wavy from the substrate (Bates and Jackson 1984).

Cross Sectional Stream Profile

The type of sediment in a stream's bed and banks influences its cross sectional form. A channel with a high percentage of fine cohesive material will tend to be narrower as it is resistant to erosion (Morisawa 1968). Alternatively, non-cohesive materials such as sand will result in wider, shallower cross sections since erosion is easier.

The form ratio, a ratio of depth over width, is a numerical expression of a channel cross section (Morisawa 1968). A deep, narrow channel is represented by a large form ratio, while a shallow, wide channel is represented by a small form ratio. Sediment deposition in the stream reduces stream depth. The explanation for this, if one recalls the Chezy equation ($Vel = C \sqrt{(RS)}$) (equation 2), is that for a constant (C), the slope (S) will vary inversely to the hydraulic radius or depth (R) to maintain a given velocity (Morisawa 1968). It has been demonstrated that a change in width, depth, and flow velocity result from a change in discharge at a given point along a stream (Morisawa 1968). In general, depth changes more slowly than width in a downstream direction (Morisawa 1968).

Carling and Reader (1982) state that stream substrates consist of a framework population and a matrix population. The framework population is dominant and consists of large, interlocking, self-supporting, rocks, cobbles and gravel. The matrix population, consisting of finer particles, fills the interstices of the framework. Fine sand can infiltrate the framework population to a certain depth range into the substrate, above and below which the interstices remain empty (Carling and Reader 1982).

Biological Concerns

Most of the information on the effects of sediment on salmonids comes from studies in British Columbia, and the United States. The application of this information to Alberta should be regarded with some caution because the fish in the Pacific Northwest are often different species or sub-species, tend to be much larger because of climate differences, and are often sea run (anadromous) salmonids. However, in the absence of local studies, this information is still useful because the process of sediment affecting salmonids is likely similar in different areas and with different species. A study by Sterling (1992) in the Tri Creeks area of west central Alberta is the only local field study dealing with effect of sediment in streambeds on salmonids.

Stream sediment is a problem for water and land managers today because it can cause habitat loss and fish mortality (Swanston 1974, Lyons and Beschta 1983, Lisle and Eads 1991, Sterling 1992, Waters 1995). While some natural sources are large contributors, the combination of sediment from natural and anthropogenic sources can cause significant amounts of sediment to be deposited (Duncan and Ward 1985) which is a major concern for land and water managers.

Forest harvesting is known to cause changes in stream channel characteristics as a result of decreased slope stability and mass erosion (Swanston 1974, Lyons and Beschta 1983). However roads are generally thought to have greater effects on sediment and water quality than timber harvesting. It is estimated that up to 90 % of the erosion and sediment produced from forestry operations comes from roads and road construction (Anderson *et al.* 1976). Erosion rates on forest roads can range from 17 - 95 + tonnes/ha/y compared to 15 tonnes/ha/y from logging operations and 022 - 0.179 tonnes/ha/y for protected forest land (Brooks *et al.* 1991, Dunne and Leopold 1978). On a logged watershed of the South Fork River in Idaho, an estimated 24 percent of sediment production (17 000 m^3 out of 72 000 m^3) was from natural sources as opposed to land use impacts (Platts *et al.* 1989). The researchers attributed the majority of increased sediment to road construction.

Roads crossing streams are the likely greatest source of sediment into streams because they disturb and expose the soil to erosion. Steep slopes at crossings allow high overland flow velocities and serve as collecting points for sediment from surface runoff (Rothwell 1983). This can be particularly problematic during storms and snowmelt runoff when water volumes and energy are high. Furthermore, revegetation at crossings is difficult because of the infertile, erodible soil exposed by excavation (Rothwell 1983). Culvert crossings are particularly troublesome because they are often constructed with large fill-sections made of bare, loose soil which act as a source for erosion and sedimentation into streams. Fish, their habitat and their food sources can be greatly affected by increased sediment in streams. This includes suspended, deposited and intruded sediment.

Suspended Sediment

Studies show that high concentrations of suspended sediment can clog and damage respiratory organs of salmonids, and increase physiological stress (Waters 1995, Cederholm and Reid 1987). If exposure is prolonged, suspended sediment can reduce territoriality, the use of cover (Gradall and Swenson 1982, Berg and Northcote 1985), and feeding and growth (Sykora *et al.* 1972 Olson *et al.* 1973, Sigler *et al.* 1984). For example, territoriality and feeding response and success in coho salmon (*Oncorhynchus kisutch* (Walbaum)) were significantly reduced by the addition of clay sediment to oval tanks for three-day periods (Berg 1982).

Suspended sediment concentrations downstream of road crossings can be many times greater than those upstream (Rothwell 1983). However, increased suspended sediment concentrations decline shortly after precipitation. The unpredictable nature of precipitation makes the monitoring of suspended sediment at crossings costly and difficult because sampling must be frequent and intense. For these reasons, it may be more productive to monitor sediment increases in the streambed, where suspended sediment is deposited.

Channel Morphology

As a source of increased sediment in streams, roads and road crossings affect channel morphology (Morisawa 1968) along with other factors such as peak flow patterns. Channel morphology, including the relative proportion of riffles and pools. spawning substrate quality, cover values, and food availability (Waters 1995, Sterling 1992, MacDonald *et al.* 1991, Bisson and Sedell 1982, Bjornn *et al.* 1977), is crucial to salmonids. Stream channels can widen from a mechanical wearing away of streambanks caused by particles carried in the water column (Morisawa 1968). Bare fill sections and roads themselves can supply sediment to the stream especially during rain and snowmelt. As such, culverts and bridges cause the channel to become shallower and wider near the crossing. Stream depth may be further reduced by sediment deposition. In this situation, stream width must increase to maintain the same flow capacity (MacDonald *et al.* 1991).

One study examined 16 streams for differences in pools and riffles between clearcut and uncut forest (Bisson and Sedell 1982). Nine of the streams had paired observations (both cut and uncut on each stream). Further, three more streams with uncut forest were paired with 3 streams with cut forest. One uncut stream was not paired. Stream reaches through clearcut areas with no buffers showed elongated riffle areas, and filled in pool areas compared to reaches with old growth forest (Bisson and Sedell 1982). This change, they believe, caused a shift in species and age composition of fish between cut and uncut stream reaches (Bisson and Sedell 1982). Bjornn *et al.* (1977) found that the abundance of juvenile salmon in small streams declined in direct proportion to the loss of pool volume due to filling by fine sediment.

Sediment Intrusion

The process by which sediment settles or is forced into the interstitial spaces of the streambed gravel is called sediment intrusion. Sediment is deposited when sources provide loads exceeding the stream's available energy to keep sediment in suspension. Culvert crossings in particular can supply a large amount of sediment for deposition and intrusion nearby. Sediment intrusion can cause a decrease in rearing and overwintering habitat for salmonids, a reduction in the diversity and abundance of aquatic invertebrates, and the mortality of embryonic salmonids (Lisle and Eads 1991, Sterling 1992, Waters 1995). Stream substrate, especially the size distribution of particles, is very important for adult salmonids and their offspring. Pore size and permeability of a streambed are proportional to the grain size of the substrate and are related to intragravel water velocity and oxygen transport (McNeil and Ahnell 1964, MacDonald *et al.* 1991, Everest *et al.* 1987).

Effects

Fine sediments have been associated with reduced juvenile bull trout rearing densities (Rieman and McIntyre 1993). For example, a study of stream habitat used by juvenile bull trout (Dambacher and Jones 1997) showed a positive association of bull trout with percent of gravel in riffles, but a negative association with percent of fines in riffles, and percent bank erosion.

Low temperatures cue some salmonids to move into the stream substrate (Hartman 1965, Chapman and Bjornn 1969, Bjornn 1971, Bustard and Narver 1975). A 5 km survey of the West Castle River in southern Alberta was conducted to find overwintering habitat used by bull trout (Boag and Hvenegaard 1997). Although one third of the area was dry on the surface, the investigators found young-of-the-year bull trout under large cobbles and small boulders living within the sub-surface flow. Cutthroat trout and bull trout were also found overwintering in small isolated pools. Reduced intragravel flow and oxygen from excess fine sediment could negatively affect young overwintering salmonids.

Sediment intrusion fills interstitial spaces of the streambed framework. This action may change the balance of habitat important to salmonids. Cobbles and small boulders may become embedded and no longer provide adequate cover and hiding places for overwintering and rearing.

Additionally, intruded sediments can harm the populations of invertebrates upon which fish feed. There are conflicting reports regarding the effects of fine sediment on invertebrate populations. A laboratory experiment by Crouse *et al.* (1981) using juvenile coho salmon indicates that when fine sediments were added to a level of 26% by volume that fish production significantly decreased as a result of lower benthic invertebrate production. A literature review (Cordone and Kelly 1961) indicates that numbers of invertebrates are reduced in stream sections with high sediment levels. This may have a negative effect on fish where benthic invertebrates are an important part of their diet.

The low frequency of high flows able to cleanse substrates may be crucial to fish spawning in small streams. Fine sediment can critically damage salmonid egg and alevin (sac fry) survival during incubation and emergence (Waters 1995, McNeil and Ahnell 1964, Reiser and White 1988, Shepard et. *al.* 1984). Intragravel water velocity and oxygen transport are two key elements for embryo survival to emergence (Sterling 1992). Sediment deposition reduces intragravel water flow, which decreases dissolved oxygen concentrations in the substrate (Chapman 1988). Physical entrapment of hatched eggs from sediment may also cause mortality (Lisle and Eads 1991).

A maximum level of 20 % fines (<8 mm) in substrates is a common level above which high mortality of salmonid embryos is expected (Reiser and Bjornn 1979, Waters 1995). Eyed steelhead trout and Chinook salmon eggs did not exhibit good survival beyond 20 % fines in a laboratory experiment especially with fines < 0.84 mm (Reiser and White 1988). At Tri Creeks, fine sediment levels were lower than this (12 %) on average. However, when levels of sediment reached 20 %, survival to emergence of rainbow trout was only 16% (Sterling 1992).

Process

The actual process of sediment intrusion is complex and not well understood. Beschta and Jackson (1979) studied sediment intrusion in a gravel bed in the controlled environment of a flume. They found that at Froude numbers (used for classification of turbulent flow (Morisawa 1968)) less than 0.9, a "sand seal" was formed by sediment (0.5

mm diameter) in the upper 5 cm of gravel, below which no intrusion occurred. Further, once the upper interstices were filled, the intrusion stopped. At Froude numbers greater than 0.9, a sand seal was still formed but was deeper (5 - 10 cm depth) because of more turbulent pulses. No sand seal was formed when 0.2 mm sand was used, and intrusion occurred from the bottom up. Intrusion into a stable streambed may be selective towards smaller particles (Beschta and Jackson 1979) because 0.2 mm sand filled the interstitial spaces to a greater degree than 0.5 mm sand.

At low rates of 0.5 mm sand input (2 500 g/min), intrusion was found to be minimised at high Froude numbers of 1.0 - 1.2 (Beschta and Jackson 1979). However, at high rates of 0.5 mm sand input (11 500 g/min), intrusion generally increased with increasing Froude numbers (Beschta and Jackson 1979). Further, 0.2 mm sand filled the gravel interstices more fully and at a greater rate even at low sediment input rate (Beschta and Jackson 1979). Culvert crossings with a high amount of sediment input to streams during high runoff could potentially cause significant amounts of sediment intrusion.

Interestingly, Beschta and Jackson (1979) found that intruded sediment was flushed from gravels to a depth of about 1 cm. Field observation supports this data, as indicated by Carling and Reader (1982). Another mechanism that can result in a clean bed surface is overlaying a veneer of clean fine pebbles, too coarse to penetrate the framework (Carling and Reader 1982).

Some argue that sediment intrusion from roads may not be a problem. For example, Duncan and Ward (1985) found no significant correlations between a singular forest road parameter and spawning gravel composition. They cite other studies that report fine sediment as temporary or seasonal because high flows cleanse the gravel.

Additional studies indicate that fine bed material may be removed locally by fish during spawning (McNeil and Ahnell 1964). However, bull trout for example, may not effectively modify substrate composition during redd construction (Shepard and Graham 1982). Even if spawning fish do remove local sediment, low dissolved oxygen levels in the streambed could still be problematic because of adjacent areas with higher levels of sediment. Further, local removal of sediment by spawning fish would not prevent future intrusion (Sterling 1992).

Duncan and Ward (1985) found the percentage of watershed area composed of sedimentary rock was correlated with fine sediment (< .063 mm) in gravel substrates ($r^2 = 0.65$, $P \leq 0.05$). However, combining percentage of sedimentary rock with the density of point sources from roads yielded even higher correlations at $r^2 = 0.75$ ($P \leq 0.01$).

Evidence supports the contention that sediment intrusion can be a long-term problem. Sediment delivered from a 150 - year storm can remain in the channel after 30 years (Beschta 1983). Platts *et al.* (1989) discuss a river that did not display a net export of fine sediment until deposition rates were reduced. Once sediment deposition was reduced, the surface sediment was removed fairly quickly, but subsurface sediment was removed more slowly. Only limited parts of some streams show seasonal cleansing (Adams and Beschta 1980). The fourth order streams in Duncan and Ward's (1985) study may have had flows high enough to cleanse gravels on a regular basis. Similar flows in smaller streams may be too infrequent to flush intruded sediment regularly.

Summary

Little is known about sediment intrusion in general and particularly in Alberta. Studies to increase our knowledge may be important for rearing and overwintering habitat for salmonids, embryonic salmonids, aquatic habitat, and organisms upon which salmonids feed. A logical focus of a sediment intrusion study in the province is road crossings because they are a primary source of erosion and associated sedimentation in streams (MacDonald *et al.* 1991). Further, small streams, less than fourth order, should be the centre point of initial studies because sediment intrusion may be prolonged. The freeze core technique (Walkotten 1976, Everest *et al.* 1980, Rood and Church 1994) appears to be an efficient method of sampling with several advantages over other streambed sampling methods. First, there is minimal loss of fine sediment upon extraction of the streambed sample. Second, layering of the substrate can be detected in this frozen state. Finally, analysis can be performed independently for substrate at different depths by separating the frozen samples at the desired levels.

Study Objectives

The trend to transfer some responsibilities from the provincial government to resource industries of Alberta puts more onus on the latter to ensure groundrules are met for minimising erosion and sedimentation. More information on the levels and occurrence of sediment intrusion are needed for their evaluation.

Monitoring and evaluation of sediment from roads and crossings are crucial to fish, their habitat and their food sources. Excess sediment can change channel morphology, and decrease habitat for overwintering, food availability, and spawning success.

The primary objective of this study involves testing to see if there was more fine sediment downstream of crossings than upstream of first to third order streams in the foothills of west central Alberta. In other words, "Do road crossings have an effect on the composition of streambed materials?". The test hypotheses were:

Ho: There is not more fine sediment in substrate samples taken downstream of crossings than upstream.

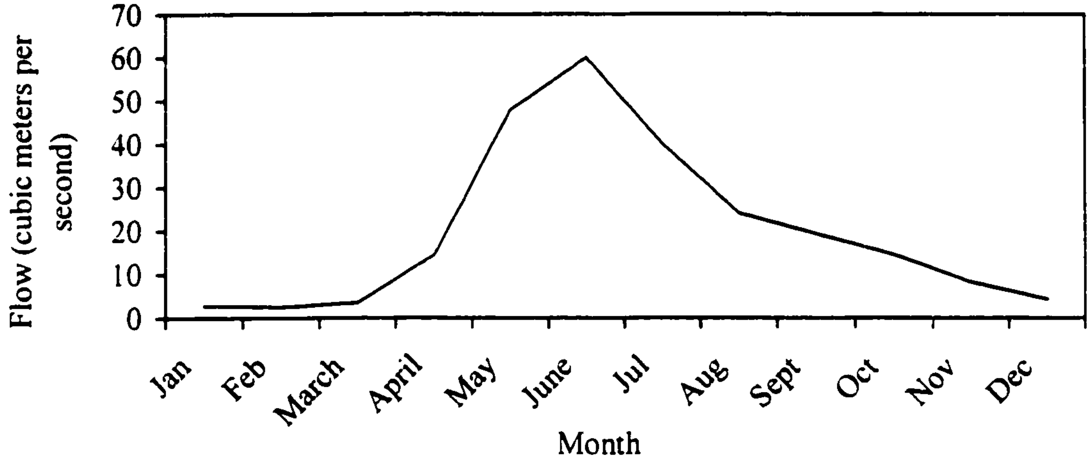
Ha: There is more fine sediment in substrate samples taken downstream of crossings than upstream.

Materials and Methods

Study Area

The study area is located in the Hinton-Edson foothill region of west central Alberta. The area is primarily forested with pure and mixed stands of lodgepole pine, white spruce and aspen (Dumanski *et al.* 1972). Elevations vary from 850 m near Edson to 2700 m near Jasper Park (Dumanski *et al.* 1972). Climate is characterised as continental with cold winters and cool summers (Dumanski *et al.* 1972). Annual precipitation varies from 500 to 900 mm, with approximately 30 to 38% occurring as snowfall between October and April (Swanson and Hillman 1977, Jablonski 1978, Nip 1991). Runoff regimen is dominated by snowmelt occurring in the months of May and early June (Figure 1). The McLeod River, used in figure 1, is higher order than the streams used in this study, but still reflects the pattern and timing of flows for the study area. The McLeod river is centrally located in the study area and has long – term data available.

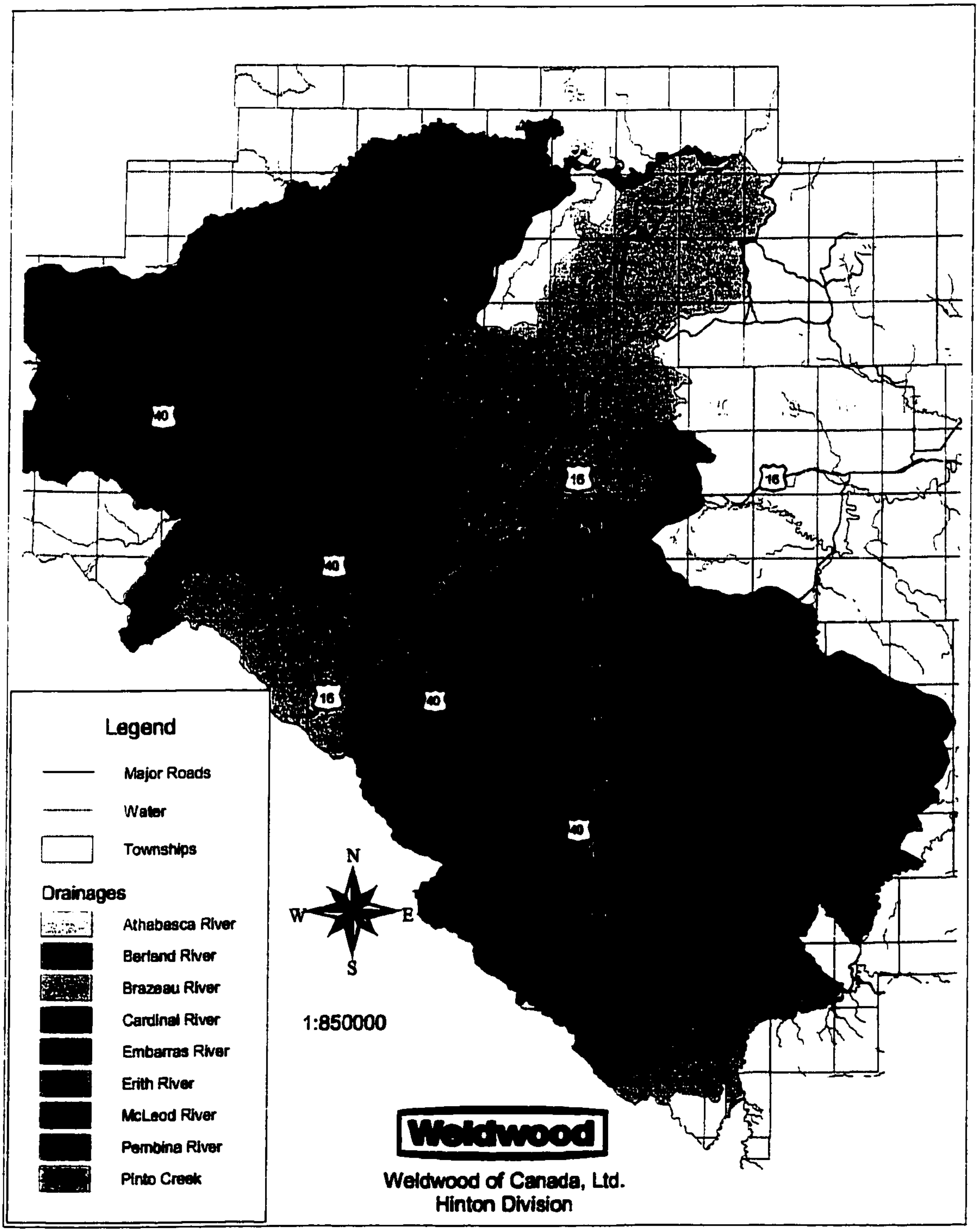
Figure 1 Average Annual Hydrograph (1954-1973) for the McLeod River above the Embarras River Lat. 53° 28 ° 10 N, Long 116 ° 37 ° 45 W (Water Survey of Canada 1974)



Soils in the region developed from glacial material and are characterised by lacustrine and aeolian deposits, till material and glaciofluvial sediment (Dumanski *et al.* 1972). Generally, soils of the Hinton-Edson area are highly susceptible to erosion (Dumanski *et al.* 1972). Sediment transport and deposition in streams from road stream crossings and other similar disturbances are common (Rothwell 1983).

Major rivers in the region are the Athabasca, McLeod, Berland and Pembina. (Figure 2). These rivers and their tributaries support wild populations of rainbow trout (*Oncorhynchus mykiss* (Walbaum)), bull trout (*Salvelinus confluentus* (Suckley)), Arctic grayling (*Thymallus arcticus* (Pallas)), and mountain whitefish (*Prosopium williamsoni* (Girard)) (Nelson and Paetz 1992). The area was selected for study because it has an extensive system of industrial roads and stream crossings developed over the last 40 to 50 years to support forestry, petroleum, and mining industries.

Figure 2 Map of major drainages in the Hinton area.



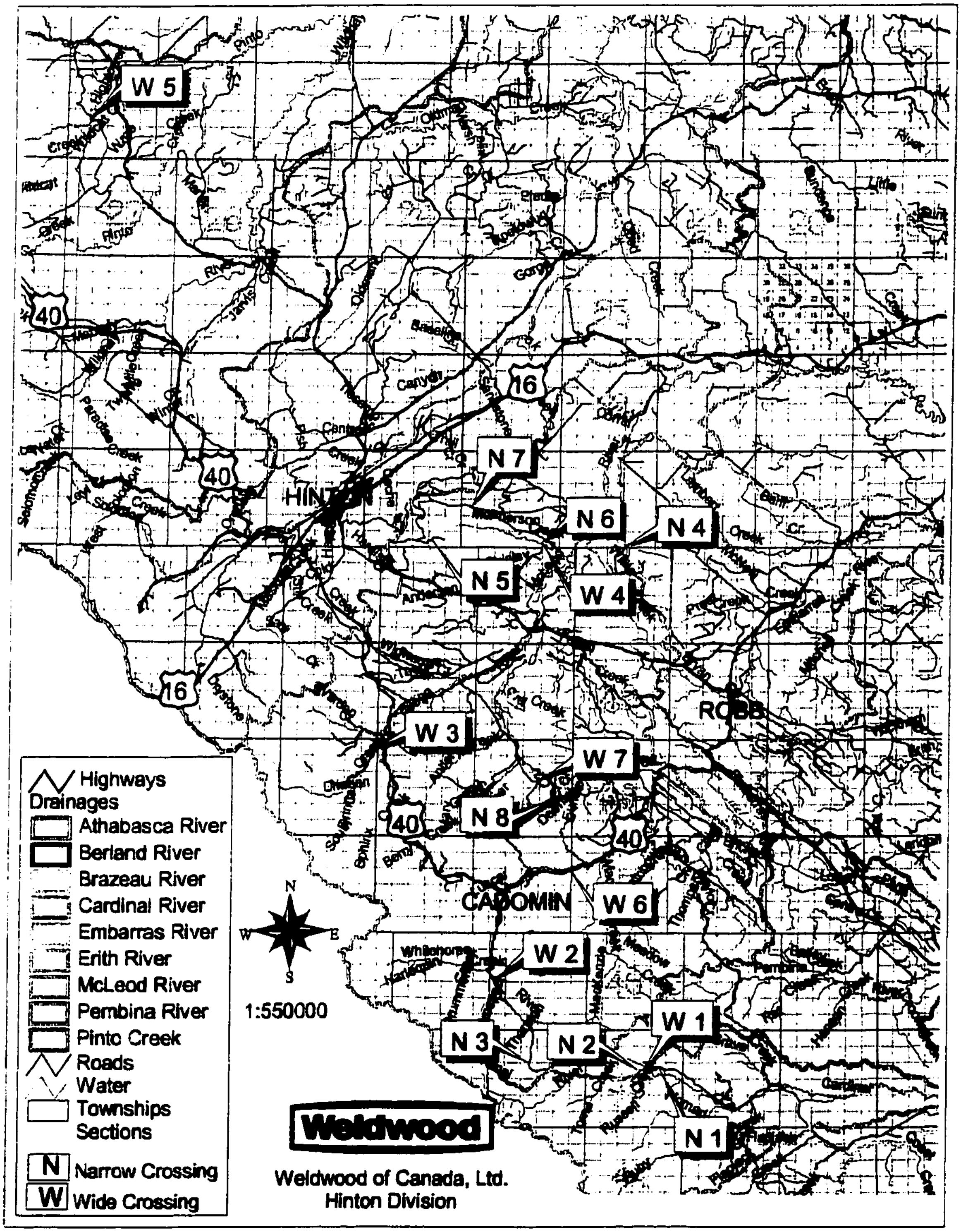
Selection of Study Stream Crossings

Streambed substrate near road stream crossings (bridges and culverts) were examined and sampled for sediment intrusion. First to third order streams were examined. Criteria used for the selection of crossings were based on surface substrate size and similarity of upstream and downstream reaches. The initial focus of the study was to concentrate on evaluating sediment intrusion in substrate suitable as, or similar to, spawning material for salmonid species endemic to the region. Consultation with local biologists and a review of the literature indicated gravel 1 to 4 cm in diameter was a preferred spawning substrate size for local rainbow trout and bull trout. Gravel bottomed streams with similar channel sections upstream and downstream of crossings were sought.

This proved to be difficult as many streams had dissimilar characteristics upstream and downstream. Further, many streams were soft bottomed or rock bottomed either upstream, downstream or both, and many had beaver dams. It was advantageous for study sites to be similar upstream and downstream to control variability. However, many possible study streams had dissimilar slope, flow, or channel and bank characteristics upstream and downstream and were thus eliminated. It was not possible to take crossing age into consideration because the small number of streams selected were too variable in age.

Out of more than 100 crossings observed, only 11 were suitable and satisfied the criteria in both years of study. Twelve streams were sampled in 1995. One of these could not be sampled in 1996 because the substrate was frozen. Eleven of the original streams were sampled in 1996 plus 3 new streams. A total of 15 streams were sampled for the study (Figure 3). The streams were stratified somewhat arbitrarily into narrow and wide classes. Six streams with an average width of less than 2.5 m were considered narrow, and five streams which were 2.5 m or greater in width were considered wide. We expected that wider streams would have greater flows and be more able to flush sediment out of gravels on a more regular basis.

Figure 3 Map of study sites located in the Hinton area.



Selection of Sampling Locations Within the Stream

Choosing the location within streams for freeze core sampling was complex. Several approaches were revealed during a literature review. MacDonald *et al.* (1991) observed that an important step in quantifying fish habitat and identifying limiting factors for fish populations is the identification and measurement of habitat units. Habitat units are defined as channel features that are ecologically important. Streams can be divided into the two basic habitat unit categories of pools and riffles (MacDonald *et al.* 1991). Hankin and Reeves (1988) recommend stratifying habitat units by type (e.g. riffles, pools, glides), and location (e.g. lower, middle, upper reaches). Further, they suggest that because each habitat type/location is sampled independently, measurements can be added across strata to give overall estimates.

Bilby (1985) chose sampling locations at the upstream edge of riffles, where velocity begins to increase. Several studies indicate that these areas of accelerated flow are preferred by many salmonids for redd construction (Reiser and Bjorn 1979). Duncan and Ward (1985) chose known spawning riffles and sampled at their upstream edge.

It was initially planned to take samples in each of 2 upstream pools and 2 upstream riffles as well as 2 downstream pools and 2 downstream riffles. However, this was not possible as pools and riffles were neither evenly distributed nor in close proximity to stream crossings. Pools and riffles were often located beyond the influence of impact of the crossings or were not readily identifiable.

A second approach was to take paired samples upstream and downstream of crossings on both narrow and wide streams. Their selection was based primarily on water velocity and, to a lesser degree, visible substrate size. It was assumed that similar velocities would represent similar conditions for transport and deposition of similar sized sediment and bedload. Velocities at several downstream locations were taken first. Then, matching velocities were sought upstream of the crossing. Two samples, 1 upstream and 1 downstream were taken in narrow streams in 1995. Three samples upstream and 3 samples downstream were taken in wide streams that year.

The sampling method was modified in 1996 to address several concerns. The first concern was that there was not enough sample matter or volume being collected to reflect the variability within the stream. Particularly because larger substrates were present in the study streams. greater sample volumes were required to adequately represent their size classes (Rood and Church 1994). The number of samples in narrow streams was increased to 3 upstream and 3 downstream. while on wide streams 5 samples upstream and 5 downstream were taken.

The second concern was that in order to find matching velocities in the first year. the sample locations were often very distant from the crossing. In other words, near the crossing, upstream and downstream velocities were dissimilar. One explanation for the inconsistent velocities near the crossings is that the crossings themselves were an influence on velocity. There was a good possibility that any sediment intrusion and deposition effects of the crossing were dissipated or become undetectable at greater distances downstream. Further, the distance upstream of the crossing also tended to be large. As such, there may have been too much variation between upstream and downstream samples.

To keep the samples within a reasonable range or distance from stream crossings, a 'zone of influence' was identified in 1996. Visual cues made this possible. There was generally a widening of the channel, shallower water depth, and often disturbed banks and different vegetation within a certain distance upstream and downstream of the crossing. This 'zone of influence' was usually within one and one half times the width of the right of way. Downstream samples were taken within this zone of influence, while upstream samples were taken outside the influence of the crossing.

With samples taken this close to the influence of the crossing, velocity was not used as a factor for sample location in 1996. Instead, for wide streams, the zone of influence (distance) was marked, and a position for a transect across the stream was chosen randomly within that distance downstream of the crossing. The transect across the stream was marked and divided into three equal sections, to ensure representation from faster and slower currents across the stream. Five sample locations were chosen randomly across the transect, with at least one sample in each of the three sections.

The habitat type of pool, riffle, or run, was noted for the downstream transect. Then the upstream transect was chosen by placing it at the first location of similar habitat that was upstream of the zone of influence. For example, if the downstream transect was randomly placed on the downstream edge of a pool, the upstream transect was placed on the downstream edge of the first pool upstream of the zone of influence. The upstream transect was divided into three sections and the five sample locations were selected in the same manner as downstream.

For narrow streams, it was not always possible to use transects. Those streams were often too narrow to fit three samples across especially if large rocks were encountered. In this case, the downstream sample locations were chosen at a random distance downstream of the crossing within the zone of influence. The habitat type – pool. riffle, run, was noted for each downstream sample. Then the upstream sample was chosen in the same habitat type, upstream of the crossing and outside the zone of influence.

In both years, samples were taken in the fall (September and October) after peak spring and summer flows to avoid large variation in flow between samples (MacDonald *et al.* 1991). Freeze core sampling would be less efficient under high flows in the spring and summer. Tear-shaped metal dams were placed around the probes to further reduce flow past them. In addition, the time of sampling was concentrated to avoid temporal variation in spawning gravel composition caused by the pattern and magnitude of hydrologic events (Adams and Beschta 1980).

Sampling

Streambed material was sampled in September and October of both years using the freeze core method (Walkotten 1976, Everest *et al.* 1980), a technique whereby streambed substrate is frozen to a probe and then extracted for analysis. The use of a constant volume method, such as the one described by Rood and Church (1994), was not possible because of the presence of large flat rocks horizontally aligned throughout substrate (Figure 4). These large rocks made the insertion of the outer core impossible. The removal of variable volume frozen core samples was also made difficult by these rocks.

Figure 4 Photograph of extracted freeze-core sample with platy rocks.

The freeze-core samples were obtained by driving a hollow steel probe, with a case-hardened conical tip, into the streambed to a depth of 30 cm. Dry ice, which sublimates at –78 °C at 1 atm (Zumdahl 1989), was inserted into the probe causing the stream substrate near the probe to freeze and adhere to the probe. Samples were cooled for 25-30 minutes. Once frozen, the substrate sample was extracted by forcibly rocking the probe back and forth until the frozen sample separated from the surrounding unfrozen substrate. Once separated, the sample was lifted out of the streambed. Following removal from streams, the frozen substrate was carefully removed from the probes by use of a cold chisel. Several well-placed strikes with the chisel and hammer were usually sufficient to fracture the frozen substrate into large pieces that could be bagged and stored while they thawed. Very minimal damage occurred to individual grains or cobbles and very little of the samples was lost by chiselling. The use of a blowtorch to melt the samples was tested but proved ineffective. In 1995, the top 15 cm of each frozen sample was bagged separately for comparison of sediment over depth. Because of the imprecise nature of the removal of material by a cold chisel, the depth of separation varied from 10-20 cm from the surface. Separation was not done for 1996 samples owing to time constraints. Once put into heavy grade polyethylene bags, the samples were thawed, stored, and later analysed in the laboratory for fine sediment content.

Sample Analysis

Sterling (1992) noted that classification of fine sediment is highly inconsistent in the literature, with the upper limit ranging from 6.35 to 0.833 mm. Experimental results on rainbow trout from Sterling (1992) showed silt and clay, and sand to a lesser degree, influenced embryo survival. These particles are all less than 2 mm in diameter. Particles in higher size classes did not influence rainbow trout embryo survival.

This study separated components less than 2 mm in diameter from the rest of the sample, and divided them into sand, silt and clay classes. Sieves were used to separate gravel and cobble from fine sediment for each sample. A portion of fine material from each sample was used in the sedimentation analysis (hydrometer method) to determine the percentages of sand, silt and clay (Klute 1986).

The average percent of fine material < 2 mm by weight was determined for comparison among streams and with other studies. These values were calculated for upstream and downstream of crossings and stratified into classes of narrow, wide and combined (narrow and wide) streams in 1995 and 1996.

The difference between upstream and downstream was then calculated for sand, silt, and clay for each stream (upstream values subtracted from downstream values) and then averaged over all streams for each year. Sediment intrusion or deposition was assumed to occur if the downstream samples contained a higher percentage of sand, silt or clay than upstream samples. Extra sediments were assumed to have originated from exposed and disturbed soils on the road crossing. If the result was less than or equal to 0, (i.e. there was more sediment present in the upstream samples than downstream of the crossing), it was assumed that the crossing did not deleteriously affect sediment levels downstream of the crossing.

Microsoft ® Excel (copyright © 1985-1996) was used to perform paired t-tests for sand, silt and clay for narrow and wide streams in 1995 and 1996. At the lowest, t-probabilities were considered significant at the 80% level. High variability and small sample sizes led to the use of this standard even though it is considered low by convention. Furthermore, from a management perspective, the adoption of an 80% confidence level was deemed acceptable. Probability values were reported so the reader could assess the relative significance among different particle sizes, stream sizes, and years of sampling.

All fine material < 2 mm (sand, silt, and clay) was analysed together to determine if variability could be reduced. Further, narrow and wide streams were pooled for analysis to determine if the increased degrees of freedom would result in a more powerful test.

Finally, analysis was done for material in the top 0 – 20 cm in 1995 samples and compared with an analysis of the material from the bottom 20-40 cm. This was done to determine if more fine sediment exists in the upper or lower strata, or if the significance was improved using one or the other.

Results and Discussion

Sample Characteristics

Freeze core samples obtained in 1995 and 1996 were variable in size and weight. In both years, samples were roughly cylindrical, 30 to 40 cm in length, and 15 to 35 cm in diameter. Samples in 1995 weighed 11.3 kg on average, with a maximum of 28 kg. The average weight of combined samples in a stream was 52.8 kg. In 1996 samples weighed 16.6 kg on average, with a maximum of 34.5 kg. There were more samples taken in each stream in 1996, so the average weight of combined samples in a stream was considerably higher, at 138 kg.

The average weight of individual samples using our methodology was larger than, or comparable to, methods used by other researchers. Lisle and Eads (1991) used a tri tube sampler and produced samples of 10 to 15 kg. A study comparing several substrate extraction methods (Grost and Hubert 1991) yielded samples averaging 1.4 kg by freeze-coring with carbon dioxide gas, 4.8 kg by excavated coring, and 3 kg by shovel extraction. A review (Rood and Church 1994) indicated variable sample weights for different sample extraction methods (Table 1).

Table 1 Summary of sample weights extracted using various methods and coolants (Rood and Church 1994)

Method Of Sample Extraction	Coolant	Weight of Extracted Samples (kg)
excavated core methods	not applicable	6 to 15
freeze-core sampling with a single tube	liquid carbon dioxide	1.5-2
tri tube corer	liquid carbon dioxide	maximum 20
single probe	liquid nitrogen	10-15
modified, constant volume, freeze-core apparatus	liquid nitrogen	maximum 13.5

Percent of Fine Sediment

The variability in individual sample volumes likely affected fine sediment volumes. Since a constant volume sampler could not be used, the percent by weight of fine sediments in each sample was used for comparison instead of actual weight. Narrow streams had the greatest average percentage of sediment < 2 mm (Table 2). Samples from these streams had a greater average percentage of fine sediment downstream than upstream. In 1996 for narrow streams, there was almost double the amount of fine sediment downstream of crossings than upstream. On average, wide streams had similar amounts of sediment upstream and downstream in both years. This suggests that wide streams have a greater ability to cleanse fine sediment from the gravel or cobble substrate. Stream competency and capacity are usually higher in larger streams as a result of greater discharge. Smaller streams with lower competency and capacity have less potential to transport (i.e. cleanse) gravel substrates unless a large-scale event occurs.

Table 2 Average fine sediment (<2 mm) in samples.

year	narrow/wide/both	upstream/downstream	average % of sediment < 2 mm by weight
1995			
	narrow	upstream	15.4
		downstream	23.9
	wide	upstream	17.4
		downstream	16.1
	narrow and wide (pooled)	upstream	16.9
		downstream	18.1
1996			
	narrow	upstream	10.9
		downstream	20.3
	wide	upstream	14.4
		downstream	15.0
	narrow and wide (pooled)	upstream	13.1
		downstream	16.8

The average percent fines in substrates for narrow streams varied from 10.9 % upstream of crossings to 23.9 % downstream of crossings. These values are fairly high even upstream of the crossings. Sterling (1992) observed that percent survival of rainbow trout embryos to emergence was 66% if the substrate contained 10 % fines < 2 mm. The survival rate dropped to 41% and 16%, for 15% and 20% fines respectively. Bjornn *et al.* (1998) in a laboratory study found that rainbow trout embryo survival to emergence decreased from 80 to 20 % for 7 % percent fines (<0.25 mm) in the substrate. This was in contrast to granitic sediments (<6.35 mm) which did not reduce survival until fines made up 20 % of the substrate (Bjornn *et al.* 1998). In the streams studied, the relatively high level of sediment upstream and downstream of crossings may lower survival to emergence. If 20% fines intruded into the gravel substrate of Athabasca rainbow trout redds, one could expect survival to emergence to be seriously compromised.

Difference in Fine Sediment from Upstream to Downstream

Sediment intrusion and deposition were evaluated by comparing upstream and downstream values. This eliminated background levels so that only the difference in sediment level was measured. As such, streams with lower sediment could be compared to streams with naturally higher sediment. Sample averages for upstream and downstream at each crossing were used to reduce variability.

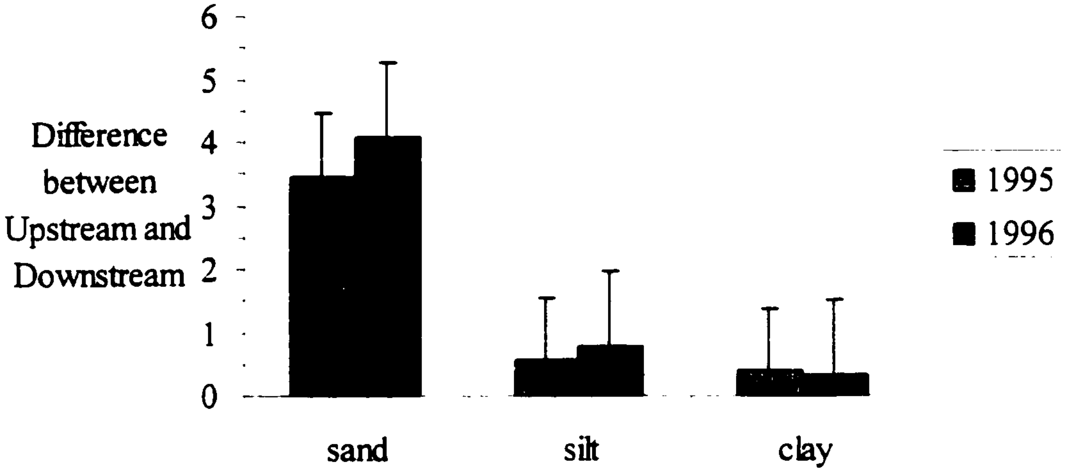
Analysis of freeze core samples obtained in 1995 and 1996 indicated that approximately one half of the streams sampled had greater amounts of sand, silt and clay downstream than upstream (Table 3). In 1995, 7 out of 12 streams showed a greater amount of sand, silt and clay downstream than upstream, but two streams showed more sand, silt and clay upstream than downstream. The other 3 streams showed 1 or 2 out of 3 size classes to be greater in the upstream section. In 1996, 7 out of 14 streams showed more sand, silt and clay downstream than upstream. In the remaining 7 streams, no more than 2 out of 3 size classes were greater upstream than downstream.

Table 3 Difference in 1995 and 1996 for fine sediment classes in 11 streams in the Hinton-Edson Area. Positive numbers reflect more fine sediment downstream than upstream.

	Difference 1995			**Difference 1996**		
stream	**sand**	**silt**	**clay**	**sand**	**silt**	**clay**
narrow 1	2.54	0.17	0.25	-0.87	-0.22	0.01
narrow 2	1.16	-0.54	-0.25	-0.27	0.28	0.00
narrow 3	0.43	-0.36	-0.12	0.78	0.23	0.03
narrow 4	18.69	1.46	0.87			
narrow 5	4.50	1.57	0.72	12.76	8.45	3.74
narrow 6	-9.02	-1.23	-0.59	6.45	2.67	1.05
narrow 7	30.11	5.00	4.03	24.79	3.92	2.44
narrow 8				5.06	0.41	0.18
wide 1	4.04	0.09	-0.05	3.16	1.00	0.11
wide 2	2.83	0.26	0.01	2.48	0.46	0.05
wide 3	-11.29	-0.12	-0.14	-2.37	0.03	0.04
wide 4	-6.70	0.15	-0.24	-1.56	0.11	-0.07
wide 5	4.08	0.16	0.20	2.44	-6.38	-3.06
wide 6				3.00	0.13	-0.01
wide 7				1.09	-0.11	-0.10

On average, wide and narrow streams had more sand. silt and clay downstream than upstream in 1995 and 1996 (Figure 5) as reflected by positive values. The proportion of sand in both years was greater than for silt and clay. There was more sand and silt in 1996 than 1995, but slightly less clay. The higher values for sand and silt may reflect better sampling procedures in 1996 that kept the samples closer to the crossings. The reason for slightly lower clay values in 1996 is unclear. However, there was no statistically significant difference between years. Regardless of year, part of the differences between sand, silt and clay may be attributable to their relative amounts in the road material. However, the road material was not sampled.

Figure 5 Average difference of fine sediment between upstream and downstream in 1995 and 1996. Positive values reflect more sediment downstream than upstream. Error bars indicate 1 standard error.



Statistical Analysis

Statistical analysis by paired t-test of sand, silt, clay, and all particles <2 mm between upstream and downstream of crossings was performed (Table 4). Significant probabilities reflect a difference between paired upstream and downstream values (1-tailed).

Narrow streams

There was more sand, silt and clay downstream of crossings on narrow streams than upstream. These values were significant at the 94% level (i.e. 1-0.054 = 94%) for 1996, and the 84% level for 1995.

Wide streams

There was significantly more silt downstream of crossings in 1995 (92% level), but no differences were detected for sand or clay. The results for 1996 were different. In 1996, there was significantly more sand downstream than upstream (89% level). The difference between 1995 and 1996 may be caused by the changes in sample locations between the two years. Samples in 1996 were taken closer to the crossings making it more likely to detect sand, which has a rapid settling velocity. On the other hand, samples in 1995 were taken farther from the crossings making it more likely to detect silt, which has a slower settling velocity.

Narrow and wide streams

Narrow and wide streams were pooled for analysis to increase the degrees of freedom for a more powerful test. The only gain for this was in the 1996 observation for sand (significant at the 97% level). Results in all other comparisons showed no gain in levels of significance. The analysis for narrow streams alone was more significant than the pooled analysis.

Table 5 Summary of statistics comparing sample top 15 cm to sample bottom 15 cm. Upstream and downstream samples for sand, silt, clay, and all material <2 mm fractions in narrow and wide streams are compared for 1995.

	year	stream size	size fraction	n		arithmetic mean downstr.	std. dev. (s) downstr.	std. error (s/n^{-2}) downstr.		arithmetic mean upstr.	std. dev. (s) upstr.	std. error (s/n^{-2}) upstr.		t-probability (1 tailed)
tops	1995	narrow	sand	7		17.3	11.4	30.2		10.3	6.4	16.8		0.043
			silt	7		1.5	1.6	4.2		0.7	0.5	1.2		0.106
			clay	7		1.1	1.4	3.7		0.5	0.5	1.4		0.096
			all <2 mm	7		19.9	14.0	37.1		11.6	7.0	18.6		0.048
		wide	sand	5		12.6	3.7	8.3		13.2	5.5	12.3		0.409
			silt	5		1.2	0.7	1.7		1.1	0.6	1.3		0.183
			clay	5		0.5	0.4	1.0		0.5	0.3	0.7		0.265
			all <2 mm	5		14.3	4.9	10.9		14.7	6.0	13.5		0.439
		narrow & wide	sand	12		15.3	9.0	31.3		11.5	5.9	20.6		0.069
			silt	12		1.4	1.3	4.4		0.9	0.5	1.8		0.080
			clay	12		0.8	1.1	3.8		0.5	0.4	1.5		0.077
			all <2 mm	12		17.6	11.1	38.6		12.9	6.6	22.7		0.065
bottoms	1995	narrow	sand	7		22.8	16.2	42.9		14.8	7.5	20.0		0.136
			silt	7		2.7	2.6	7.0		1.2	1.1	2.9		0.177
			clay	7		1.8	2.1	5.5		1.0	0.8	2.2		0.165
			all < 2 mm	7		27.4	20.4	54.1		17.4	9.1	24.2		0.141
		wide	sand	5		15.3	5.0	11.1		17.3	9.0	20.1		0.352
			silt	5		1.7	0.8	1.8		1.7	0.9	1.9		0.185
			clay	5		0.7	0.5	1.0		0.8	0.4	0.9		0.105
			all < 2 mm	5		17.6	6.1	13.6		19.8	9.4	21.0		0.341
		narrow & wide	sand	12		19.7	13.0	44.9		15.9	7.9	27.3		0.206
			silt	12		2.3	2.1	7.2		1.7	1.0	3.3		0.181
			clay	12		1.34	1.7	5.8		0.9	0.7	2.3		0.189
			all < 2 mm	12		23.27	16.3	56.6		18.4	8.9	30.8		0.197

Variability

Variability of sediment levels less than 2 mm was high. Coefficients of variation ranged from 24 – 72 %. In all likelihood, this is a reflection of high in-stream variability and a small sample size. Future studies should attempt to include more sample streams and or more sampling within a few streams.

Top of Column vs. Bottom of Column

The top 10-20 cm of 1995 samples were bagged separately to compare fine sediment with depth. When only the tops of the samples were used for paired t-tests of upstream versus downstream, there were greater significant differences than with the bottom of the column in narrow streams (Table 5). The same was not true for wide streams.

Even though analysis using the tops had greater significance than the bottoms, the bottoms had more fine sediment overall (Table 5). In approximately 75% of individual samples there was more fine sediment present in the lower stratum than the upper stratum. This is consistent with other studies that report varying degrees of sediment intrusion at different depths (Beschta and Jackson 1979, Carling and Reader 1982).

The difference in sediment levels between upper and lower strata may be important to different fish species and size classes. In the study area, rainbow trout are small (Sterling 1990, Nelson and Paetz 1992), and may only use the upper strata of the streambed for spawning and cover. Less sediment intrusion in the upper layers may be beneficial for such small fish. However, larger bull trout may use upper and lower strata for spawning and cover. Even if fish are able to remove fines during redd formation, sediment can move into the cleared gravel during the incubation period (Sterling 1992).

Table 4 Summary of statistics for upstream and downstream samples for sand, silt, clay, and all material <2 mm fractions in narrow and wide streams for 1995 and 1996.

year	stream size	size fraction	n		arithmetic mean downstr.	std. dev. (s) downstr.	std. error (s/n^{-2}) downstr.		arithmetic mean upstr.	std. dev. (s) upstr.	std. error (s/n^{-2}) upstr.		t-probability (1 tailed)
1995	narrow	sand	7		20.3	13.8	36.4		13.4	5.3	14.0		0.106
		silt	7		2.1	2.1	5.6		1.3	0.7	1.9		0.157
		clay	7		1.4	1.7	4.6		0.8	0.5	1.4		0.139
		all < 2	7		23.9	17.2	45.5		15.4	6.2	16.4		0.112
	wide	sand	5		13.9	3.9	8.7		15.3	5.8	13.0		0.341
		silt	5		1.6	0.7	1.6		1.5	0.7	1.5		0.080
		clay	5		0.6	0.4	1.0		0.7	0.3	0.8		0.294
		all < 2	5		16.1	5.0	11.2		17.4	6.3	14.0		0.352
	narrow & wide	sand	12		17.6	10.9	37.9		14.2	5.3	18.5		0.159
		silt	12		1.9	1.6	5.7		1.4	0.7	2.4		0.128
		clay	12		1.1	1.4	4.8		0.7	0.4	1.5		0.145
		all < 2	12		20.6	13.7	47.4		16.3	6.0	20.8		0.149
1996	narrow	sand	7		15.6	10.4	27.5		8.7	2.1	5.4		0.046
		silt	7		4.0	3.5	9.2		1.7	0.6	1.7		0.055
		clay	7		1.7	1.6	4.3		0.7	0.3	0.8		0.054
		all < 2	7		21.3	14.8	39.2		10.7	2.6	6.8		0.034
	wide	sand	7		11.8	2.5	6.5		10.7	3.5	9.2		0.108
		silt	7		1.8	0.7	1.9		2.5	2.9	7.8		0.253
		clay	7		0.7	0.3	0.8		1.2	1.5	3.9		0.181
		all < 2	7		14.4	3.1	8.1		14.4	6.6	17.4		0.483
	narrow & wide	sand	14		13.7	7.5	28.1		9.7	2.9	11.0		0.026
		silt	14		2.9	2.7	10.0		2.1	2.1	7.8		0.185
		clay	14		1.2	1.2	4.6		0.9	1.1	4.0		0.224
		all < 2	14		17.9	10.9	40.7		12.5	5.2	19.3		0.040

Freeze Core Sampling

Freeze core techniques were modified to sample first to third order streams in the foothills of west central Alberta. As indicated earlier, the use of a constant volume sampler such as the one described by Rood and Church (1994) proved impossible because of large rocks aligned horizontally in the substrate.

Freezing the substrate with dry ice produced samples with weights comparable to those in the literature. Dry ice was used instead of liquid nitrogen, as it was easier to transport and handle in the field. Liquid nitrogen was difficult to use in the field because of fragile containers. Leakage of liquid nitrogen was a problem during transport and while decanting into smaller containers. Further, it was more difficult and expensive to obtain liquid nitrogen than dry ice. Sealed with duct tape in camping coolers, dry ice lasted several days with minimal loss. Sixty-five to 90 L of dry ice pellets were sufficient to extract 10 samples.

The process of freeze core sampling is labour intensive, which limits the number of samples taken in a day. Careful and efficient use of time and resources improve sampling productivity. A field crew of 2-3 with 10 probes can extract, store and label about 20 samples per day if streams are not too distant from one another. More samples could be extracted if additional probes were available. Time can be further economised by allowing samples to melt off the probes into pails or bins (rather than removal with a cold chisel), while other samples are taken with the additional probes.

Variability within and among streams was high. Future studies should endeavour to obtain samples from 7 or more comparable streams. If the species of concern only uses the upper strata, then 6-10 or more samples taken from the top 20 cm of substrate might produce more consistent and reliable results. However, if larger species that use upper and lower strata are of concern, then lower strata should also be sampled.

Another application of freeze core sampling would be for intensive monitoring of sediment deposition and intrusion in sensitive streams. By working on only a few streams, more samples could be taken on each. A particular stream of interest could be sampled before the installation of the crossing. The results could then be compared to samples taken after crossing construction and over time. Effectiveness of erosion control and guideline compliance could be evaluated in this way. While our crossings were well established before sampling took place, samples from creeks with newly installed crossings might display a greater impact. For example, the difference between narrow and wide streams might not exist on newly disturbed streams. Further, the variability among streams of the same size might be smaller.

It must be noted that this study did not identify any actual spawning sites. It is unknown whether salmonids spawned within the zone of influence of study sections or not. In a future, more intense study of new crossings, it would be beneficial to identify actual spawning sites before and after construction of the crossings to fully assess any impact.

Management Implications and Considerations

From a management perspective, one may conclude from this study that the narrow streams are of greater concern in this study than the wide streams because they have a much greater percentage of fine sediment downstream than upstream (Table 2, 4).

Four narrow stream (narrow number 4, 5, 7, and 8) warrant particular concern because their sediment levels are quite a bit higher downstream than upstream (Table 3). Narrow stream number 6 may also be of concern, because there was more fine sediment in the downstream samples in 1996. It is unknown why this stream had negative differences in 1995 and positive differences in 1996. Perhaps it was related to the proximity of the 1996 samples to the crossing.

Even though narrow streams may warrant the greatest amount of attention, the implications for wide streams cannot be ignored. For instance, three of the narrow streams of concern (narrow 5, 6, and 7) all drain into one larger stream (wide stream 4, McPherson Creek). Perhaps the cumulative impact of tributary crossings to McPherson creek outweighs inputs from the McPherson crossing. In fact, samples from the McPherson creek crossing yielded 23 percent of fine sediment < 2 mm. This is above levels that could be damaging to salmonid embryo survival.

Of the 3 particle size classes < 2 mm, sand is found in greater amounts downstream compared to upstream (up to 30%). In comparison, silt and clay have differences between downstream and upstream of up to 8% and 4% respectively. One could surmise that the road material had a larger proportion of sand, than silt and clay, however the road material was not sampled. Another possibility is that sand, which takes less energy to detach, was transported from the road in greater amounts. With regard to Athabasca rainbow trout, it may be preferential, though not desirable, to have excess sand rather than excess silt or clay. This is because increased silt and clay were found to have a greater effect on rainbow trout embryonic survival than sand in the Tri Creeks study (Sterling 1992).

The timing and location of road crossing construction is crucial. Potential sediment contributions will be highest during and after construction until vegetation can be established. Construction should take place outside of the window of spawning and emergence. Further, the location of the crossing should not affect preferred spawning habitat for the concerned species. This is a logistically difficult task if spring spawners such as rainbow trout (Nelson and Paetz 1992) and fall spawners such as bull trout (Nelson and Paetz 1992) are present in the same stream!

Conclusions

In conclusion, freeze core sampling with dry ice can be used effectively to sample streambed material in first to third order streams in west central Alberta. Percent fines < 2 mm in streams sampled had more sediment than desirable for developing embryonic fish in sections upstream and downstream of crossings. Narrow streams had significantly more fine sediment downstream than upstream and more fine sediment overall than wide streams. Significance levels were augmented in the second year because samples were extracted closer to the crossing. There was generally more fine sediment found in the lower streambed strata (20-40 cm depth). However, greater consistency and hence stronger significance was found in the upper strata.

Increased sand downstream of crossings in narrow streams is the area of biggest concern simply because of the magnitude of differences between upstream and downstream. There is less worry for silt and clay in many streams because the magnitude of difference is small (0.01-2 %). Five out of 8 narrow streams warrant further investigation.

However, high sediment levels overall in wide streams must be addressed. An individual crossing on a wider, and likely higher order, stream may not contribute enough sediment to show a significant difference from upstream to downstream. However if there are several tributaries with several crossings, all contributing sediment, there is a potential for more ubiquitous habitat disturbance in the larger stream. Further investigation would be warranted.

A potentially useful application for freeze core sampling exists in the intensive monitoring in a few, sensitive streams. For instance, greater numbers of samples taken before and after crossing construction and also over time would allow the evaluation of erosion control and guideline compliance. Any future study should attempt to include more samples within any given stream.

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