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Assessing stream channel stability thresholds

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ASSESSING STREAM CHANNEL STABILITY THRESHOLDS

by

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ASSESSING STREAM CHANNEL STABILITY THRESHOLDS

Director: Donald F. Potts DFP

The purpose of this study is to develop a methodology that can be used to evaluate stream channel stability thresholds on a stream-by-stream basis. Therefore, an allowable increase in the size of peak flows can be determined.

Harvesting timber has been documented to increase peak discharges by decreasing evapotranspiration, interception, and compacting surfaces. Increased peak discharges can initiate more frequent movement of stream bed material. Increased bedload movement can cause un-natural aggradation and/or degradation generating stream channel instability.

In this report, relationships between increased discharges and channel stability are discussed. Fourteen gravel- cobble- and boulder-bed streams with a total of 51 study reaches in western Montana were selected for investigation of bed-material mobility. Detailed channel features (cross section, bed particle size distribution, slope) and watershed characteristics (area, precipitation) were measured and used to estimate dominant discharge. Site specific stream characteristics (pebble size distribution, stream slope, stream width and depth) are utilized in bedload movement formulas to predict thresholds of stream stability.

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INTRODUCTION

Timber harvesting, grazing, road building, urbanization, and other types of land disturbance temporarily increase water yield (Ursic 1991, King 1989, Baker 1986, Miller 1984, Leopold 1980, Troendle 1979). Land disturbance can modify the amount of vegetation, alter the porosity of the soil, and modify the amount and timing of snow melt (Troendle 1987). As a result, the amount of water available for evapotranspiration, infiltration, or held by the soil decreases, and streamflow can increase (Troendle and Leaf, 1981). Increased streamflow and increased peak discharges may adversely effect streams by creating a disequilibrium between sediment transport and sediment supply. This imbalance in the sediment transport regime can lead to accelerated aggredation or degradation of the streambed, changing the stream's morphological makeup of such important features as the pool-riffle sequence (Lisle 1982).

Many forms of land disturbance, including timber harvesting, road building, and urbanization are connected with increased discharge. For example, Arnold et al. (1982), studied Sawmill Brook and found that land disturbance increased the frequency of bankfull discharge. Increased runoff caused extensive bank erosion in the main channel and increased the bedload discharge. The increased frequency of moderate floods caused channel widening. The change in sediment transport regime caused a change from a meandering to a braided channel pattern. The authors concluded that with continued urbanization of the basin, the present disequilibrium of the channel would be enhanced, resulting in channel instability.

Processes of scour and fill appear to partly control bank stability and the adjustment of stream channel width (Andrews 1982). Increased movement of river-bed material is also found to be responsible for problems connected with shifting channels, loss of capacity, and increasing the size of the river bed material (Arnold et al. 1982, Reid et al. 1984). Degradation of stream channels associated with increased peak discharges can lead to increased suspended sediment, turbidity, and conductivity. More suspended sediments decrease overall water quality, which, in turn reduces stream water value for human and wildlife consumption and usually adversely impacts fish habitat.

Bankfull discharge is often called dominant discharge, or the channel forming flow. Increases in water yield caused by land disturbance can increase the frequency of bankfull discharge. Increasing peak flows in a stream has the same effect as decreasing the return period for major storm events. For example, what was formerly a 25-year flood might be expected to occur once every ten years. All the flooding, bank scour, sediment transport, and erosive energy associated with larger storms happens with smaller, more frequent storms (McInerney 1990).

Landforms and stream systems may not always respond progressively to altered conditions. Rather, dramatic morphologic change can occur abruptly when critical discharges are exceeded (Schumm 1972). This may account for some of the difficulty in connecting management activities to cumulative watershed effects. The importance in maintaining a healthy stream system by maintaining healthy channel conditions is so widely acknowledged as to hardly warrant additional explanation. I accept that land disturbance increases the frequency of channel forming flows and increased morphologic change are the result. The question is, at what discharge does the channel become destabilized? This is hard to answer because the variation within and between streams is enormous. Transport of sediment by rivers has been studied extensively for more than a century and derived equations predicting bedload transport still differ in application and results. Stream attributes that are associated with channel instability are among the most difficult to quantify because of their high inherent variability.

Stream stability does not require immobility of all stream bed particles. It is common to detect movement of stream bed materials even at low flows (Leopold and Rosgen

1990). Yet, at some point, there is enough movement of sediment to cause changes in the streams micro- and macro-morphological features. Jackson and Beschta (1980) describe this phenomena as Phase I and Phase II bedload transport. Phase I, sometimes called size-selective transport (Ashworth 1989) involves the transport of fine, predominantly sand-sized bed materials over stable riffles. Phase II occurs when flows are high enough to provide enough force to move practically all sizes of riffle armor. Phase I is found to be more consistent over time and space, where as phase II seems to provide a more non-uniform direction and unsteadiness over time at a given stream discharge.

The typical stream stability administrative threshold for National Forests in the Northern Region is a 10% increase in average annual water yield. This across-the-board water yield increase has been highly criticized and is of concern to many hydrologists regarding it's technical soundness (Harr 1981). Megahan (1979) suggests that changes in average annual monthly peak flows have no meaningful effect on sediment transport and that allowable increases in annual water yields in relationship to channel conditions are suspect, because channel shaping flows are related to the size and duration of <u>peak flows</u>' not monthly or yearly <u>averages</u>. The "threshold of concern" is applied uniformly across the landscape without reference to local site conditions. Not all stream channels can handle a 10%

increase in average annual water yield before detrimental conditions occur. Some can handle much more before the occurrence of channel instability. A procedure that identifies and surveys key stream features and uses appropriate predictive formulae to assess thresholds is more appropriate than using the current threshold of an average annual increase of 10%.

Grant (1986) emphasized that there is no allowance (using a 10% threshold) for the fact that both hydrologic response to forest practices and geomorphic response to changes in hydrology vary widely between basins. For this reason, a credible methodology for assessing stream stability thresholds on a stream-by-stream basis is crucial. This methodology can also be useful in decomposing the broad issue of cumulative watershed effects (CWE's) assessment procedures by addressing one of its constituent parts (Grant 1986).

Nearly all the symptoms of CWE's can be traced to increases in peak flows (USDA Forest Service 1981). Methods to reduce cumulative effects by reducing sources of increased runoff are possible. Rice (1980) describes two principal strategies for mitigating CWE's and detrimental impacts to the stream system from logging activities. They are to "schedule activities to desynchronize the arrival of individual effects at some critical point downstream; and to reduce the individual effects so that their combined effect (synchronized or not) is acceptable at all points in the hydrologic system". Rice (1980) goes on to report that although best management practices can be achieved on individual sites, the cumulative effect of many individual impacts might be unacceptable. The cumulative impacts that follow any management practice should be taken into consideration by land managers. Therefore, an accurate stream-specific and site-specific estimation of increased peak discharges and their respective impacts must be considered when scheduling all land altering prescriptions.

STUDY OBJECTIVES

The objective of this study is to develop a technically-sound, literature-supported methodology to evaluate stream channel stability thresholds on a stream-by-stream basis.

The objective will be accomplished in three basic steps: 1) review literature on predictive equations (FACTORS AFFECTING BEDLOAD STABILITY) and evaluation of their potential application to the objective, 2) comparison of selected predictions for 51 study reaches, and 3) presentation of a usable methodology.

APPROACH AND ASSUMPTIONS FOR ASSESSING STABILITY

My basic assumption is that the stability of any channel can be determined by the onset of mobility of the largest particles (Grant 1987). This assumption is widespread and has been demonstrated in the literature (Pickup 1976; Jackson and Beschta 1982; Carling 1988; Sidle 1988; Booth 1990), which suggests that the d_{84} size fraction (the size for which 84% of the bed particles are finer) is the critical fraction which must be moved before the bed is really destabilized. Finer materials are simply winnowed from the bed matrix during less-than-critical flows. When the d_{84} size particles on the riffle are moveable by bankfull discharge, the system is not in dynamic equilibrium (Kappesser 1992). Therefore, by assessing an allowable increase in the size of peak flows resulting from land disturbance, a threshold can be established based on the mobility of the largest streambed materials.

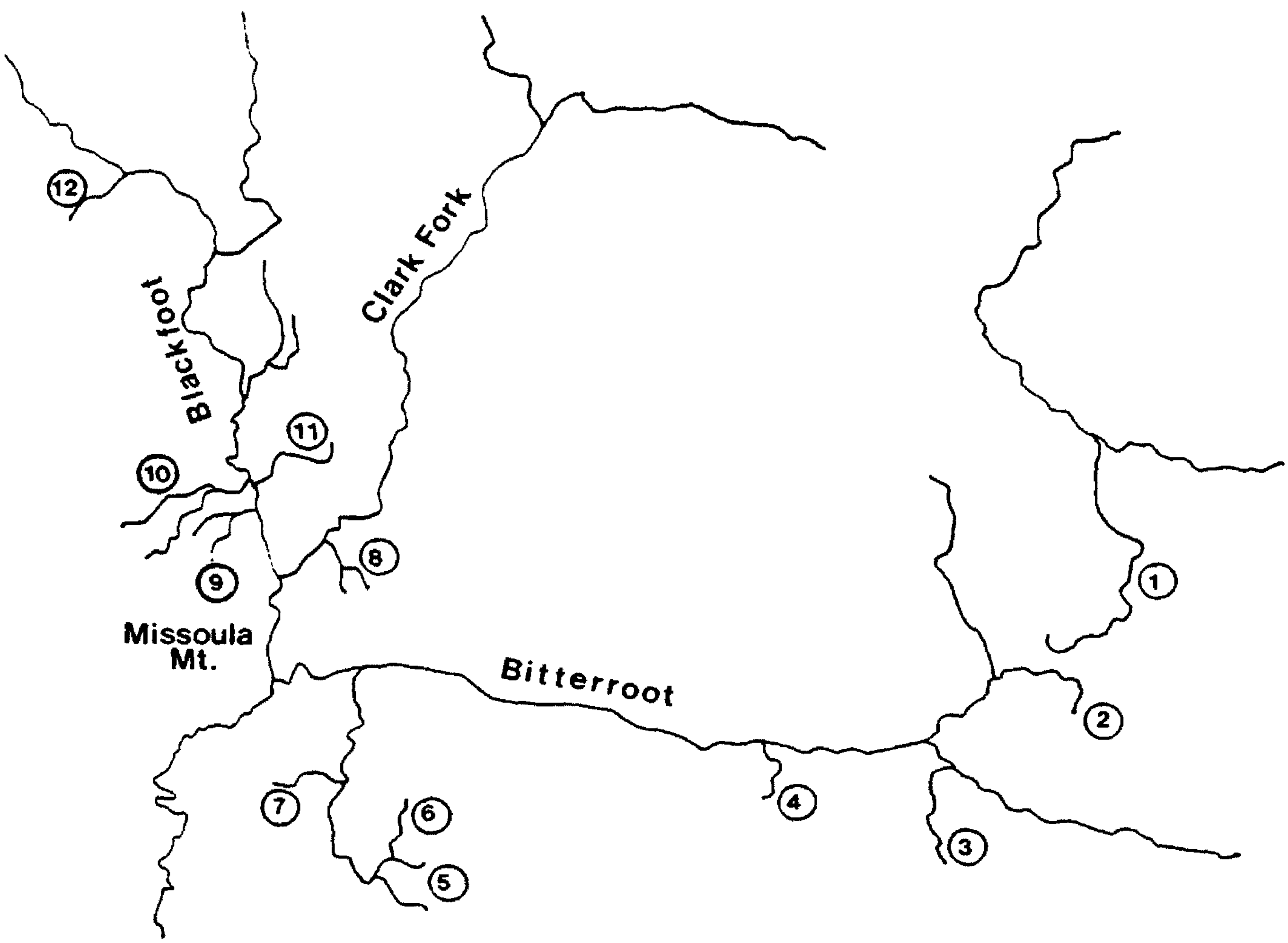
STUDY SITES

Fourteen gravel- cobble- and boulder-bed streams in western Montana were sampled. Fifty-one stream reaches, in the fourteen identified streams, were examined to determine geologic materials (granitic, belt series, and carbonates), and stream sizes (first-, second-, and third-order).

Three study sites were established on both Buck Creek and Arkansas Creek. These streams are a concern to the Montana Cumulative Watershed Effects Cooperative because of the past management impacts and they are believed to be at "the threshold of concern". In addition to Buck Creek and Arkansas Creek, study sites were located along low-order tributaries to the Bitterroot, Blackfoot, and Clark Fork Rivers (see Figure 1). The study reaches are representative of medium- to high-gradient gravel- cobble- and boulder-bedded streams. The characteristics of studied watersheds and individual stream reaches appear in Table 1. To assure a good representation of stream types and geologic materials, stream reaches were identified on topographic and geologic maps prior to field investigation.

The watershed areas above studied stream reaches ranged from 1.45 - 67 mi^2 with Schwartz Creek being the smallest and Trail Creek being the largest. Stream width ranged from 1.3 - 12.8 meters with Schwartz Creek being the narrowest and Trapper Creek being the widest. Watershed areas were determined by planimetering on 1:24,000 topographic maps. Mean annual precipitation was determined from mountain precipitation maps prepared by U.S. Soil Conservation Service (1977). Mean annual precipitation ranged from 20 - 77 in. with Arkansas Creek receiving the least precipitation and East Fork of Lolo Creek receiving the most precipitation.

Figure 1.
Study sites are located in low-order tributaries to the Bitterroot, Blackfoot, and Clark Fork Rivers.



1 = Trail Creek
2 = Camp Creek
3 = Trapper Creek
4 = Camas Creek
5 = Lost Park Creek
6 = East Fork Lolo Creek
7 = Howard Creek
8 = Schwartz Creek
9 = Twin Creek
10 = Gold Creek
11 = Arkansas Creek
12 = Buck Creek

Table 1.
Watershed characteristics and channel geometry for the 51 sampled streams in western Montana.

STREAM	STUDY REACH	WATERSHED AREA (mi^2)	AVERAGE ANNUAL PRECIP (in)	SLOPE (%)	BANKFULL STREAM WIDTH (m)	PARTICLE SIZE d_{50} (mm)	d_{84} (mm)
Buck Cr	1	2.68	35	1.75	2.9	75	130
	2	2.64	35	1.75	3.8	45	130
	3	1.66	36	3.00	2.4	33	60
Arkansas Cr	1	1.60	20	1.10	3.1	34	86
	2	3.10	20	1.70	2.7	32	48
	3	3.40	20	1.70	1.9	40	75
Camp Cr	upper	5.21	30	0.25	3.3	36	100
	lower	8.82	30	0.50	11.8	60	100
	EF	7.66	30	0.90	3.9	30	60
	WF	7.53	30	2.00	3.2	30	60
Moose Cr	4	4.03	30	6.00	2.6	47	170
NF Salmon	1	43.06	30	1.50	8.7	70	145
	2	39.00	30	1.00	7.0	63	155
	5	5.01	30	2.50	4.7	58	130
	6	4.63	30	1.75	4.2	63	130
EF Lolo	1	3.20	77	1.50	5.1	95	152
	2	3.40	77	1.00	5.0	70	130
	3	7.20	68	2.75	6.4	95	224
	4	12.60	67	1.50	3.8	83	170
	5	13.40	63	0.25	4.5	70	150
	6	14.10	63	0.90	4.1	80	180
Camas Cr	1	5.05	55	0.20	5.8	90	160
Trail Cr	low	66.59	30	2.00	11.8	60	100
	upper	40.15	30	0.50	7.8	70	110
Gold Cr	Prims	14.60	33	3.00	7.3	77	140
	Bridge	20.50	33	0.75	5.8	90	160
Howard Cr	1	7.70	37	0.25	1.7	45	75
	2	11.50	37	1.75	2.7	45	100
	3	11.80	37	0.50	3.3	20	60
	4	14.00	38	0.50	3.9	40	110
	5	19.20	37	1.25	4.3	75	165

Table 1. Continued

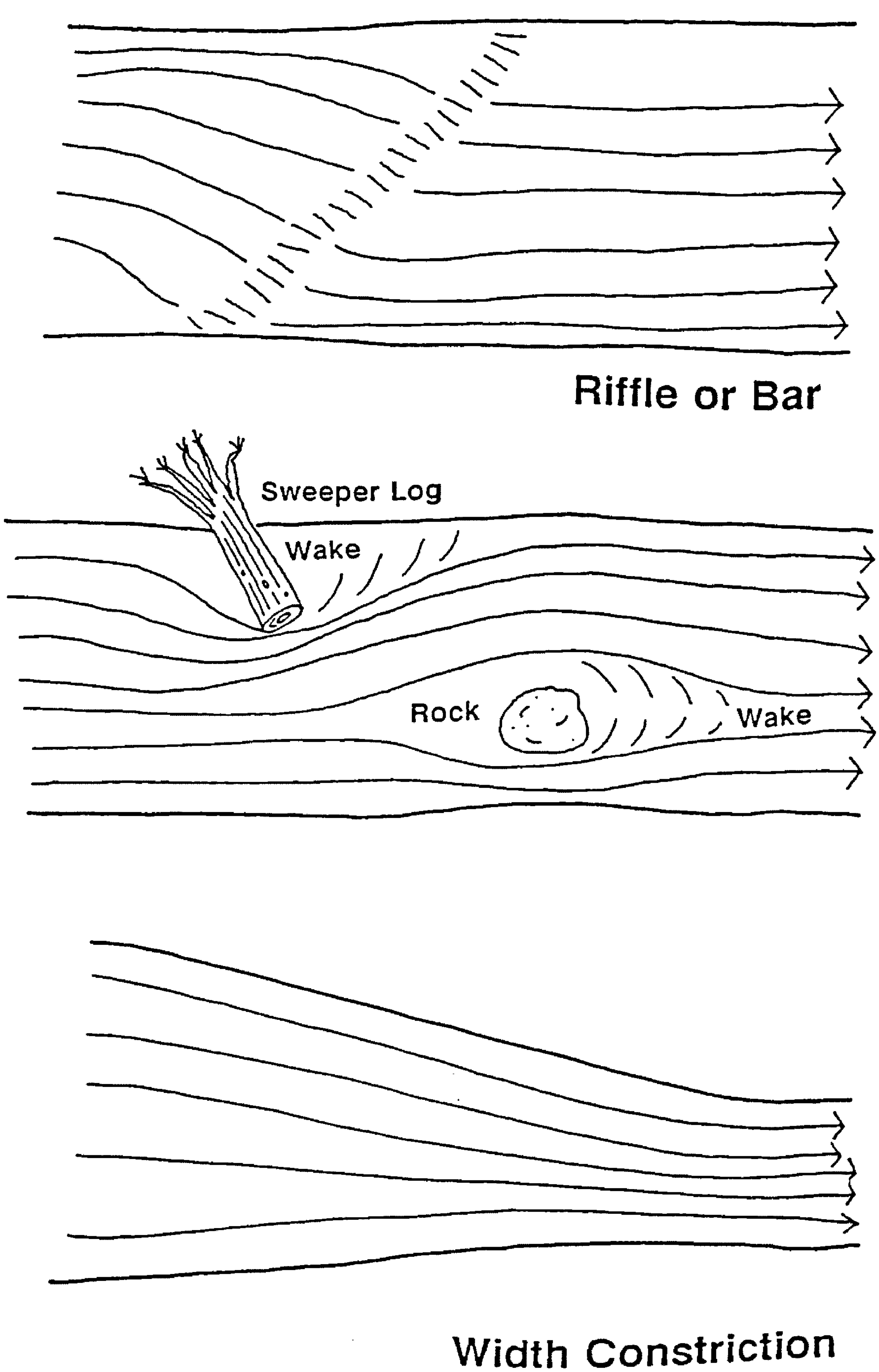
Lost Park	1	9.40	70	2.50	5.0	105	270
	2	9.50	67	2.50	3.9	95	220
	3	9.75	65	2.00	5.7	90	160
	4	9.80	63	1.50	5.6	70	95
Schwartz Cr	1	1.45	22	1.75	1.5	30	50
	2	1.98	22	2.50	2.2	35	60
	3	2.08	22	3.50	1.7	40	75
	4	4.65	22	1.00	1.3	25	45
	5	8.63	22	0.25	2.8	35	50
	6	9.56	22	1.50	3.4	50	75
West Twin	1	4.20	31	2.50	3.4	83	170
	2	4.40	30	5.00	3.9	87	215
	3	4.47	29	2.25	3.7	116	210
	4	4.55	28	3.00	3.3	93	200
	5	4.80	27	2.90	4.2	91	180
	6	7.31	27	2.10	4.2	80	180
Trapper Cr	1	22.26	65	0.80	12.3	70	120
	2	23.00	65	0.90	12.8	70	150
	3	23.04	65	0.25	11.9	70	130
	4	27.04	65	0.25	11.3	65	100

Land management impacts (roads, timber harvesting, and urbanization) varied among studied basins. The range of management disturbance among basins was from nearly pristine (Trapper Creek) to approximately 75% effected by timber harvesting (Buck Creek).

Criteria for Study Site Identification

Individual study reaches and cross sections were chosen in the field after potential reaches were identified from 1:24,000 maps. Criteria for each study reach were riffles or runs of a non-braided channel with self-formed bed and banks. The study cross sections were located away from structures and sources of unnatural bed material (i.e., road crossings, mass failures). Critical velocity, discharge, and shear stress equations are limited in application and require certain "uniform flow" conditions in which bed slope, water surface slope, and total energy gradients are parallel (Grant 1992). Generally, the study section should be located where streamlines are parallel to the bank and to each other. Although perfect conditions are hard to find in natural channels, some features that should be avoided are bends, changes in cross sectional geometry, backed-up water or obstructions to flow which include channel bars, large boulders, or woody debris (see figure 2). These features disrupt uniform flow conditions by causing convergence,

Figure 2.
Some features or obstructions in a typical channel configuration that disrupt uniform flow (Grant 1992)



divergence, acceleration, or deceleration of streamflow (Grant et al. 1992).

Since the objective of this analysis is to estimate stream stability thresholds for the purpose of restricting peak discharge increases, then it is reasonable to locate at least one or two study sites along critical stream reaches. A critical stream reach is defined as the reach most sensitive to change and will be the area least likely to withstand an increase in peak flows (Grant 1992). Study sites should also be located along stream reaches that would give a representative sample of the whole watershed. I recommend a minimum of five reaches per stream evaluation that should be sampled to appraise the stability of the total stream.

FACTORS INFLUENCING BED STABILITY

Stream-bed Movement

Estimating particle transport is difficult for various reasons. The first and foremost reason for this difficulty is that natural stream channels are non-uniform in space and the balance of forces on individual particles at the surface of a bed changes drastically in time (Wiberg and Smith 1987). Transport occurs during infrequent, short duration floods and varies markedly in response to change in water velocity and armoring (Thompson 1985). Stream-beds with uniform particle size distribution are said to have a single critical shear stress that initiates bedload movement. Stream-beds with a non-uniform particle size distribution (typical of mountain streams) have more complex velocity profiles inducing associated individual shear stresses to move each particle size (Bathurst et al. 1987). The associated complexity in natural mountainous stream channels has been the topic of a considerable amount of research deriving appropriate bedload movement equations.

Bathurst et al. (1987), state that particle sizes typically lie in the ranges 1 - 100 mm in gravel-bed rivers and 1 - 1000 mm in boulder-bed rivers. The forces required to set the different size fraction of a given sediment into motion may then differ to the extent that at any given flow, some sizes of particles may be in motion while others are stationary. Tractive forces may exceed the threshold for small diameter particle movement but the same tractive force may not exceed the threshold of the larger sized materials adjacent to the smaller particles. It may therefore be impossible to define a single critical flow for the initiation of all sizes.

Several studies have shown that for non-uniform sediments (gravel- cobble- and boulder-bed rivers) the smaller particles are sheltered behind the larger particles and require a higher flow to set them into motion than is required for uniform (sand-bed rivers) particles of the same size. Similarly, the larger particles can be moved by lower flows than would be necessary for uniform particles of the same size because of their protrusion into the forces of the flow (Andrews 1983, Proffitt and Sutherland 1983). As discharge exceeds the critical value for movement of the coarsest fraction, there is approximately equal mobility of all size fractions (Andrews 1983). This phenomena is the result of the balance derived from the presence of the coarse material and from their exposure/hiding effect (Bathurst et al. 1987). The threshold tractive stress for particles of a different size in a given reach actually was found to vary little and essentially all particles start to move at a time when there is widespread instability of the cover layer (Andrews 1983). This is consistent with data from several studies (Laronne and Carson 1976), which indicated no substantial differences in mobility with size, that for the d_{50} being no more than 30% different from d_{16} or d_{84}. Carson and Griffith 1987 concluded that in gravel-bed rivers, the mobility of gravel particles is basically much the same irrespective of size. As a result, the use of a single representative particle size is suitable when computing total bed material transport with those integrated for different size fractions.

It should also be demonstrated that if the size of the cover layer changes during a flood, the actual capacity at any moment in time after the onset of the flood is an unknown or hasn't been studied thoroughly (Carson and Griffith 1987).

Bankfull as a Index of Dominant Discharge

There have been many studies determining the relationship between bedload movement and the stream water elevation (above or below bankfull). Carling (1988) considers bankfull discharge the effective discharge in maintaining channel capacity, and only during flows equal to or higher than bankfull, are the largest bed materials entrained in quantity. This conclusion seems to differ somewhat from other investigations (eg. Leopold and Rosgen 1990, Andrews 1983). Leopold and Rosgen demonstrated the mobility of different size fractions using the d_{35}, d_{50}, and d_{84} size particles at less than bankfull discharge. They hand-placed many painted rocks of known diameter in straight lines across several stream reaches. The position of several rocks changed during various stages, but all were less than bankfull. The d_{84} size fraction was found to have about the same percentage moved as the smaller d_{35} size.

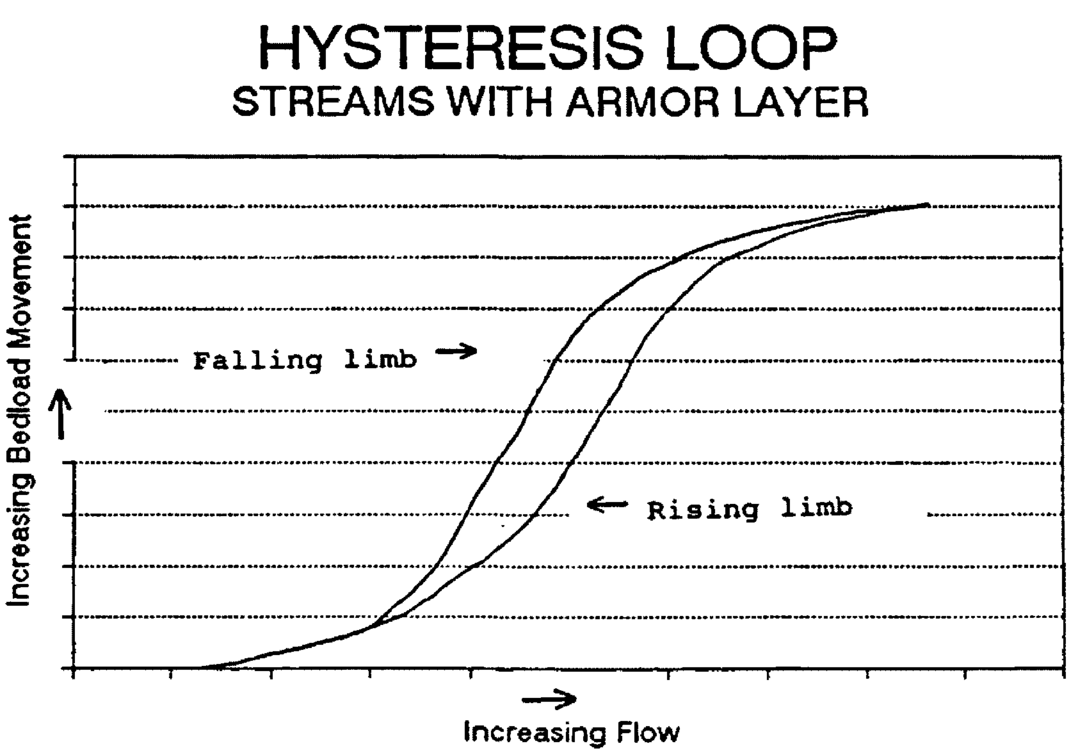
Different phases of bedload transport can be identified through these studies. Partial mobilization of the bed demonstrated by Leopold and Rosgen (1990) at flows less than bankfull entrain the larger particles. This phase of sediment transport effectively maintains an equilibrium in channel capacity and sediment discharge theoretically exists essentially until flow equals zero. The prior condition differs from what is considered dominant discharges. Dominant discharges are distinguished from equilibrium flows as events where bedload is mobilized in large enough quantities to propagate morphological changes in the stream channel. This clarification of terms is of utmost importance when defining stability thresholds.

The Stream Cover or Armor Layer

The presence of an armored layer, or tightly packed surface layer can increase the tractive forces that are required for a substantial amount of bedload transport. There are many factors that influence the degree of armoring a stream has or the amount of force it takes to disassemble this layer. Most streams or stream sections that do not possess a tightly packed armor layer tend to be inherently unstable and movement of all particle size fractions can occur frequently. It has been recognized that the critical mean velocity for the onset of bed material movement is significantly higher than that needed to maintain movement once particles have been entrained by the flow (Thompson 1985). This is caused by stationary particles on the bed tending to interlock with each other with smaller ones being shielded from the flows by the larger ones.

In streams that have an armored surface, an increase of bedload transport is found during the falling limb (discharge decreasing with time) of the hydrograph. This post-peak increase in bedload transport is believed to result from the breaking up of the shielded particles (Reid, Frostick, and Layman 1985). The dismantling of the armor layer generates a hysteresis effect (see Figure 3) causing more bedload movement during the falling limb of the hydrograph (even with a lower discharge and lower velocities) than is found at equivalent discharges during the rising limb in streams that exhibit an armored surface.

Figure 3.
A diagram of the hypothesized hysteresis loop of flood wave and bedload movement in streams with armored beds.



This hypothesized hysteresis loop was observed during bedload sampling on Camp Creek and North Fork Salmon River during the 1991 spring runoff.

Some discussion has arisen about defining the degree of armoring that a stream bed has. The term "pavement" has been suggested for stream beds that disassemble less frequently than armored stream beds. The term "armor" was given to surface layers that are coarser than the rest of the bed solely because of winnowing of fines (<8mm). Parker et al. (1982) defined armor as a static bed condition formed by a winnowing process. Pavements were seen as originating through rearrangement of bed material only during extreme floods and only rarely is there movement of the pavement bed material. In contrast, armored beds were recognized as being subject to frequent gravel transport during high flows (Bray and Church 1980). Using Bray and Church's distinction of pavement, Parker and Klingman (1982) also concluded that pavement is a mobile-bed phenomenon. Carson and Griffith (1987) use the term "cover layer" to avoid confusion and can be applicable to either "pavement" or "armor", irrespective of how they have been used in the past.

I see no advantage in getting caught up in differentiating between armored- and paved-stream beds. The terms cover layer, surface layer, armor layer, and pavement are used to describe characteristics associated with the upper-most layer one particle thick. They were found to be used interchangeably throughout the literature and an acceptable criteria has not been formulated to separate those terms.

Particle Size Distribution

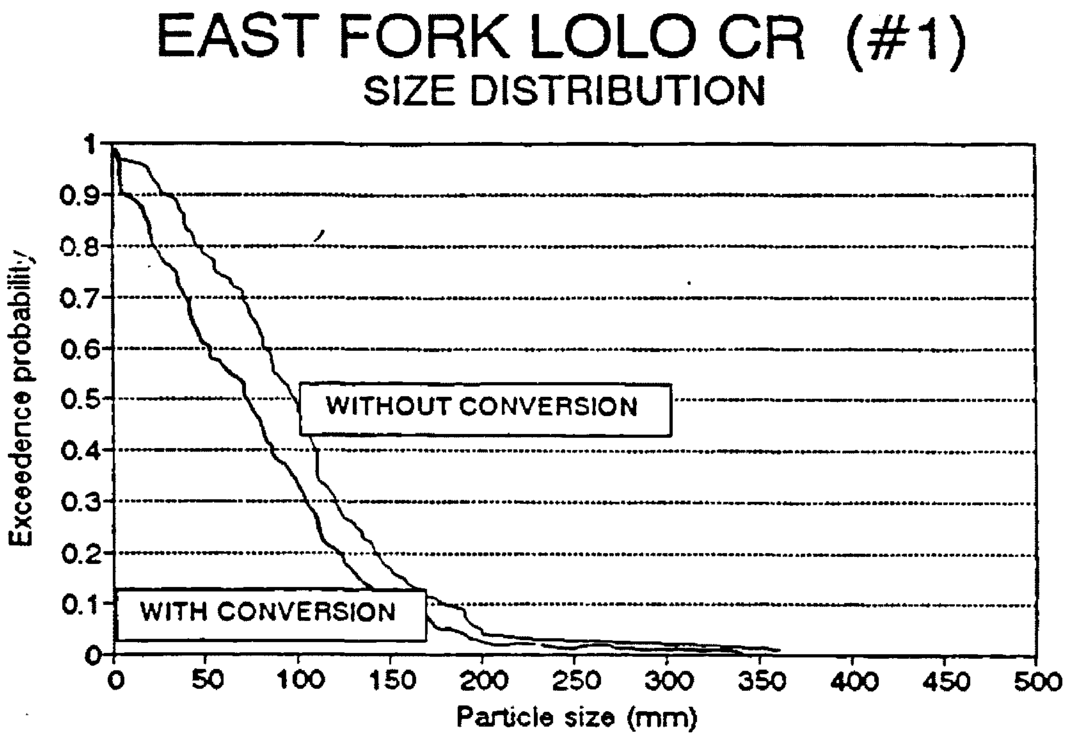
An accurate sample of the stream-bed particle population is required to determine thresholds for the stream channel. Developed sequences of pools and riffles are associated with a notable longitudinal variation in the size distribution of stream bed materials (Sidle 1988). Riffles tend to have coarser bed material than do adjacent pools. This indicates the action of the local sorting mechanisms which occur during periods of high flow (Kappesser 1992).

Determination of the stream bottom particle size distribution is essential in describing the transportation rates of assorted sized stream particles. Several sources of variation, (including longitudinal and latitudinal) must be considered when determining the particle size distribution for a given stream reach. Several methods of determining distributions of particle sizes are available, including sieving/weighing, and systematic pebble counts. Each method has its associated advantages and biases.

Sampling stream-bed particle size distribution by sieving/weighing requires bulk samples usually deeper than the upper surface. Subsurface materials are finer in gravel-bottom streams thus sieving/weighing will underestimate the size distribution of stream bed materials. Therefore, a higher percentile of the fine materials are measured using this method. Pebble counts require point sampling of different sized individuals on a semi-flat surface. The differences in exposed areas associated with different particle sizes have been found to create a bias toward picking coarser material. This bias is proportional to the exposed surface area and therefore to the square of the mean diameter. It increases the probability of choosing larger particles and results in an over-prediction of the pebble size distribution by sampling a higher percent of the larger stream bed particles. Leopold (1970) uses a weighting factor inversely proportionate to the square of the diameter of the b-axis to alleviate this bias. Figure 4 displays the uniquely different curves that were found in West Twin Creek by using Leopold's weighting factor and not using it. Notice that the d_{50} and d_{84} decreased by approximately 25 millimeters each when the weighting factor is included for East Fork of Lolo Creek #1.

The effects of this bias is greater in stream-beds with large materials than in streams that are dominated by smaller cobbles and sand grains. This is the result of more surface area being exposed by larger particles and caution should be used when incorporating Leopold's weighting factor for all streambed sizes.

Figure 4.
An example of using Leopold's conversion to alleviate bias toward larger particles.



Particle Shape

Shape of the individual stream-bed particles is another variable affecting particle movement. However, studies show weak evidence that the sphericity index (Krumbein 1941) or the flatness index (Cailleux 1947) have any clear influence on shear stress. The shapes that should most affect particle movement are distinctly flat, bladed or rod-like. Carling (1983) states that this is attributed to the stochastic nature of individual particle entrainment processes and that there is a relatively limited range of grain-shapes available in a natural stream system.

Bankfull Discharge and Channel Cross section

Careful field measurements of the cross section profile of the stream channel are important. Various definitions of the term "bankfull" appear in scientific literature. The distinguishing feature of the bankfull reference level as defined by Parrett, Omang, and Hull (1983) is the abrupt change in bank slope from near vertical to near horizontal. Riggs (1974) defines bankfull as that part of the stream channel bounded by the streamward edges of the floodplain or by the lower edge of permanent vegetation. Because of the variability and irregular location on channel banks, vegetation has been criticized as a inaccurate index of bankfull (Riley 1972, Williams 1978).

Stream Slope

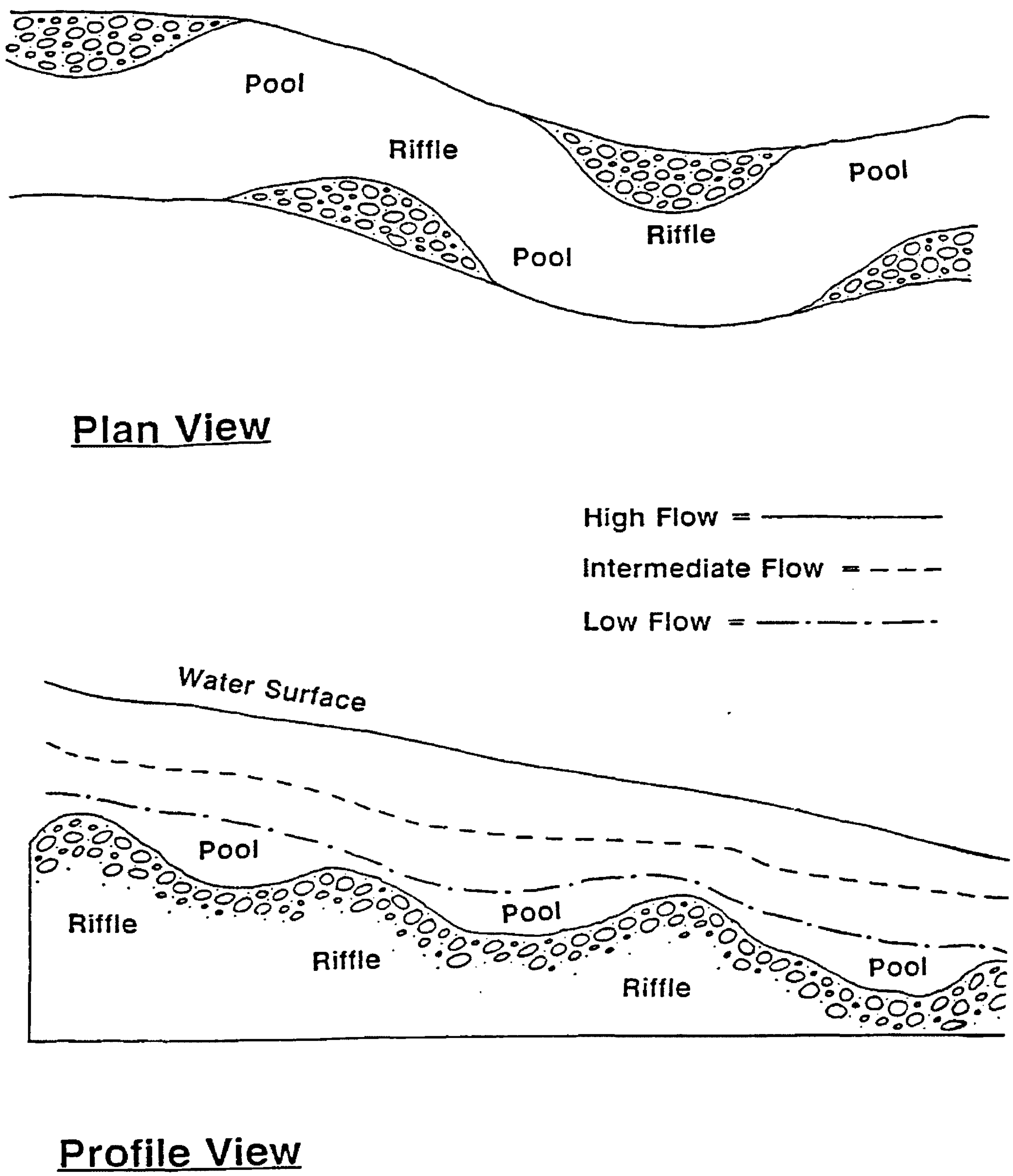
Gradient or slope of the stream bed is inversely proportional to discharge and directly proportional to sediment load and grain size. Slopes of the water surface was found to vary up to 5% between stream reaches and was found to decrease in (most study reaches) with distance from the headwaters. Total stream gradient (over the total length of the stream) is surmised (Grant 1992) to stay essentially constant through increases and decreases in the flow regime. High flows are believed to increase water surface slope at the microscale (Grant 1992) (see figure 5). This change in water surface gradient is most extreme in pool segments and sometimes is found to be negligible in riffle segments. Stream gradient is commonly taken as constant in the application in bedload formulae, yet as seen in figure 5, it can fluctuate during the passage of a flood wave.

Prediction of Increases in Peak Discharges

Increases in peak flow resulting from land manipulation are varying in both space and time depending on vegetation type, climate, soil, and topography (Hess 1984). Unfortunately, as MacDonald (1993 unpublished interim report) points out, the widely varying literature doesn't allow an accurate model to be developed or inferred. Examples of some possible generalizations follow.

Haupt (1979) demonstrated that large openings in the canopy on north aspects can enhance flooding and cause higher spring peak flows "for many years" after logging, whereas in large openings on south aspects, because of snow melt desynchronization, it could actually reduce peak flows.

Figure 5.
Diagram of a longitudinal profile and plan view of a pool-riffle sequence representing the change in slope at high, intermediate, and low flow (Grant 1992).



In snow dominated regimes, studies have shown that depositional snowpack increases in the openings, and average peak water equivalent increased with the largest effect occurring in the wettest years (Troendle and King 1985).

Changes in streamflow have historically been documented in small watersheds where the effects of peak discharges are believed to be more significant than in large ones (Leopold 1980). It is also easier to establish a cause and effect relationship in small watersheds. Chang (1989), presented a study with strong evidence that changes in streamflow from a large forested watershed can be significant if a sizeable portion of its drainage area is clear-cut. Post-logging streamflow changes were characterized by increases in annual and monthly water yields and annual peak flows, as well as earlier annual peak flow. The results (Chang 1989) are in good agreement with the findings of most previous studies conducted in smaller watersheds.

Harr (1975), found that peak flows increased significantly after road building, but only when roads occupied at least 12% of the watershed. This observation is consistent with the literature on the effects of urbanization on peak flow increases. Most increases were largest in the fall when maximum increase differences in soil water content existed between cut and uncut watersheds. Harr (1975) also found that maximum increases in stormflow occurred after a 175-acre watershed was 82% clear-cut. This clear-cut covers an extreme proportion of this watershed which resulted in maximum peak flows. See Appendix 1 for a summary of forest management-related peak flow changes.

There is not enough information to determine the type of relationship (linear, exponential, etc.) that exists between the percent of watershed harvested and discharge increases, but a reliable prediction of the magnitude of change in peak flow is essential (Harr 1981). Harr (1987) discussed some common misconceptions associated with forestry and discharge increases. They are: (1) there is a 12% compaction threshold; (2) desynchronization of flows is beneficial; and (3) wet mantle runoff is unaffected by clearcutting. He goes on to report that "if a threshold is to be used, it must be based on the physical characteristics of the stream in question." "Some extremely stable stream systems can accommodate much higher flows without any degradation of the stream channel, and to restrict harvest operations in such watersheds to the same degree as in watersheds where some channel reaches are unstable makes little sense."

FIELD METHODS AND COMPUTATIONAL PROCEDURES

Stream-channel Geometry

The first step in estimating channel stability thresholds will be surveying channel cross sections to determine channel-geometry (area and roughness) at bankfull. Bankfull width and height should be determined primarily on geomorphic features (Williams 1978), and secondarily on the lower edge of permanent vegetation (Riggs 1974). Channel-dimensions can be measured using a 20-meter measuring tape, measuring rod, and a level. Depth from bankfull height should be measured at least every ten centimeters across the channel to identify individual stream-bed particles. See Appendix 2 for detailed cross sections of all study sites.

Bankfull height and width are not always discernible on both sides of the stream and sometimes not well defined, particularly when the stream is entrenched in the floodplain. In all study reaches, one side of the channel should have a discernable bankfull level. A simple bubble leveling device on a tightly stretched line can be used to locate the bankfull height on the undiscernible side.

An estimate of water surface slope is required for critical discharge and velocity formulas. The slope of riffle or run segments are believed to control the forces acting on individual particles within the riffle. Therefore, an average slope of the water surface over a 10-20 meter distance was used. Measuring surface gradient on a 1-20 meter interim can be made using a hand held clinometer, a measuring rod, and a 20 meter measuring tape. Study site selection should ensure that the water surface and bedform run parallel with the same slope. It is extremely important to accurately survey the stream slope because gradient is one of the driving variables behind predictive bedload movement formulas.

Stream-bed Size Distribution

Determination of the stream bottom size distribution is essential in describing the transportation rates of assorted stream particles. Diplas (1987) emphasizes that the choice of using a single particle diameter to describe the mobility of bed mixtures is not adequate because in natural stream channels a wide range of grain sizes is the norm. An accepted method of determining the stream bed size distribution can be obtained by using a systematic point sampling pebble count (Wolman 1954). This method was chosen over sieving/weighing because it is easier and represents the surface layer (one particle thick) instead of a core sample involving subsurface materials.

After a study reach had been identified, a grid pattern of sampling points is then set up to point-sample 100 pebbles systematically. Wolman (1954) found that a sample size of 100 was adequate in obtaining an accurate description of the particle size distribution. Pebbles are randomly selected by closing your eyes, reaching down with one finger to a spot at the tip of your boot, and the first pebble that your finger comes in contact with, you open your eyes and grab that pebble and measure. The intermediate, median, or b-axis diameter (not the shortest or longest axis) of each pebble is measured. The cumulative percent of material finer than a given size can then be determined. Particle size information is usually reported in terms of d_i, where i represents some distinct percentile of the distribution. For example the d_{84} represents the particle size that 84% of the total sample is finer than. See Appendix 3 for the particle size distribution of all study reaches. Leopold's (1970) weighting factor for mitigating the sampling bias toward larger particles was not used in this analysis. This choice is based on the large stream bed particles that exist in the sampled reaches. This weighting factor reduced the size distribution dramatically in these reaches probably giving more representation of the smaller particles but possibly underestimating the largest particles in the population.

The use of calipers in measuring particle diameters was very time consuming and it was difficult to measure deeply imbedded cobbles. A ruler was faster and easier, especially for the largest particles that cannot be lifted.

Assessing Natural Peak Discharges

For each study site, the magnitude of floods of various return periods are estimated, based on channel-geometry, watershed characteristics, or both channel and watershed characteristics (Omang et al. 1986). An interactive program, FLOOD.EXE (Anderson 1992) is available to provide the flood discharge estimates.

The use of XSPRO (Grant et al. 1992) is very useful in estimating bankfull discharge for a given cross-section. This model uses two equations (Jarrett 1984, Thorne and Zevenbergen 1985) to estimate the amount of flow, and average velocity, that will be found at bankfull stage. Table 2 displays dominant discharge estimates for all study sites using methods derived by: Omang et al. (1986), Jarrett (1984), and Thorne and Zevenbergen (1985). Appendix 4 displays the two- through one-hundred year return flows using Omang et al. (1986).

Three of the study sites are located at USGS gauging stations with peak discharge records. This allows predictive formulas to be compared with measured peak discharges. Figure 6 displays recurrence intervals of peak discharges in gauged streams. Consideration must be made of the differing predictions between "bankfull" and the "2-year return period" flows. I am not suggesting that they are equivalent, but that they are both indicators, of dominant discharge. Bankfull discharge has been reported to vary between streams with an average (mode) of 1.5 years on the annual maximum series, but can range from 1 to 32 years

Table 2.
Estimated dominant (bankfull) discharge for all study reaches using formulas derived by (Jarrett 1984, Thorne and Zevenbergen 1985), and 2-year return period floods using multi-regression formulae of (Omang and others 1986).

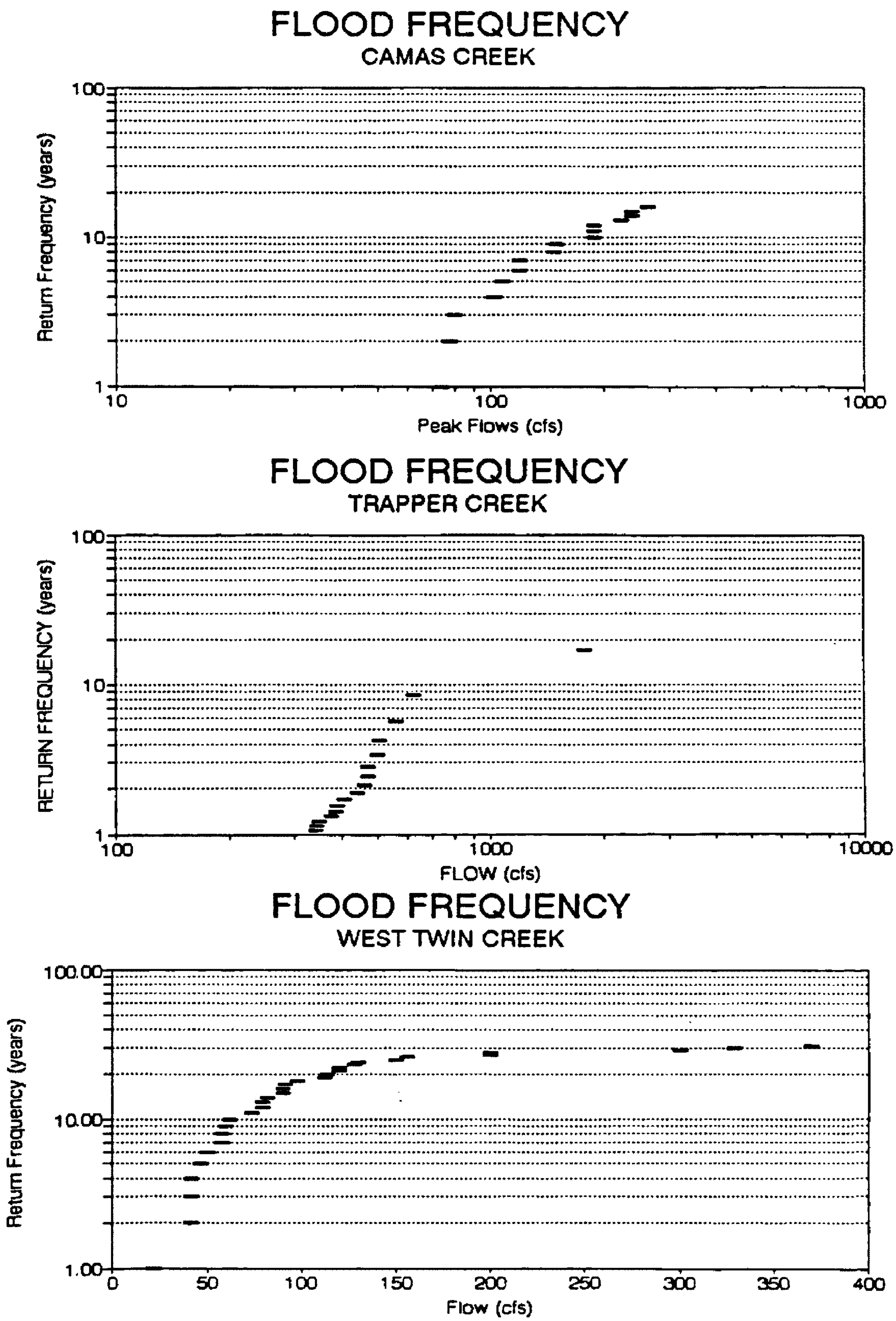
		2yr RETURN	DOMINANT (BANKFULL) DISCHARGE	
STREAM NAME	STUDY REACH	OMANG ET AL. (1986)	JARRETT (1984)	THORNE AND ZEVENBERGEN (1985)
BUCK	1	20.2	20.9	37.5
	2	24.1	30.5	54.2
	3	12.5	8.1	23.0
ARKANSAS	1	6.1	29.0	50.6
	2	13.0	2.1	5.3
	3	14.0	7.4	15.9
CAMP	top	25.1	9.9	8.5
	EF	37.4	28.3	49.6
	WF	29.8	23.7	54.9
	bottom	53.7	44.3	51.0
HOWARD	1	18.1	2.8	2.8
	2	34.7	10.3	18.4
	3	44.9	15.2	21.2
	4	56.8	23.7	26.6
	5	73.0	29.8	37.9
NF SALMON	1	208.1	118.3	187.0
	2	152.5	65.9	81.1
	4	17.7	9.2	19.5
	5	36.8	27.3	49.9
	6	31.3	25.1	39.3
WEST TWIN	1	30.7	25.5	42.5
	2	30.5	24.4	44.6
	3	22.6	39.7	58.4
	4	25.2	31.2	54.9
	5	50.0* 27.4	43.6	77.9
	6	27.6	31.9	20.9
SCHWARTZ	1	4.6	2.1	5.0
	2	7.9	3.9	8.9
	3	6.2	3.2	7.8
	4	6.9	2.5	5.0
	5	19.7	13.8	15.9
	6	21.2	17.0	33.3

Table 2. Continued

TRAPPER	1		388.1	117.9	152.6
	2		422.4	122.5	156.5
	3		443.8	198.7	165.0
	4	350.0*	469.1	122.2	107.3
LOST PARK	1		104.8	49.6	63.8
	2		82.6	31.9	14.5
	3		124.3	37.5	10.3
	4		117.7	31.2	55.6
EF LOLO	1		75.0	27.3	38.2
	2		74.1	40.4	55.6
	3		127.0	27.6	44.3
	4		92.9	36.1	49.9
	5		108.1	35.0	26.6
	6		100.0	19.1	15.9
GOLD	Prims		109.0	122.2	253.9
	bridge		98.4	111.2	119.7
TRAIL	low		354.9	426.1	352.0
	upper		174.7	154.4	176.7
CAMAS	1	80.0*	79.0	54.2	43.2

All calculations are in cubic feet per second
* Use of Figure 6 from actual gauging stations (USGS).

Figure 6.
Recurrence frequencies of peak discharges in USGS gauged streams at Camas, Trapper, and West Twin Creek.



(Williams 1978). The use of a 2-year return interval for bankfull is for convenience in using the best prevailing models for their predictions. A bankfull discharge frequency can be obtained on a stream-by-stream basis using the methods described by Williams (1978).

Bedload Movement Formulae

While numerous formulae exist for predicting instantaneous bed-material transport rates, the sparse data for gravel- cobble- and boulder-bed rivers makes the choice of an appropriate formula difficult for field use. The formulae reported here relate critical shear stress, critical discharge, and critical velocity to the size of the largest particle that can be put into motion.

CRITICAL SHEAR STRESS APPROACHES

The Critical Shear Stress Formula of Shields (1936)

Tractive stress or shear stress refers to the dragging force of the flow on the channel boundary per unit area of the boundary. Shields determined his critical tractive force by extrapolating a graph of observed sediment discharge verses tractive stress to a transport rate of zero. When the transport rate equals zero, the threshold for particle movement was found and plotted against its associated tractive stress. An important consideration which can not be overlooked is that Shields used the relationship between the critical tractive stress for bed material movement in flume channels with beds of 'uniform' sands. The equation derived by Shields gives the expression,

$$\tau_c = \tau_{*c}\ (p_s - p)\ \mathrm{gd} \qquad \text{(Eq. 1)}$$

where τ_c = critical shear stress

τ_{*c} = the Shields parameter or critical dimensionless shear stress (entrainment function)

d = particle diameter

g = acceleration due to gravity

p = water density

p_s = sediment density

Implicitly, τ_c is an average value for particles of given size d, depending upon exposure and other factors (Shields 1936).

Customarily Shields parameter (critical dimensionless tractive force) is assigned a value of 0.04 to 0.06 for flows with high Reynolds numbers. Differences (previously discussed) in stream beds with uniform size particles and stream beds with non-uniform size particles justify caution when applying formulae derived specifically for uniform size particles (as Shields was) when applying to streams with non-uniform beds. Other studies have addressed this problem trying to satisfy the need for predictive formulas in non-uniform stream beds.

Schoklitsch (in Graf 1984) recommended a critical dimensionless shear stress of 0.076 for non-uniform particles greater than 7mm. Rosgen (1993) reports critical dimensionless shear stress validation for various stream types. All "A" and "B" type streams were found to have critical shear stress in excess of 0.06. Type "A-2" streams have critical shear stress in excess of 0.15 (see Figure 7).

Kappesser (1992) used the Shields equation as his tractive force alternative of his riffle armor stability index procedure. The critical grain size can be determined by the formula,

$$d_c = 47.84\ \tau$$

where,

d_c = critical grain size

τ = shear stress ($\dot{\gamma}RS$).

Kappesser uses a mixture of metric and english units in deriving the constant 47.84. The shear stress (τ) = VRS, where τ = shear stress (lb per ft^2), v = unit weight of water (62.4 lbs per cubic foot), S = slope (meter per meter), and R = hydraulic radius (ft). While not expressed explicitly in the paper, I suspect this procedure assumes a critical dimensionless shear stress of 0.06.

Andrews (1983) found that the value of τ_{*c} was found to be highly influenced by the size distribution of the riverbed. Andrews work with gravel-bed streams, indicated that the τ_{*c} (entrainment function) value of Shields seemed to be incapable with non-uniform sediments.

The Critical Shear Stress Formula of Andrews (1983, 1984)

Andrews data indicated that the τ_{*c} value of .056 from Shields is too high and suggests an τ_{*c} value of .03 for natural gravel-bed streams. Using Andrews value of .03 for the entrainment function value, he came up with the expression for the critical tractive stress,

$$\tau_c \approx .0834 \; (d_i \; / \; d_{50})^{-0.872} \qquad \text{(Eq. 2)}$$

where τ_c = critical dimensionless shear stress for particles in the surface layer

d_i = size fraction of surface material at the i^{th} percentile

d_{50} = subsurface or parent material at the 50^{th}

percentile.

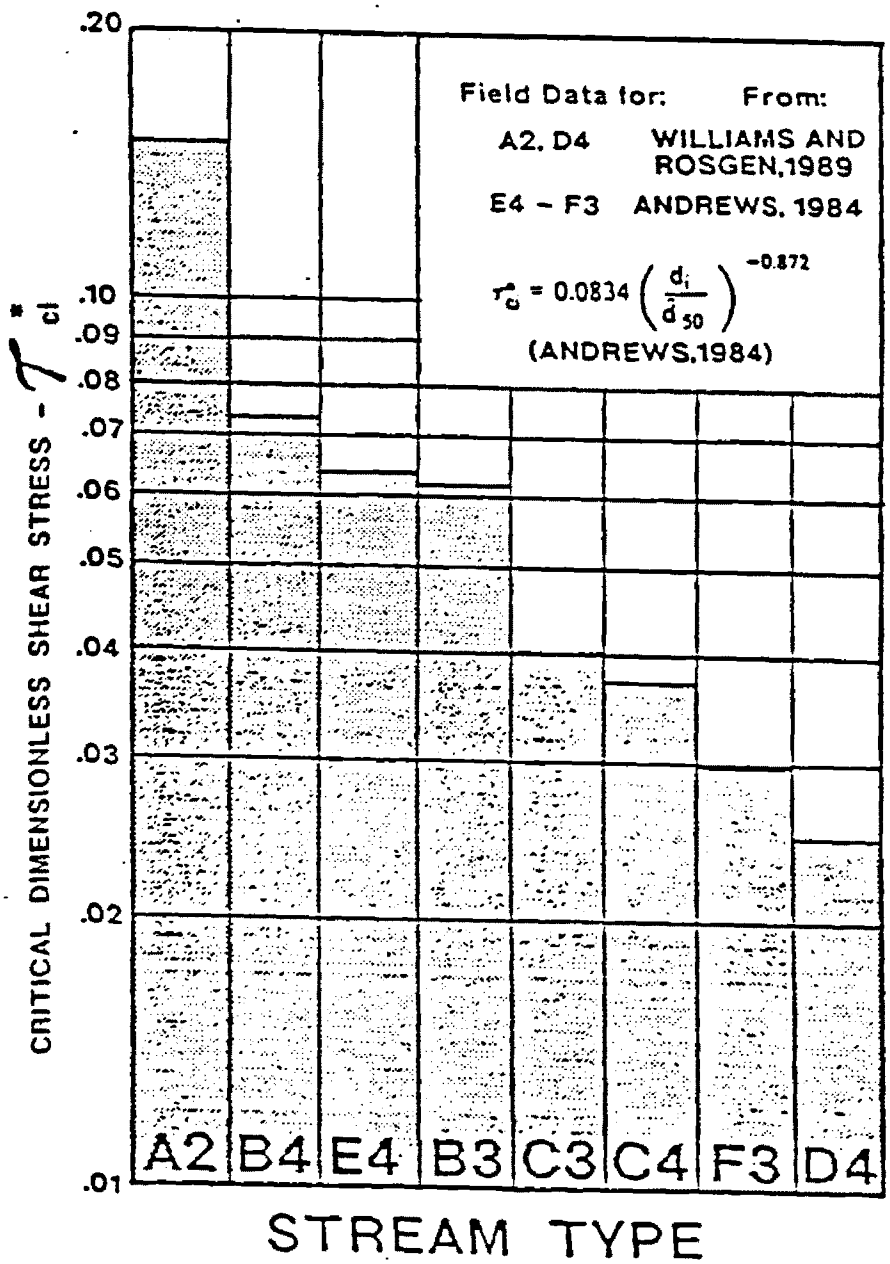
Andrews (1983) demonstrates that the critical shear stress ,τ_*, varies almost inversely with the particle size d_i.

Ordinarily the median diameter for the surface layer is 1.5 to 3 times the median diameter for the subsurface layer (Parker et al., 1982). Andrews has quantified the critical tractive stress empirically with field data, giving, for the range $0.3<d_i/d_{50}<4.2$. Andrews equation gives a τ_c value that as shown above varies almost inversely with particle size. This yields a relatively narrow interval of critical shear stress for all size fractions. Because of this small interval, the smaller particles in the distribution can still be entrained by flows weaker than the flows necessary for the larger particles, but the range of critical flow is relatively narrow.

Andrews used a critical particle diameter of d_{50}. This parameter was also used for the d_{84} when the assumptions of stream stability (previously discussed) are related to the larger d_{84} particle size.

Rosgen's (1993) analysis of Andrews' data indicates that the majority of streams Andrews studied were in low-gradient, moderately or slightly entrenched stream types (Types C & D). These streams types have critical dimensionless shear stresses typically below 0.06 (see Figure 7).

Figure 7.
Relationship of field verification of critical dimensionless shear stress values for various stream types (Rosgen 1993).



CRITICAL DISCHARGE APPROACHES

The Critical Discharge Formula of Bathurst et al. (1987)

As an alternative to using the Shields or Shields like formulas, Bathurst et al. (1987) took the Schoklitsch approach by using the unit water discharge, q, instead of shear stress, τ, to predict critical conditions for particle movement. Bathurst agrees with Schoklitsch's premiss that for natural rivers, the critical conditions for sediment transport are often exceeded in only one part of the channel, thus the use of shear stress as a criterion could be unsuitable for natural conditions.

Bathurst found empirically, by using data from flumes and rivers with boulder and gravel beds and slopes in the range 0.1 to 10 per cent, that the critical discharge has several advantages over critical shear stress to predict the initiation of particle transport. He came up with the expression for the bed as a whole,

$$q_c = 0.21\ (s^{-1.12}\ g^{1/2}\ d_{16}^{3/2}) \qquad \text{(Eq. 3)}$$

where q_c = unit critical water discharge for initiation of motion

d_{16} = particle diameter for the 16th percentile of the surface layer

s = stream gradient

g = acceleration due to gravity.

This empirical equation is recommended by Bathurst et al. (1987) for critical discharge in mountain rivers with slopes in the range of 0.25 to 10 per cent. The critical conditions predicted by Eq. 3 does not apply to all fractions of the sediment sizes if the size distribution is wide. Bathurst et al. (1987) states that Eq. 3 predicts the initiation of movement of the smaller sizes while the larger sizes are still stationary. Due to the phenomena of hiding and exposure effects, predicting the initiation of movement for any size fraction can be obtained by using Eq. 4,

$$q_c = 0.15\ (s^{-1.12}\ g^{1/2}\ d_i^{3/2}) \qquad \text{(Eq. 4)}$$

where q_c = unit critical water discharge for initiation of motion

d_i = particle diameter for the i^{th} percentile of the surface layer

s = stream gradient

g = acceleration due to gravity.

The critical discharge of Q_{cr} can be obtained by multiplying q_{cr} by the stream width,

$$(Q_{cr} = q_{cr} * \text{stream width}).$$

This is one approach, reputed to be more reliable for steep, gravel and boulder bedded channels where Shields' criterion does not apply. Common field measurements favored this approach, thus, Schoklitsch's equation propagated more studies on the relationship between bedload transport and critical discharge.

CRITICAL VELOCITY APPROACHES

The Critical Velocity Formula of Thompson (1985)

Thompson (1985) questioned equations that have been derived from flume data. He argues that coefficients in gravel-bed rivers are about twice those in gravel-bed flumes. Thompson states that differences are attributed to longitudinal flow profiles of natural rivers being less uniform than in flumes. Thus, for a particular velocity, slope, and sediment size, the depth will be larger in a river than in a flume. This depth differences generate an overestimation of critical discharge for the initiation of natural stream bed materials. He believes that with a hypothesis of a high Reynolds number, only water velocity near to the bed and the diameter of the particles need be known to predict bedload transport. Thompson derived the expression:

$$U_c = 6.2d^{0.06s}s^{-0.148} \quad \text{(Eq. 5)}$$

where U_c = critical velocity for particle movement

d = particle diameter of surface layer

s = stream gradient.

There are many advantages using the Thompson critical velocity approach. The primary advantage is that it greatly reduces the dependence upon local slope. This is an important aspect of the Thompson velocity equation because local slope is one of the hydraulic variables most susceptible to errors in field measurement. Difficulty in accurately measuring stream gradient was encountered during this study and reducing that possible error has practical significance.

Bathurst's critical discharge formulae can overestimate the total discharge that would initiate bedload movement with a slightly lower estimate of slope. Critical discharge per unit stream width is also questioned because the calculated critical discharge per unit width of stream is multiplied by the stream width to get a threshold for total discharge. Spatial changes in depth, velocity, tractive stress, and stream power need to be integrated across the channel width rather than being based on mean parameters for the channel (Thompson 1985).

The Hjulstrom Curve (1935)

The Hjulstrom Curve has been widely used by hydrologists to predict particle transportation, erosion, and deposition in terms of velocity and particle size (see Figure 8). It is very easy to use and as a result it is often referenced in bedload transport studies.

The graphical representation shows the behavior of sediment as the velocity function changes. This curve is often recommended for assessing sediment transport but has been criticized that it is often misused (Novak 1973). Novak argues that the curve is extrapolated into size ranges (under natural stream conditions) that were not employed in its development. However, in a field study of streams with streambed particle diameters up to 330 millimeters, Helley (1969) found agreement with the range of velocities and the initiation of particle transport predicted by Hjulstrom's curve. This evidence of the diagram's predictive power justifies its consideration with larger particles. Modified diagrams have been created to extend the line separating erosion, transportation, and sedimentation into larger particle sizes (> 200 mm) for streams that exhibit cobbles and boulders (Sundborg 1967). The modified diagrams were not needed for the sizes of particles found in our study reaches.

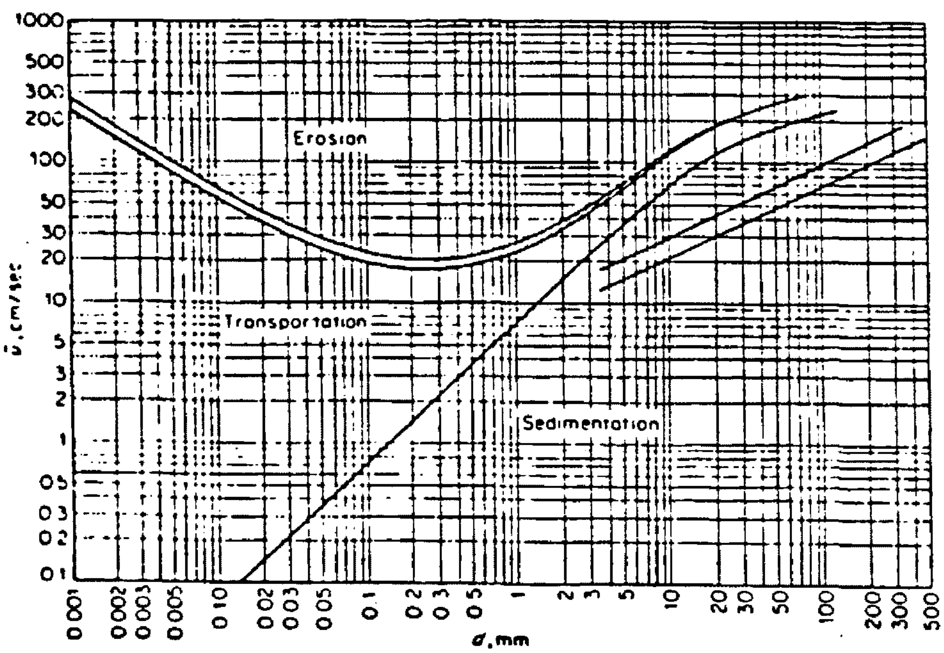


Figure 8. The Hjulstrom Curve (1935) used to predict erosion, transportation, and sedimentation criteria for streambed particles.

Hjulstrom (1935), in deriving his curve, used the "average velocity across the profile of a river" and states that the bottom velocity is approximately .6 times the average velocity in stream conditions at least one meter in depth. This assumption has been criticized by questioning the proposed relationship between bottom and average velocities (Graf 1984). Helley (1969) in his field study using current meters to measure average velocity and bedload samplers to measure particle transport shows that bed velocities necessary to initiate motion of coarse particles agree closely with the range in velocities predicted from the .6 times average velocity theory.

DEVELOPING INDICES OF BED STABILITY

Based on the Hjulstrom curve, the US Bureau of Reclamation (USBR, 1977) gives simple equations for both critical bed velocities and bed velocity where,

$$V_c = 0.155 * \sqrt{D} \qquad \text{(Eq. 6)}$$

and $$V_b = 0.7\ V$$

where V_c = critical bed velocity (m/s)

V_b = velocity along bottom at dominant (bankfull) discharge

d = particle diameter (mm)

V = mean velocity (m/s).

Jowett (1989, in Gordon, et al. 1992) defines relative bed stability (RBS) as the ratio of the critical condition to the existing condition during dominant discharge. This was defined for use specifically with the Hjulstrom curve. Thus,

$$\text{Relative Bed Stability (RBS)} = V_c \ / \ V_b$$

where V_c and V_b, are the critical bed velocity and the velocity at dominant (bankfull) discharge, respectively. The simple interpretation of the RBS index is that when V_c equals V_b (RBS = 1), the stream is at the threshold of stability.

For example, assume that the average velocity at bankfull discharge in a cross-section of a hypothetical stream has been estimated with XSPRO (Grant et al 1992) to be 0.37 m/s. The Wolman pebble count procedure revealed a d_{50} = 150 mm. Using the USBR (1977) equations reported earlier,

$$V_c = 0.155 * \sqrt{150} = 1.9 \text{ m/s}$$

and,

$$V_b = 0.7\ (0.37) = 0.26 \text{ m/s}$$

and therefore,

$$RBS = 1.9 / 0.26 = 7.3$$

This is much higher than 1.0, the value at which the 50th percentile bed particles would be expected to move. Thus the bed would be considered highly stable at bankfull discharge.

We see no reason why the RBS couldn't similarly be determined using analogous shear stress ratios,

$$\tau_c \ / \ \tau_{bankfull}$$

or discharge per unit channel width ratios,

$$q_c \;/\; q_{bankfull}.$$

Similarly, these ratios can be established for design flows. For example,

$$\tau_c \;/\; \tau_{2yr\text{-}flood} \text{ and } q_c \;/\; q_{2yr\text{-}flood}$$

or

$$\tau_2 \;/\; \tau_{5yr\text{-}flood} \text{ and } q_c \;/\; q_{5yr\text{-}flood}$$

For example, assume that the five year-flood discharge in a cross-section of a hypothetical stream has been estimated (Omang et al. 1986) to be 22.6 cfs. The Wolman pebble count procedure revealed a d_{84} = 60 mm. Using the most conservative equation for this particular reach (Eq. #4, Bathurst et al. 1987) reported earlier,

$$q_c = 0.15\ (.030^{-1.12} * 9.8^{1/2} * .060^{3/2}) = .345\ m^2/s$$

with,

Stream width = 2.4 m

1 cms = 35.314 cfs

therefore,

$$.345\ m^2/s * 2.4\ m * 35.314 = 30\ cfs.$$

If,

$$Q_{5yr\text{-}flood} = 22.6\ cfs$$

therefore,

RBS = 30 / 22.6 = 1.33.

The RBS is close to 1.0. The d_{84} bed particles would not be expected to move with the five year flood, although the bed is very near to its threshold (at discharges equal to the five year flood).

PROPOSED METHODOLOGY FOR USING THE "RELATIVE BED STABILITY" INDEX

A. Evaluate and survey watershed and channel characteristics

(OFFICE PROCEDURE)

1. Identify possible study site locations on USGS 1:24000 maps.
2. Determine watershed areas above potential study sites. Estimate average annual precipitation from SCS Mountain Precipitation maps for each study watershed.

(FIELD PROCEDURE)

3. Field locate stream reaches and cross sections for at least five stream reaches including a representation of the most susceptible reaches (Grant et al. 1992)
4. Make detailed field measurements of channel cross section and slope of the water surface through each study reach.

5. Determine streambed particle size distribution (Wolman 1954) across each study cross section.

B. Estimate stream stability threshold

6. Calculate estimated dominant (bankfull) discharge using XSPRO (Grant et al. 1992) and/or mean annual flood using FLOOD v1.1 (Anderson 1993) and use highest value.

7. Calculate critical and bankfull velocity, discharge, and shear stress using Hjulstrom's, Thompson's, Bathurst's, and Shield's equations. The critical values of these parameters are based on the estimates of the d_{84} or d_{50} particle sizes determined in step 5 above.

C. Develop indices of bed stability

8. Calculate the Relative Bed Stability as

$$RBS = (\text{critical value} / \text{bankfull value})$$

for any of the methods in step 7, or perhaps only the most conservative, or perhaps an average of the four parameter ratios.

9. Identify reaches at or near their threshold

(GUIDELINES FOR USING THE "RELATIVE BED STABILITY" INDEX)

→ *RBS < 1 = beyond threshold*

→ *1 < RBS < 1.5 = at or very close to threshold (should be red flagged)*

→ *1.5 < RBS < 2 = nearing threshold (require professional decision)*

→ *RBS > 2 = bed stability should not be effected by management induced peak discharge increases*

RESULTS OF FIELD STUDY

Figures 9 and 10 display that high-gradient streams (slope >1%) produce similar estimated thresholds using Eq. 4 and Eq. 5, where as Eq. 4 seems to be highly affected by slope in the low gradient stream reaches (<1%). Thus the highest variability exists between Eq. 4 and Eq. 5 when stream slopes are less than one percent. The variability decreases as stream slope increase up to one percent then constant variability was found as slope increased to 6%. In our comparisons, if we used slope as the independent variable and Eq. 4 (critical discharge) as the dependent variable, the standard error of Eq. 4's estimate decreased from 38 cubic

Table 3.
Critical discharge estimated for all study reaches using Eq. 4 (Bathurst et al. 1987), and Eq. 5 (Thompson 1985) compared to the <u>highest</u> estimate of bankfull discharge from Jarrett, Thorne, and Omang.

STREAM NAME		STUDY REACH NUMBER	CIRTICAL DISCHARGE Eq. 4	Eq. 5	HIGHEST PREDICTED Q @ BANKFULL
BUCK	(d_{50})	1	91.7	76.0	37.5
	(d_{84})	1	209.3	105.7	37.5
	(d_{50})	2	55.8	74.6	54.2
	(d_{84})	2	274.2	140.9	54.2
	(d_{50})	3	12.1	23.8	23.0
	(d_{84})	3	29.7	34.1	23.0
ARKANSAS		1	50.3	61.9	50.6
		1	202.5	108.0	50.6
		2	24.6	10.1	13.0
		2	45.2	13.0	13.0
		3	24.2	23.2	14.0
		3	62.1	33.9	14.0
HOWARD		1	221.0	24.9	18.0
		1	475.2	33.8	18.0
		2	40.0	37.3	34.7
		2	131.5	60.2	34.7
		3	58.5	36.8	44.9
		3	303.8	71.1	44.9
		4	195.4	83.6	56.8
		4	891.2	153.5	56.8
		5	198.2	115.4	73.0
		5	646.9	185.2	73.0
LOST PARK		1	175.7	186.2	104.8
		1	724.4	328.2	104.8
		2	117.9	120.0	82.6
		2	415.6	198.6	82.6
		3	204.0	147.8	124.3
		3	483.6	208.7	124.3
		4	189.8	124.3	117.7
		4	300.0	149.3	117.7
SCHWARTZ		1	12.0	9.7	5.0
		1	25.8	13.2	5.0
		2	14.9	15.2	8.9
		2	33.4	21.0	8.9
		3	9.6	10.4	7.8
		3	29.8	16.4	7.8
		4	14.8	9.5	6.9
		4	35.7	13.5	6.9

Tabled 3. Continued

	5	249.6	57.0	19.7
	5	426.1	70.6	19.7
	6	69.5	60.9	33.3
	6	127.8	77.7	33.3
CAMAS	1	1845.1	268.0	79.0
CAMAS	1	3634.6	351.5	79.0
GOLD	BRIDGE	622.8	341.7	119.7
GOLD	BRIDGE	1476.3	482.6	119.7
GOLD	PRIMS	131.3	269.3	253.0
GOLD	PRIMS	321.9	385.5	253.0
EF LOLO	1	273.3	129.4	75.0
	1	553.0	171.6	75.0
	2	266.8	149.6	74.1
	2	675.3	216.9	74.1
	3	173.9	136.5	127.0
	3	629.7	228.4	127.0
	4	166.3	128.5	92.9
	4	487.4	197.6	92.9
	5	1134.5	183.7	108.1
	5	3558.8	290.2	108.1
	6	300.8	106.5	100.0
	6	1015.3	173.3	100.0
TRAIL	UP	904.8	448.6	176.7
TRAIL	UP	1782.3	588.3	176.7
TRAIL	LO	229.9	731.4	426.1
TRAIL	LO	494.7	993.7	426.1
TRAPPER	1	842.8	427.5	388.1
	1	1891.8	590.8	388.1
	2	768.7	429.1	422.4
	2	2411.3	677.9	422.4
	3	3000.2	713.1	443.8
	3	7593.1	1034.0	443.8
	4	2549.2	516.8	469.1
	4	4864.5	669.2	469.1
WEST TWIN	1	83.9	93.6	42.5
	1	246.1	144.0	42.5
	2	47.5	86.9	44.6
	2	184.7	149.6	44.6
	3	169.8	148.0	58.4
	3	413.7	211.3	58.4
	4	78.8	106.4	54.9
	4	248.5	168.5	54.9
	5	100.8	140.8	77.9
	5	280.5	212.0	77.9

Table 3. Continued

	6	1572.7	180.2	27.6
	6	5307.9	293.1	27.6
NF SALMON	1	294.8	323.2	208.1
	1	879.0	500.4	208.1
	2	319.0	214.8	152.5
	2	1231.0	368.7	152.5
	5	67.8	89.2	49.9
	5	227.5	144.8	49.9
	6	102.2	91.3	39.3
	6	303.1	140.9	39.3
MOOSE	4	10.2	26.6	19.5
	4	70.6	57.5	19.5
CAMP	UP	306.8	29.0	25.1
CAMP	UP	1420.6	93.7	25.1
CAMP	LO	469.4	168.9	49.6
CAMP	LO	935.3	222.5	49.6
CAMP	EF	65.7	69.9	54.9
CAMP	EF	185.8	105.9	54.9
CAMP	WF	22.0	47.8	53.7
CAMP	WF	62.3	72.4	53.7

* Each study reach includes the d_{50} and the d_{84} particle size for stability analysis. The first line for each study reach shown in Table 3 is the d_{50} and the second is the d_{84}.

Table 4.
Shield's formula (using the Schoklitsch recommended τ_{cr} of 0.076 instead of 0.06) to calculate the critical diameter or the largest particle moved in the channel at bankfull discharge.

STREAM NAME	STUDY REACH NUMBE	HYDRAULIC RADIUS (feet)	SLOPE (m/m)	PARTICLE DIAMETER d_{50} & d_{84} (mm)	CRITICAL PARTICLE DIAMETER (mm)
BUCK	1	0.87	0.0175	(d_{50}) 75	35.6
	1	0.87	0.0175	(d_{84}) 130	35.6
	2	0.92	0.0175	45	37.5
	2	0.92	0.0175	130	37.5
	3	0.61	0.03	33	42.6
	3	0.61	0.03	60	42.6
ARKANSAS	1	1.03	0.011	34	26.5
	1	1.03	0.011	86	26.5
	2	0.30	0.017	32	11.9
	2	0.30	0.017	48	11.9
	3	0.45	0.017	40	18.0
	3	0.45	0.017	75	18.0
HOWARD	1	0.49	0.0025	45	2.9
	1	0.49	0.0025	75	2.9
	2	0.66	0.0175	45	26.9
	2	0.66	0.0175	100	26.9
	3	0.75	0.005	20	8.8
	3	0.75	0.005	60	8.8
	4	0.89	0.005	40	10.5
	4	0.89	0.005	110	10.5
	5	0.89	0.0125	75	26.0
	5	0.89	0.0125	165	26.0
LOST PARK	1	0.97	0.025	105	57.0
	1	0.97	0.025	270	57.0
	2	0.93	0.025	95	54.2
	2	0.93	0.025	220	54.2
	3	0.86	0.02	90	40.3
	3	0.86	0.02	160	40.3
	4	0.81	0.015	70	28.3
	4	0.81	0.015	95	28.3
CAMAS	1	1.21	0.002	70	5.7
	1	1.21	0.002	110	5.7
GOLD	bridge	1.52	0.0075	90	26.7
	bridge	1.52	0.0075	160	26.7
	Prims	1.38	0.03	77	96.6
	Prims	1.38	0.03	140	96.6

Table 4. Continued

SCHWARTZ	1	0.39	0.0175	30	15.8
	1	0.39	0.0175	50	15.8
	2	0.43	0.025	35	25.0
	2	0.43	0.025	60	25.0
	3	0.35	0.035	40	28.3
	3	0.35	0.035	85	28.3
	4	0.44	0.01	25	10.2
	4	0.44	0.01	45	10.2
	5	0.82	0.0025	35	4.8
	5	0.82	0.0025	50	4.8
	6	0.80	0.015	50	28.0
	6	0.80	0.015	75	28.0
EF LOLO	1	0.76	0.015	95	26.7
	1	0.76	0.015	152	26.7
	2	1.01	0.01	70	23.7
	2	1.01	0.01	130	23.7
	3	0.67	0.0275	95	42.8
	3	0.67	0.0275	224	42.8
	4	1.00	0.015	83	35.0
	4	1.00	0.015	170	35.0
	5	1.07	0.0025	70	6.3
	5	1.07	0.0025	150	6.3
	6	0.72	0.009	80	15.2
	6	0.72	0.009	180	15.2
TRAPPER	1	1.11	0.008	70	20.8
	1	1.11	0.008	120	20.8
	2	1.13	0.009	70	23.9
	2	1.13	0.009	150	23.9
	3	1.64	0.0025	70	9.6
	3	1.64	0.0025	130	9.6
	4	1.27	0.0025	65	7.4
	4	1.27	0.0025	100	7.4
WEST TWIN	1	0.93	0.025	83	54.1
	1	0.93	0.025	170	54.1
	2	0.75	0.05	87	87.9
	2	0.75	0.05	215	87.9
	3	1.04	0.0225	116	54.9
	3	1.04	0.0225	210	54.9
	4	1.04	0.03	93	72.7
	4	1.04	0.03	200	72.7
	5	1.01	0.029	91	68.5
	5	1.01	0.029	180	68.5
	6	1.03	0.0021	80	5.0
	6	1.03	0.0021	180	5.0

Table 4. Continued

NF SALMON	1	1.29	0.015	70	45.3
	1	1.29	0.015	145	45.3
	2	1.07	0.01	63	24.9
	2	1.07	0.01	155	24.9
	5	0.82	0.025	58	48.0
	5	0.82	0.025	130	48.0
	6	0.84	0.0175	63	34.3
	6	0.84	0.0175	130	34.3
MOOSE	4	0.57	0.06	47	79.4
	4	0.57	0.06	170	79.4
TRAIL	up	1.66	0.005	70	19.4
	up	1.66	0.005	110	19.4
	lo	2.55	0.02	60	119.2
	lo	2.55	0.02	100	119.2
CAMP	up	0.64	0.0025	36	3.7
	up	0.64	0.0025	100	3.7
	lo	1.11	0.005	60	13.0
	lo	1.11	0.005	95	13.0
	EF	0.99	0.009	30	20.9
	EF	0.99	0.009	60	20.9
	WF	0.89	0.02	30	41.5
	WF	0.89	0.02	60	41.5

Figure 9.
A graphical display of the variability using Eq. 4 with slopes less than 1 percent. The variability decreases as stream slope increase up to one percent then constant variability was found as slope increased to 6%.

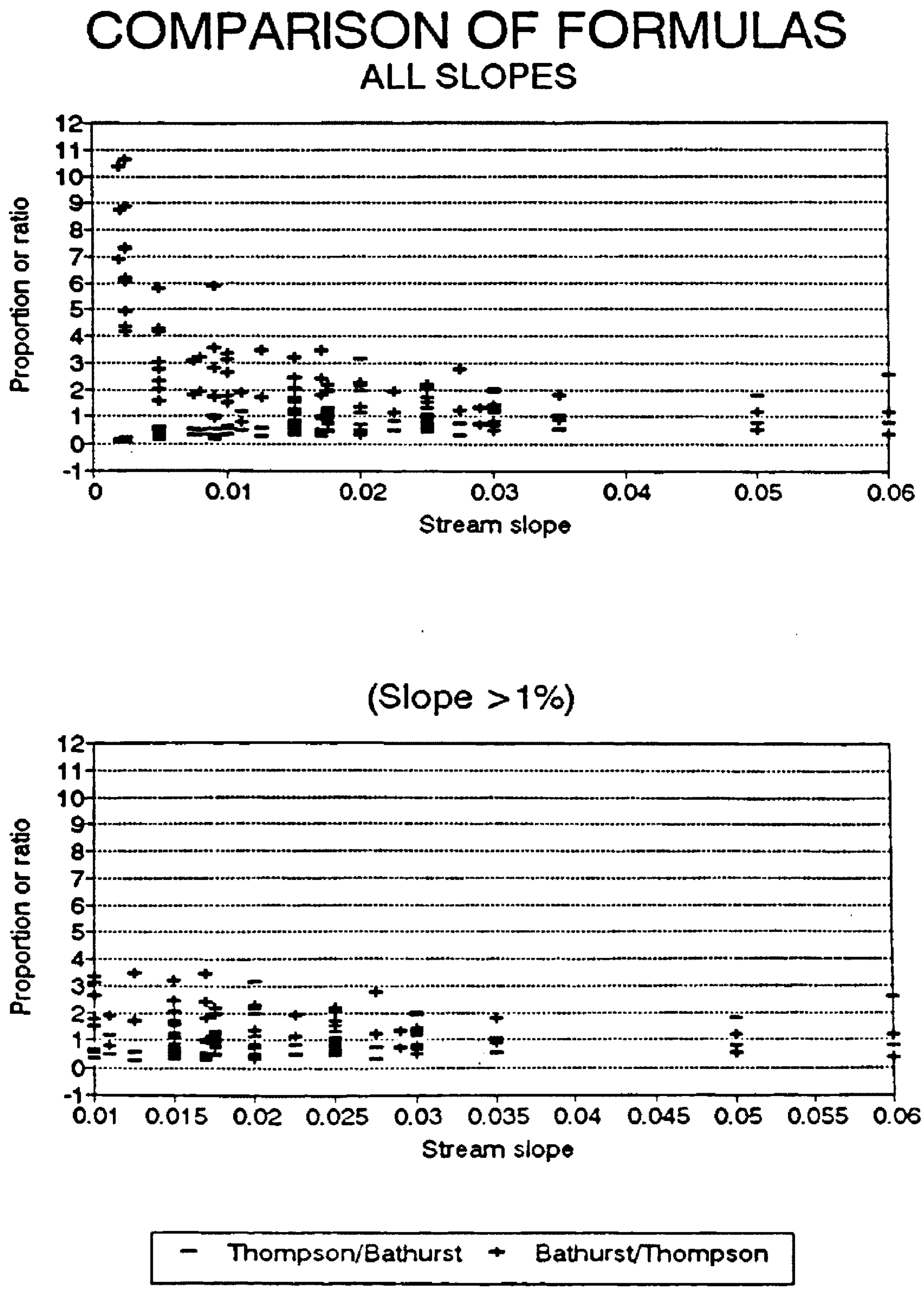
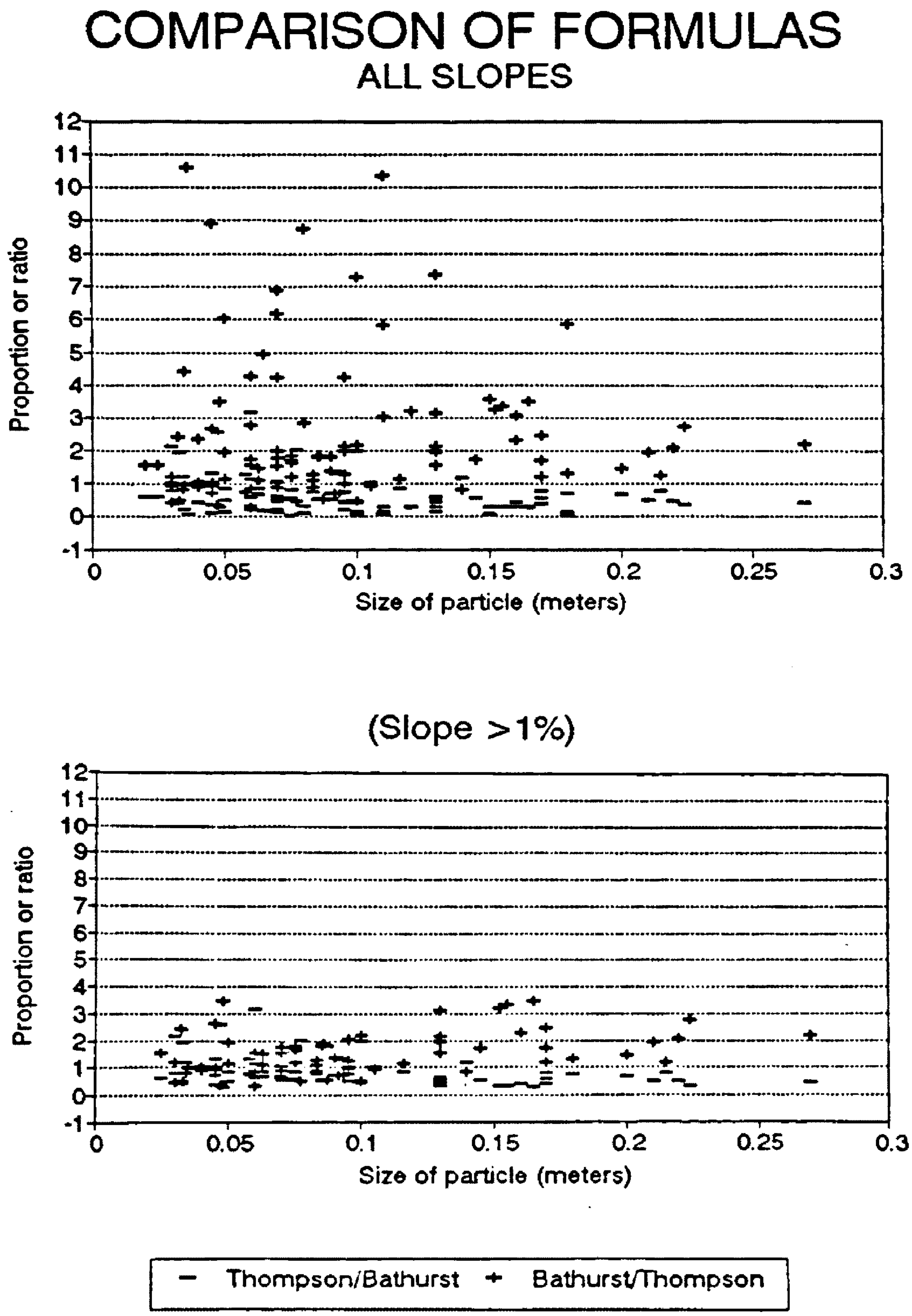


figure 10
A graphical display of the variability using Eq 4. with slopes less than 1 percent. No apparent bias is seen correlating the different equations with particle size.



feet per second (CFS), to 6.4 CFS by not including slopes less than one percent. Low gradient streams generated 5 to 18 times higher values of critical discharge using Eq.4, than by using Eq. 5 for identical slope and d_{84}. This can lead to over-predicting the stream stability threshold. Our suggestion would be to use Eq. 5 or Eq. 6 in those circumstances. Notice that using a 10% increase in peak discharge will not destabilize even the most unstable streams using the d_{84} criteria.

Most stream reaches were found to be very stable (see Table 5) using Eq. 1, 4, 5, and 6, therefore, critical conditions would not exist at bankfull. There were some stream reaches found to be near threshold ($1 < RBS < 1.5$) using the most conservative equations (highest bankfull and lowest critical discharge). These stream reaches were Buck Creek #3, Arkansas Creek #2, WF Camp Creek, Gold Creek at Prims Meadow, Trapper Creek #4, Lost Park #3, and Lower Trail Creek. Using Shields equation, Trail Creek (lower) was found to be out of equilibrium ($RBS < 1$). In this case the d_{84} is moved by discharges equal to or less than bankfull.

Stream reaches with a RBS between 1.5 and 2 are considered to be vulnerable and a professional decision is recommended to assess allowable peak discharge increases. Stream reaches that fall within this interval are Arkansas Creek #1, Howard Creek #2, Lost Park #3, EF Lolo #3&6, and Trapper Creek #1&2. The stream channel can handle up to 2 times its natural peak discharge. Stream channels that exhibit over a 2 RBS are considered very stable. Most of the studied stream reaches have a RBS > 2 and their bed stability should not be vulnerable to increased flow resulting from land disturbance.

The decision to accept a RBS > 2 as indicative of stable channel conditions is based on the literature evaluation. Peak discharges reported in small disturbed forested watersheds have exceeded peaks in undisturbed watersheds by less far less than 200% for" large" storms. Even in heavily urbanized watersheds, peak discharge increases are typically less than 200% (Hollis 1975).

The Hjulstrom curve appears to be suitable (with caution) for the types of streams surveyed in this study. All stream study reaches were found to be in the sedimentation (or depositional) zone with five reaches very near the transportation zone. The stream sections near the transportation zone were Buck Creek #3, West Twin Creek #5, Gold Creek at Prims Meadow, NF Salmon #1, and WF Camp Creek. Again, as shown above, there is good agreement using the Hjulstrom method with the critical shear stress/discharge formulas.

Modified versions of the Hjulstrom curve have been created to extend the line separating erosion, transportation, and sedimentation into larger particle sizes (> 200 mm). Novak (1973) recommends using a modified version but Helley

(1969) reports a field study with similar stream conditions to this study, where the curve was found to be useful. Due to the agreement with the shear stress and critical discharge formulas, I didn't feel that the modified diagrams are needed for the sizes of particles encountered in this study.

If a smaller-sized particle, such as the d_{50}, is used (see Table 5) to predict critical conditions, the results would include many more channels near their "threshold of concern". For example, Moose Creek has a bimodal distribution with a large d_{84} and a moderate d_{50}. Using Eq. 3, it was calculated to be very stable using the larger particles (RBS = 3.6), but beyond its stability threshold by using a lesser particle size (RBS = 0.5). Similar results were found using different approaches. Using Shield's approach, Moose Creek was determined to have a critical particle size of 100 mm. Moose Creek has a d_{50} of 47 mm which is significantly lower than its d_{84} of 170 mm. The d_{84} is significantly higher than the critical particle size at bankfull, although its d_{50} was found to be well beyond its threshold.

The d_{84} has been widely accepted as the measure of channel stability (Pickup 1976, Jackson and Beschta 1982, Carling 1988, Sidle 1988, Booth 1990, and Kappesser 1992). Using the d_{50} results, we identified six stream reaches to be beyond their threshold and thirty eight reaches very near (RBS < 1.5). This conservative estimate of critical conditions seems unrealistic. Therefore, the d_{84} has my recommendation.

Table 5.
The "Relative Bed Stability" for all study sites using the d_{84}.

STREAM NAME	STUDY REACH NUMBER	Bathurst	Thompson	Hjulstrom	Shields
BUCK	1	5.6	2.8	6.9	3.7
	2	5.1	2.6	6.3	3.5
	3	1.3	1.5	6.3	1.4
ARKANSAS	1	4.0	2.1	4.4	3.2
	2	3.5	1.0	11.3	4.0
	3	4.4	2.4	9.2	4.2
HOWARD	1	26.4	1.9	6.4	26.1
	2	3.8	1.7	6.1	3.7
	3	6.8	1.6	4.5	6.8
	4	15.7	2.7	5.6	10.5
	5	8.9	2.5	5.9	6.4
LOST PARK	1	6.9	3.1	6.1	4.7
	2	5.0	2.4	5.5	4.1
	3	3.9	1.7	4.5	4.0
	4	2.5	1.3	3.6	3.4
SCHWARTZ	1	5.2	2.6	16.6	3.2
	2	3.8	2.4	15.0	2.4
	3	3.8	2.1	15.7	3.0
	4	5.2	2.0	9.0	4.4
	5	21.6	3.6	7.9	10.4
	6	3.8	2.3	6.9	2.7
CAMAS	1	46.0	4.5	5.9	19.4
GOLD	bridge	12.3	4.0	4.8	6.0
	Prims	1.3	1.5	2.7	1.4
EF LOLO	1	7.4	2.3	6.6	5.7
	2	9.1	2.9	6.0	5.5
	3	5.0	1.8	5.9	5.2
	4	5.2	2.1	4.2	4.9
	5	32.9	2.7	4.0	23.9
	6	10.2	1.7	4.3	11.8
TRAPPER	1	4.9	1.5	2.7	5.8
	2	5.7	1.6	2.9	6.3
	3	17.1	2.3	2.4	13.6
	4	10.4	1.4	1.9	13.4

Table 5. Continued

WEST TWIN	1	5.8	3.4	8.2	3.1
	2	4.1	3.4	10.0	2.4
	3	7.1	3.6	7.3	3.8
	4	4.5	3.1	6.7	2.8
	5	3.6	2.7	5.7	2.6
	6	192.3	10.6	16.0	35.7
NF SALMON	1	4.2	2.4	3.9	3.2
	2	8.1	2.4	4.5	6.2
	5	4.6	2.9	8.4	2.7
	6	7.7	3.6	9.5	3.8
MOOSE	4	3.6	2.9	13.6	2.1
TRAIL	up	10.1	3.3	3.6	5.7
	lo	1.2	2.3	2.6	0.8
CAMP	up	56.6	3.7	10.3	26.8
	lo	18.9	4.5	7.8	7.3
	EF	3.4	1.9	4.3	2.9
	WF	1.2	1.3	3.6	1.4

Table 6.
The "Relative Bed Stability" for all study sites using the d_{50}

STREAM NAME	STUDY REACH NUMBER	Bathurst	Thompson	Hjulstrom	Shields
BUCK	1	2.4	2.0	5.2	2.1
	2	1.0	1.4	3.7	1.2
	3	0.5	1.0	4.7	0.8
ARKANSAS	1	1.0	1.2	2.8	1.3
	2	1.9	0.8	9.2	2.7
	3	1.7	1.7	6.7	2.2
HOWARD	1	12.3	1.4	5.0	15.6
	2	1.1	1.1	4.1	1.7
	3	1.3	0.8	2.6	2.3
	4	3.4	1.5	3.4	3.8
	5	2.7	1.6	4.0	2.9
LOST PARK	1	1.7	1.8	3.8	1.8
	2	1.4	1.5	3.6	1.8
	3	1.6	1.2	3.4	2.2
	4	1.6	1.1	3.1	2.5
SCHWARTZ	1	2.4	1.9	12.9	1.9
	2	1.7	1.7	11.4	1.4
	3	1.2	1.3	10.8	1.4
	4	2.1	1.4	7.4	2.4
	5	12.7	2.9	6.6	7.3
	6	2.1	1.8	5.6	1.8
CAMAS	1	23.4	3.4	4.7	12.4
GOLD	bridge	5.2	2.9	3.6	3.4
	Prims	0.5	1.1	2.0	0.8
EF LOLO	1	3.6	1.7	5.2	3.6
	2	3.6	2.0	4.4	3.0
	3	1.4	1.1	3.8	2.2
	4	1.8	1.4	2.9	2.4
	5	10.5	1.7	2.7	11.2
	6	3.0	1.1	2.9	5.3
TRAPPER	1	2.2	1.1	2.1	3.4
	2	1.8	1.0	2.0	2.9
	3	6.8	1.6	1.8	7.3
	4	5.4	1.1	1.5	8.7

Table 6. Continued

WEST TWIN	1	2.0	2.2	5.7	1.5
	2	1.1	1.9	6.4	1.0
	3	2.9	2.5	5.3	2.1
	4	1.4	1.9	4.5	1.3
	5	1.3	1.8	4.0	1.3
	6	57.0	6.5	10.6	15.9
NF SALMON	1	1.4	1.6	2.7	1.5
	2	2.1	1.4	2.9	2.5
	5	1.4	1.8	5.6	1.2
	6	2.6	2.3	6.6	1.8
MOOSE	4	0.5	1.4	7.2	0.6
TRAIL	up	5.1	2.5	2.9	3.6
	lo	0.5	1.7	1.7	0.5
CAMP	up	12.2	1.2	6.2	16.9
	lo	9.5	3.4	6.2	4.6
	EF	1.2	1.3	3.0	1.4
	WF	0.4	0.9	2.6	0.7

If we compare the critical discharges (Table 3.) and estimated flows at 2, 5, 10, 25, 50, and 100 year return frequencies (Appendix 4.), you will notice that only the large events (10 to 100 year return period) provide the required discharges to produce real channel instability.

SUMMARY

There are three conclusions and management choices that can be made based on channel characteristics and the predicted stability thresholds. The first is that the channel is already unstable **(RBS < 1)**, and that the largest bed materials are mobilized easily and frequently. If this is the case, increases in peak discharges may be unacceptable. If the predicted critical flow is somewhat higher than bankfull but less than an accepted threshold level **(1 < RBS < 2.0)**, then a decision must be made as to how much flow increase is allowable based on all other risk factors. I recommend that with a RBS < 1.5, management activities that may increase flow should be avoided. A RBS > 1.5 but < 2 will require a professional decision and mitigation, if possible.

The third outcome, likely to be seen with many boulder- and cobble-bedded channels, is that increases in peak discharges resulting from forest management activities will not exceed the threshold of concern **(RBS > 2)**. The d_{84} size fraction will not be mobilized with management-induced increased discharge or peak flows, and stream-bed instability should not be a management constraint.

The third outcome was found in the majority of the 51 stream reaches that were studied in this thesis. This is fitting with non-extreme occurrences and is believed to be the result of inherently stable stream channels associated with the geomorphic formations found in western Montana.

CONCLUSION

Predictive formulas for particle movement are empirically derived and all have possible errors. Nevertheless, they provide estimates of forces and resistances that permit some reliable generalizations concerning stream channel stability. If the largest bed-particles are stable, then the stream channel itself is likely to be stable, despite movement of smaller material (Grant 1986). When conditions arise in which stream competence is high enough to initiate movement of the largest particles (d_{84}), the stream is considered to be unstable and the "threshold of concern" has been reached.

We have a poor understanding of the quantitative relationship between forest management and peak flow increases. Therefore, it is probably not possible to suggest some <u>absolute</u> limit to the amount of land disturbance that can be tolerated in a watershed before the onset of channel destabilization, it is recommended to proceed on a conservative basis in watersheds that have channel conditions that may be sensitive to increases in short duration peakflows (King 1989). For this reason, the best equation or the equation that should be used to determine stability threshold is the "most conservative", or the equation predicting the lowest value of discharge thresholds. Because Eq. 4 was shown to be highly variable with slopes less than one percent, we recommend that one of the other equations should be used in those circumstances. When the stream slope is greater than one percent, the most conservative of all equations should be implemented.

After the completion of my field work, the question was raised if there was a relationship between Rosgen Stream Types (Rosgen 1993) and RBS. I attempted to classify each stream reach, but was not able to adequately assess an entrenchment ratio because my field observations only included bankfull depth and not a flood-prone area. Flood-prone area has to be surveyed in the field, therefore, I could not preform this analysis. Stream classifications are being used more and more in forest management decisions. Therefore, I highly recommend further research on the relationship between Rosgen Stream Type and RBS.

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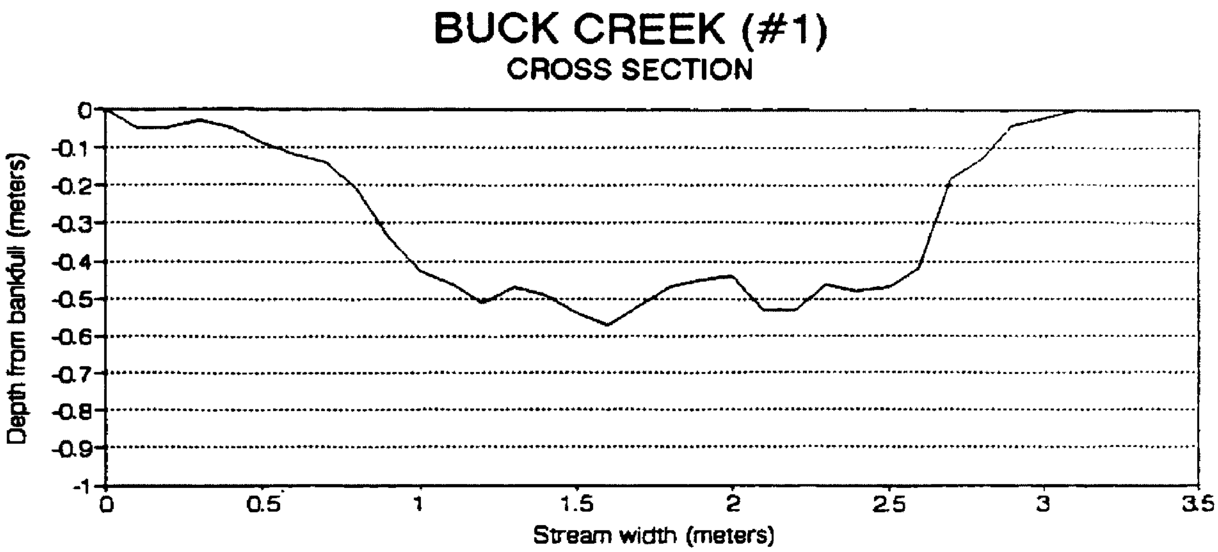
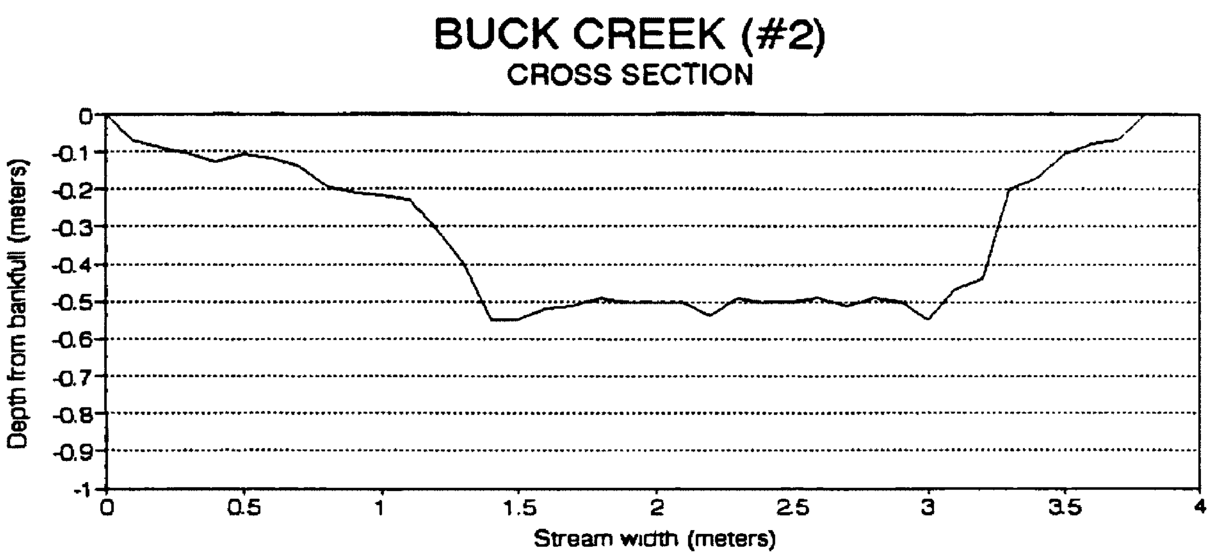
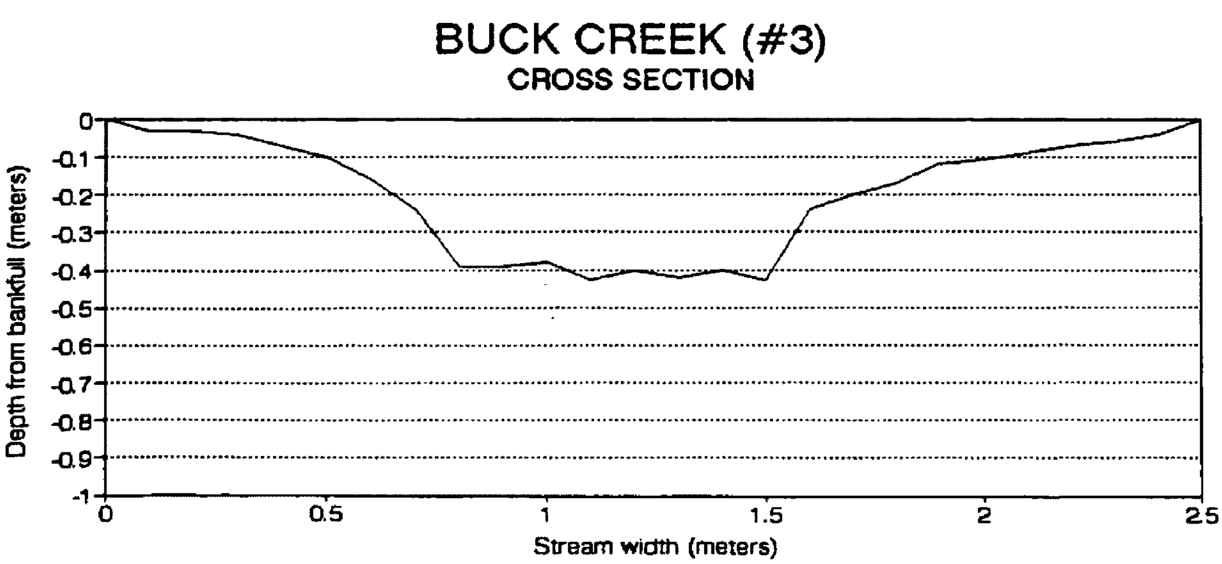
Appendix 1.
A summary of forest management-related peak flow changes.

WATERSHED NAME	AREA %	FOREST TYPE	% CANOPY REMOVED	PEAK Q CHANGE
Cabin Creek Alberta (Golding 1981)	212	LPP/Picea	21% (cc)	**+24%**
Fool Creek Colorado (Troendle and King 1985)	289	LPP/Picea	40% (strip)	**+23%**
Hinton Creek Alberta (Golding 1981)	1497	LPP/Picea	50% (cc)	**+59%**
Casper Creek California (Ziemer 1981)	424	PSME/ABGR	75% (select)	**+300%** (sm storms) **+0%** (lg storms)
Casper Creek California (Wright et al. 1990)	424	PSME/ABGR	15% (roads)	**130%** (sm storms) **0%** (lg storms)
Alsea Creek Oregon (Harris 1973)	70	PSME	82%	**+17%** (lg storms)
Palmer Creek BC (Cheng 1980)	1800	LPP/Picea	50% (burn)	**+50%**
Camp Creek BC (Cheng 1991)	3390	LPP/Picea	30% (cc)	**+21%**

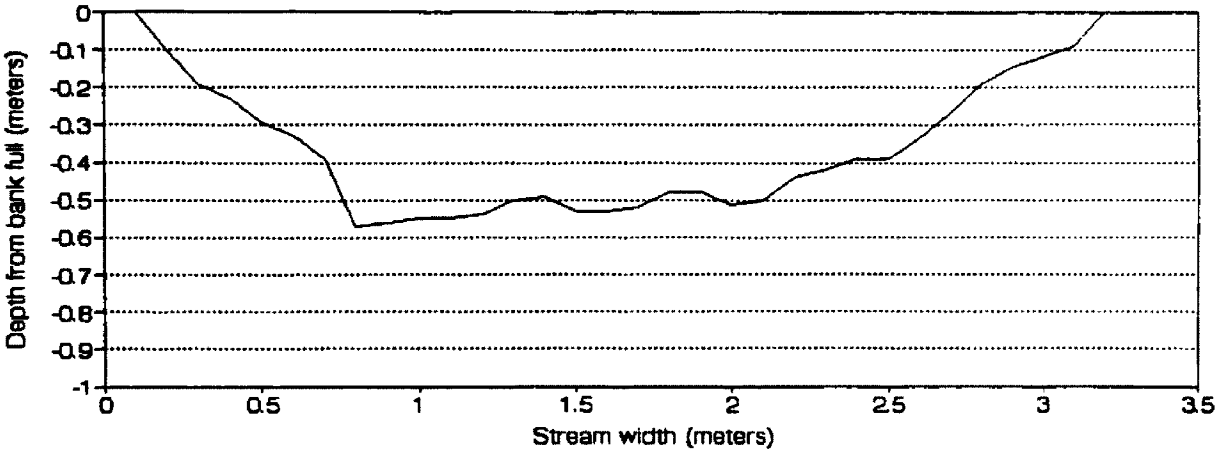
Appendix 2.
Detailed stream cross sections for all study sites.



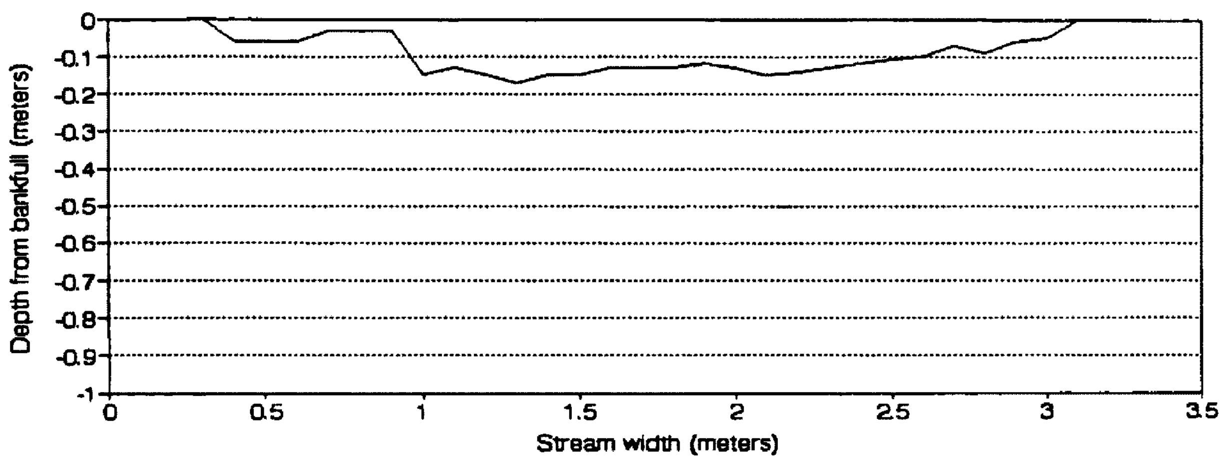




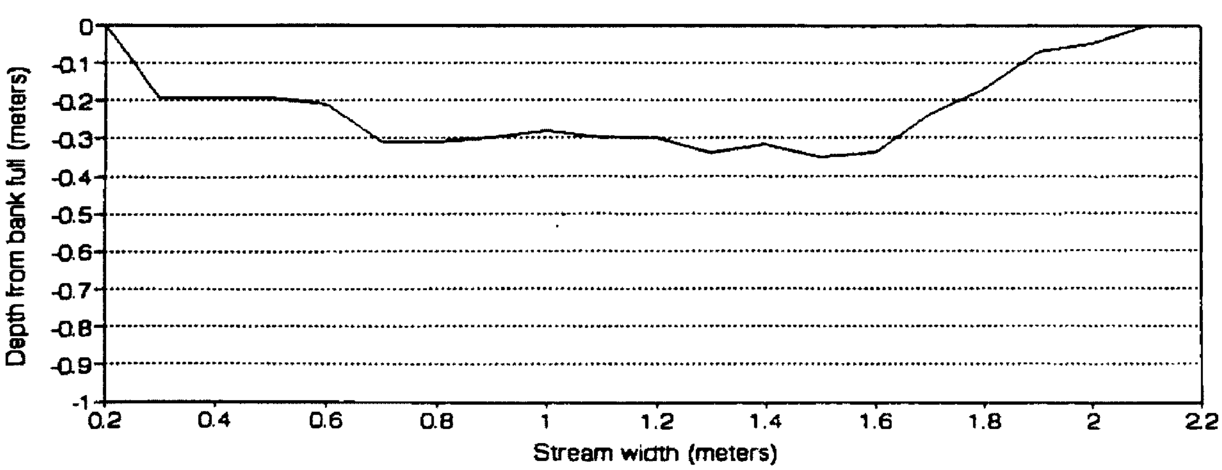
ARKANSAS CREEK (Lower)
CROSS SECTION

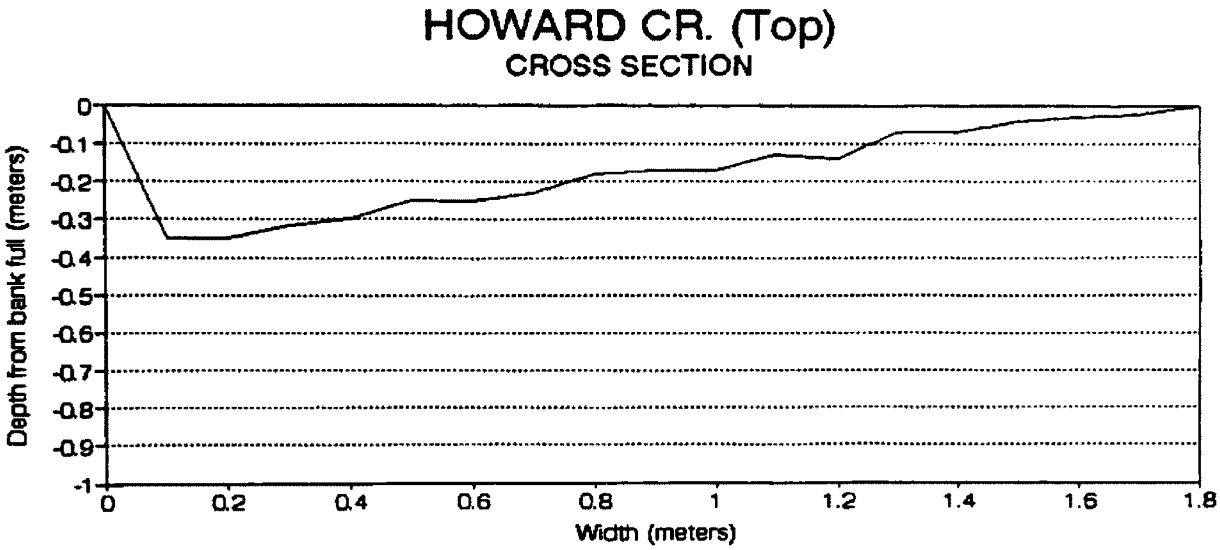


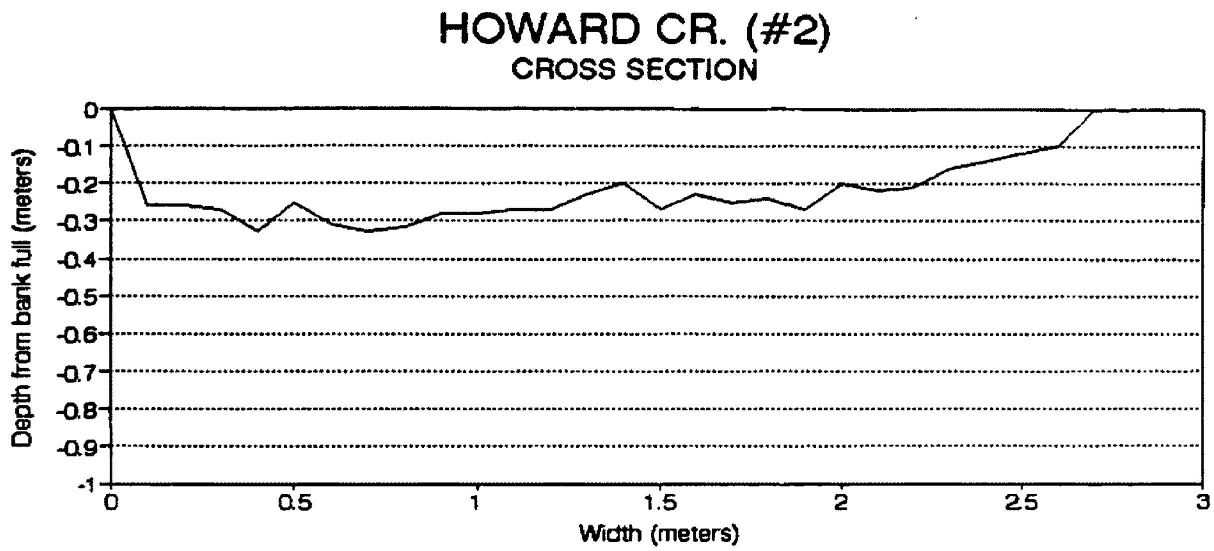
ARKANSAS CREEK (#2)
CROSS SECTION

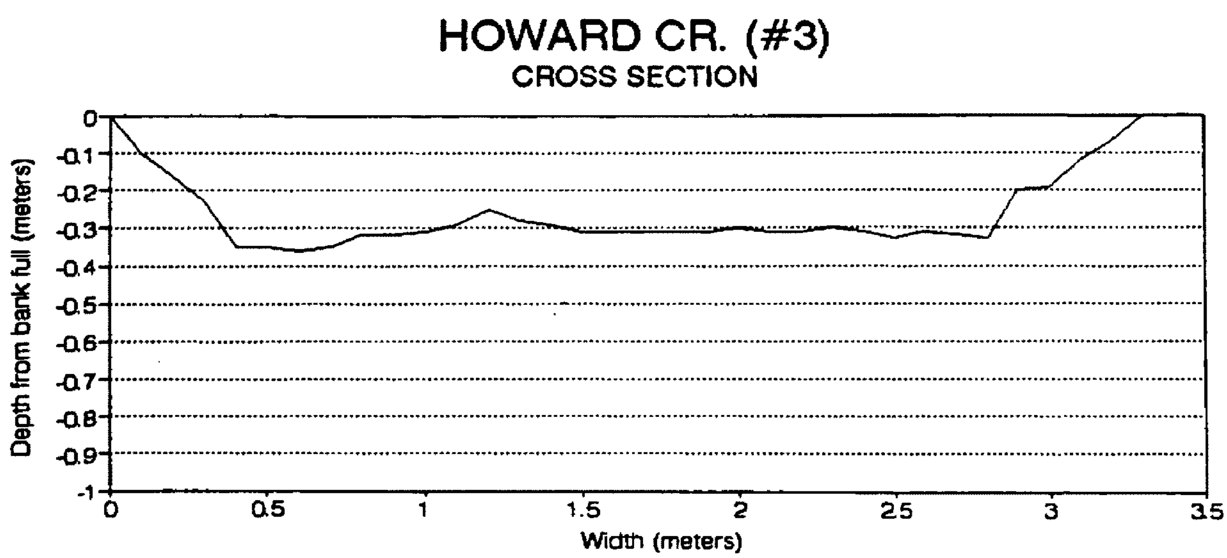


ARKANSAS CREEK (Forked P-Pine)
CROSS SECTION

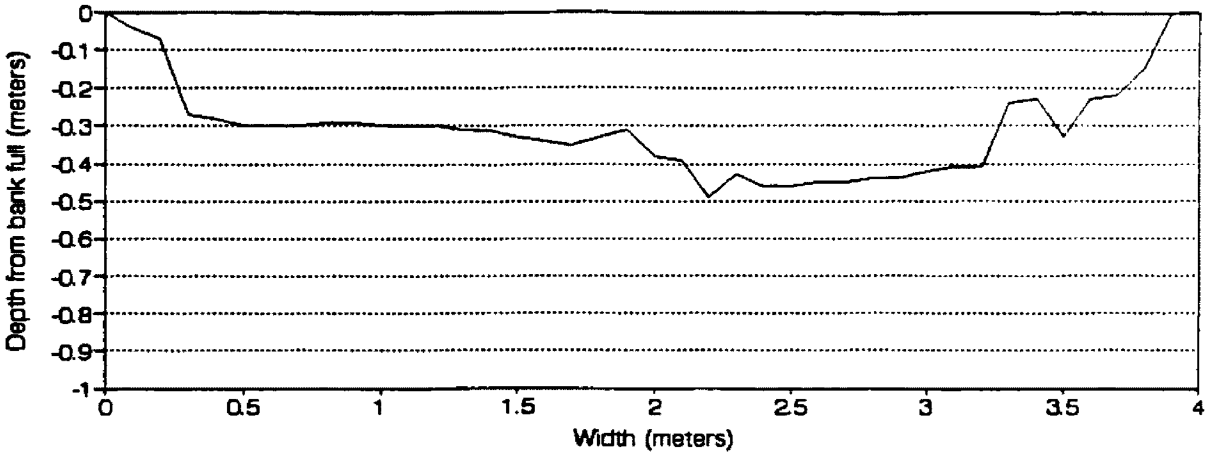



HOWARD CR. (Top)
CROSS SECTION
Depth from bank full (meters)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Width (meters)

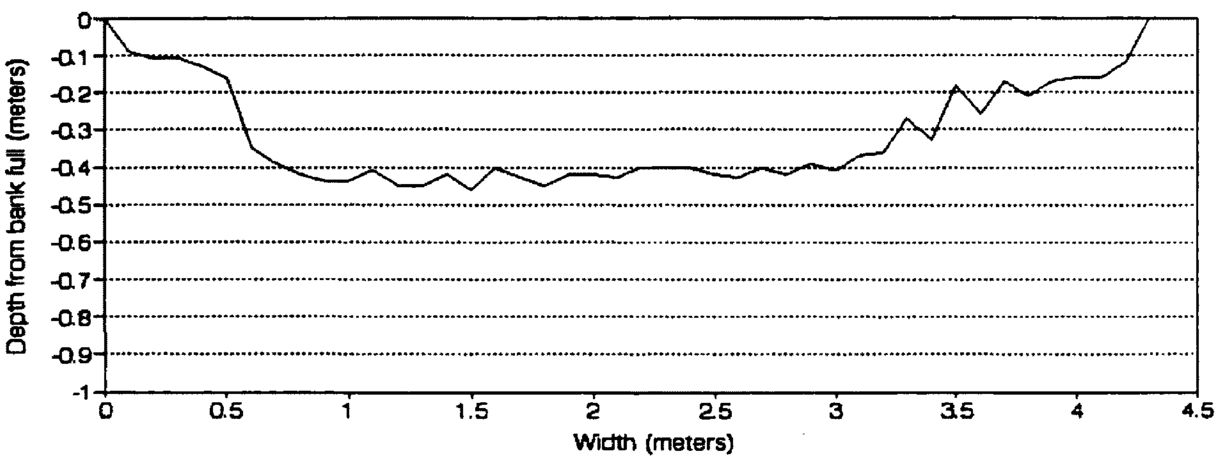

HOWARD CR. (#2)
CROSS SECTION
Depth from bank full (meters)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
0.5
1
1.5
2
2.5
3
Width (meters)


HOWARD CR. (#3)
CROSS SECTION
Depth from bank full (meters)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
0.5
1
1.5
2
2.5
3
3.5
Width (meters)

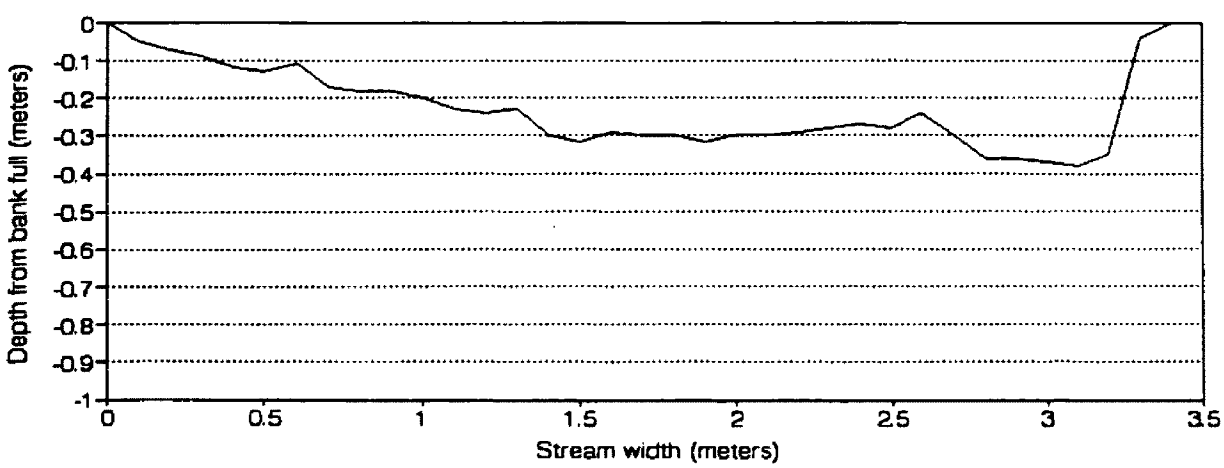
HOWARD CR. (#4)
CROSS SECTION



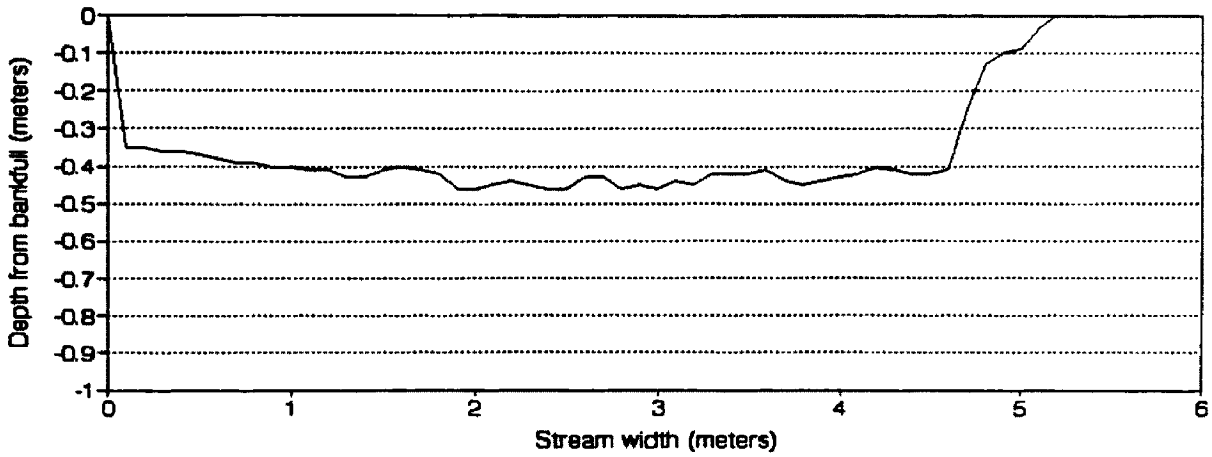
HOWARD CR. (#5)
CROSS SECTION



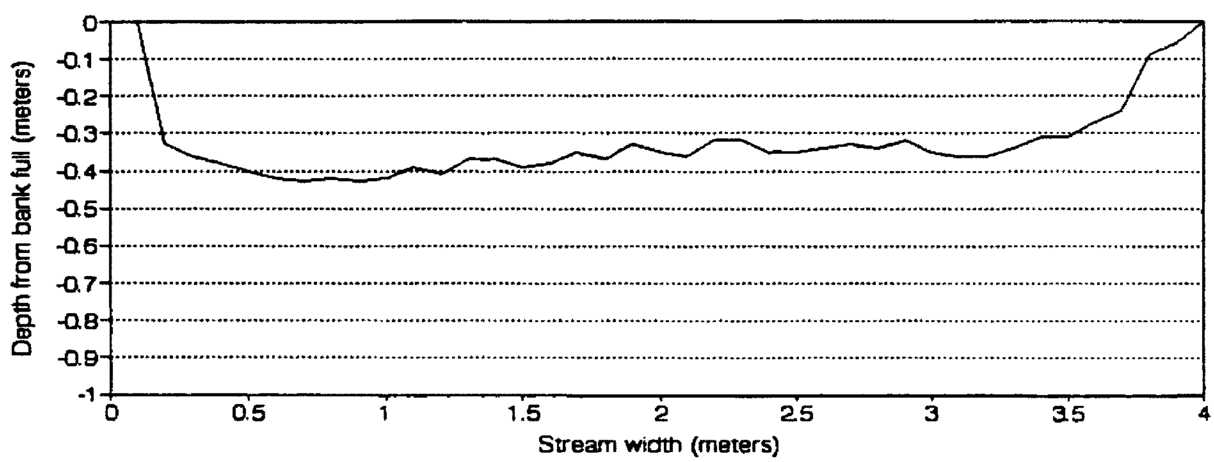
UPPER CAMP CREEK
CROSS SECTION



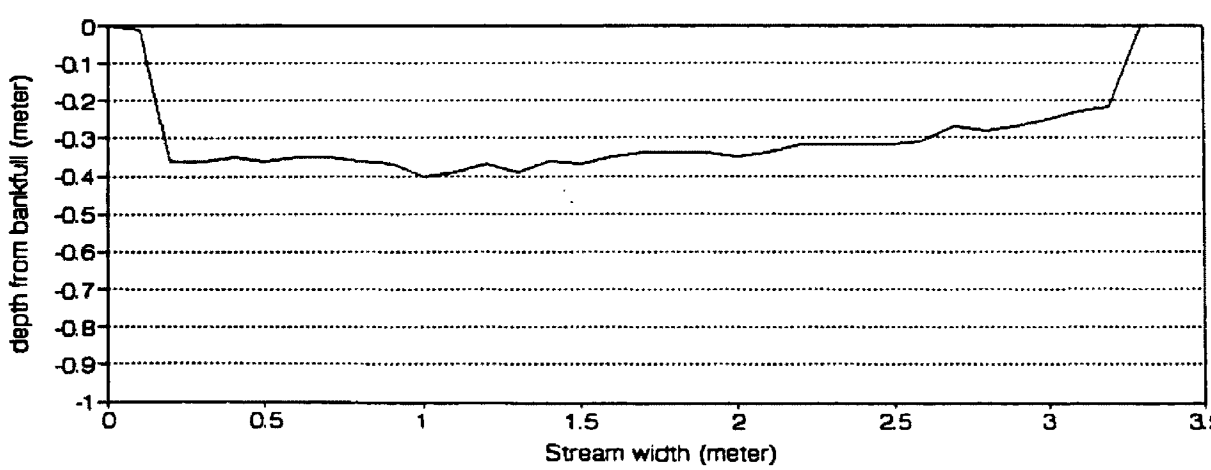
CAMP CREEK (Bottom)
CROSS SECTION



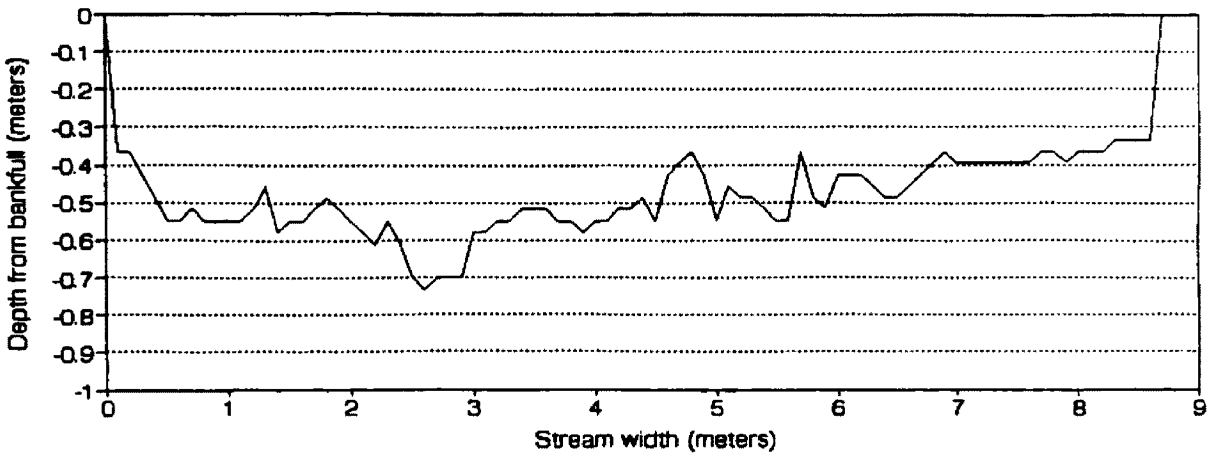
EAST FORK of CAMP CREEK
CROSS SECTION



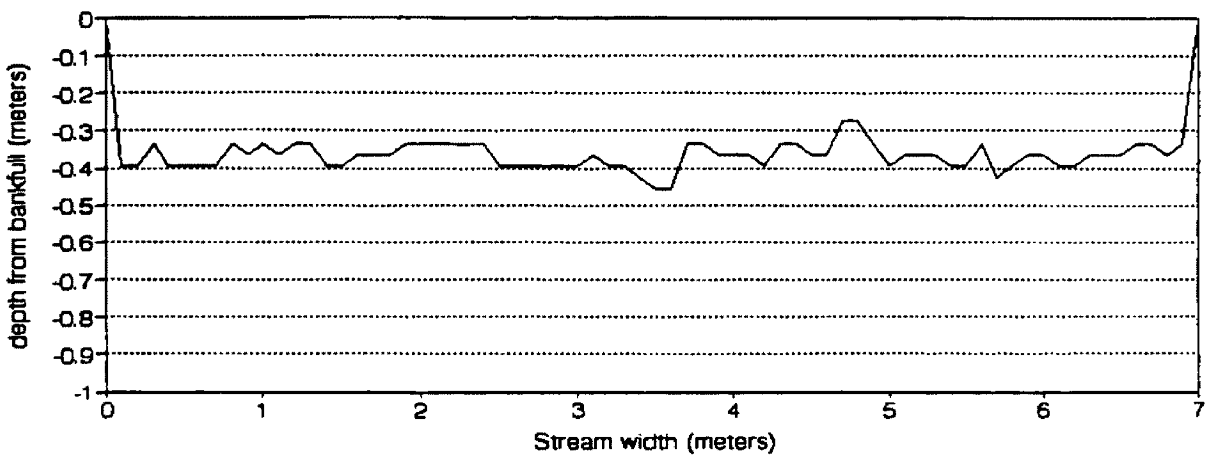
WEST FORK of CAMP CREEK
CROSS SECTION



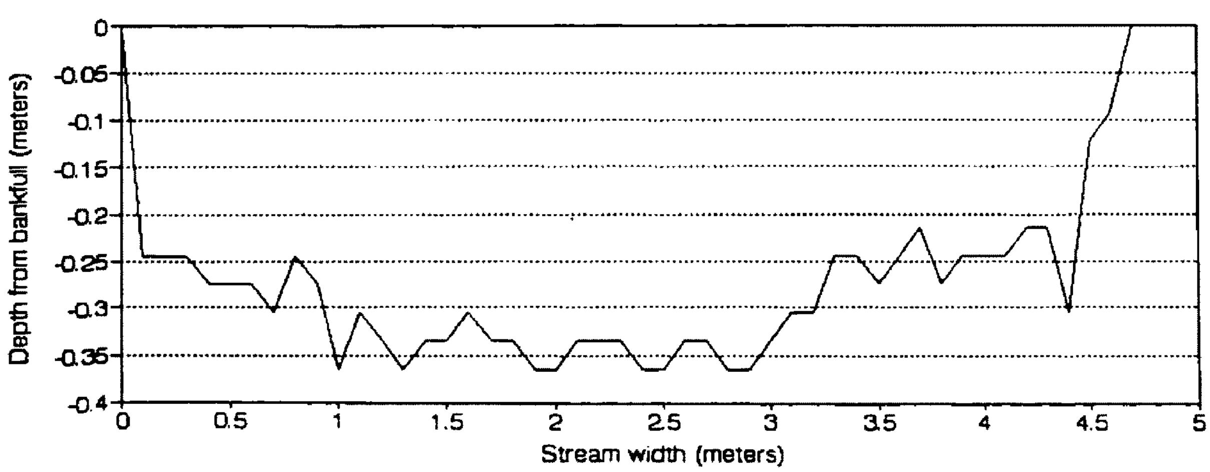
NORTH FORK #1
CROSS SECTION

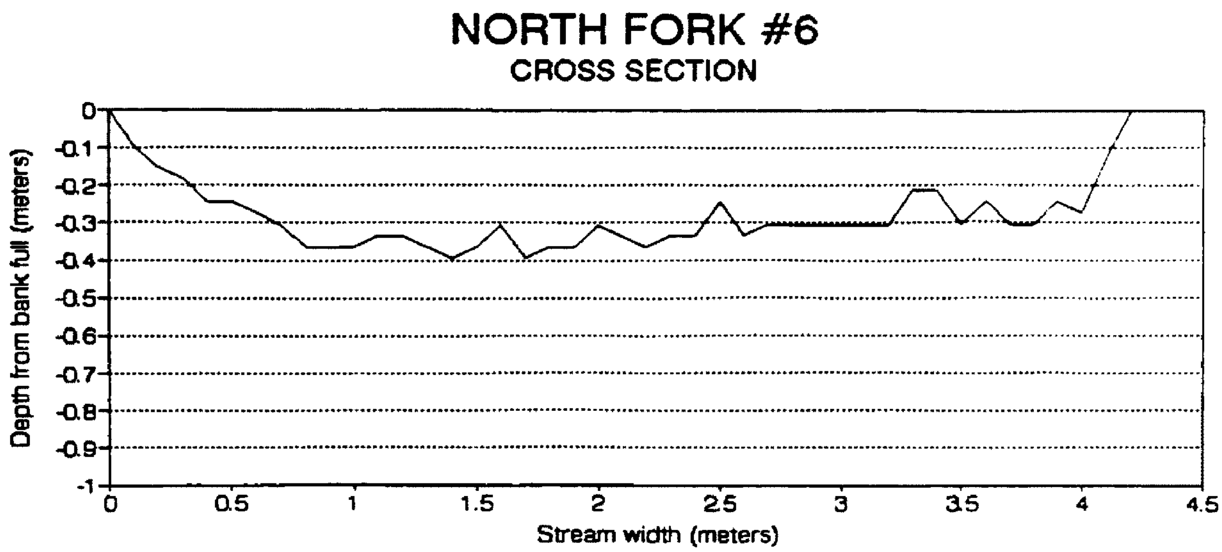


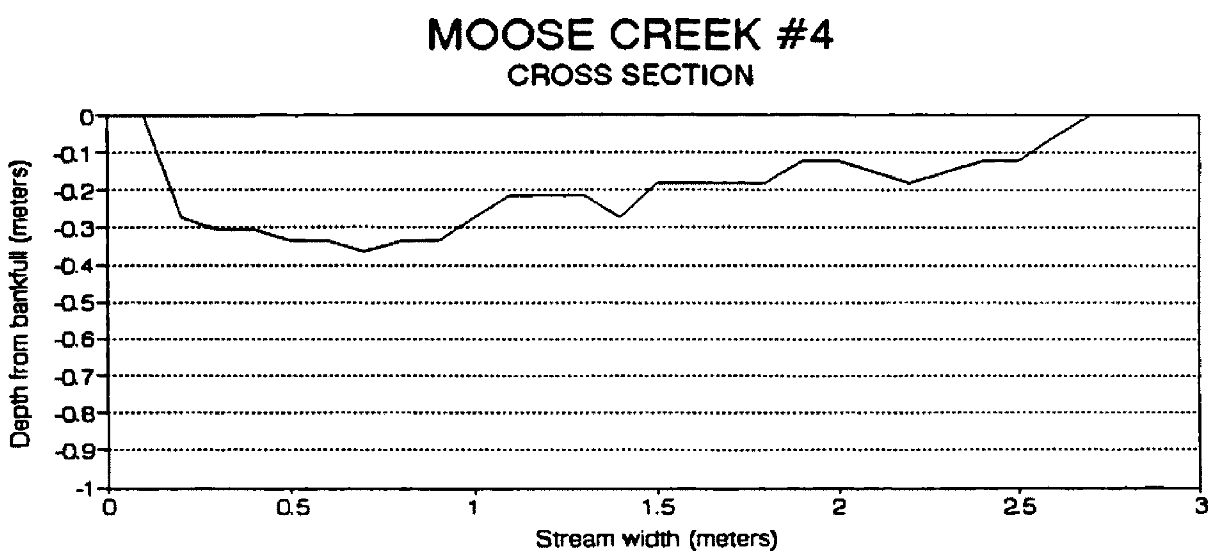
NORTH FORK #2
CROSS SECTION

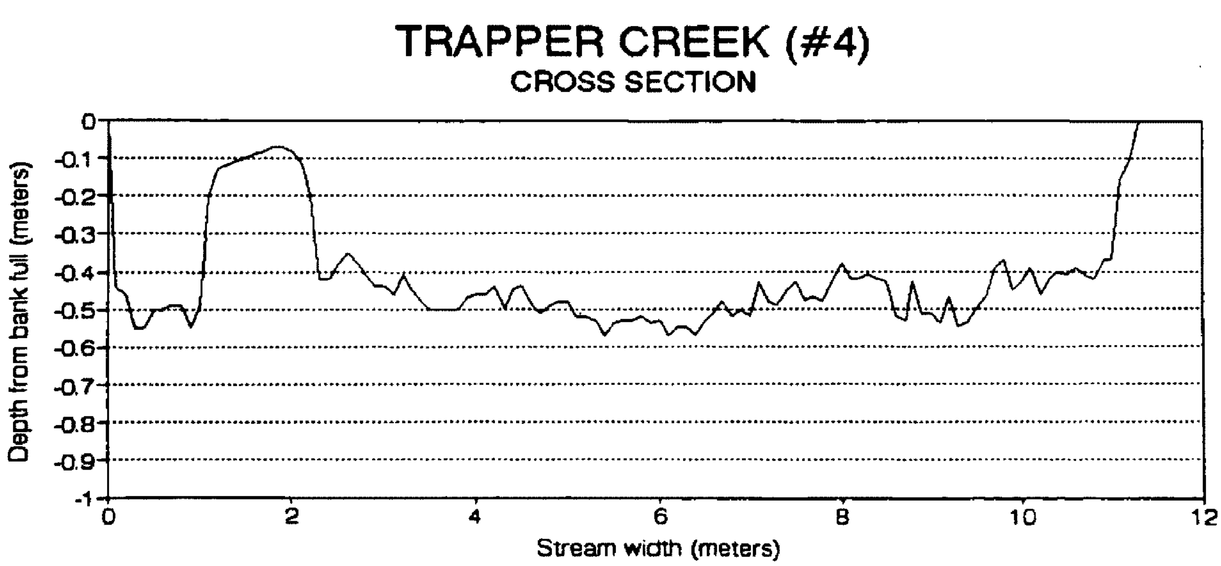


NORTH FORK #5
CROSS SECTION

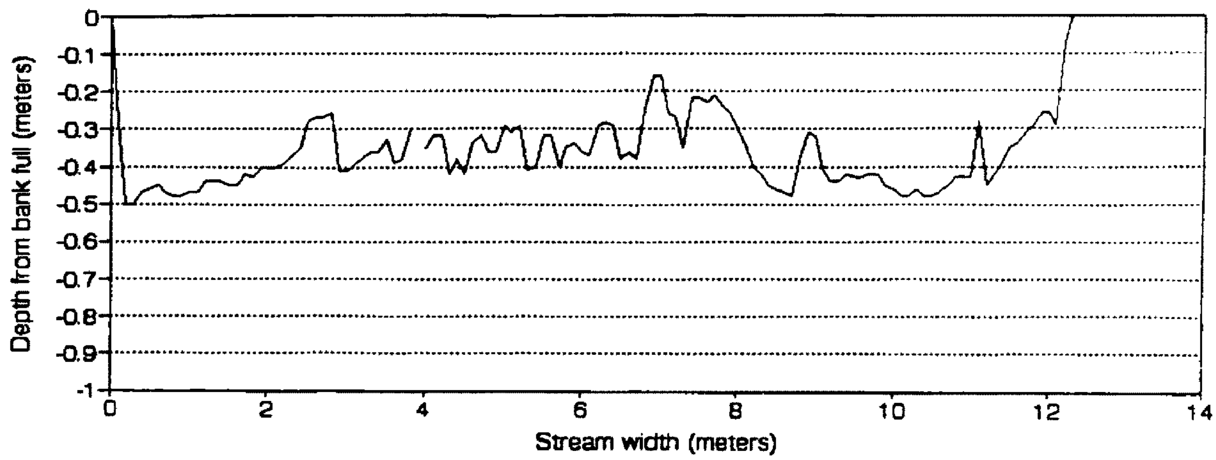



NORTH FORK #6
CROSS SECTION
Depth from bank full (meters)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Stream width (meters)

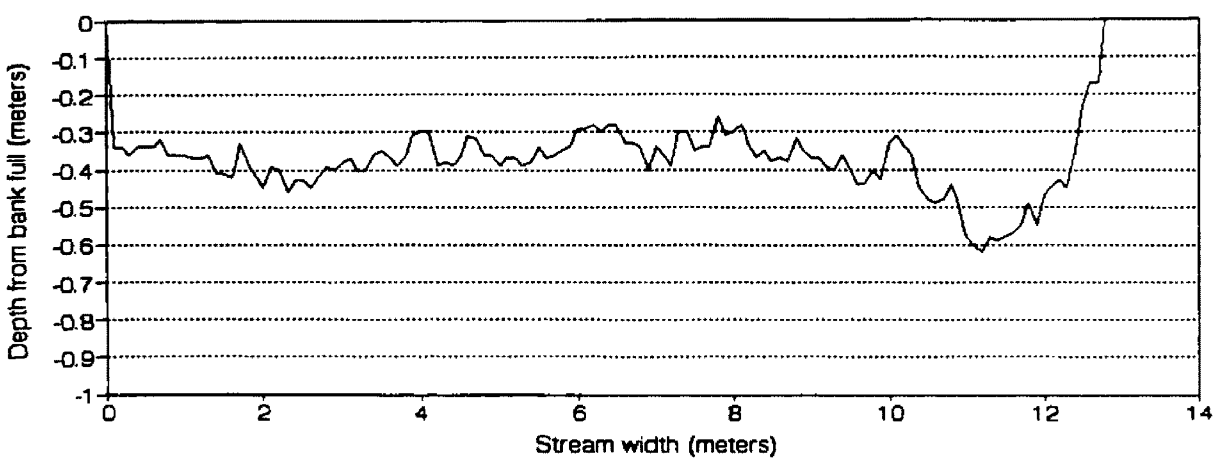

MOOSE CREEK #4
CROSS SECTION
Depth from bankfull (meters)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
0.5
1
1.5
2
2.5
3
Stream width (meters)


TRAPPER CREEK (#4)
CROSS SECTION
Depth from bank full (meters)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
2
4
6
8
10
12
Stream width (meters)

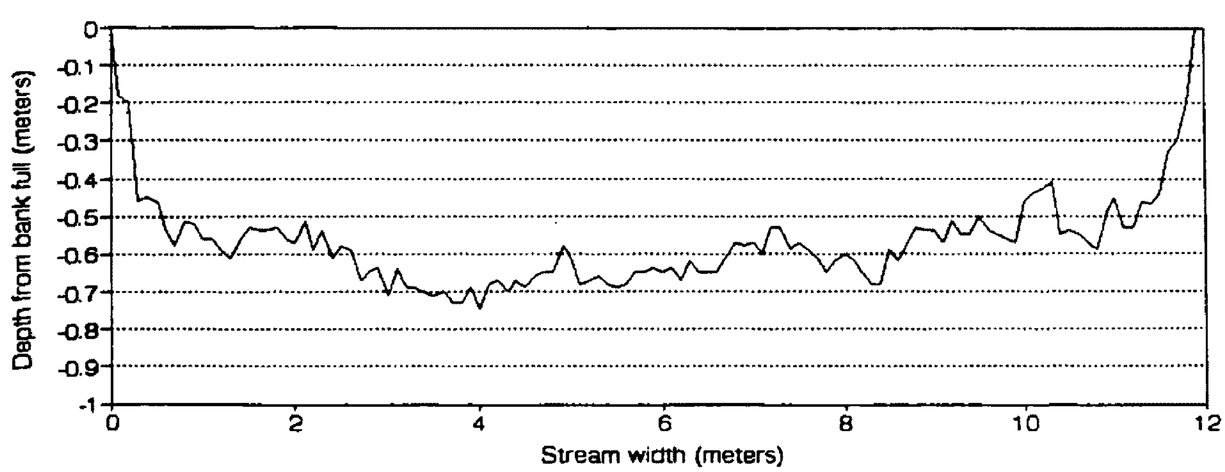
TRAPPER CREEK (#1 trailhead)
CROSS SECTION



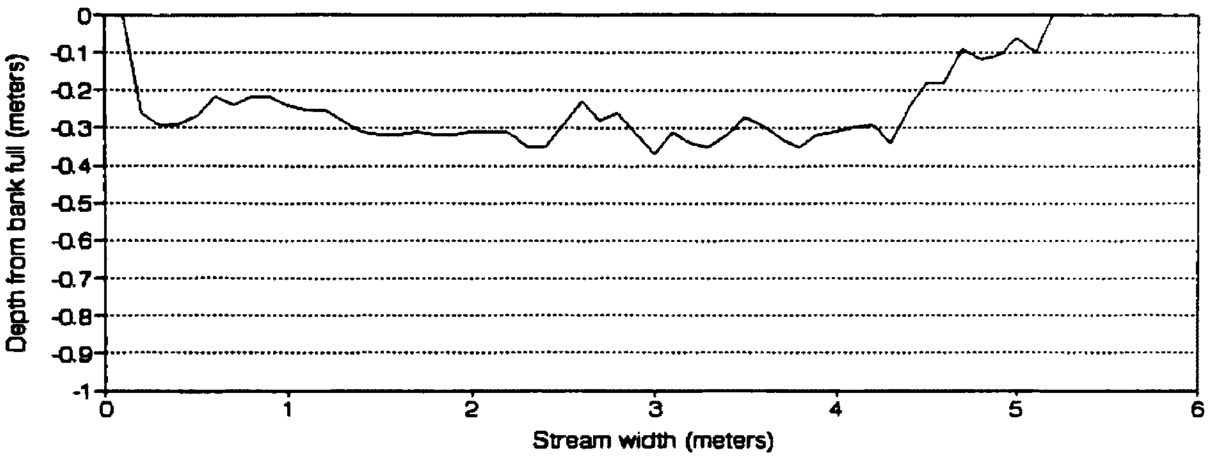
TRAPPER CREEK (#2)
CROSS SECTION



TRAPPER CREEK (#3)
CROSS SECTION



EAST FORK LOLO CR (#1)
CROSS SECTION



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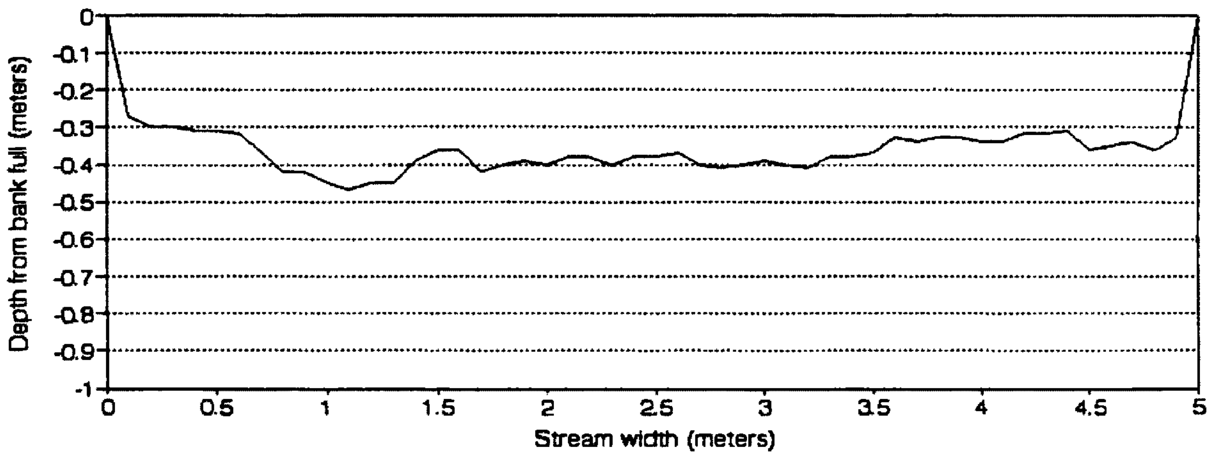
CROSS SECTION



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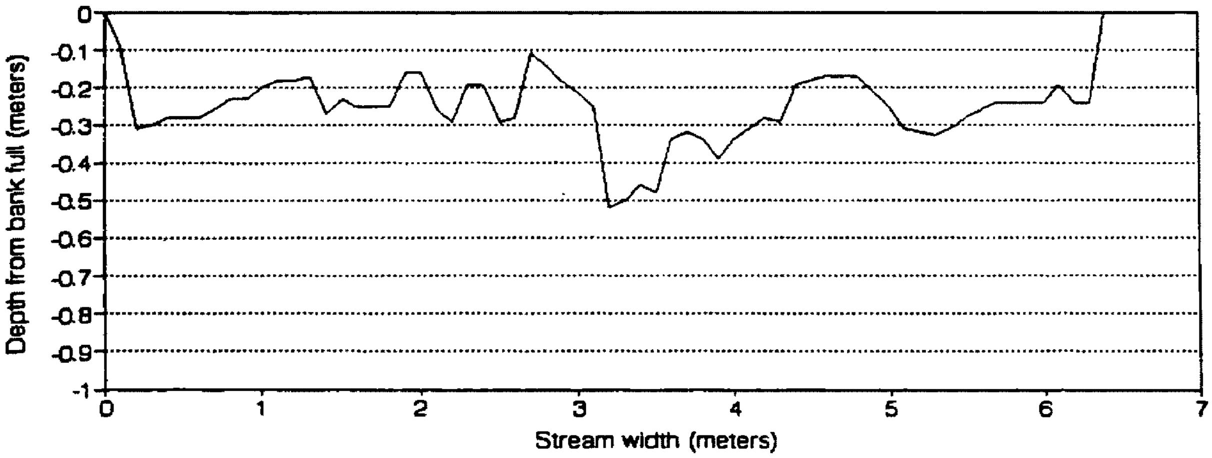
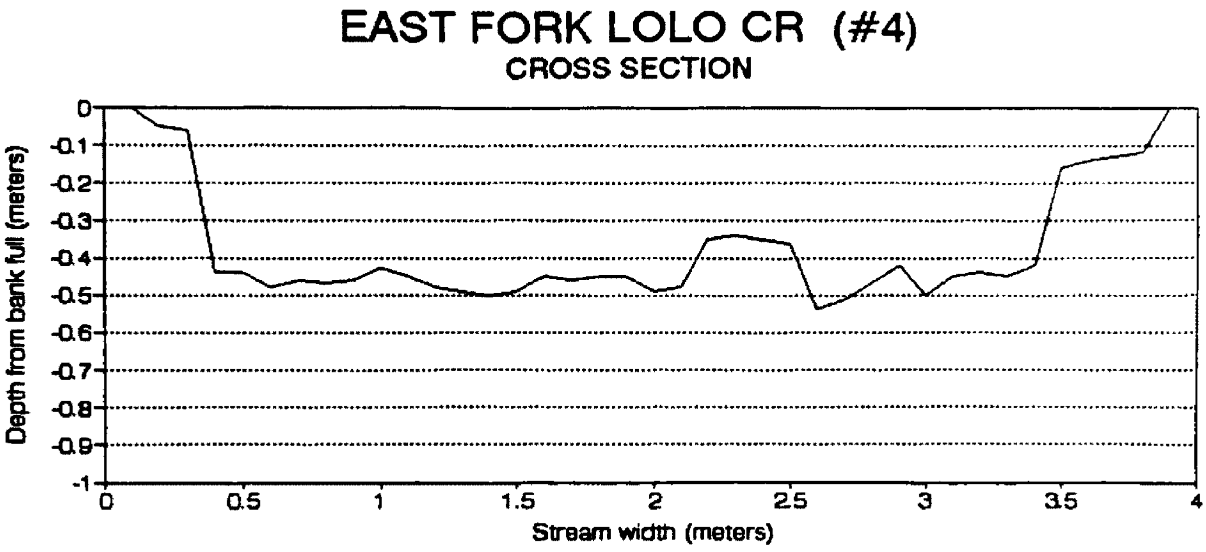
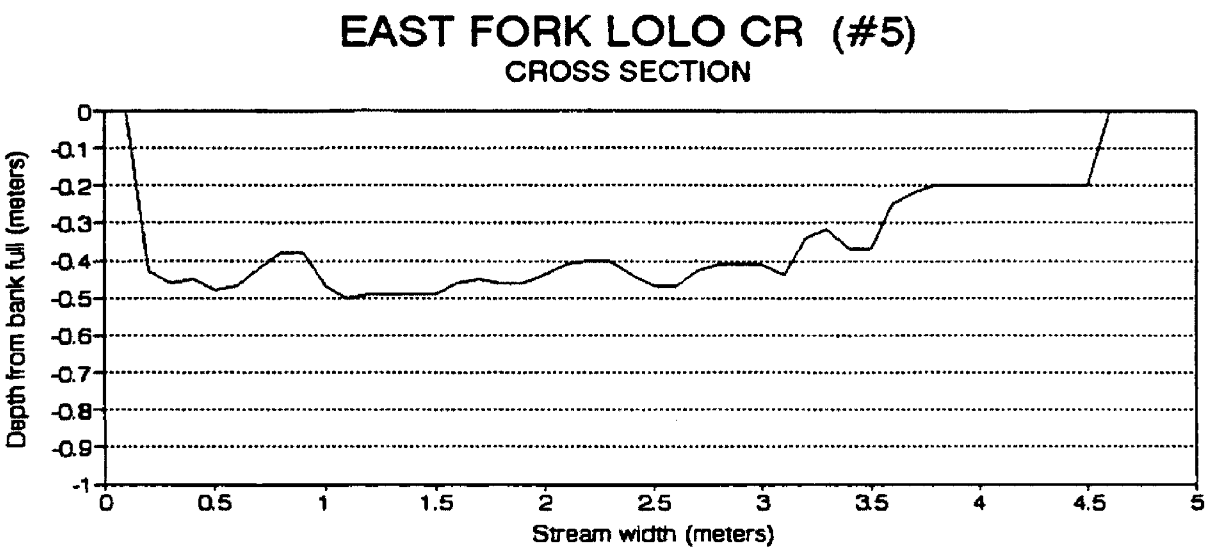
CROSS SECTION




EAST FORK LOLO CR (#4)
CROSS SECTION
Depth from bank full (meters)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
Stream width (meters)


EAST FORK LOLO CR (#5)
CROSS SECTION
Depth from bank full (meters)
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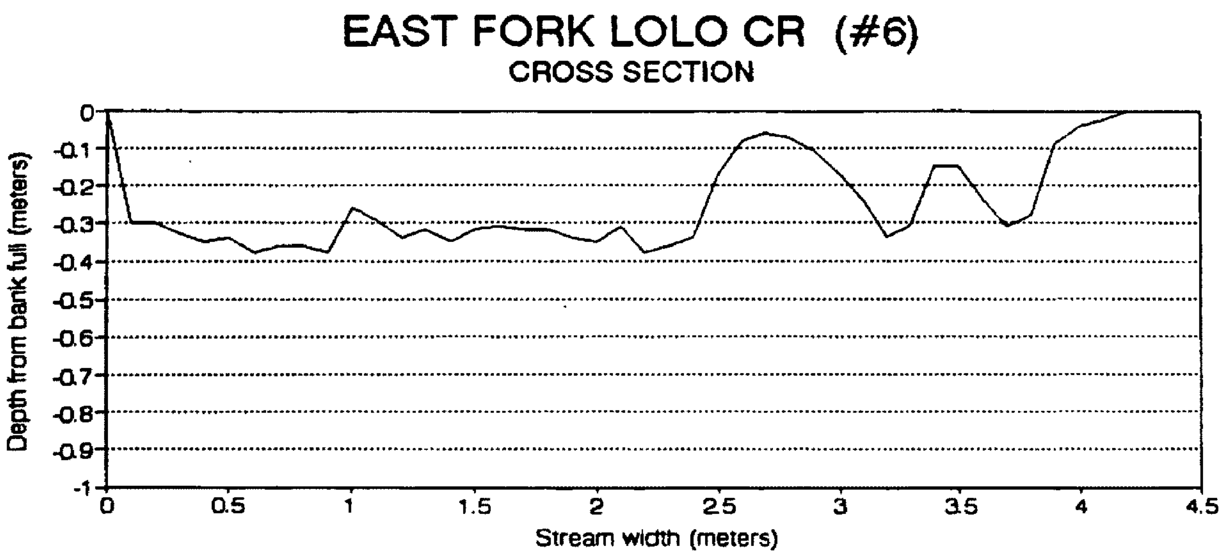
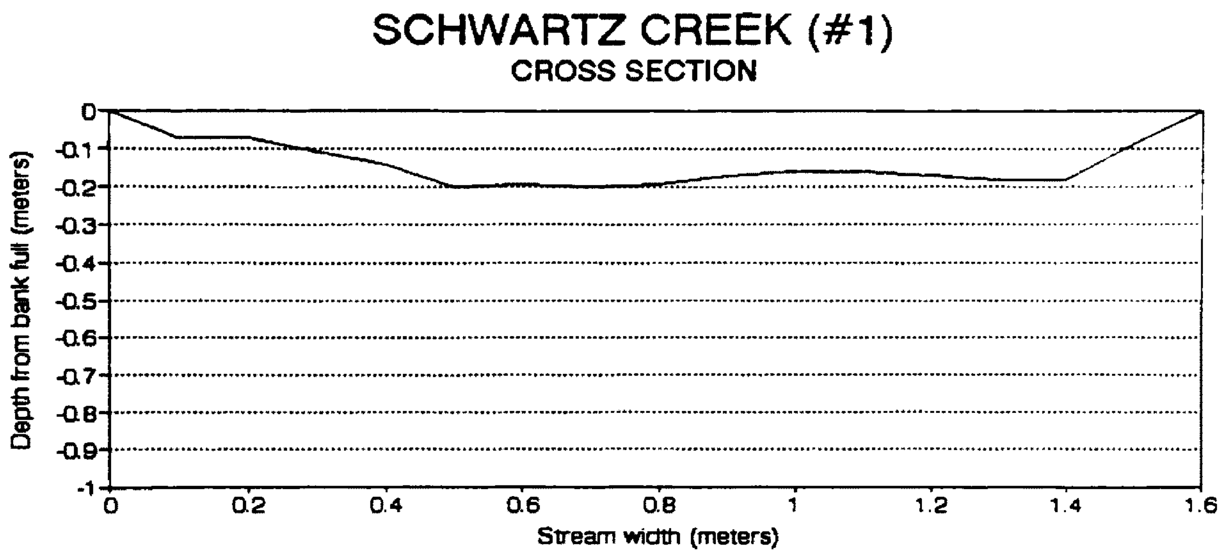
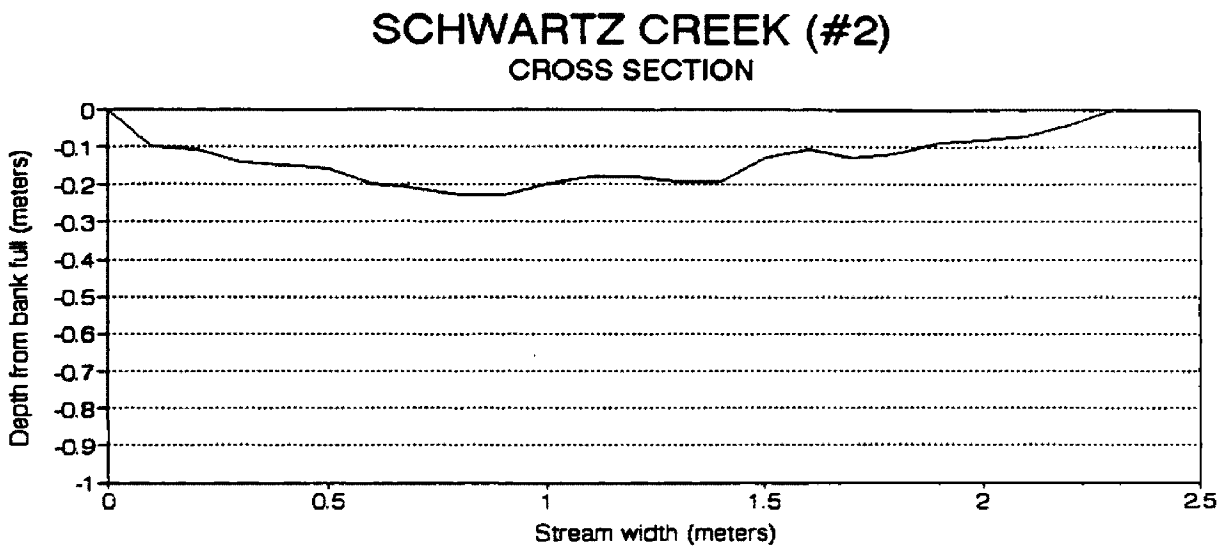
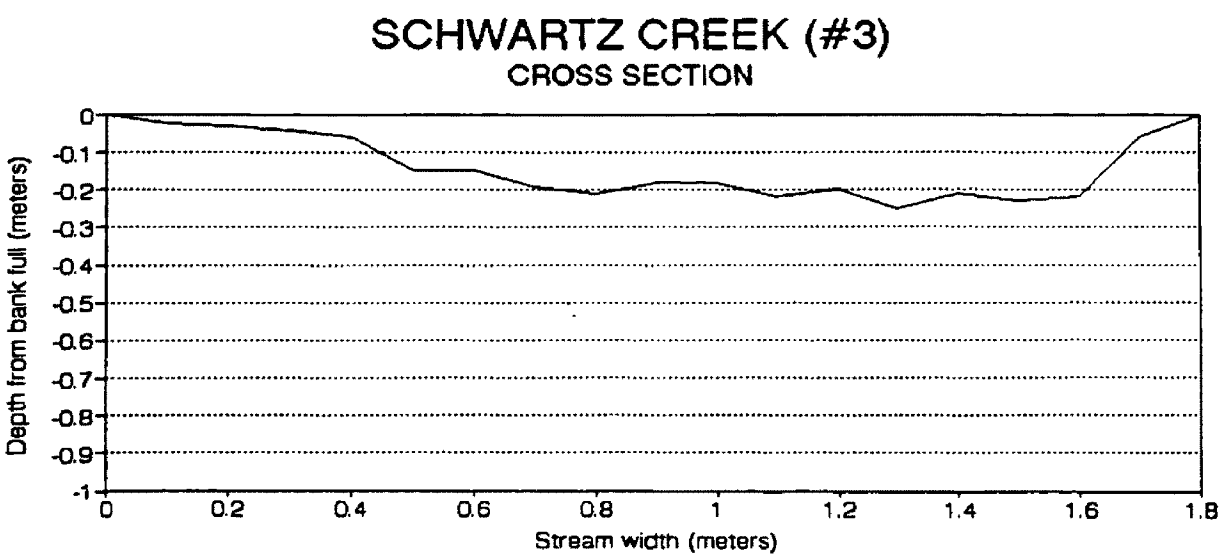
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Stream width (meters)

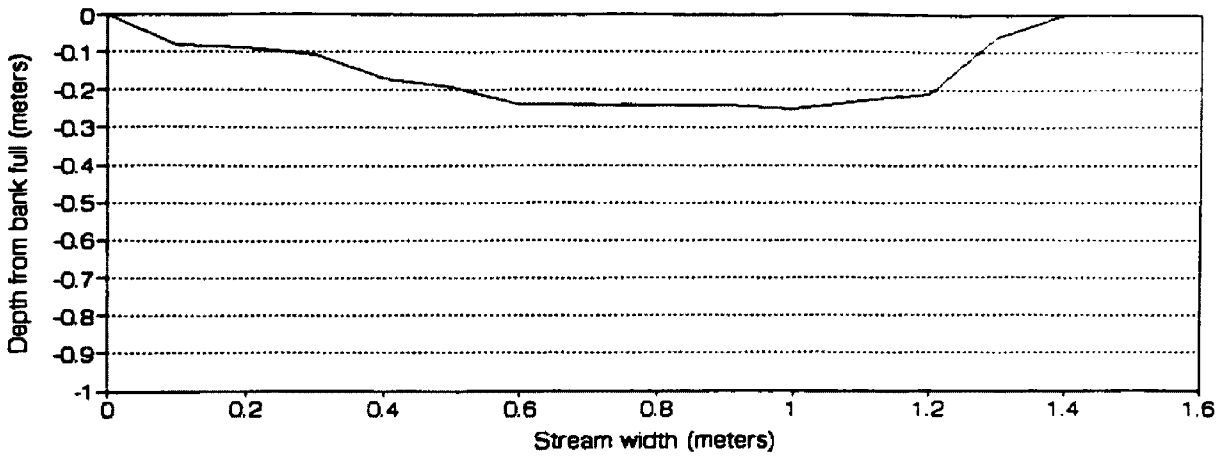

EAST FORK LOLO CR (#6)
CROSS SECTION
Depth from bank full (meters)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Stream width (meters)


SCHWARTZ CREEK (#1)
CROSS SECTION
Depth from bank full (meters)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Stream width (meters)

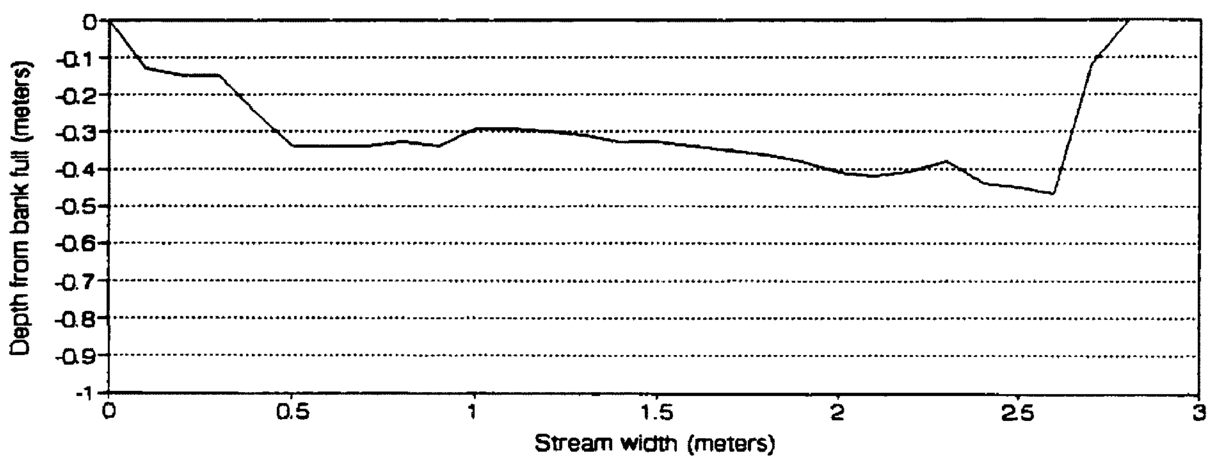

SCHWARTZ CREEK (#2)
CROSS SECTION
Depth from bank full (meters)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
0.5
1
1.5
2
2.5
Stream width (meters)


SCHWARTZ CREEK (#3)
CROSS SECTION
Depth from bank full (meters)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Stream width (meters)

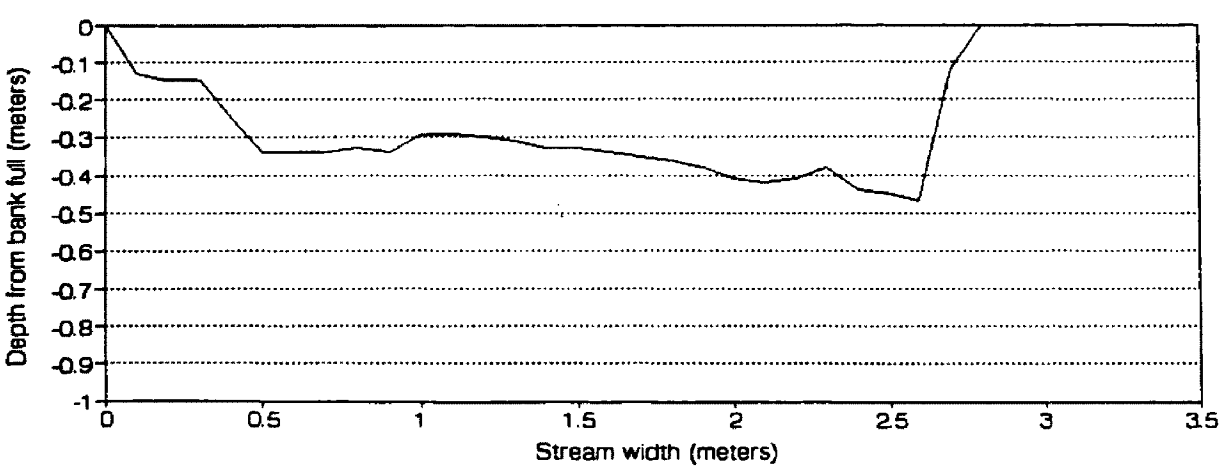
SCHWARTZ CREEK (#4)
CROSS SECTION



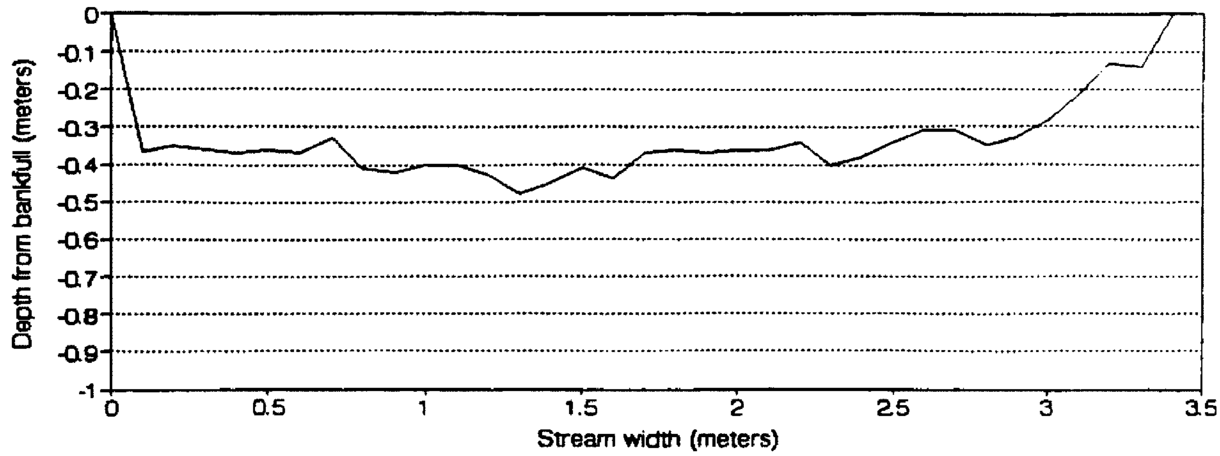
SCHWARTZ CREEK (#5)
CROSS SECTION



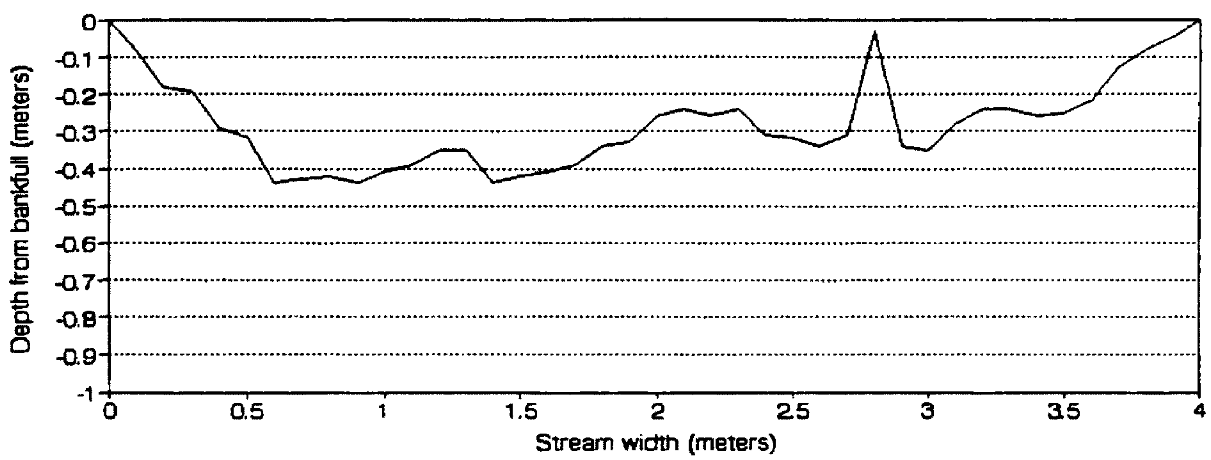
SCHWARTZ CREEK (#6)
CROSS SECTION



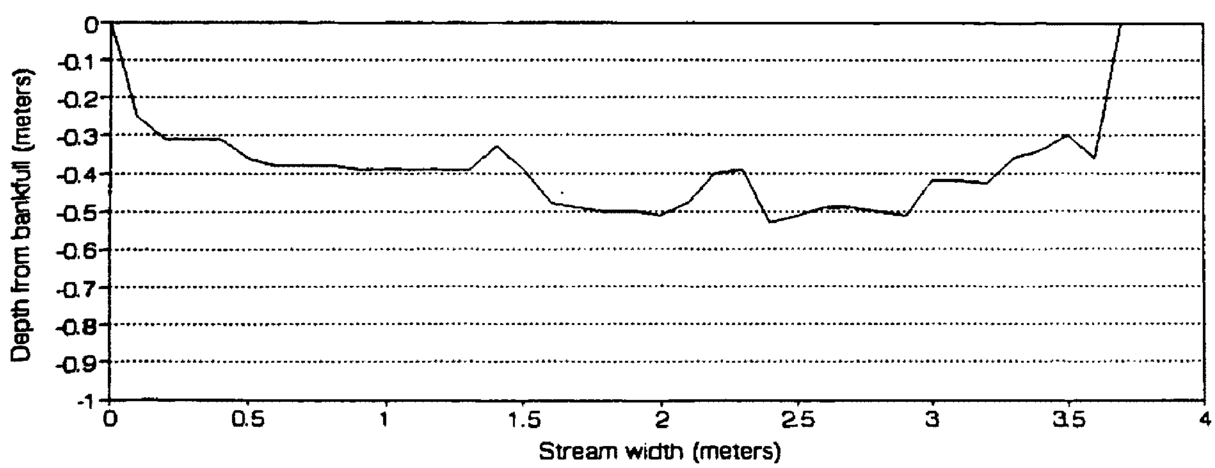
WEST TWIN CREEK (#1)
CROSS SECTION



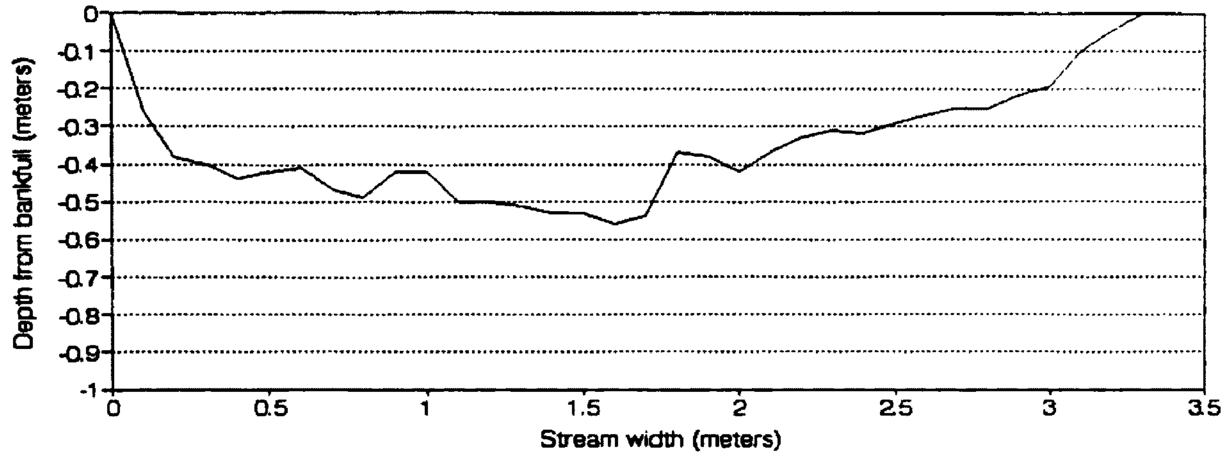
WEST TWIN CREEK (#2)
CROSS SECTION



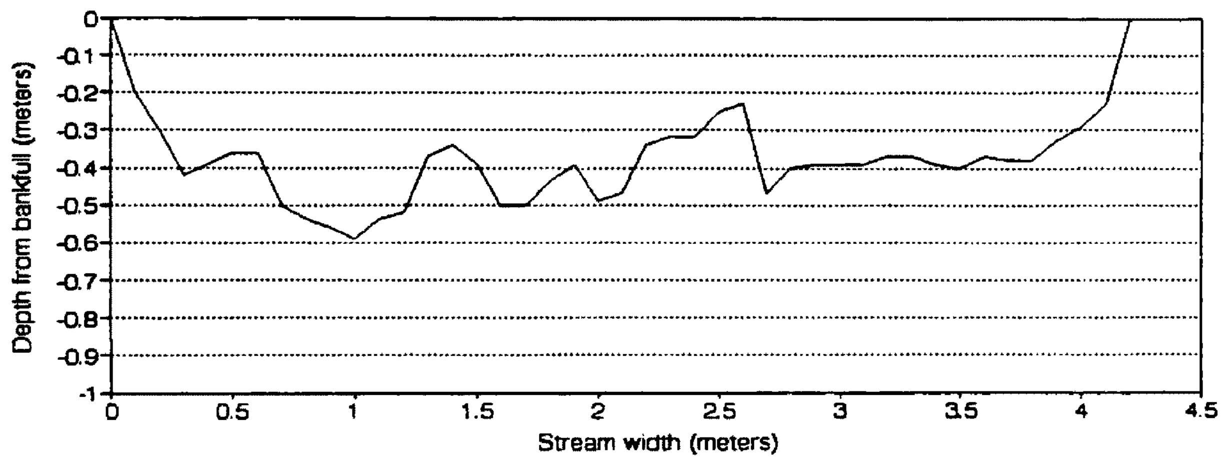
WEST TWIN CREEK (#3)
CROSS SECTION



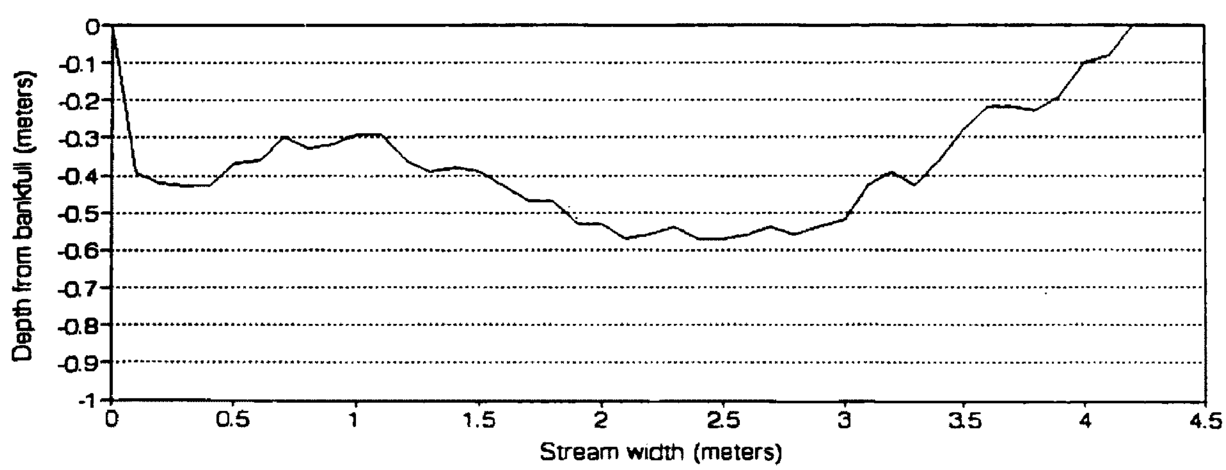
WEST TWIN CREEK (#4)
CROSS SECTION



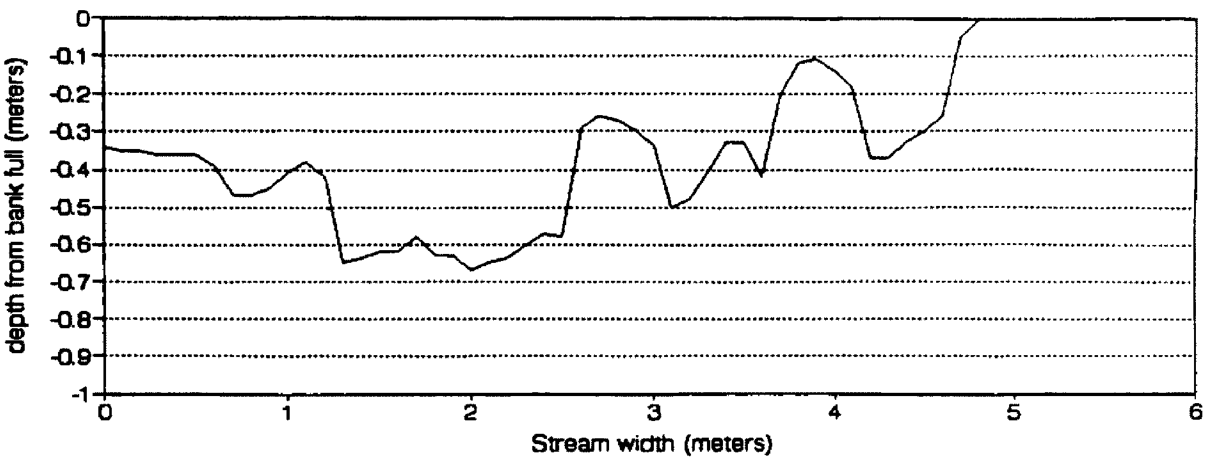
WEST TWIN CREEK (#5)
CROSS SECTION



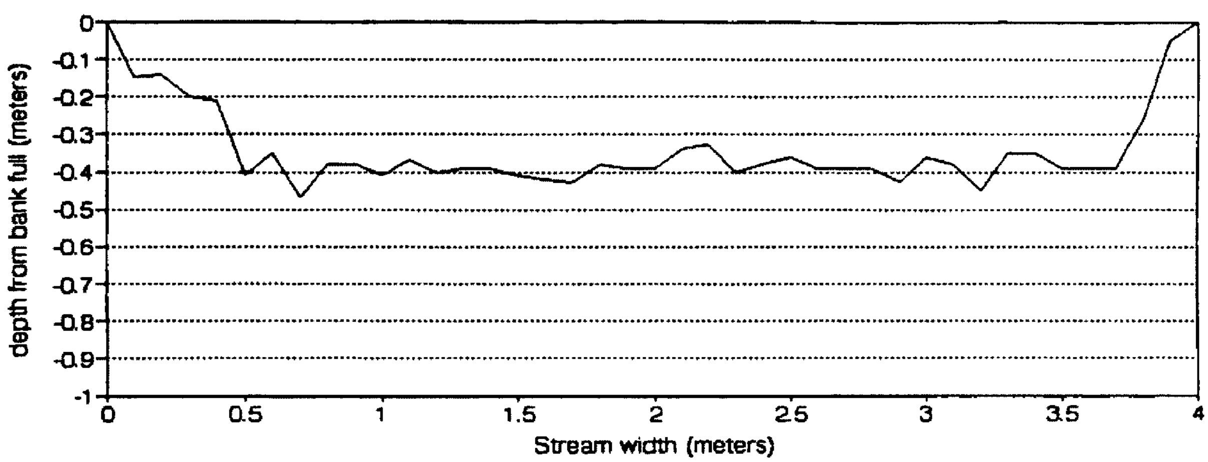
WEST TWIN CREEK (#6)
CROSS SECTION



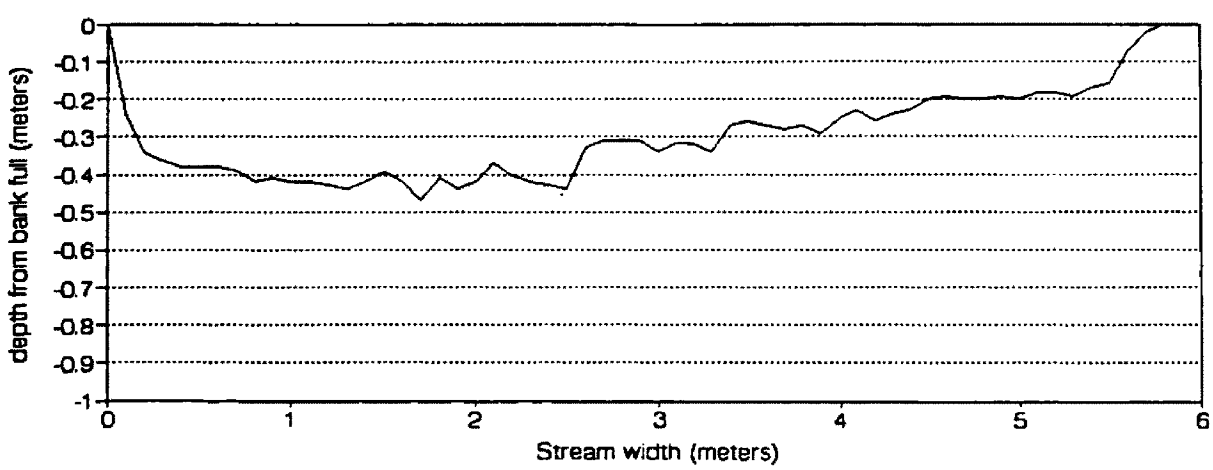
LOST PARK CREEK (#1)
CROSS SECTION



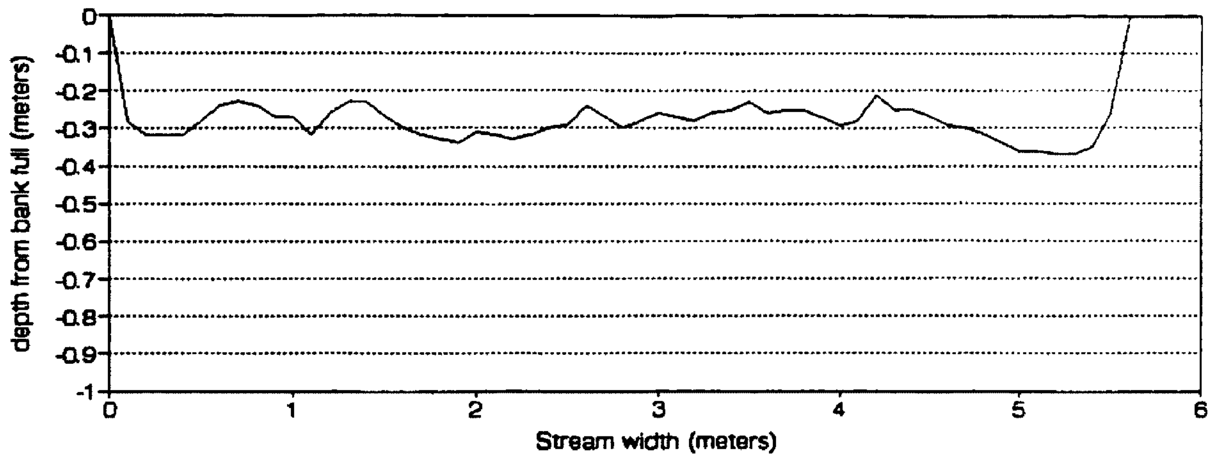
LOST PARK CREEK (#2)
CROSS SECTION



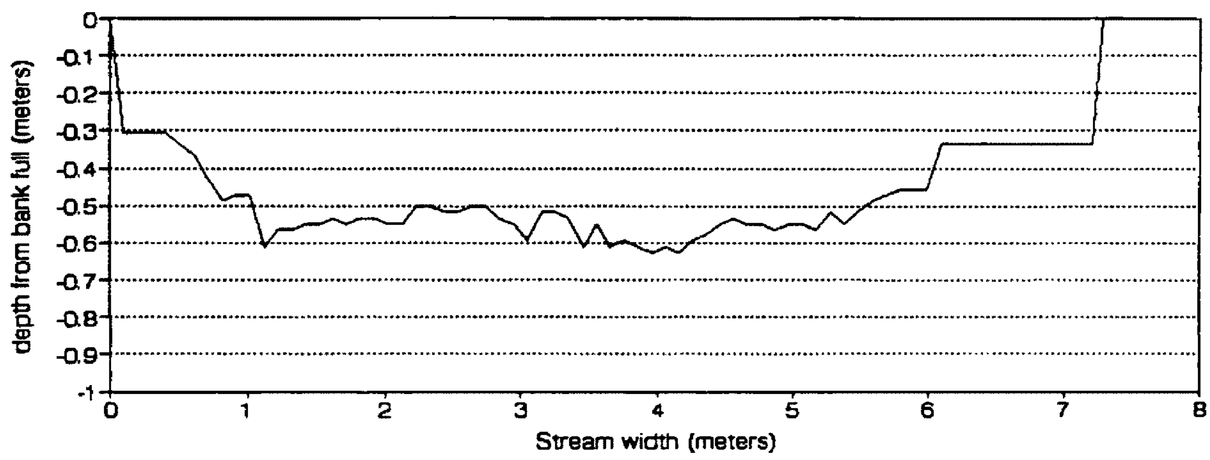
LOST PARK CREEK (#3)
CROSS SECTION



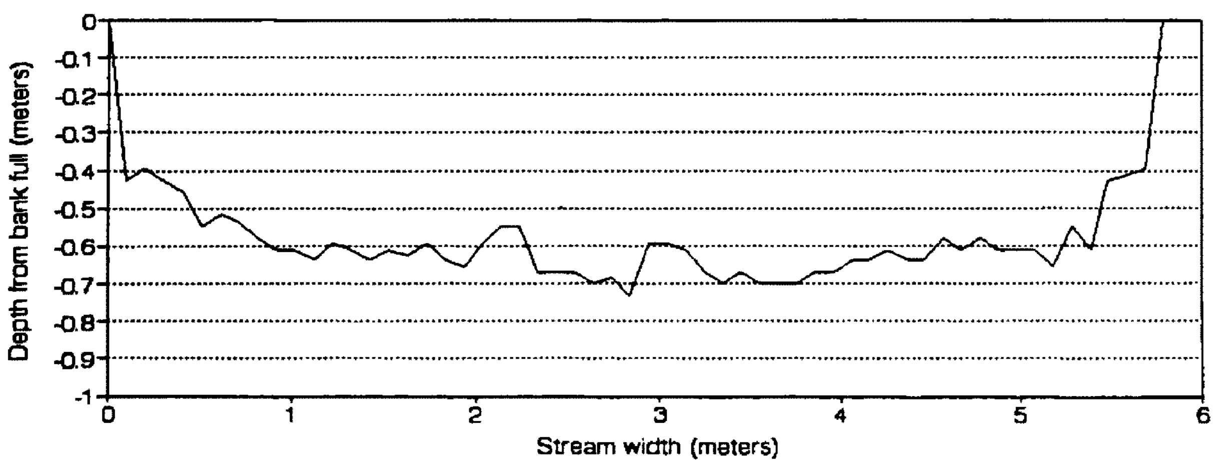
LOST PARK CREEK (#4)
CROSS SECTION

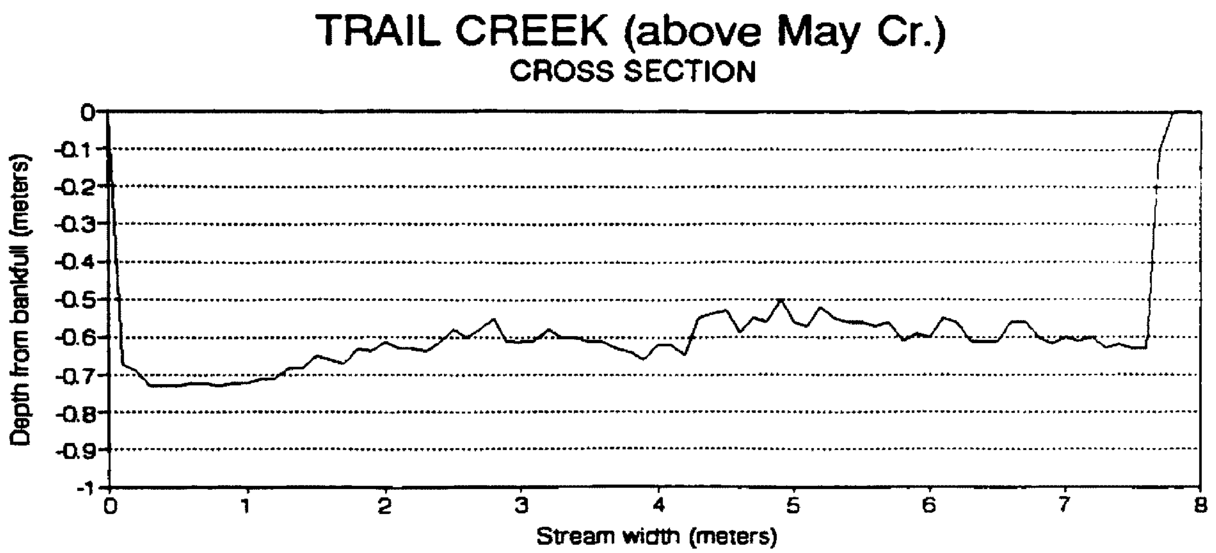


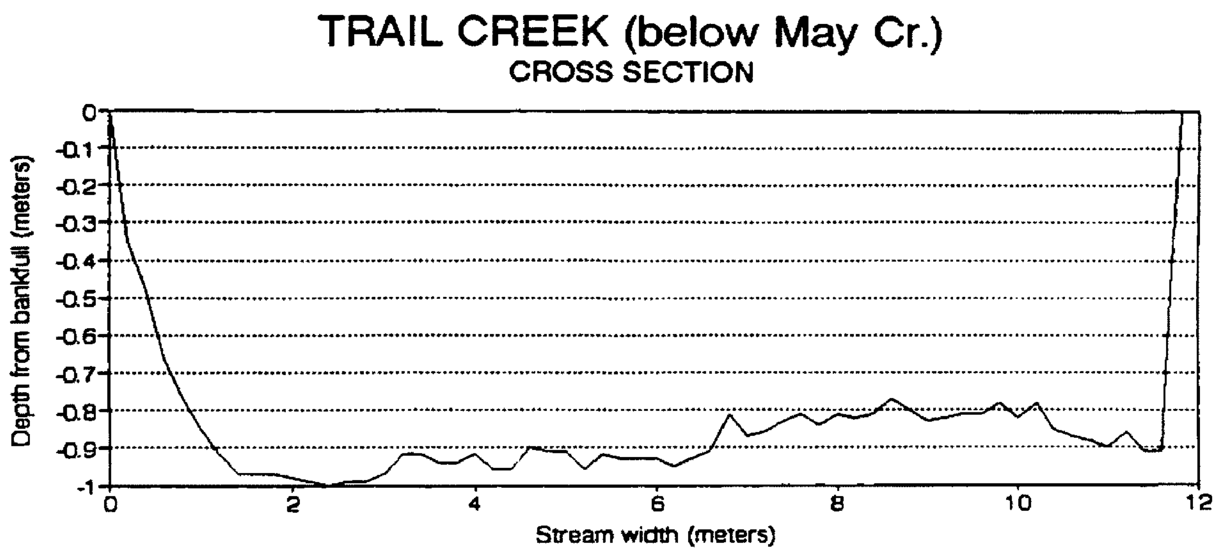
WEST FORK of GOLD CREEK (Prims)
X-SECTION

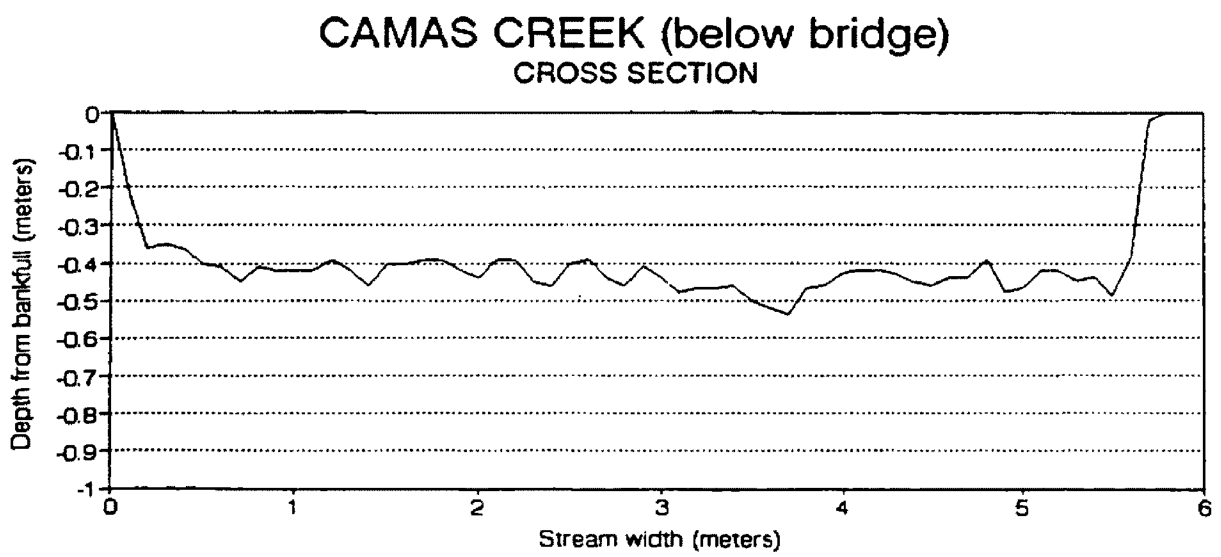


GOLD CREEK at bridge
Cross-section

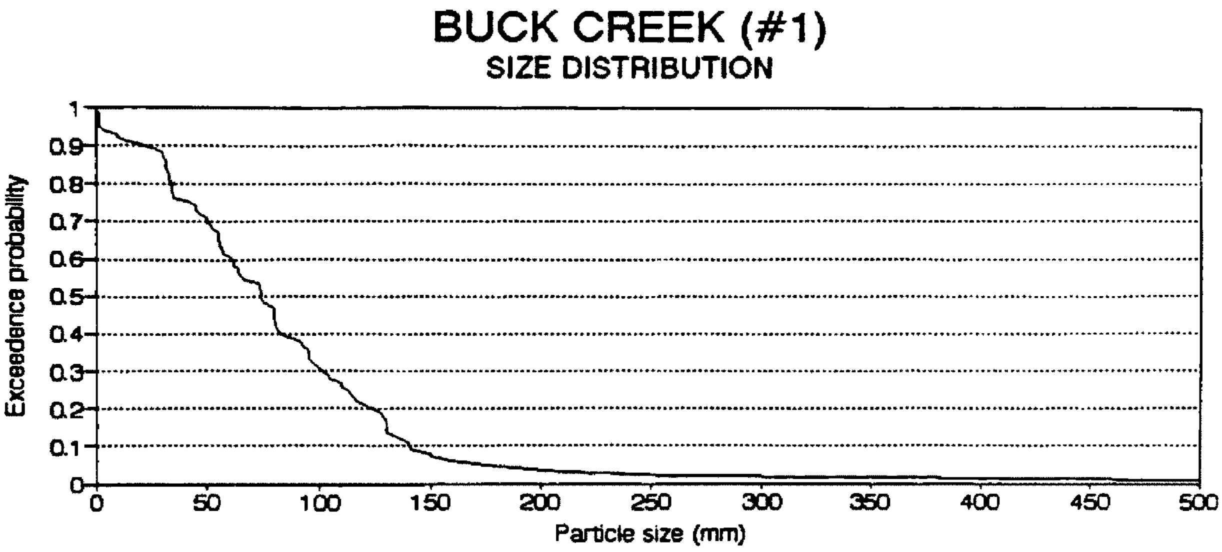


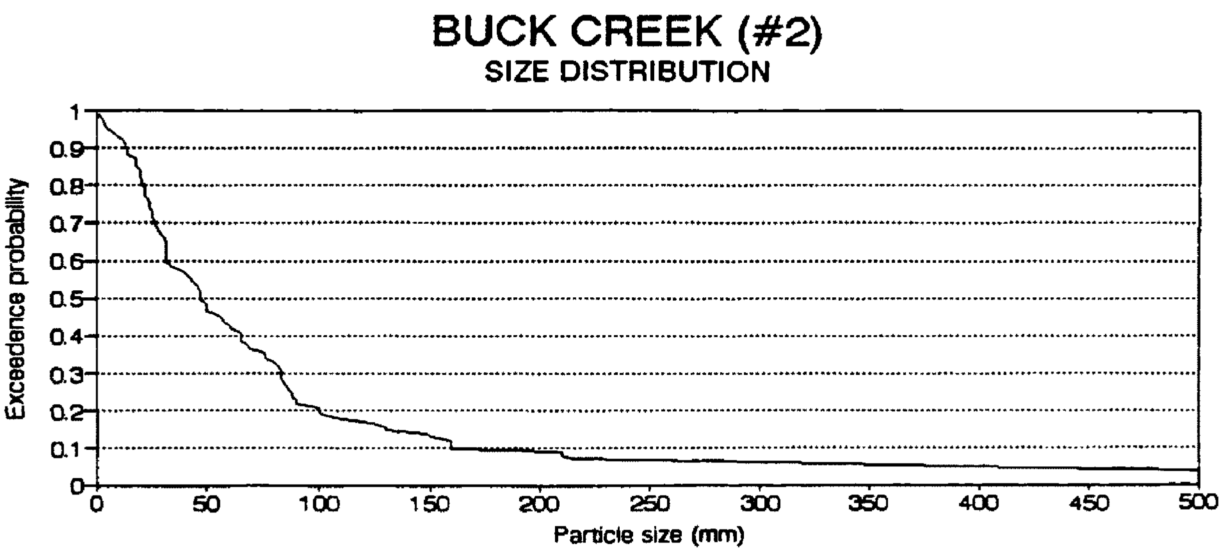

TRAIL CREEK (above May Cr.)
CROSS SECTION
Depth from bankfull (meters)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
1
2
3
4
5
6
7
8
Stream width (meters)

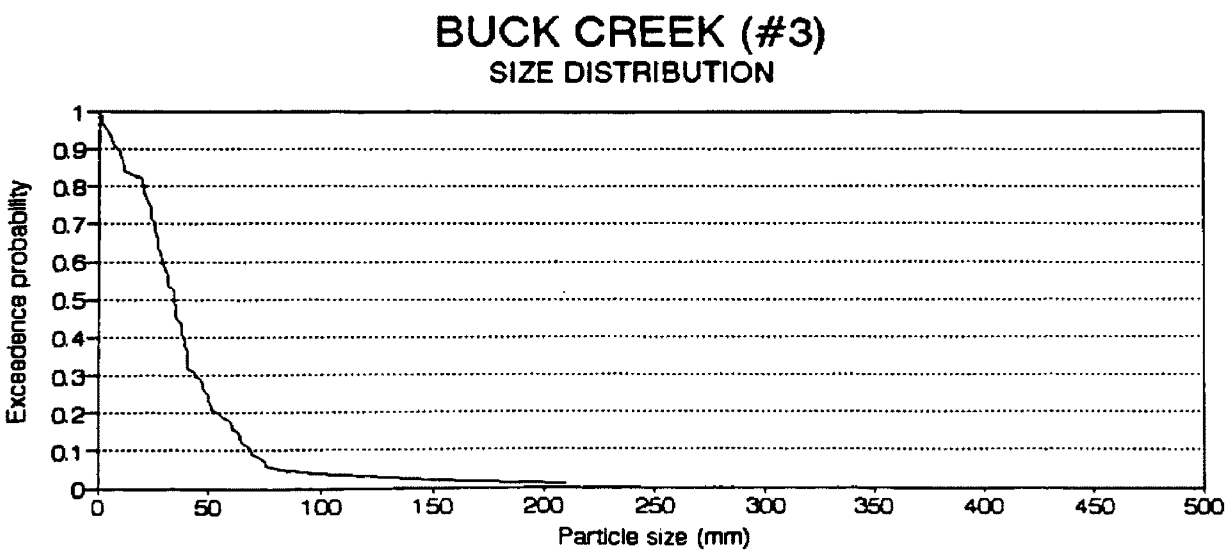

TRAIL CREEK (below May Cr.)
CROSS SECTION
Depth from bankfull (meters)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
2
4
6
8
10
12
Stream width (meters)


CAMAS CREEK (below bridge)
CROSS SECTION
Depth from bankfull (meters)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
1
2
3
4
5
6
Stream width (meters)

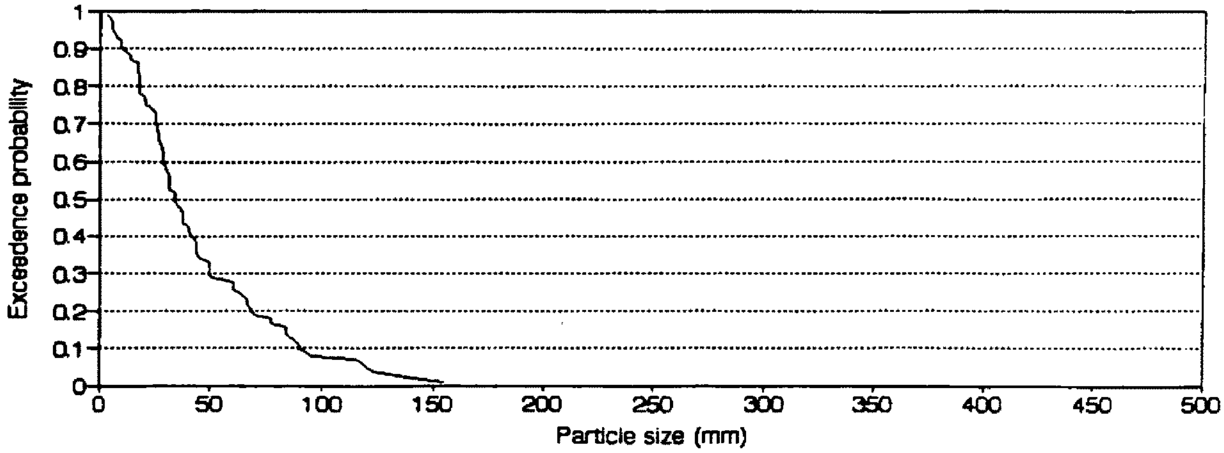
Appendix 3.
Stream-bed pebble size distribution for all study sites



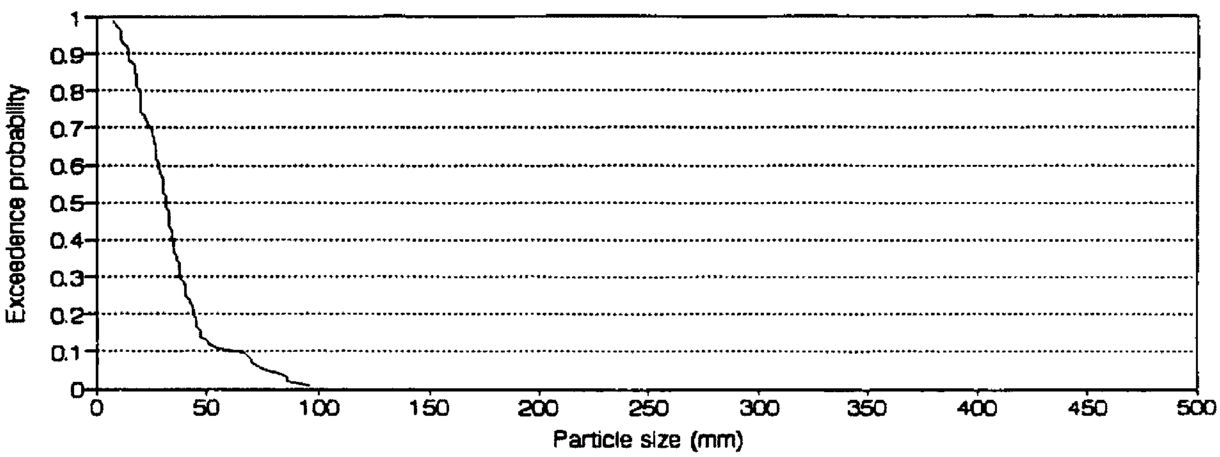




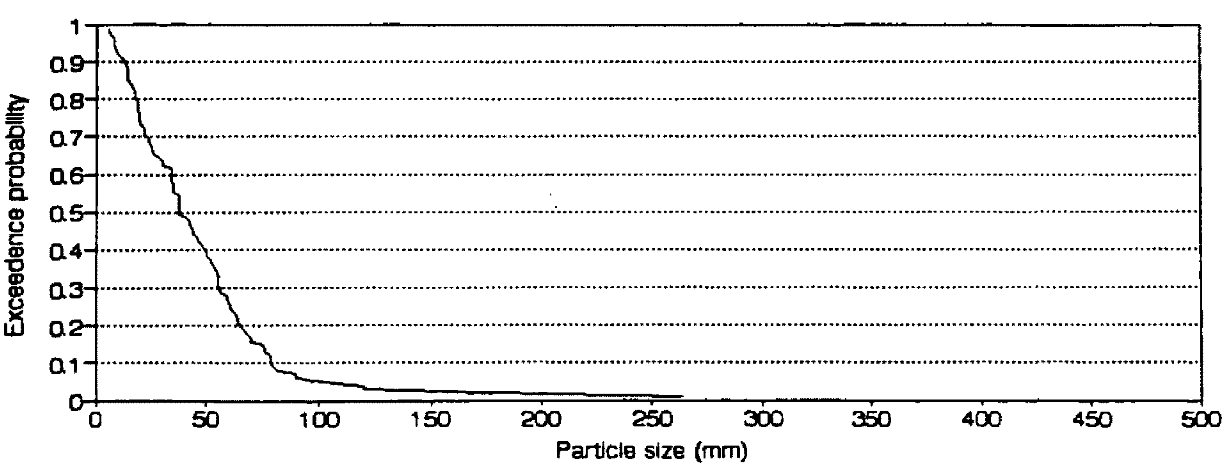
ARKANSAS CREEK (Lower)
SIZE DISTRIBUTION

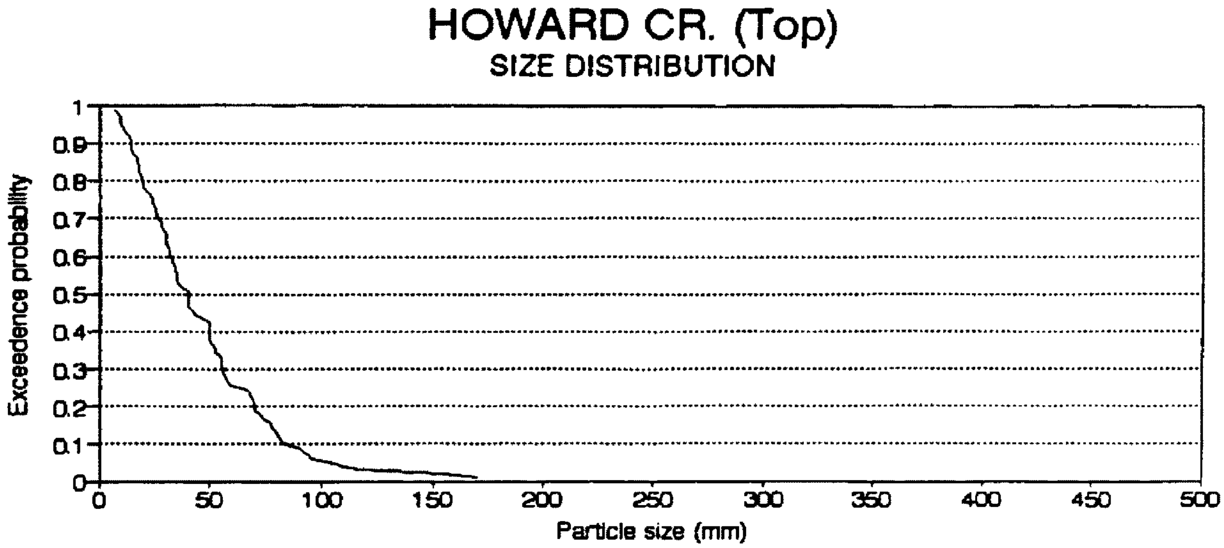


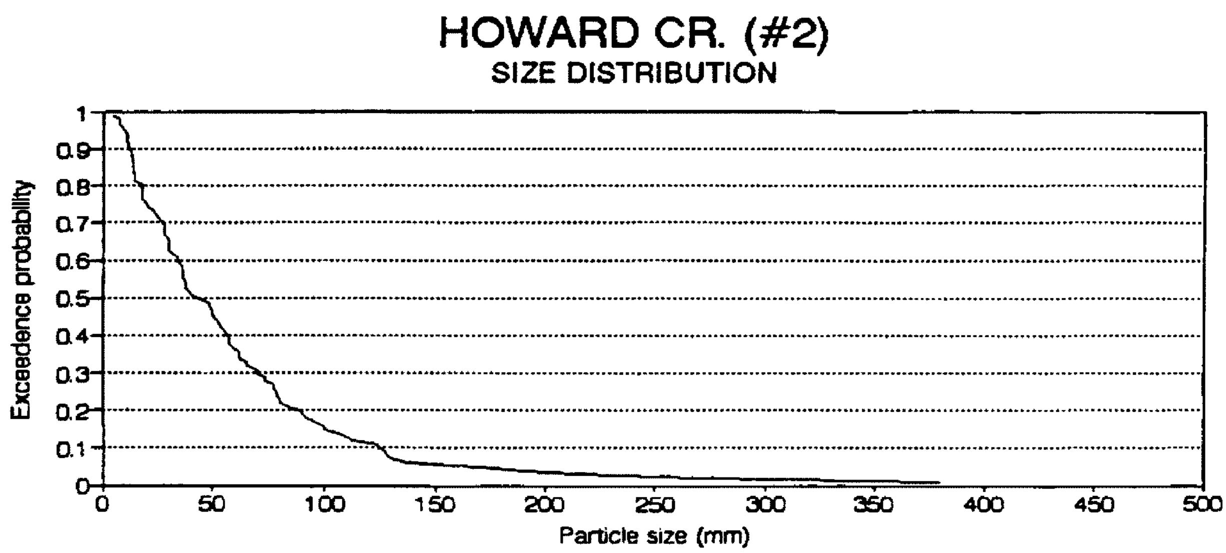
ARKANSAS CREEK (#2)
SIZE DISTRIBUTION

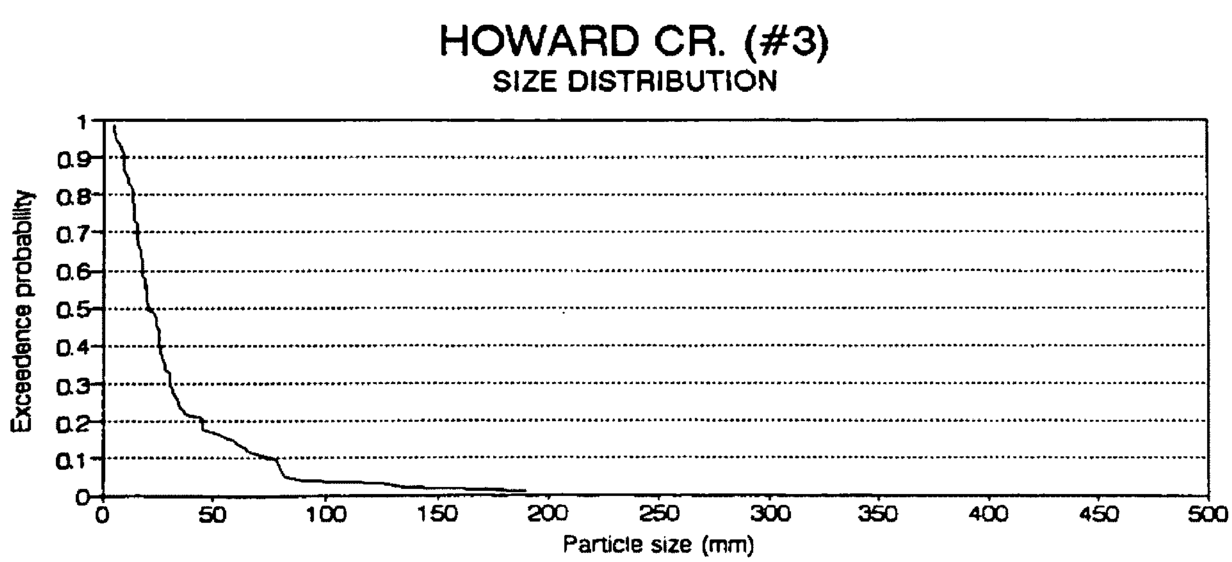


ARKANSAS CREEK (Forked P-Pine)
SIZE DISTRIBUTION

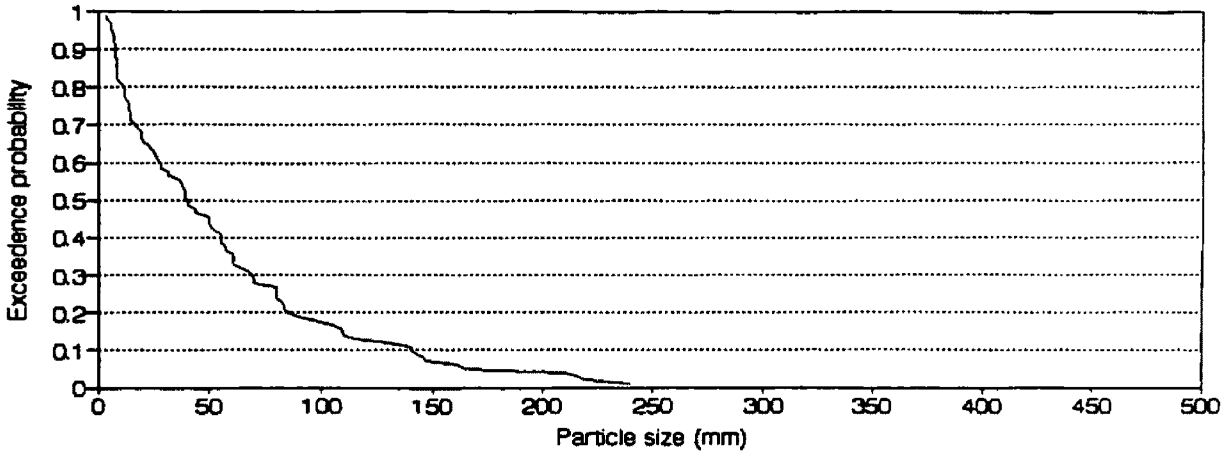



HOWARD CR. (Top)
SIZE DISTRIBUTION
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)

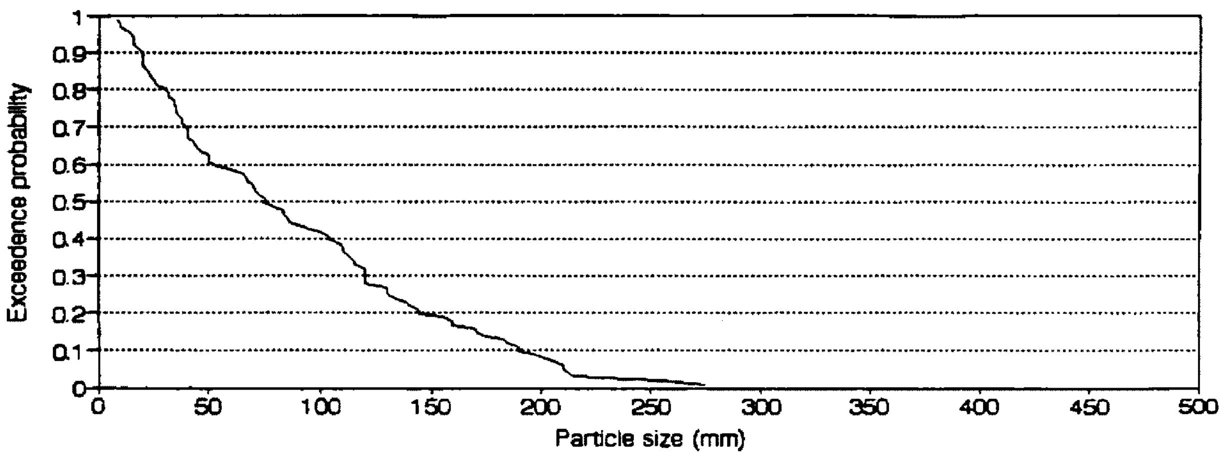

HOWARD CR. (#2)
SIZE DISTRIBUTION
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


HOWARD CR. (#3)
SIZE DISTRIBUTION
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)

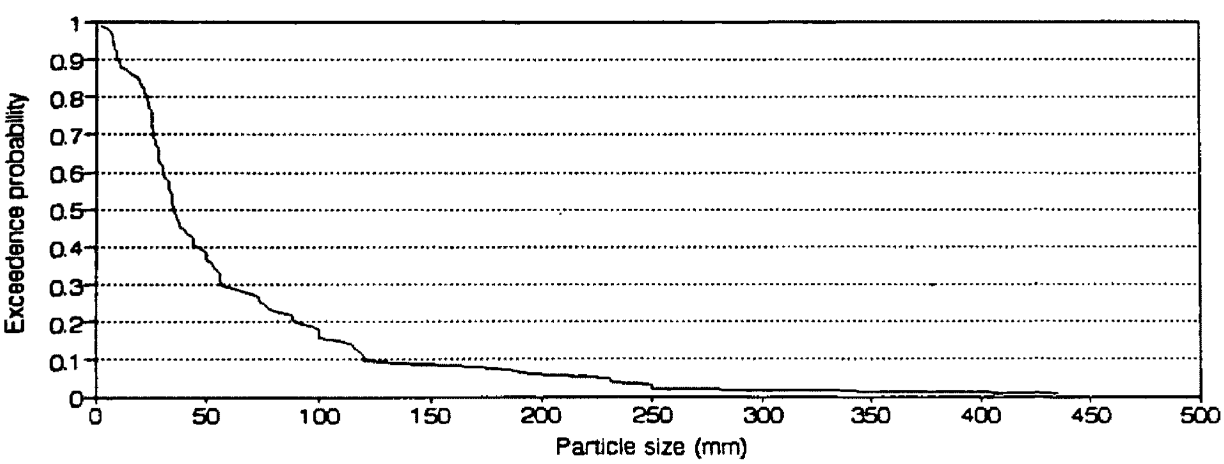
HOWARD CR. (#4)
SIZE DISTRIBUTION



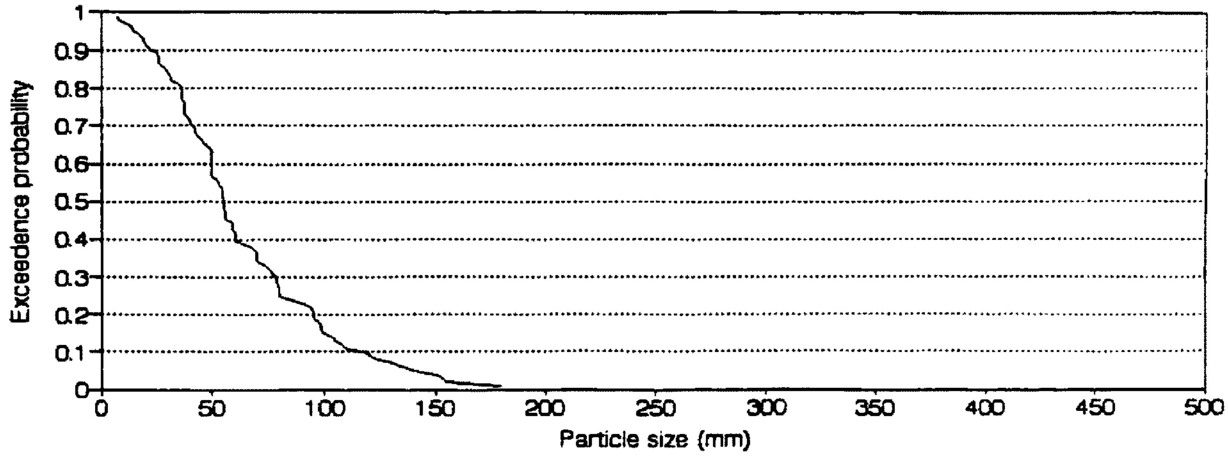
HOWARD CR. (#5)
SIZE DISTRIBUTION



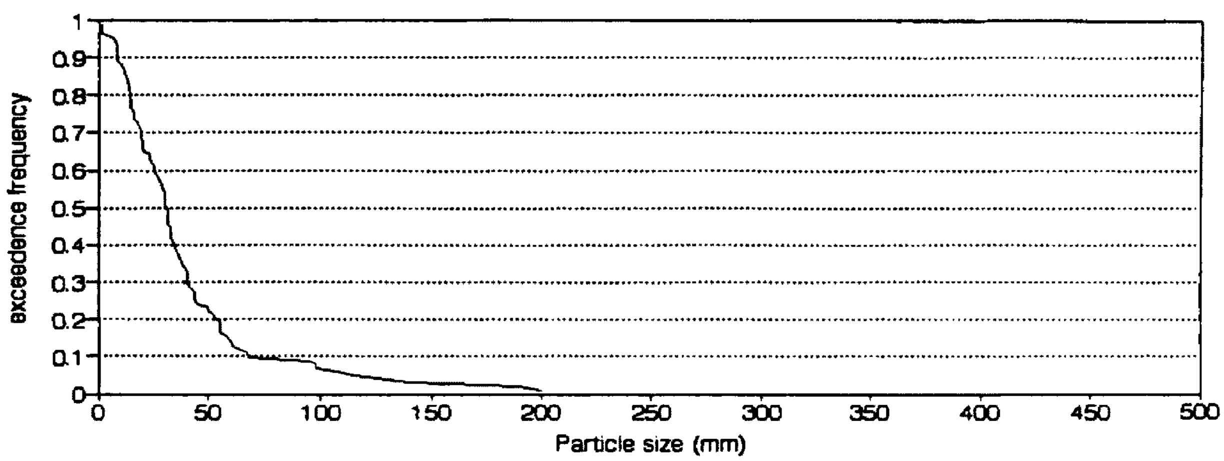
UPPER CAMP CREEK
SIZE DISTRIBUTION



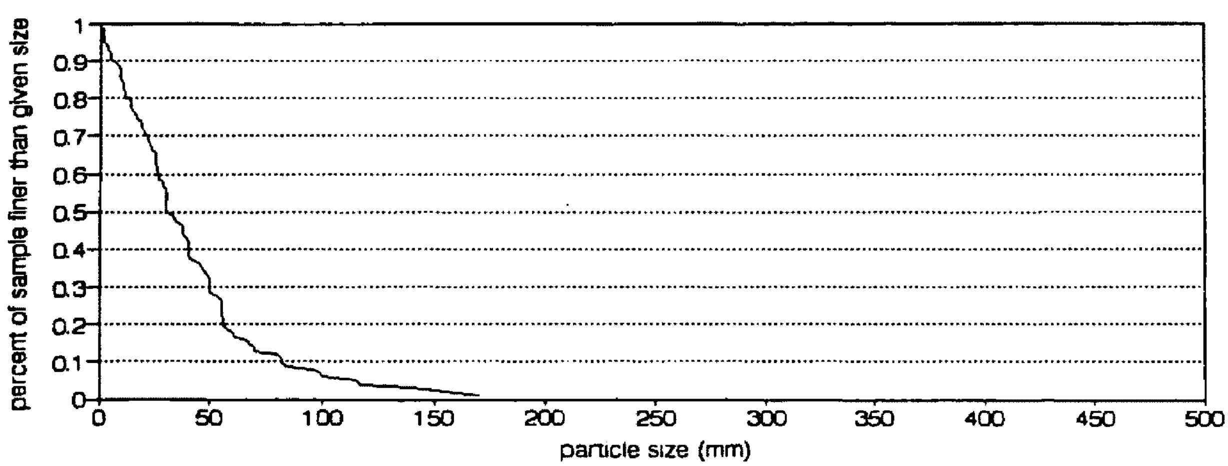
CAMP CREEK (Bottom)
SIZE DISTRIBUTION

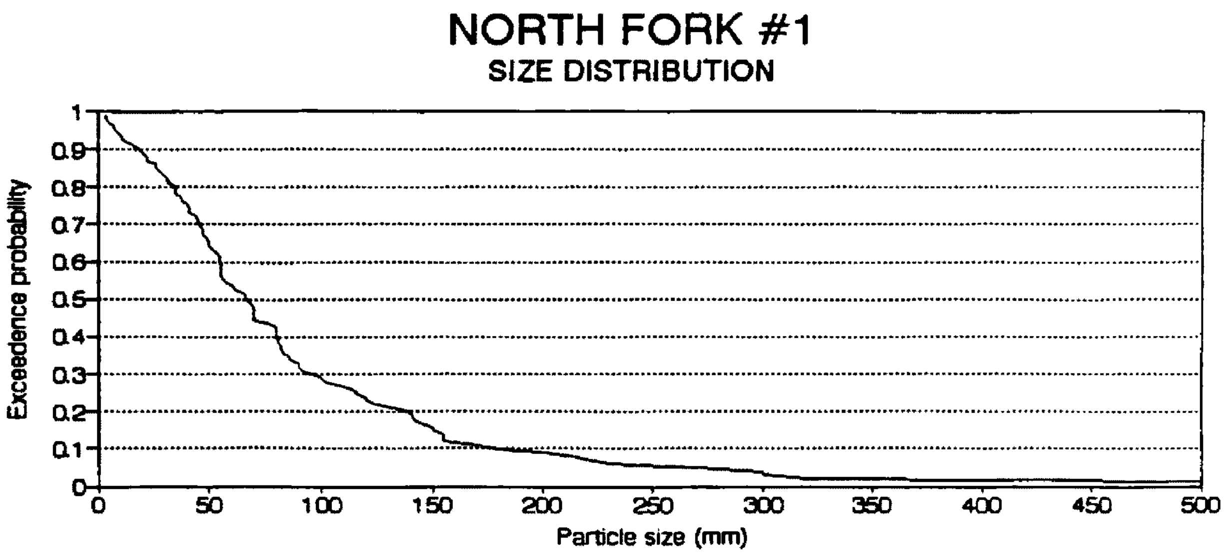


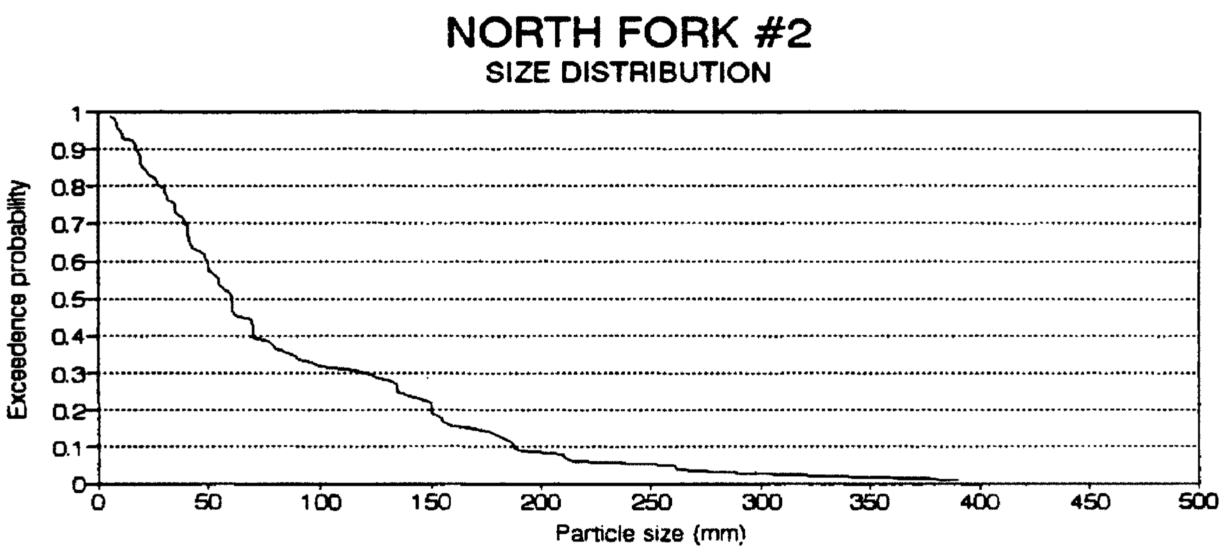
EAST FORK of CAMP CREEK
SIZE DISTRIBUTION

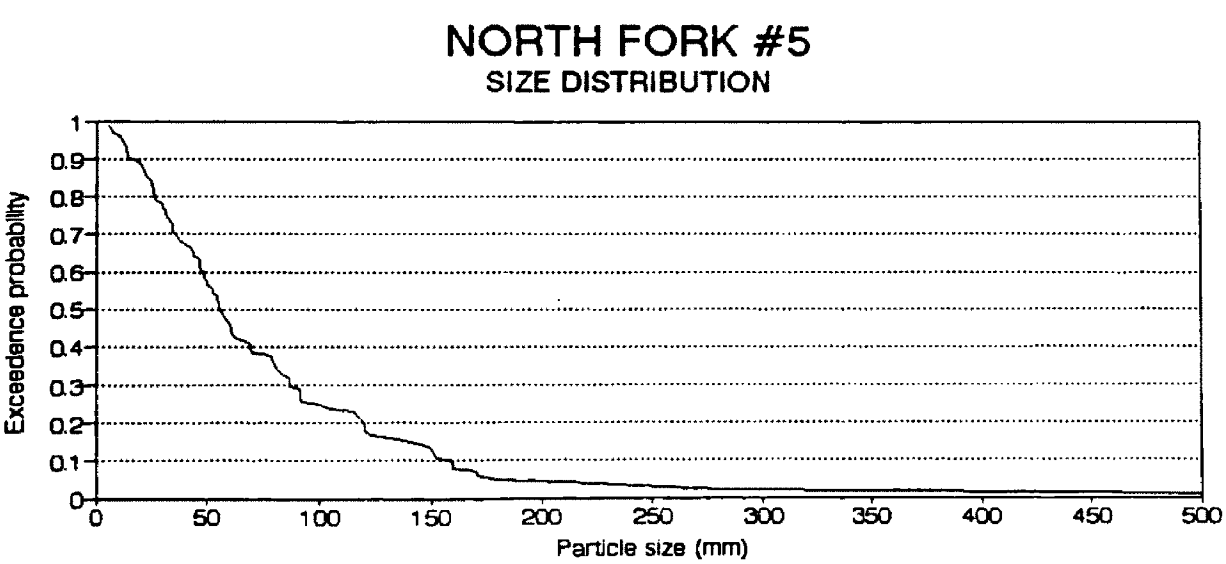


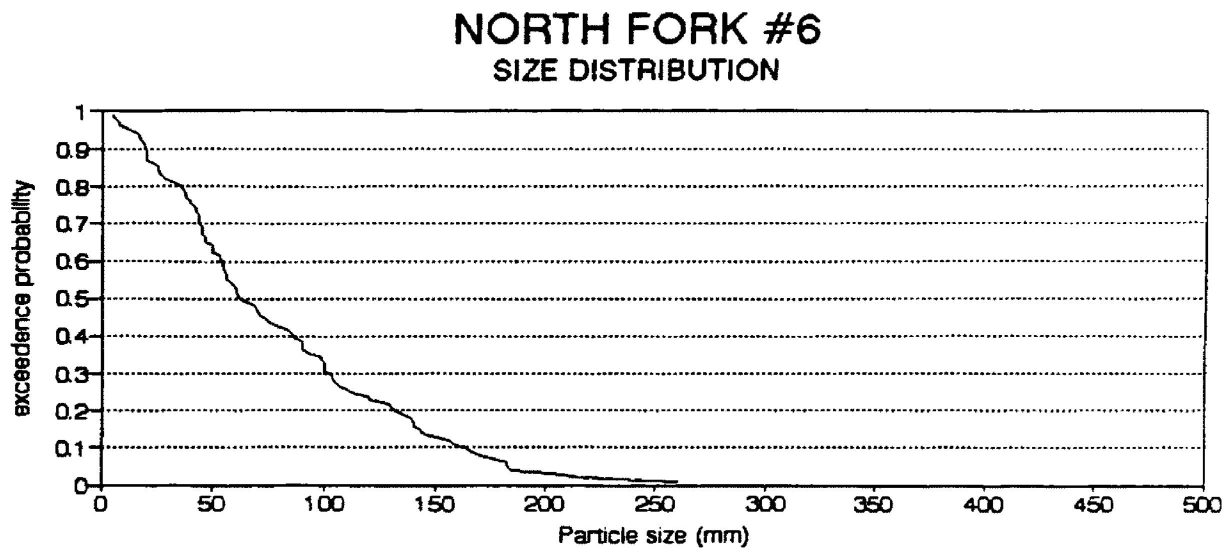
WEST FORK of CAMP CREEK
SIZE DISTRIBUTION

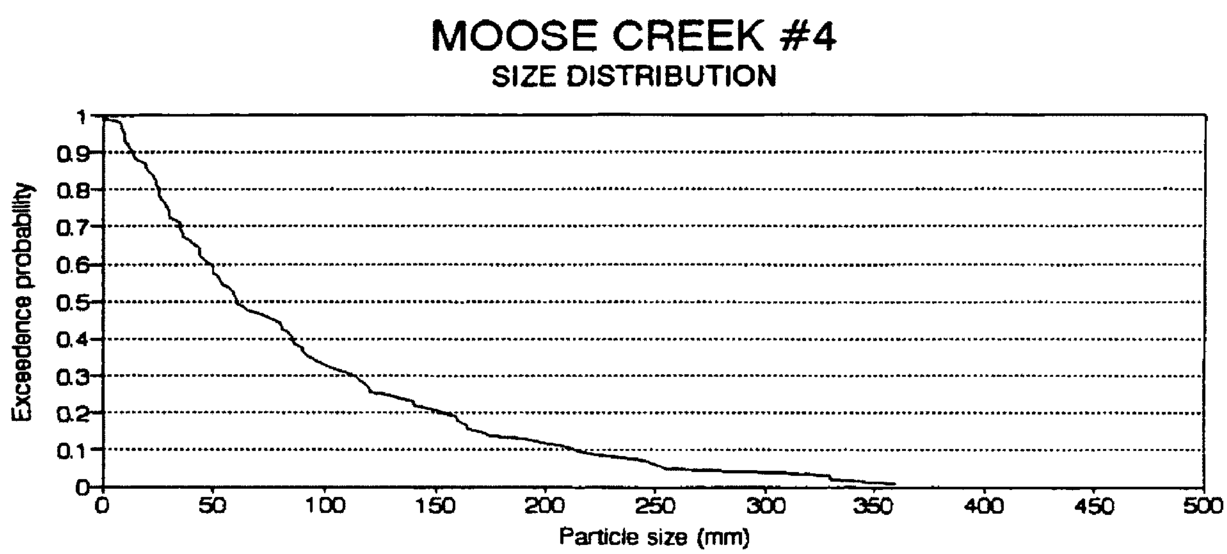


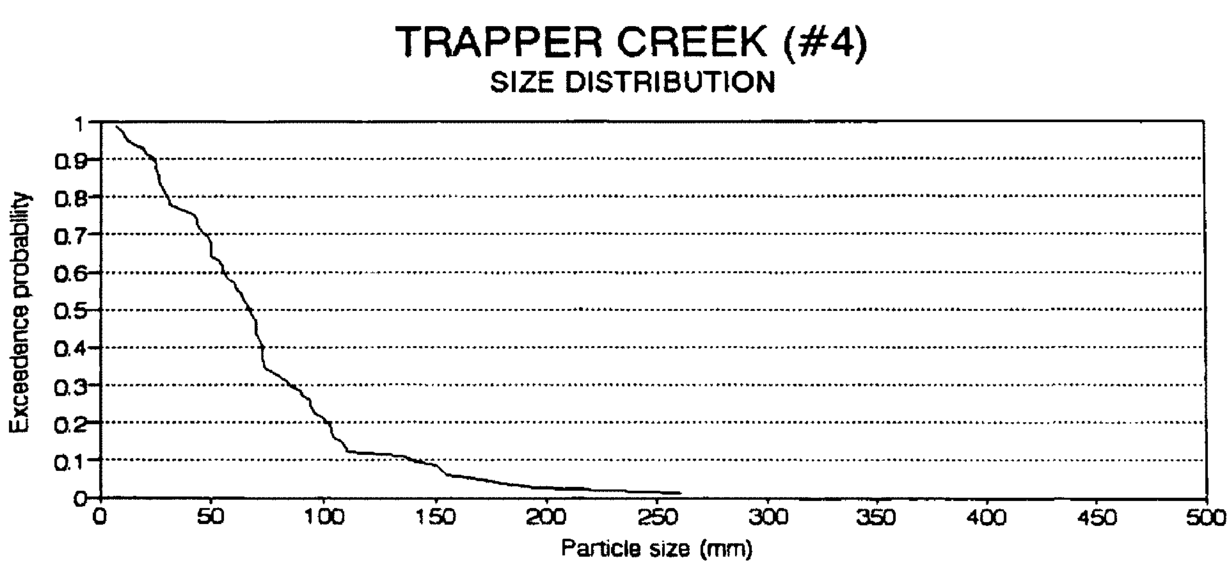

NORTH FORK #1
SIZE DISTRIBUTION
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 50 100 150 200 250 300 350 400 450 500
Particle size (mm)

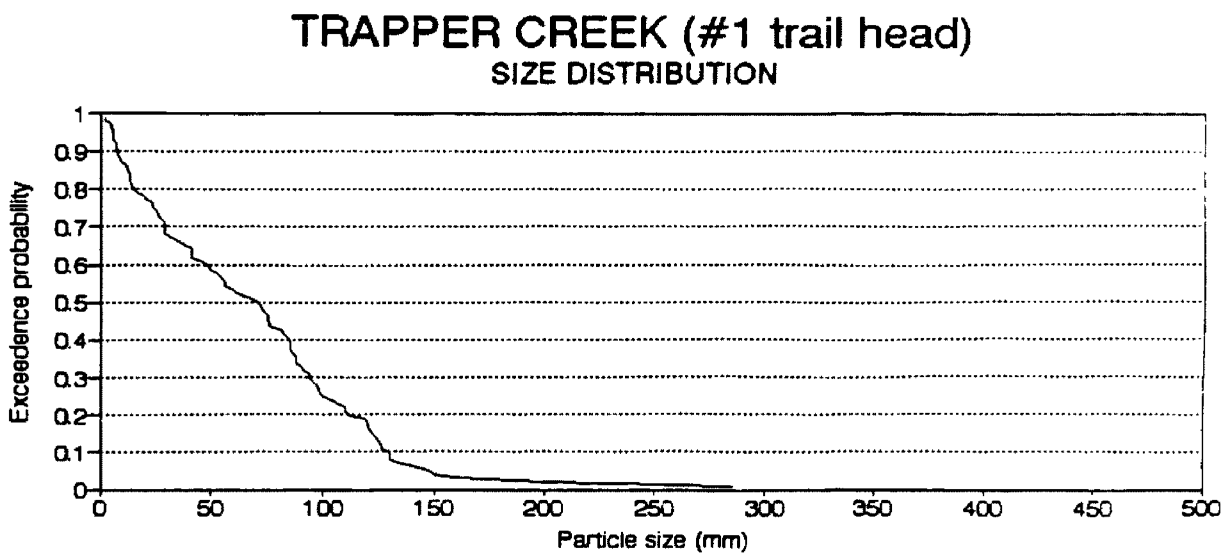

NORTH FORK #2
SIZE DISTRIBUTION
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 50 100 150 200 250 300 350 400 450 500
Particle size (mm)

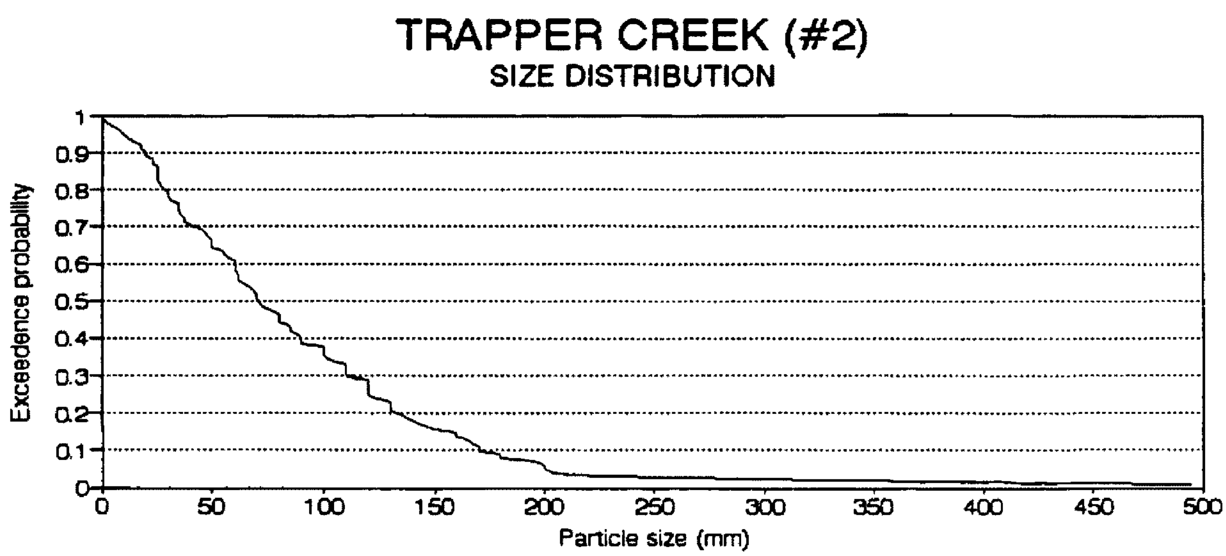

NORTH FORK #5
SIZE DISTRIBUTION
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 50 100 150 200 250 300 350 400 450 500
Particle size (mm)

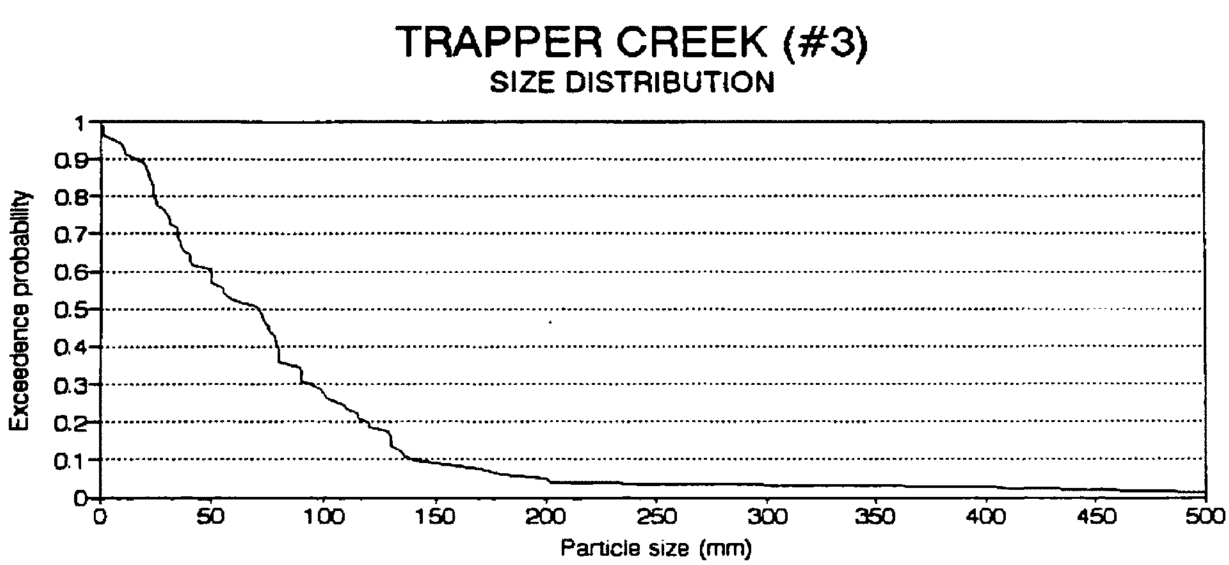

NORTH FORK #6
SIZE DISTRIBUTION
exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


MOOSE CREEK #4
SIZE DISTRIBUTION
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)

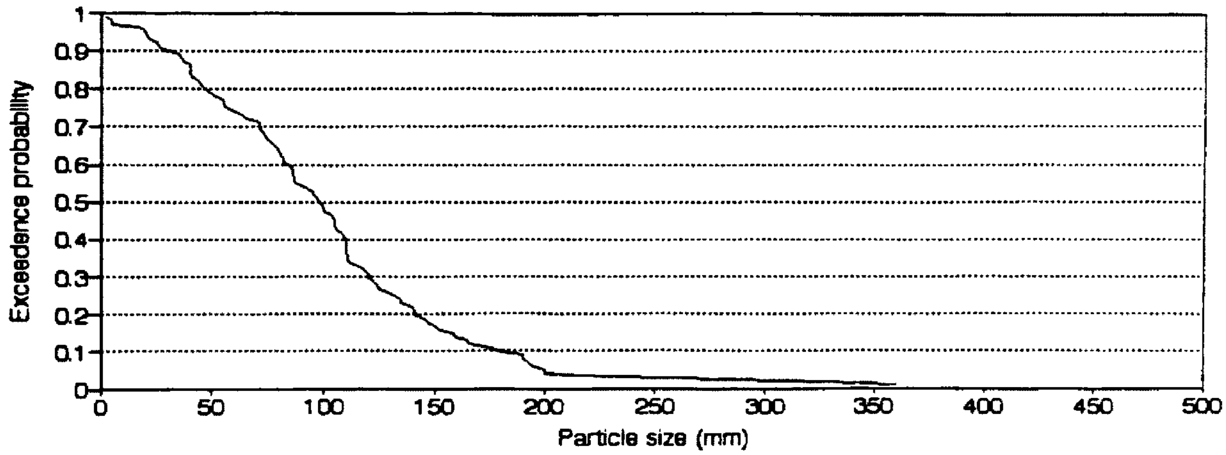

TRAPPER CREEK (#4)
SIZE DISTRIBUTION
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


TRAPPER CREEK (#1 trail head)
SIZE DISTRIBUTION
Exceedence probability
Particle size (mm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
50
100
150
200
250
300
350
400
450
500

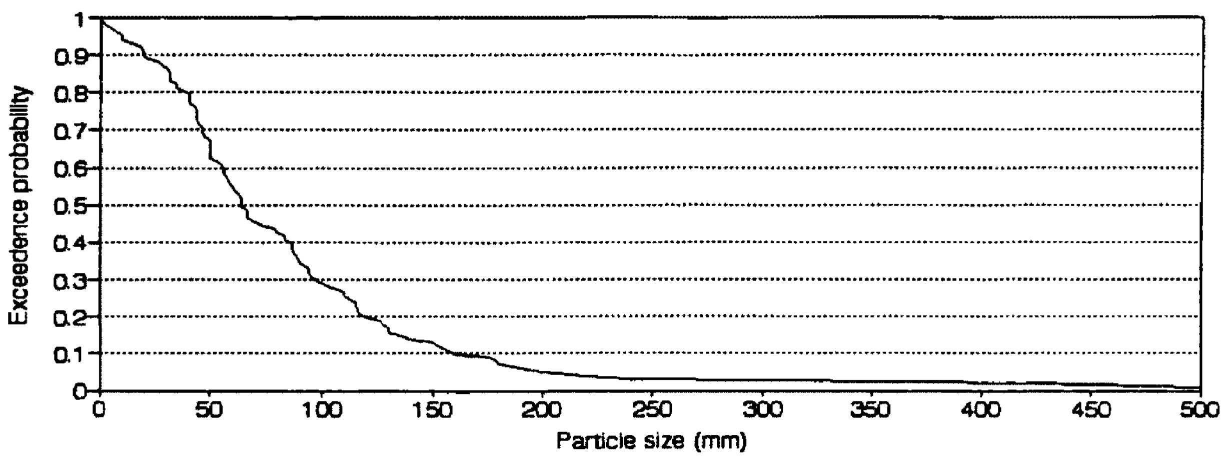

TRAPPER CREEK (#2)
SIZE DISTRIBUTION
Exceedence probability
Particle size (mm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
50
100
150
200
250
300
350
400
450
500


TRAPPER CREEK (#3)
SIZE DISTRIBUTION
Exceedence probability
Particle size (mm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
50
100
150
200
250
300
350
400
450
500

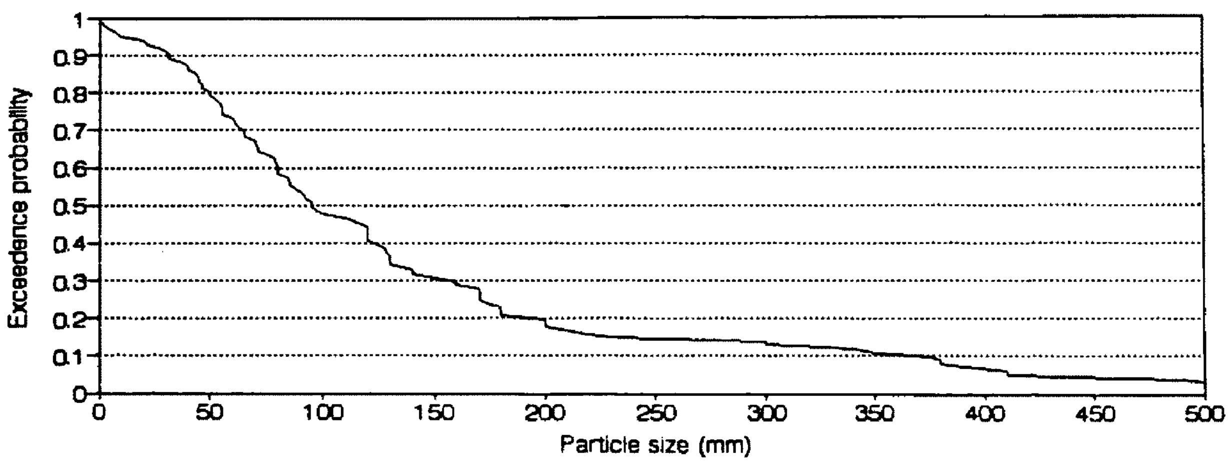
EAST FORK LOLO CR (#1)
SIZE DISTRIBUTION



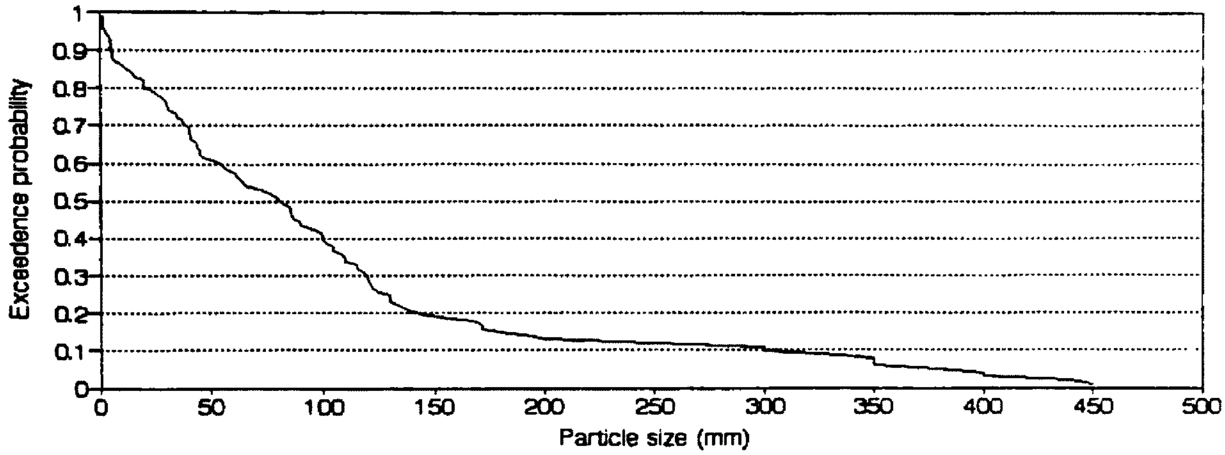
EAST FORK LOLO CR (#2)
SIZE DISTRIBUTION



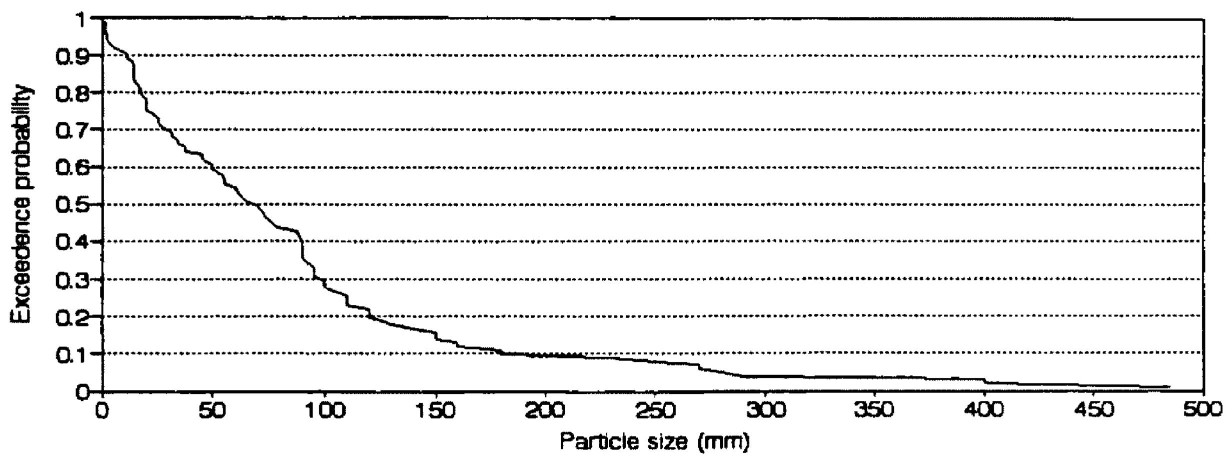
EAST FORK LOLO CR (#3)
SIZE DISTRIBUTION



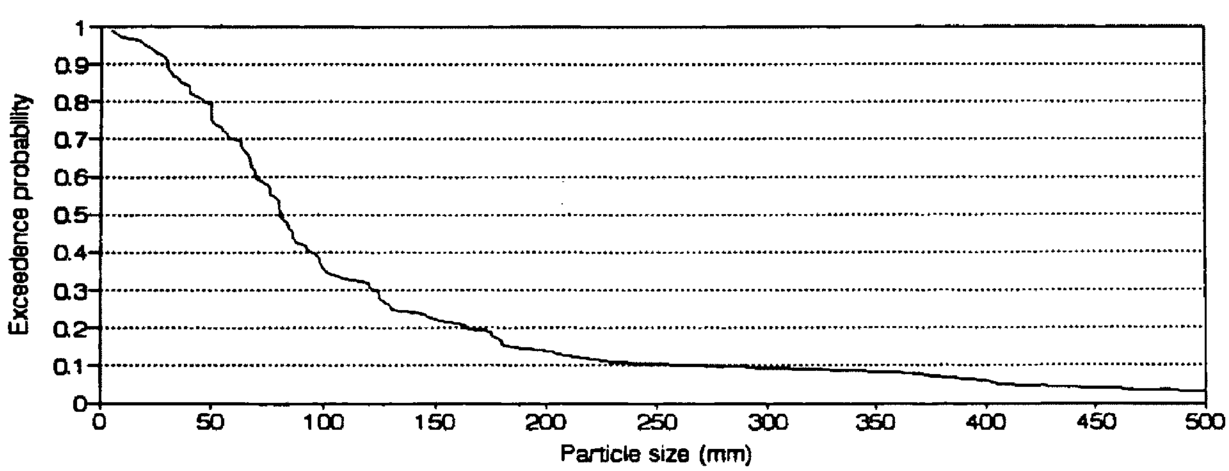
EAST FORK LOLO CR (#4)
SIZE DISTRIBUTION

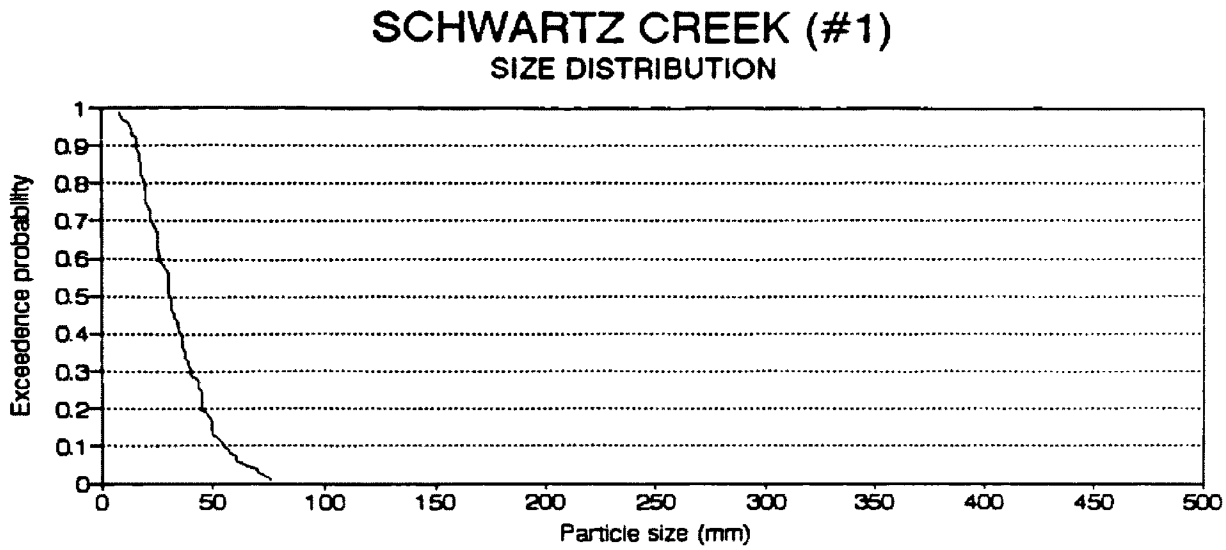


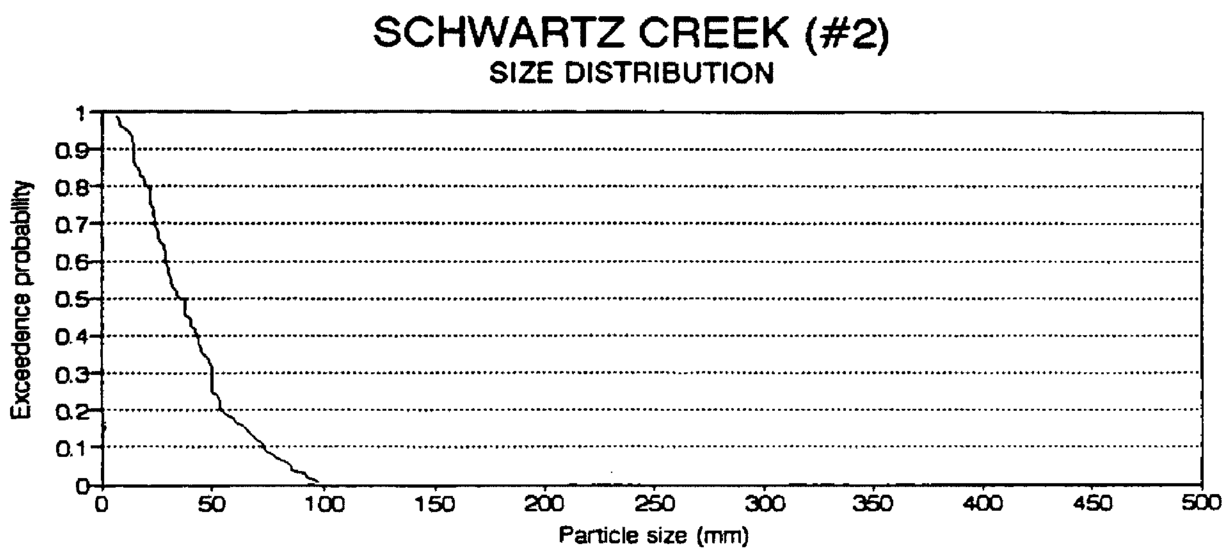
EAST FORK LOLO CR (#5)
SIZE DISTRIBUTION

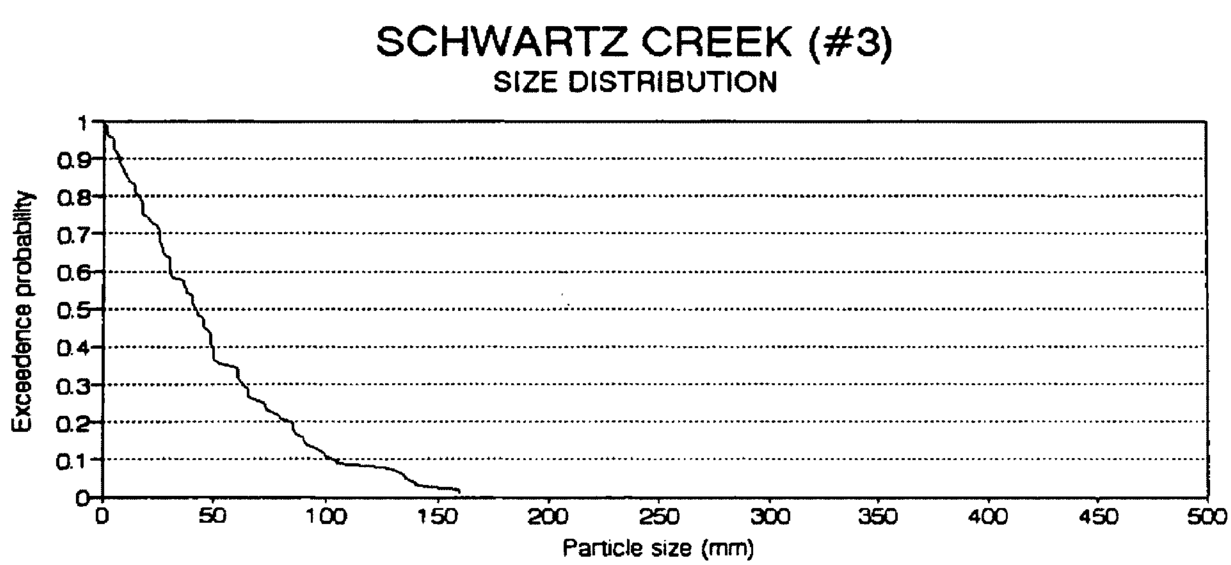


EAST FORK LOLO CR (#6)
SIZE DISTRIBUTION




SCHWARTZ CREEK (#1)
SIZE DISTRIBUTION
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


SCHWARTZ CREEK (#2)
SIZE DISTRIBUTION
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


SCHWARTZ CREEK (#3)
SIZE DISTRIBUTION
Exceedence probability
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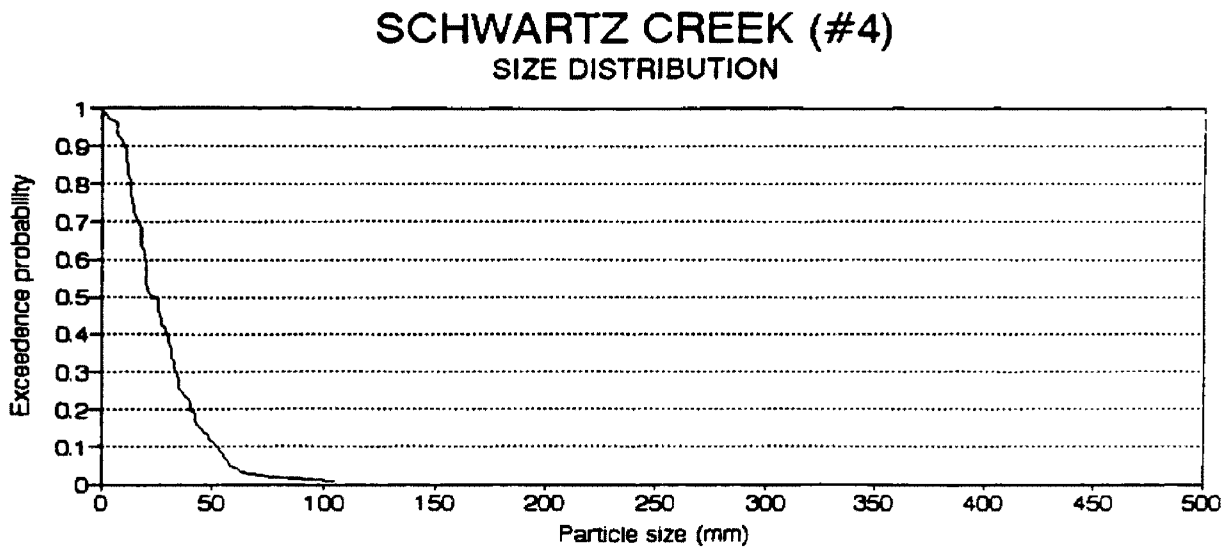
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


SCHWARTZ CREEK (#4)
SIZE DISTRIBUTION
Exceedence probability
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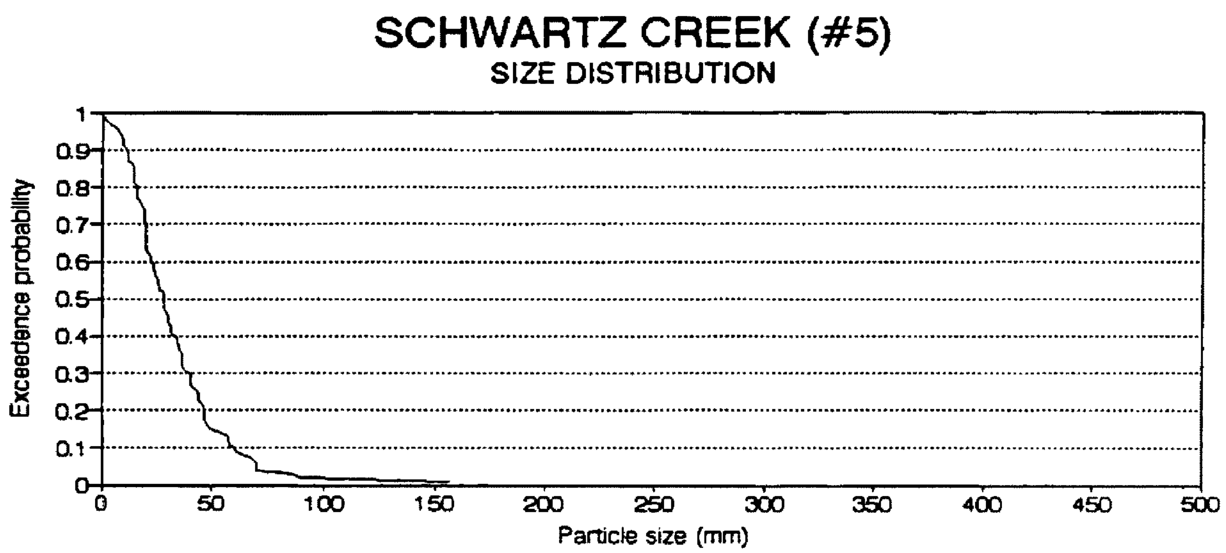
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


SCHWARTZ CREEK (#5)
SIZE DISTRIBUTION
Exceedence probability
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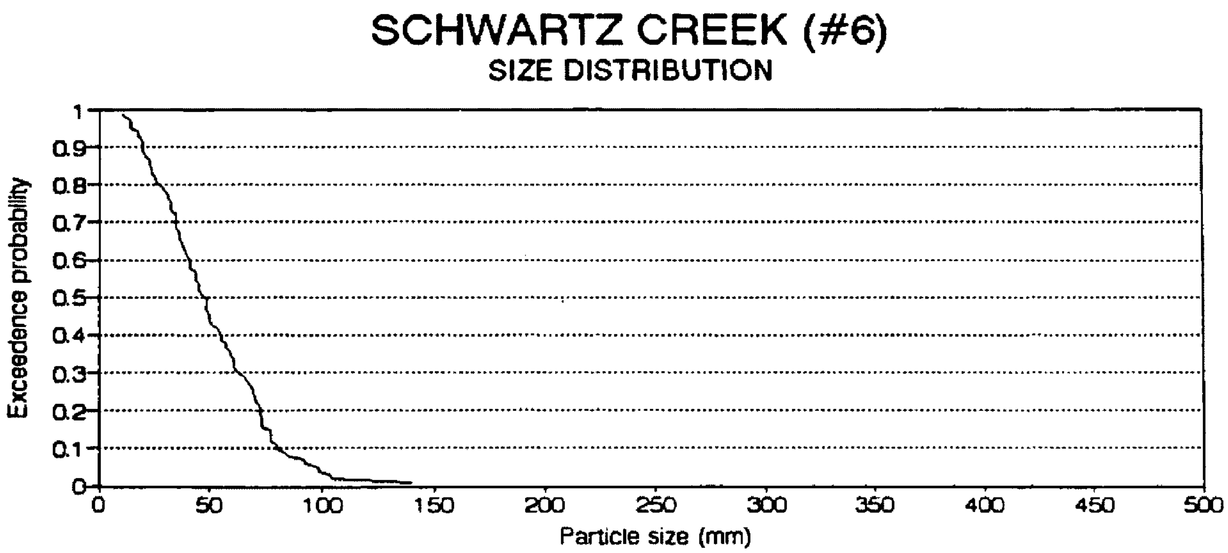
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


SCHWARTZ CREEK (#6)
SIZE DISTRIBUTION
Exceedence probability
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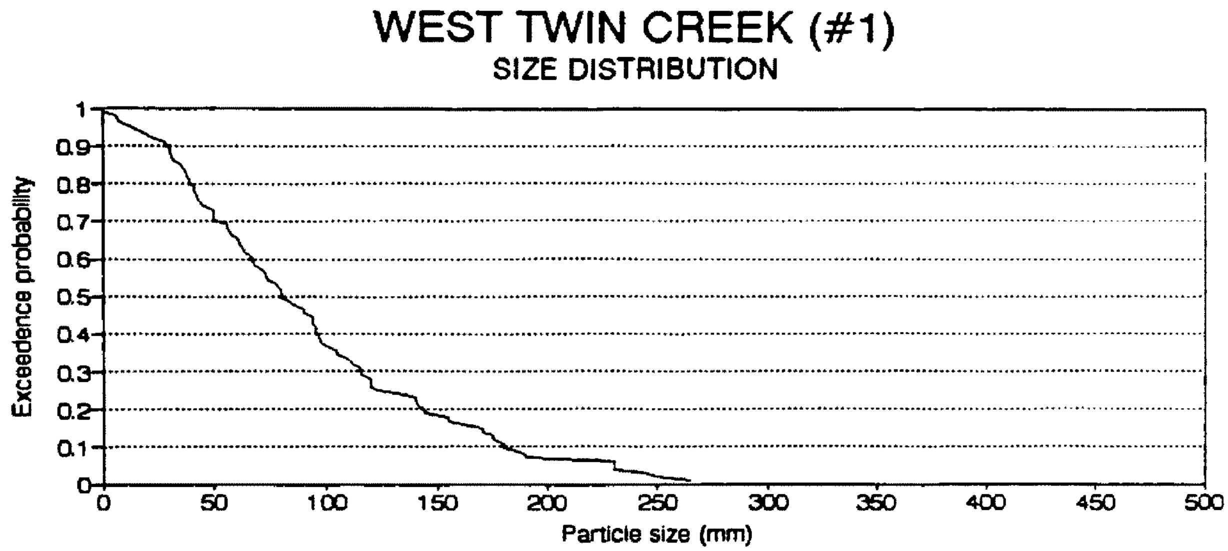
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


WEST TWIN CREEK (#1)
SIZE DISTRIBUTION
Exceedence probability
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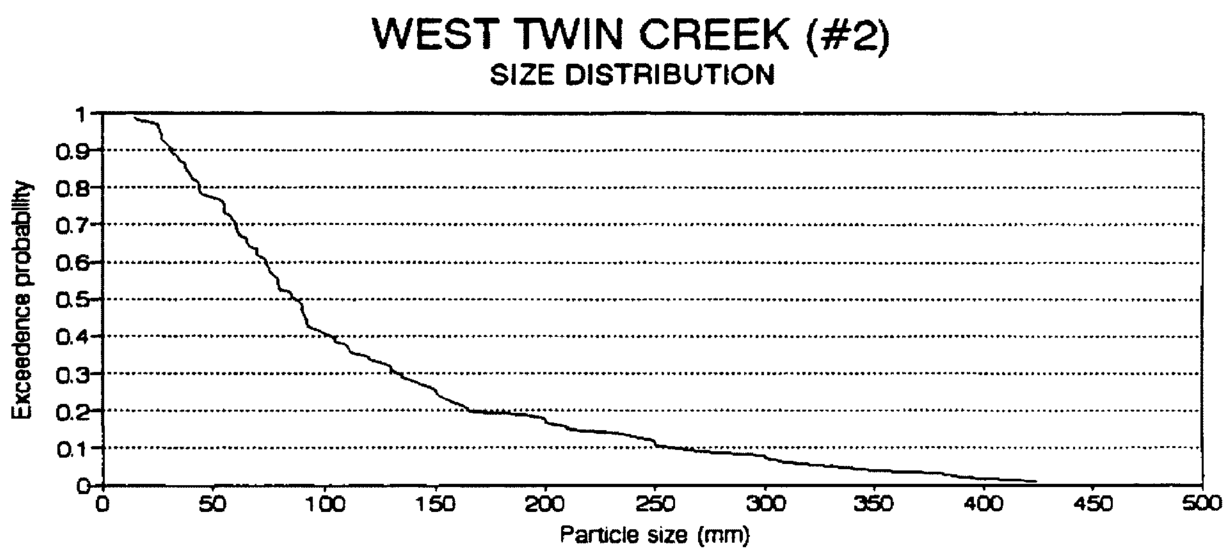
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


WEST TWIN CREEK (#2)
SIZE DISTRIBUTION
Exceedence probability
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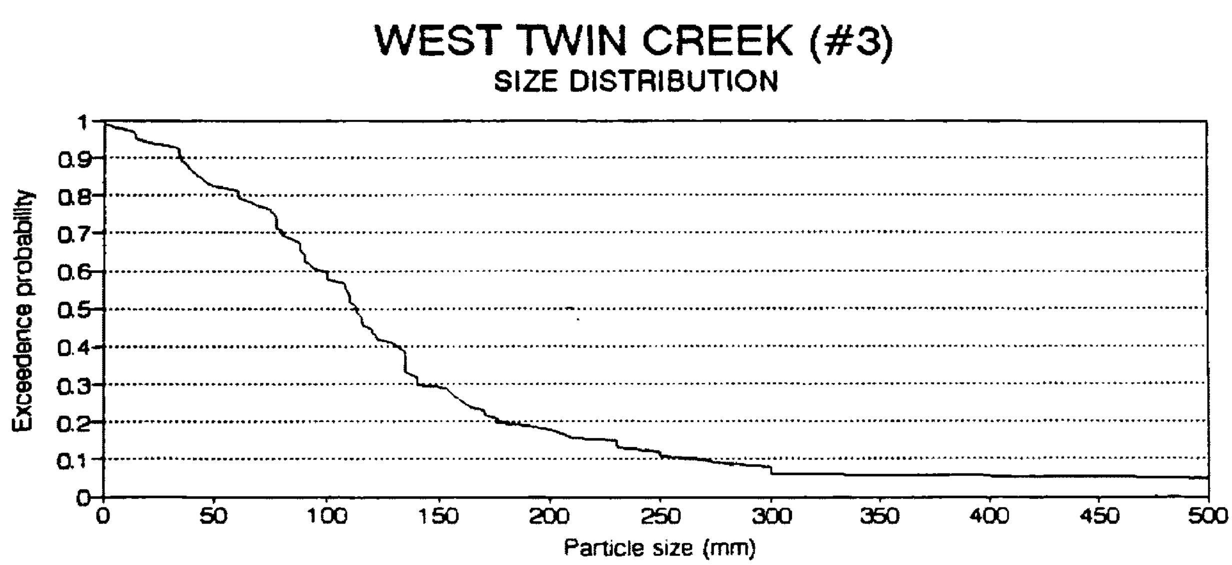
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


WEST TWIN CREEK (#3)
SIZE DISTRIBUTION
Exceedence probability
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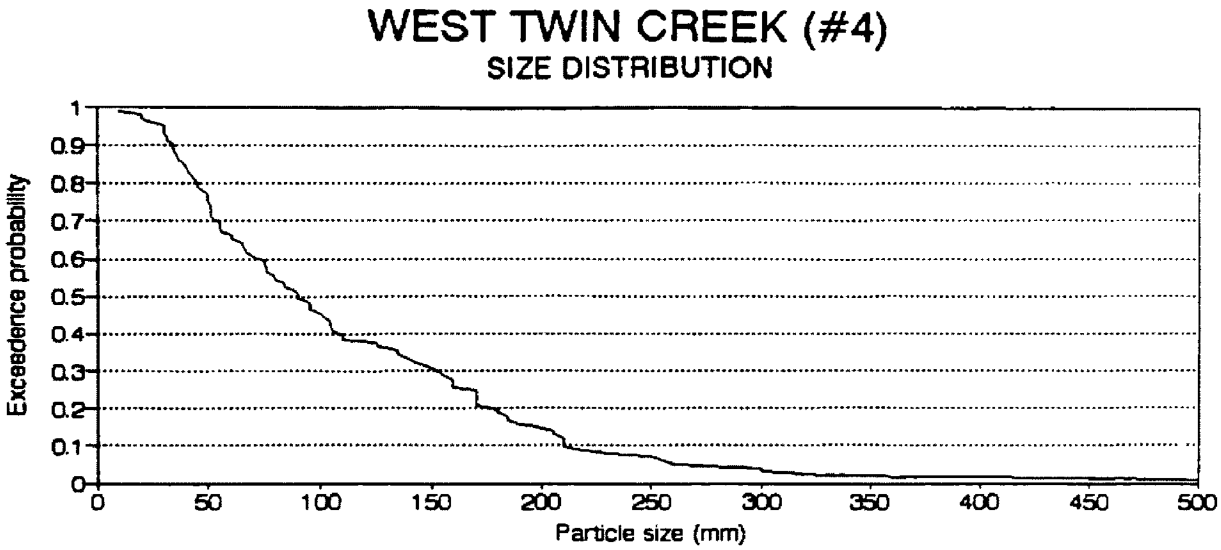
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


WEST TWIN CREEK (#4)
SIZE DISTRIBUTION
Exceedence probability
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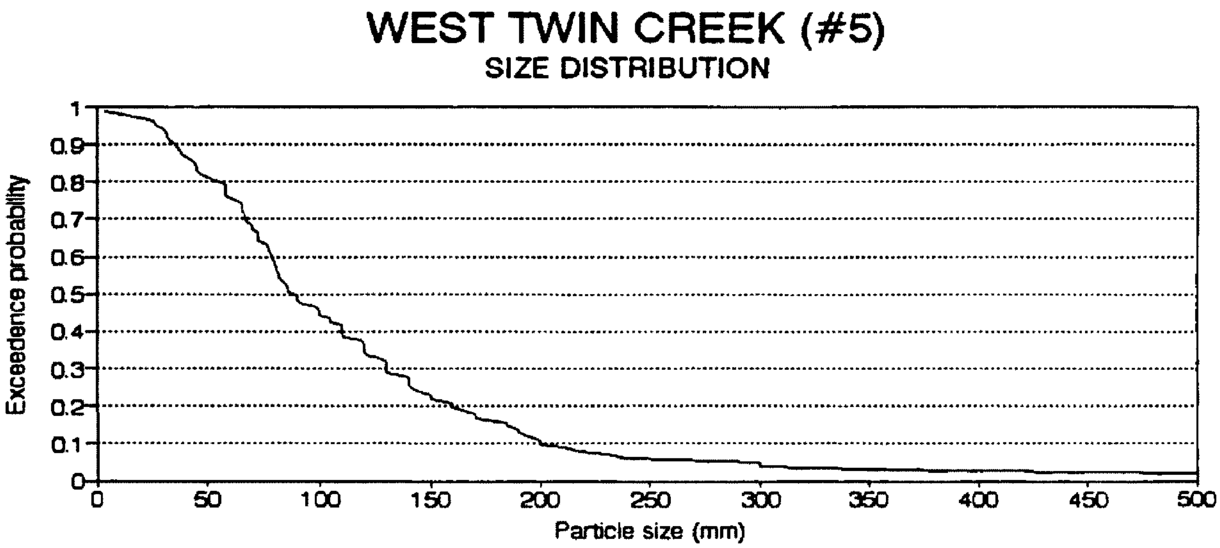
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


WEST TWIN CREEK (#5)
SIZE DISTRIBUTION
Exceedence probability
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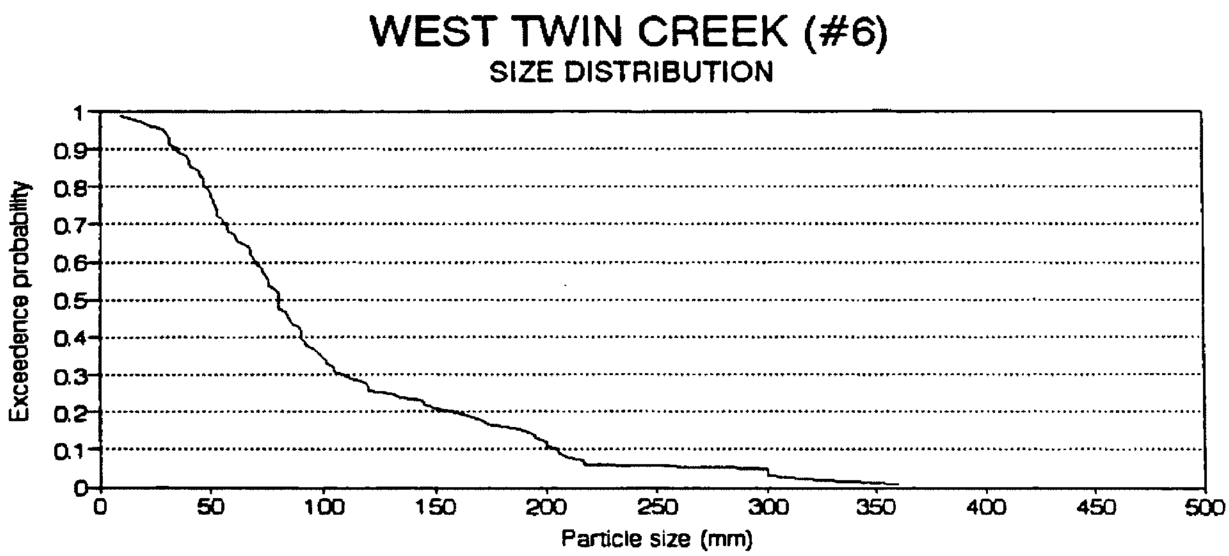
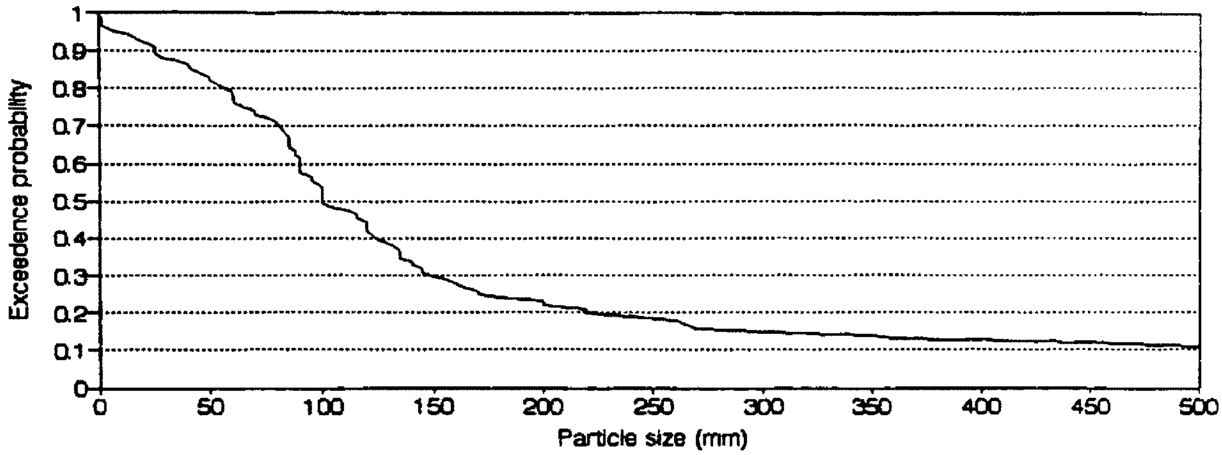
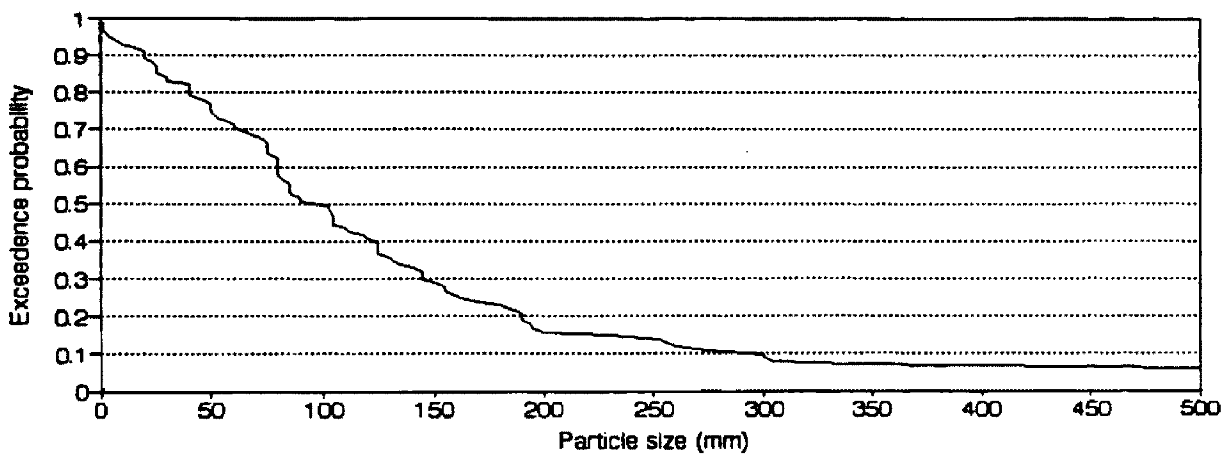
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


WEST TWIN CREEK (#6)
SIZE DISTRIBUTION
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)

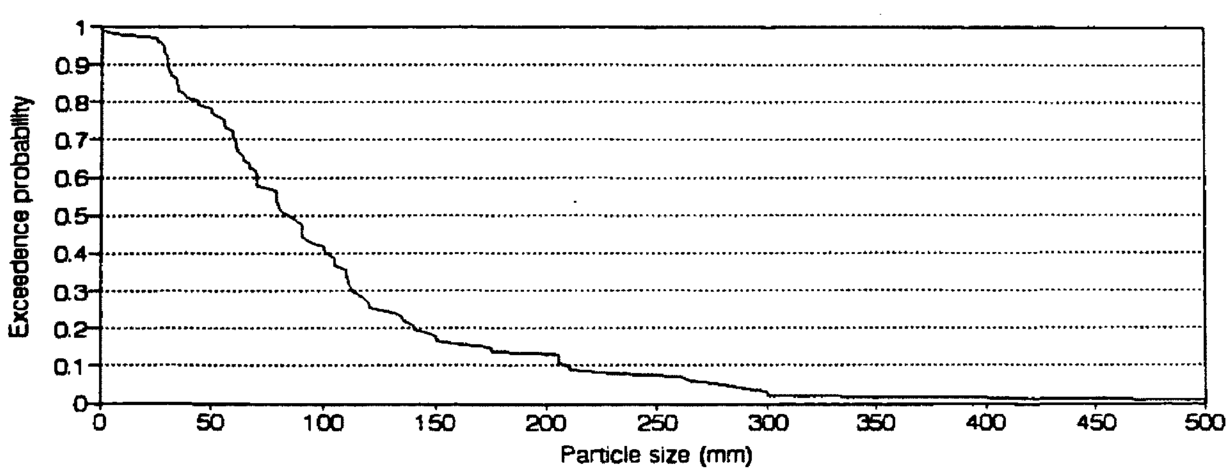
LOST PARK CREEK (#1)
SIZE DISTRIBUTION

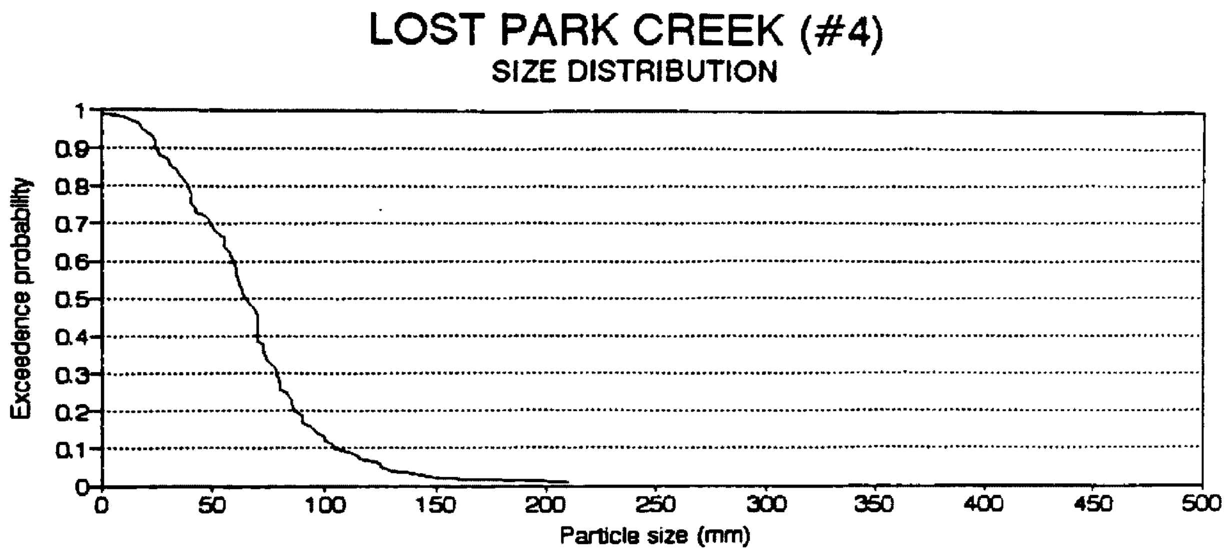


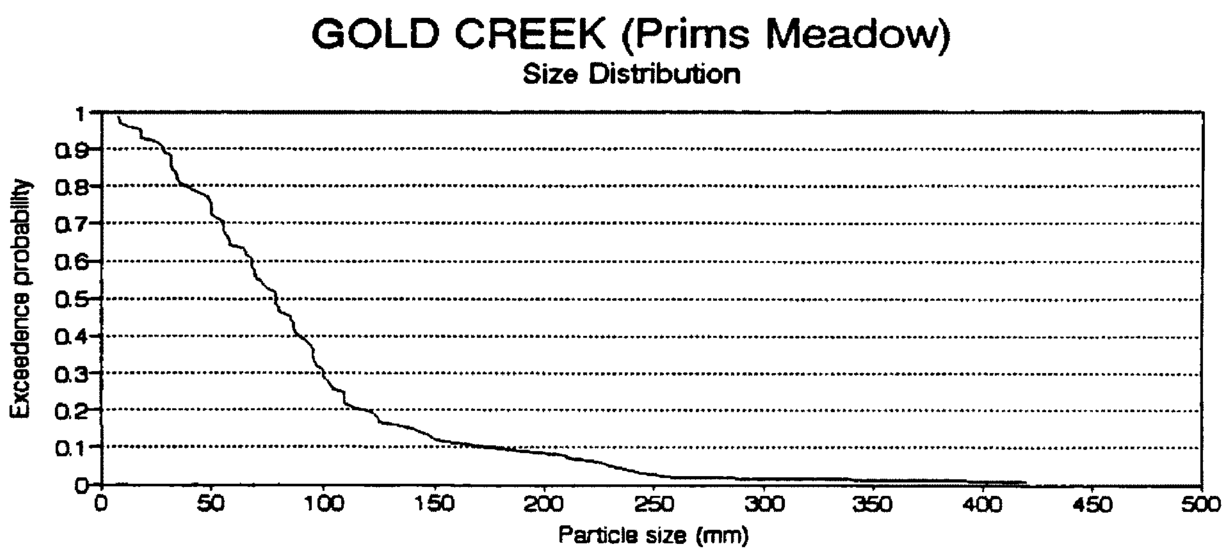
LOST PARK CREEK (#2)
SIZE DISTRIBUTION

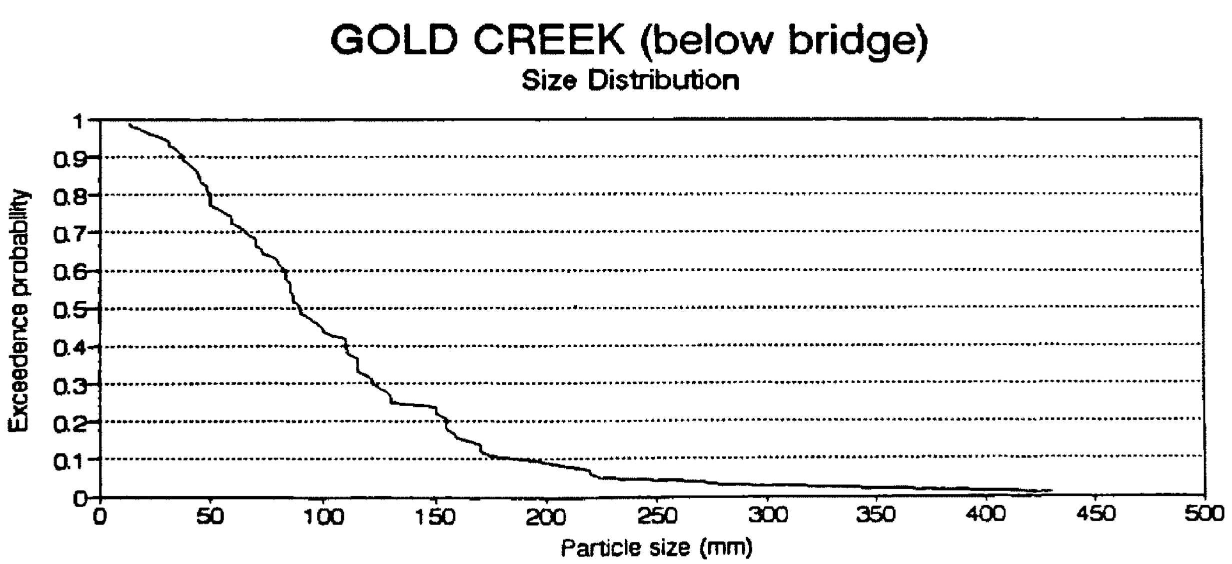


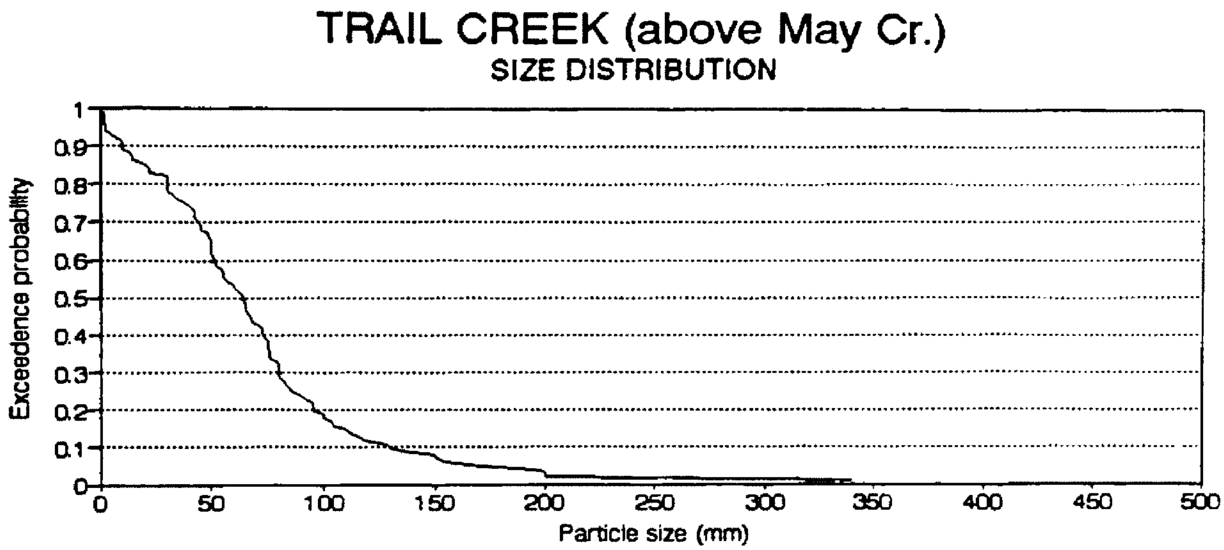
LOST PARK CREEK (#3)
SIZE DISTRIBUTION

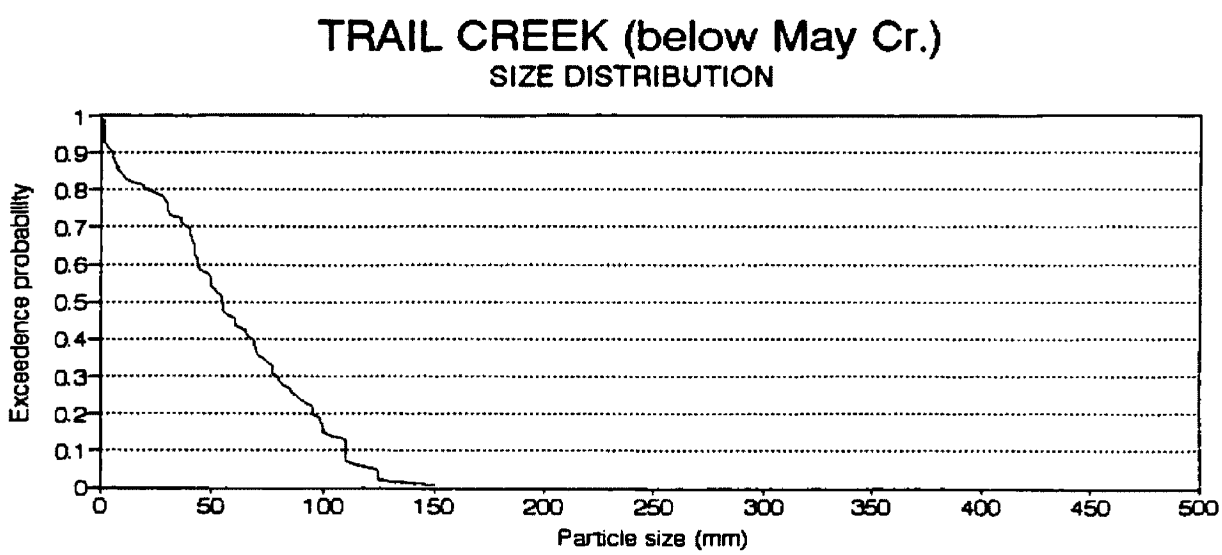


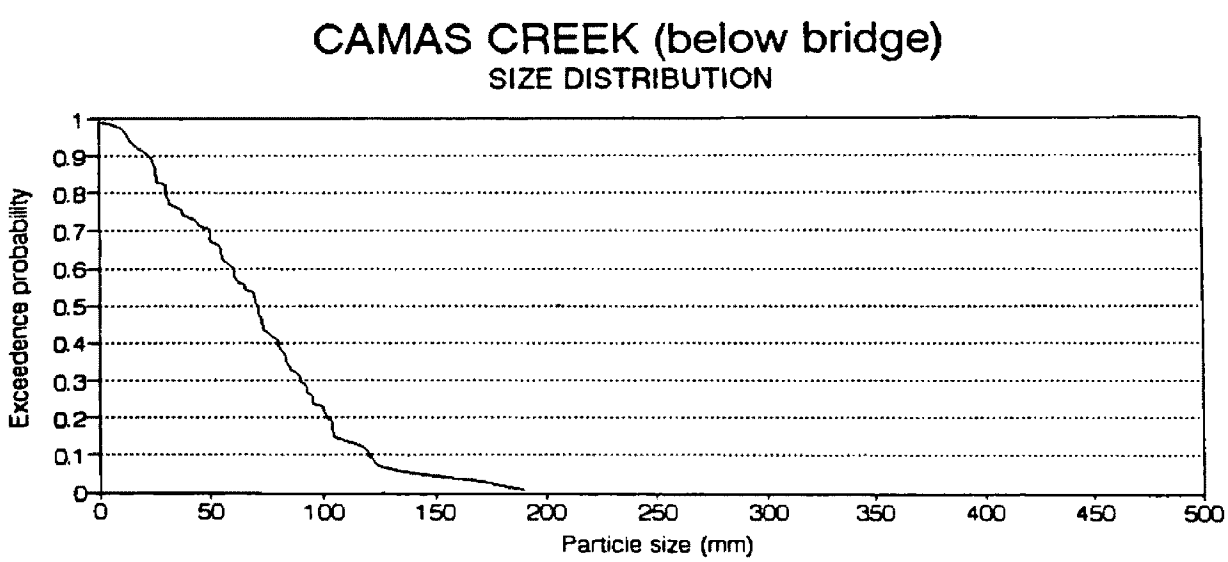

LOST PARK CREEK (#4)
SIZE DISTRIBUTION
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


GOLD CREEK (Prims Meadow)
Size Distribution
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


GOLD CREEK (below bridge)
Size Distribution
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


TRAIL CREEK (above May Cr.)
SIZE DISTRIBUTION
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


TRAIL CREEK (below May Cr.)
SIZE DISTRIBUTION
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)


CAMAS CREEK (below bridge)
SIZE DISTRIBUTION
Exceedence probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Particle size (mm)

Appendix 4.
Estimated peak discharge for all study reaches with two through one-hundred year return periods using both channel geometry and watershed characteristics using the multi-regression formula of (Omang et al. 1986).

STREAM NAME	STUDY REACH NUMBER	TWO YEAR	FIVE YEAR	TEN YEAR	TWENTY FIVE YEAR	FIFTY YEAR	ONE HUNDRED YEAR
BUCK	1	20.2	35.6	49.9	66.4	81.5	96.1
	2	24.1	41.9	58.6	77.6	95.1	111.9
	3	12.5	22.6	32.1	43.3	53.8	63.8
ARKANSAS							
	1	6.1	12.0	17.8	25.0	31.7	38.3
	2	13.0	24.4	35.4	48.6	60.5	72.4
	3	14.0	26.3	37.9	51.9	64.5	77.1
HOWARD	1	18.1	31.8	44.1	58.2	70.2	82.2
	2	34.7	58.6	79.9	103.4	123.3	143.3
	3	44.9	74.8	101.4	130.3	155.0	179.6
	4	56.8	93.2	125.6	160.3	189.7	219.1
	5	73.0	117.9	157.6	199.3	234.1	269.4
CAMP	top	25.1	44.0	61.4	81.3	98.9	116.3
	EF	37.4	64.1	88.4	115.5	139.1	162.7
	WF	29.8	51.7	71.7	94.2	113.8	133.3
	bottom	53.7	89.9	123.1	159.1	190.7	222.0
NF SALMON							
	1	208.1	319.9	419.9	517.3	597.3	681.1
	2	152.5	239.0	315.8	392.5	455.2	520.7
	3	72.3	118.8	160.9	205.6	243.7	282.3
	4	17.7	31.7	44.6	59.8	73.2	86.5
	5	36.8	63.1	87.5	114.7	139.2	163.2
	6	31.3	54.2	75.5	99.4	120.9	142.0
WEST TWIN							
	1	30.7	53.2	74.0	97.5	118.7	139.5
	2	30.5	53.0	73.9	97.4	118.6	139.4
	3	22.6	40.0	56.2	74.8	91.3	107.7
	4	25.2	44.4	62.3	82.8	101.0	119.1
	5	27.4	48.2	67.6	89.7	109.4	128.9
	6	27.6	48.6	67.8	89.6	108.6	127.6

Appendix 4. Continued

SCHWARTZ							
	1	4.6	9.2	13.6	19.3	24.5	29.6
	2	7.9	15.2	22.2	30.9	38.9	46.8
	3	6.2	12.2	17.9	25.1	31.6	38.1
	4	6.9	13.4	19.4	26.9	33.4	40.0
	5	19.7	36.0	50.8	68.2	83.1	98.3
	6	21.2	38.5	54.3	72.7	88.3	104.4
TRAPPER							
	1	388.1	541.4	684.1	809.7	923.4	1033.0
	2	422.4	586.2	739.3	872.8	994.1	1111.1
	3	443.8	614.0	773.7	912.2	1038.6	1160.3
	4	469.1	646.7	812.6	955.5	1084.5	1209.9
LOST PARK							
	1	104.8	157.7	205.2	252.4	294.7	334.6
	2	82.6	126.6	165.8	205.5	240.6	274.0
	3	124.3	186.2	242.3	297.3	347.0	394.0
	4	117.7	177.2	231.2	284.5	332.4	377.9
EF LOLO							
	1	75.0	114.6	151.3	188.5	224.1	256.3
	2	74.1	113.2	149.4	186.2	221.1	252.8
	3	127.0	189.3	246.7	302.7	354.6	402.9
	4	92.9	141.1	183.7	226.4	263.5	299.2
	5	108.1	163.7	213.1	262.1	304.9	346.3
	6	100.0	152.0	198.0	244.0	283.9	322.5
GOLD							
	Prim	109.0	173.3	231.9	292.0	344.3	396.4
	brid	98.4	157.4	210.2	264.7	310.6	357.3
TRAIL							
	low	354.9	527.8	682.7	826.7	943.5	1068.0
	upper	174.7	271.5	357.7	443.0	512.8	585.8
CAMAS							
	1	79.0	123.4	164.3	206.4	245.3	281.8

* All calculations are in cubic feet per second.