Flushing Flow Requirements of Mountain Stream Channels

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FLUSHING FLOW REQUIREMENTS OF

MOUNTAIN STREAM CHANNELS

ABSTRACT

Maintenance of instream fisheries habitat downstream of water development projects has long been recognized as environmentally desirable. More recently, concern has focused on the need for and the determination of flushing or channel maintenance flow releases. These high magnitude, short duration streamflow releases may mimic the natural runoff hydrograph and maintain channel conveyance capacity and spawning and rearing habitats for fish. Increasing interest in transbasin water diversion in the Central Rocky Mountain Region has focused attention on the flushing flow requirements of steep, rough mountain channels. My objectives were to describe the historic response of such channel types to flow depletion, evaluate sediment dynamics within discrete habitat types, and develop criteria for flushing flow determination.

A comparison of hydraulic geometry and channel morphology above and below diversion structures on different channel types indicated that low gradient (< 1.5 percent) reaches responded to flow depletion by significantly reducing their depth, area and conveyance capacity. Regression equations were developed to estimate these responses. Steeper gradient reaches (> 1.5 percent) maintained channel dimensions over extended time periods and are not as critical from the standpoint of flushing flow.

Investigations of bed material and sediment transport characteristics at nine study reaches on four mountain streams indicated very low gradient pools (< 0.30 percent) are the critical habitat type for flushing flow studies. Within these habitats, analysis of bedload transport relations indicated that a threshold of flushing is reached at flows of about 12 times the average annual discharge, above which net pool scour occurs. Flushing flows should

exceed this threshold for a duration dependent on the transport differential entering and exiting the pools during intermediate and low flow events. A multiple regression model incorporating stream power, channel shape, bed material characteristics, and basin erodibility was developed to aid in predicting this bedload transport differential. To maintain spawning gravel recruitment through these steep, rough channels, a flow event in the range of the peak flood having a five-year recurrence interval appears to be required.

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NOMENCLATURE

C_s	=	suspended sediment concentration (mg/l)
D	=	mean water depth (ft)
DD	=	drainage density (miles/miles^2)
Dd	=	deposition depth (mm)
d	=	bankfull channel depth (ft)
d_a	=	bankfull channel depth under altered conditions (ft)
d_m	=	mean diameter of sediment (ft, mm)
d_p	=	bankfull channel depth under present conditions (ft)
d_s	=	sediment particle diameter (ft, mm)
d_{16}	=	particle size for which 16 percent by weight is finer (ft, mm)
d_{50}	=	particle size for which 50 percent by weight is finer (ft, mm)
d_{84}	=	particle size for which 84 percent by weight is finer (ft, mm)
d_{90}	=	particle size for which 90 percent by weight is finer (ft, mm)
G	=	gradation coefficient of bed material
g	=	gravitational constant (32.2 ft/s^2)
Ho	=	null hypothesis
K	=	dimensionless shear stress or Shield's parameter
K_T	=	total flow resistance of channel
K_s	=	that portion of flow resistance contributed by bed particles
L	=	meander wavelength (ft)
p	=	sinuosity (ft/ft)
Q_a	=	the Q_{P2} under altered flow conditions (ft^3/s)
Q_{AA}	=	average annual discharge (ft^3/s)
Q_b	=	water discharge determining the bedload transport rate (ft^3/s)
Q_{BL}	=	bedload transport rate (tons/day)

NOMENCLATURE (CONTINUED)

Q_p	=	the Q_{P2} under present conditions (ft^3/s)
Q_{P2}	=	peak water discharge having a two-year recurrence interval (ft^3/s)
Q_{SL}	=	suspended sediment load discharge (tons/day)
Q_w	=	water discharge (ft, mm)
q_{bl}	=	unit bedload discharge (lbs/ft/day)
q^*	=	dimensionless volumetric bedload discharge
R	=	hydraulic radius (ft)
R'	=	submerged specific gravity of sediment
S	=	slope (ft/ft)
T	=	transportability index (Dd/d50)
V	=	mean water velocity (ft/s)
v	=	water velocity (ft/s)
W	=	wetted top width (ft)
W/D	=	ratio of wetted top width to mean water depth (ft/ft)
w	=	bankfull channel width (ft)
γ_s	=	specific weight of sediment (lbs/ft^3)
γ_w	=	specific weight of water (lbs/ft^3)
ρ	=	fluid density ($lb\text{-}s^2/ft^4$)
τ_c	=	critical shear at incipient motion (lbs/ft^2)
τ_o	=	shear stress acting on channel boundary (lbs/ft^2)
τ^*	=	dimensionless shear stress

CHAPTER ONE

INTRODUCTION

The maintenance of suitable instream habitat downstream of water development projects in the western United States is recognized as environmentally desirable (Wesche and Rechard, 1980). While "minimum" flow releases for fisheries are becoming more commonplace (Reiser et al, 1989), one topic being actively debated by water development interests and resource management agencies is the determination of channel maintenance or flushing flow requirements (Reiser et al, 1987). Such instream flows may mimic the natural spring snowmelt runoff hydrograph in the Central Rocky Mountain region, maintain conveyance capacity of stream channels by reducing aggradation and riparian encroachment (Rosgen et al, 1986), and preserve spawning, incubation and rearing habitats for fish populations.

Given the quantities of project water typically requested for channel maintenance purposes, two basic questions have been raised. First, do different channel types physically respond to streamflow depletion at similar rates? If they respond differently, the magnitude and duration of flushing flow requirements may vary by channel type. Such information would aid in the identification of critical reaches for future channel maintenance flow studies. Second, can hydrologic thresholds be identified for different channel and habitat types which provide guidance for the determination of flushing flow regimes? From a management perspective the study of fluvial processes is inherently time and cost intensive and such thresholds could serve as criteria for the establishment of maintenance flows, thereby reducing the need for more detailed investigations.

To address the two questions stated above, the goals of this research have been to: 1) determine the need for flushing flow releases on relatively steep, rough mountain stream channels;

and, 2) develop criteria upon which a methodology can be based for determining the proper magnitude and duration of such releases. The need for this research has been magnified by the State of Wyoming's plan for large scale water development of mountain watersheds by transbasin diversion. To achieve these goals, specific objectives have been to:

1. Evaluate the need for flushing flow releases by stream channel type by describing and comparing the physical response of mountain stream channels in the Central Rocky Mountain region to flow depletion;
2. Evaluate relative transport capabilities through discrete habitat types and provide insight regarding maintenance flow requirements by describing sediment transport and storage processes, both temporally and spatially, through steep, rough mountain channels under conditions of limited to abundant sediment supplies;
3. Develop a bedload transport model, based upon an extensive field sampling program, applicable to the determination of flushing flow regimes for mountain stream channels.

In the chapters which follow, the subheading "Stream Channel Response" refers to research activities and results related to Objective 1. Likewise, the subheading "Sediment Dynamics" will refer to research pertaining to Objectives 2 and 3.

CHAPTER TWO

GOVERNING PRINCIPLES AND RELATED RESEARCH

The investigation of flushing flow requirements for mountain stream channels is an interdisciplinary exercise. A synthesis of knowledge in the physical and biological sciences is required to approach the problem. Disciplines involved include not only hydrology, hydraulics and sedimentology, but also geomorphology, fisheries biology and botany. Given the breadth of these disciplines, this review will focus on the specific research objectives. For a more thorough discussion of the broader topics and a review of current methods used for flushing flow determination, the reader is directed to Reiser, Ramey, and Wesche (1989).

Stream Channel Response

Climate, geology, soils, land use and vegetation combine to determine the hydrologic and sediment regimes of rivers (Morisawa and Laflure, 1979). Correspondingly, the nature and quantity of the sediment and water conveyed largely determine the morphology of stable alluvial channels (Schumm, 1977). As river channels adjust to prevailing rates of water and sediment transport over time, an equilibrium condition can be reached between available energy and sediment load under the specific environmental conditions of a watershed. This state of equilibrium, however, does not imply a static condition. Rivers are constantly adjusting to seasonal and annual variations in water discharge and sediment load. Such adjustments are not always continuous but can occur in a complex manner after a threshold is reached (Schumm, 1977). While long-term changes in climate, geology, soils and vegetation will ultimately affect channel dimensions, perturbations such as floods or alterations in land use can accelerate the adjustment process (Patrick et al, 1981).

The state of equilibrium in river channels has been defined variously as dynamic equilibrium, quasi-equilibrium, graded, regime, and steady state (Richards, 1982). All such equilibrium concepts imply a balance between a river's transport capacity and the sediment supplied to it. Quasi-equilibrium has been defined as follows (Andrews, 1986):

"Alluvial channels adjust over a period of years, so that the sediment supplied to the channel is transported with the available discharge. When there is no net accumulation or depletion of sediment in the bed, banks, or flood plain, the average hydraulic characteristics width, depth, velocity, roughness, slope, and channel pattern, through a reach of channel at a given discharge, will be nearly constant. Such river channels are in quasi-equilibrium."

Lane (1955) presented the following qualitative relationship to illustrate the principle of channel equilibrium:

$$q_{bl}\, d_m \sim Q_w\, S$$

where, q_{bl} is the unit bedload discharge; d_m is mean sediment size; Q_w is water discharge; and, S is slope of the channel bed. While Lane's relation is not dimensionally correct (the specific weight of water (lbs/ft^3) should be included on the right side of the proportionality), it does point out that a change in one variable in the proportionality requires an adjustment in one or more of the other variables to re-establish equilibrium. For example, if streamflow is decreased, the stream power (Q_wS) available for sediment transport is reduced. To maintain equilibrium and prevent aggradation, either channel slope must increase and/or sediment load and/or particle size must be reduced. This assumes the channel is alluvial and the system is energy limited.

Expanding upon Lane's relationship, Schumm (1969) developed the following proportionalities for Q_w and q_{bl} based on quantitative relations developed for stable alluvial rivers in semiarid and subhumid regions:

$$Q_w \sim \frac{w, d, L}{S}$$

and

$$q_{bl} \sim \frac{w, L, S}{d, p}$$

where, w is bankfull channel width; d is bankfull channel depth; L is meander wavelength; and, p is sinuosity.

Combining these relations, Schumm (1969) was able to qualitatively illustrate how an alluvial river may adjust to achieve a new equilibrium when streamflow and sediment load are altered from their previous levels.

The response of fluvial systems to various forms of river regulation has been documented by several researchers. Reduced channel capacity is a common adjustment to flow depletion. Williams (1978) documented the reduction in channel size of the North Platte and Platte Rivers in Nebraska in response to decreases in water discharge caused by dams and diversions. Average annual peak flow was reduced to 10 to 20 percent of pre-regulation conditions. As a result, channel width of the Platte near Grand Island decreased from 3400 to 870 ft from the late 1800's to 1962. Bray and Kellerhals (1979) reported reduced channel capacity in the Peace River, Canada resulting from an estimated 210,000 cfs reduction in spring flows. Also, because the tributary inflow of sediment has been unchanged, the mainstem is aggrading at major confluences. Gregory and Park (1976) documented a 54 percent reduction in channel capacity on the River Tone, England, below the Clatworthy Reservoir. This reduction persisted for 6.8 miles downstream to the point where the contributing watershed area was at least four times that of the area draining into the reservoir. Huang (1977) examined changes in channel geometry and capacity due to dams on seven alluvial rivers in Kansas. He concluded the streams below the dams tended to be narrower and deeper due to degradation and increased channel roughness. Channel capacity tended to increase at sections near the dams due to reduced sediment loads, and to decrease at sections below the degradation.

Our ability to predict change based on the degree of flow regime alteration is limited (Simons and Milhous, 1981). Several quantitative approaches have been developed to describe the geomorphic processes that form stream channels and to estimate the degree of morphologic adjustment that may occur due to a given streamflow alteration. These approaches can be grouped into four categories, including physical models, mathematical models, sediment mass balance, and hydraulic geometry and formative discharge relations (Platte River Hydrology Work Group, 1989). Each of these methods attempts to quantify interactions between channel shape, streamflow regime and sediment transport. While increasing attention is being given the first three approaches, this study has focused on the latter, hydraulic geometry and formative discharge.

Channel shaping occurs over a range of streamflows, the magnitude and duration of which are dependent on watershed factors and the temporal distribution of discharge. Channel dimensions are altered by erosion and deposition until the flow regime can be accommodated by the channel. The concept of formative discharge can be described as an index of these channel shaping flows and is typically represented by one of two quantifiable flow levels, the bankfull discharge or the effective discharge. Bankfull discharge is the flow at which water just begins to overtop the streambanks (Leopold et al, 1964). Wolman and Miller (1960) observed that the bankfull discharge for sand bed channels appeared to dominate the channel formation process, having a suitable combination of magnitude and frequency of occurrence to control channel dimensions. The 1.5-year return interval discharge calculated from the annual peak flow series has often been used as an estimator of bankfull discharge, although considerable variation has been observed due primarily to gradient and geology (Wolman and Leopold, 1957; Williams, 1978).

The concept of effective discharge was first developed by Wolman and Miller (1960) and further defined by Andrews (1980). While large flood events are characterized by high sediment transport rates, their low frequency of occurrence limits their role in total sediment transport over the long term. As shown in Figure 1, intermediate discharges having a greater frequency of occurrence carry the largest portion of the sediment load despite their lower transport rates. This modal sediment transporting discharge that represents the range of discharges which carry the largest part of the load is the effective discharge. Andrews (1980) studied gravel-cobble bed streams in Colorado and Wyoming and found that the computed effective discharges had recurrence intervals ranging from 1.18 to 3.26 years.

Hydraulic geometry can be defined as a set of empirical models, first devised by Leopold and Maddock (1953), which provides a quantitative description of stream behavior either at a particular cross-section, along a particular stream, or among similar streams (Knighton, 1977). Simple power functions are considered to be a suitable expression of the relations between dependent variables such as width (w), depth (d), and velocity (v), and discharge (Q). These equations take the form:

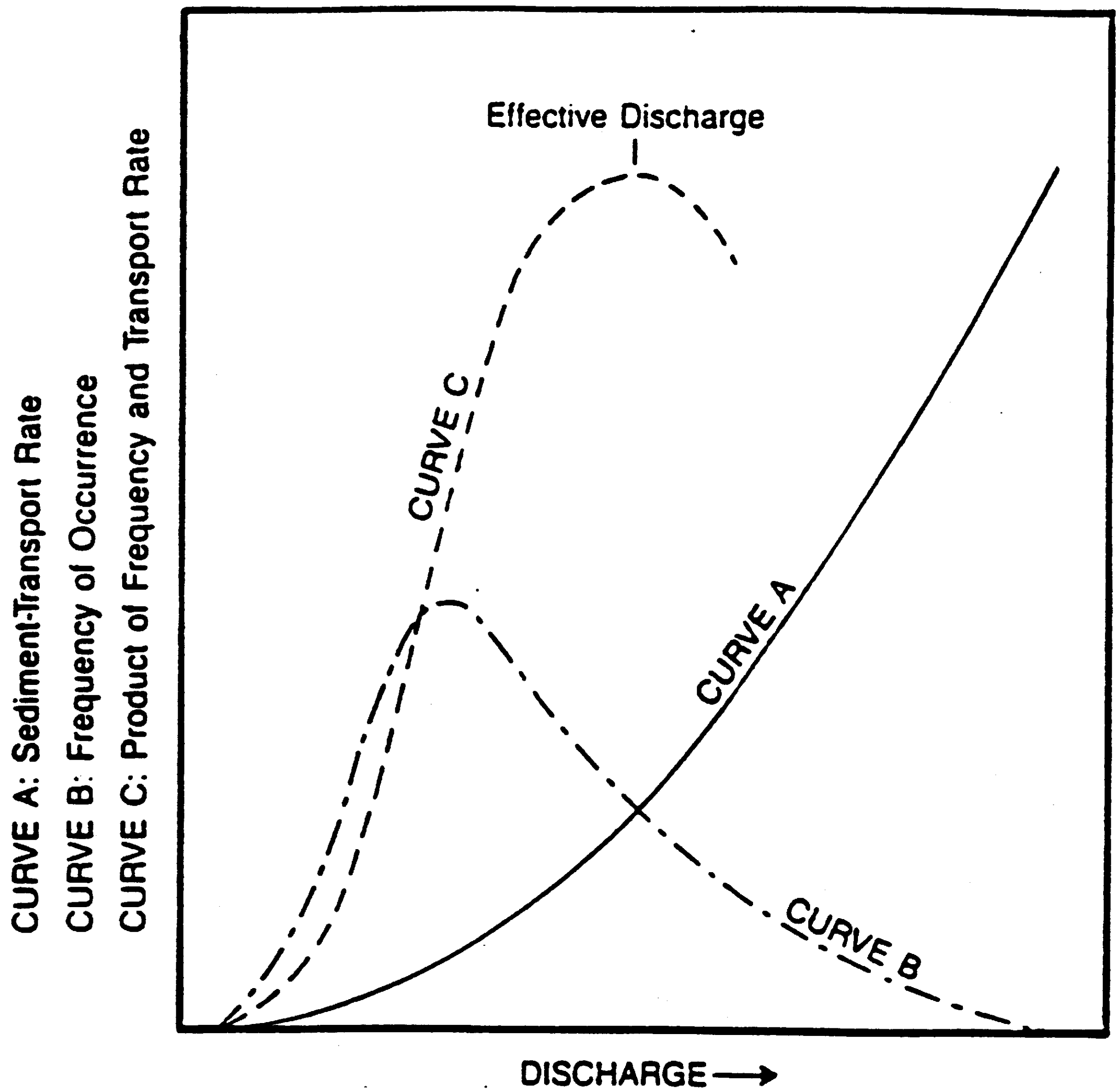


Figure 1. Definition of effective discharge. Relations between discharge and A) sediment transport rate; B) frequency of occurrence; and C) product of frequency and transport rate. (from Andrews, 1980; after Wolman and Miller, 1960).

$$w = aQ^b$$

$$d = cQ^f$$

$$v = kQ^m$$

As discharge is the product of width, depth, and velocity, from continuity it follows that the sum of the exponents and the product of the coefficients should equal 1.0.

Hydraulic geometry developed at a particular cross-section over a range of discharges is referred to as "at-a-station", while relations along a particular stream or between a group of streams are called "downstream" hydraulic geometry. For this latter type, the independent variable Q can be defined as the average annual discharge, bankfull discharge, the effective discharge, or some other estimate of formative discharge.

Hydraulic geometry has been developed for numerous alluvial streams worldwide. Park (1977) found considerable variation among exponents from streams of diverse climatic, physiographic and geologic environments, leading him to conclude equations of universal applicability were likely not feasible. Kellerhals (1982) suggested the best method to predict new channel dimensions following flow depletion was to investigate similar streams that experienced similar impacts. Likewise, Bovee (1982) proposed the use of hydraulic geometry relations developed from similar streams to evaluate potential channel adjustments resulting from river regulation. The research undertaken for this project is based upon these conclusions and suggestions, as well as the lack of such information in the literature regarding steep, rough mountain stream channels.

Sediment Dynamics

Two opposing forces interact to affect the motion of a sediment particle on a stream bed. These are the applied force resulting from the hydrodynamics of the flow (including the drag force in the direction of the flow and the lift force normal to the flow) and the resisting force associated with the submerged weight of the particle. If the applied forces exceed the resistance, the particle is entrained. At the threshold of motion, the applied and resisting forces are in balance.

The threshold of motion for sediment particles has been studied by numerous investigators since the 18th century. Research into threshold conditions has focused on two hydraulic properties of the streamflow, the critical mean velocity and the critical shear stress (tractive force). The critical velocity, often referred to as the permissible velocity, is defined as the maximum mean velocity of a channel that will not cause erosion of the channel boundary (Chang,1988). Fortier and Scobey (1926) published maximum permissible velocities for straight, low gradient canals having various boundary material compositions, while the ASCE Task Committee (1967) developed graphical relations summarizing these data as well as the work of Hjulstrom (1935). Lane (1955) presented correction factors which can be applied when water depths are less than 1.0 meter.

The critical shear stress approach has received more attention from researchers than the critical velocity approach. Shields (1936) was the first to quantitatively define the critical shear stress required for the entrainment of sediment particles. Under this approach, the hydrodynamic forces acting on a particle are equated with the force acting to keep the particle at rest. The controlling equation for the resisting force takes the form:

$$\tau_c = K(\gamma_s - \gamma_w)d_s$$

while the equation for the hydrodynamic forces is:

$$\tau_o = \gamma_w RS, \text{ where;}$$

τ_c = critical shear at incipient motion (lbs/ft^2)

τ_o = shear stress acting on channel bed (lbs/ft^2)

γ = specific weights of sediment (s) and water (w) (lbs/ft^3)

R = hydraulic radius of the stream cross-section (ft)

S = energy slope (ft/ft)

d_s = particle size (ft)

K = Shields' parameter or dimensionless shear stress.

The constant K in the above equation is the dimensionless shear stress at incipient motion and is commonly referred to as the Shields' parameter. This assumes that the inertial forces are large in relation to the viscous forces, such as encountered in natural streams having fully turbulent flow (high Reynolds numbers). K is not a constant for relatively high viscous forces (low Reynolds number). The often-used Shields diagram, as presented by Chang (1988), illustrates this variation of K. Shields (1936) reported a constant value of 0.06 for K under hydrodynamically rough surface conditions such as encountered in gravel bed streams. This value, however, was developed using uniform bed particles. More recent research has tended to support somewhat lower K values when non-uniform grain size distributions have been studied (Shen and Lu, 1983; Odgaard, 1984). This reduction has been attributed to increased turbulence at the streambed associated with the largest particles present. Andrews (1983), reported a K value of 0.033 based on studies of 24 alluvial gravel-bed rivers in Colorado, while Milhous and Bradley (1986) suggested a Shields' parameter of 0.035 for gravel-bed mobilization to release trapped fine sediments.

Sediment transport in streams is an important aspect of fluvial processes not only from the standpoint of river morphology and adjustment, but also for fisheries habitat. The quantity of sediment transported is related to the factors which control the supply of sediment as well as the factors which determine the carrying capacity of the stream. The former include land use in the watershed, vegetative cover, soil conditions, streambank stability, and precipitation characteristics, while the latter factors include discharge, slope, sediment size and particle size distribution. The sediment load in a stream is commonly categorized by the mode of transport. "Bedload" is defined as that part of the load moving on or near the streambed by rolling, saltation or sliding. The "suspended load", by definition, moves in suspension in the water column. That portion of the combined bedload and suspended load contributed by the channel boundary is termed the "bed-material load" (Chang, 1988).

The field measurement of sediment discharge is a tedious, time-consuming exercise. Despite careful site selection and rigorous application of technique, results are often plagued by inherent spatial and temporal variability, both natural and procedural. Leopold (1962) stated that the portion of the total load moving as bedload still could not be measured satisfactorily in real rivers under field conditions. Since the time of Leopold's statement, while considerable experimentation and calibration research has led to the development of the Helley-Smith sampler (Emmett, 1980), the sampling of bedload remains a difficult operation requiring experienced operators to obtain reliable results (Chang, 1988).

Given the inherent problems associated with direct measurement of sediment discharge, numerous prediction models have been developed. In general, these formulae have been derived for noncohesive sediments under steady, uniform flow conditions and have relied upon empirical relations developed under flume and field conditions. Chang (1988) classifies sediment transport formulae into three categories based upon the underlying hydrodynamic approach (shear stress, stream power, parametric) and the portion of the load considered (bedload, suspended load, bed-material load).

A recent review of the literature indicated that of the numerous sediment transport models developed, only two have received somewhat widespread usage for flushing flow analysis (Reiser, et al, 1989). These are the Meyer-Peter and Muller (1948) and the Parker, et al, (1982) formulae. Both models rely on a shear stress approach to predict bedload transport in gravel-bed streams. Results with both have varied widely.

The Meyer-Peter and Muller formula was developed on the basis of flume experiments using mixed and uniform sand particles, natural gravels, coal particles, and barite particles having a specific gravity above 4. Sediment sizes ranged from 0.02 to 1.2 inches (0.5-30mm). The relationship was based on the assumption that the sediment transport process is governed by the same parameters that govern incipient motion. The original form of the equation is:

$$(Q_b/Q)\gamma_w(K_s/K_r)^{3/2}RS = .047(\gamma_s-\gamma_w)d_m + .25(\gamma_w/g)^{1/3}{q_{bl}}^{2/3}$$

where,

Q = water discharge (ft^3/s)

Q_b = water discharge determining the bedload transport rate (ft^3/s)

γ_w = specific weight of water (lbs/ft^3)

γ_s = specific weight of the sediment (lbs/ft^3)

K_s/K_r = ratio of total bed shear utilized in mobilization

R = hydraulic radius (ft)

S = energy slope (ft/ft)

d_m = mean diameter of the sediment (ft)

g = gravitational constant (32.2 ft/s^2)

q_{bl} = bedload transport rate in submerged weight/time/width.

K_r is the Manning's n value, calculated from the velocity, hydraulic radius and slope of the channel, while K_s is determined from the Strickler equation:

$$K_s = .034\ d_{90}^{1/6}$$

where d_{90} is the bed particle size (ft) of which 90 percent by weight is finer.

For practical application, the Meyer-Peter and Muller formula is often transformed to the following equation:

$$q_b = 8/\rho^{1/2}(\tau_o - \tau_c)^{3/2}$$

where, ρ is the fluid density, τ_o is the actual bed shear stress for flow conditions, and τ_c is the critical shear stress.

The latter equation is in the form of many sediment transport functions which express the transport rate as a function of the excess shear stress on the channel boundary. Although the Meyer-Peter and Muller formula is often applied in gravel bed rivers, several investigators have reported poor agreement between predicted and observed transport rates for channel slopes above 0.001 (Parker et al, 1982; Simon and Senturk, 1977). Doehring and Ethridge (1978) concluded that traditional bedload formulae such as the Meyer-Peter and Muller equation may be undesirable for use in high energy/steep slope/limited sediment supply environments such as the mountain streams of the Northern Colorado Front Range.

Parker (1978; 1979) developed a bedload transport formula which pertains specifically to gravel and coarser bed streams. Using 278 experimental and field data sets from an Oregon stream, Parker fit the data to the following relation:

$$q^* = (11.2)[(\tau^* - .03)/\tau^{*3}]^{4.5}$$

where:

$q^* = q/[d_{50}(R'd_{50})^{1/2}]$

R' = submerged specific gravity of sediment (1.65)

d_{50} = grain size for which 50% is finer by weight

q = volumetric bed load discharge per unit width

τ^* = Shields' parameter = $\tau/(\rho R' d_{50})$.

Although the Parker equation is relatively new and has not received widespread use, it does have the advantage of being specifically derived for gravel/cobble bed streams and is based on field data.

Several studies have recently compared the predictions of sediment transport formulae with observed data (Alonso, 1980; Brownlie, 1981; Yang,1986). Gomez and Church (1989), based upon the results of testing 12 bedload transport equations including the Parker and the Meyer-Peter and Muller models, concluded that none of the studied formulae is capable of generally predicting bedload transport in gravel bed rivers. Following a review of similar analyses, Chang (1988) concluded that due to the enormous uncertainties (e.g., hydrologic, geologic) of sediment transport, it is difficult to recommend any one equation for universal application. The user must clearly understand basic assumptions and physical limitations, and calibrate any selected equation with field data from the site of application. This need for calibration is the basis for this study.

CHAPTER THREE

DESCRIPTION OF STUDY AREA

Big Sandstone Creek Watershed

The Big Sandstone Creek drainage was selected for study due to its natural, undeveloped character and its importance for future water development. Located on the west slope of the Sierra Madre Mountains of south-central Wyoming in the Upper Little Snake River watershed (Figure 2), Big Sandstone Creek has been considered for development under the proposed Fish Creek Collector System. Three stream reaches were selected for study: 1) the North Fork of Big Sandstone Creek (NFBSC) near the proposed diversion; 2) the South Fork of Big Sandstone Creek (SFBSC) near the proposed diversion; and, 3) Big Sandstone Creek proper (BSC) immediately below the confluence of the North Fork and the South Fork. The relative locations of the three reaches are shown on Figure 3, while Figure 4 presents a typical view of BSC during spring snowmelt runoff.

The North Fork study reach is located at an elevation of approximately 8660 feet above mean sea level (msl) in the north west quarter of Section 12, T14N, R87W. This forested watershed encompasses 2.28 sq. miles and has a mean basin elevation of 9520 feet. Average annual flow is estimated to be 3.6 cubic feet per second (cfs), while the gradient of the reach is 2.8 percent.

The South Fork study reach is located in the southwest quarter of Section 12, T14N, R87W at an elevation of approximately 8650 feet above msl. This watershed encompasses 2.95 sq. miles and has a mean basin elevation of 9540 feet. Average annual flow is estimated to be 3.9 cfs, while the gradient of the reach is approximately 3.4 percent.

The Big Sandstone study reach is located 1200 feet below the confluence of the North and

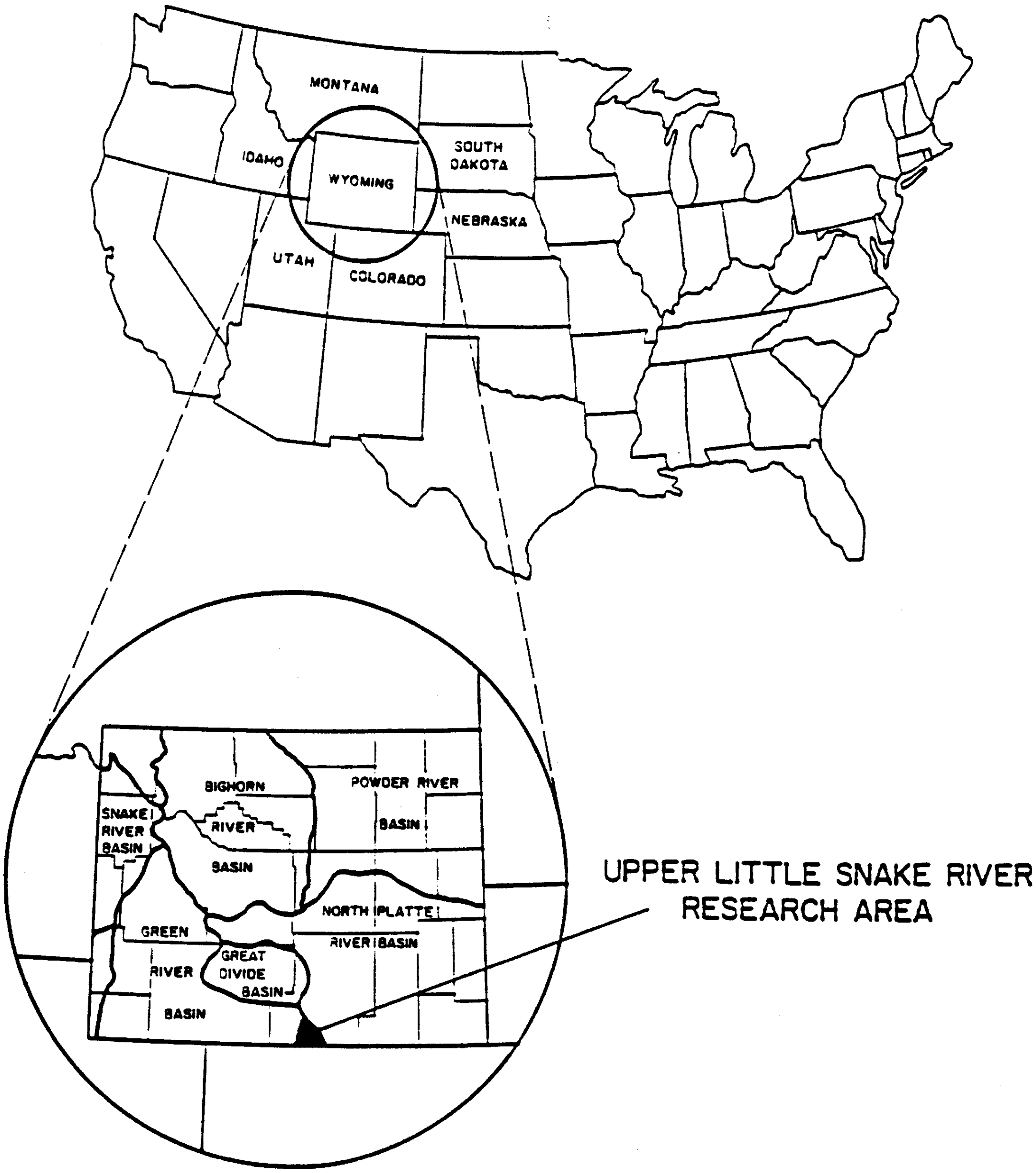


Figure 2. Location map of the upper Little Snake River research area.

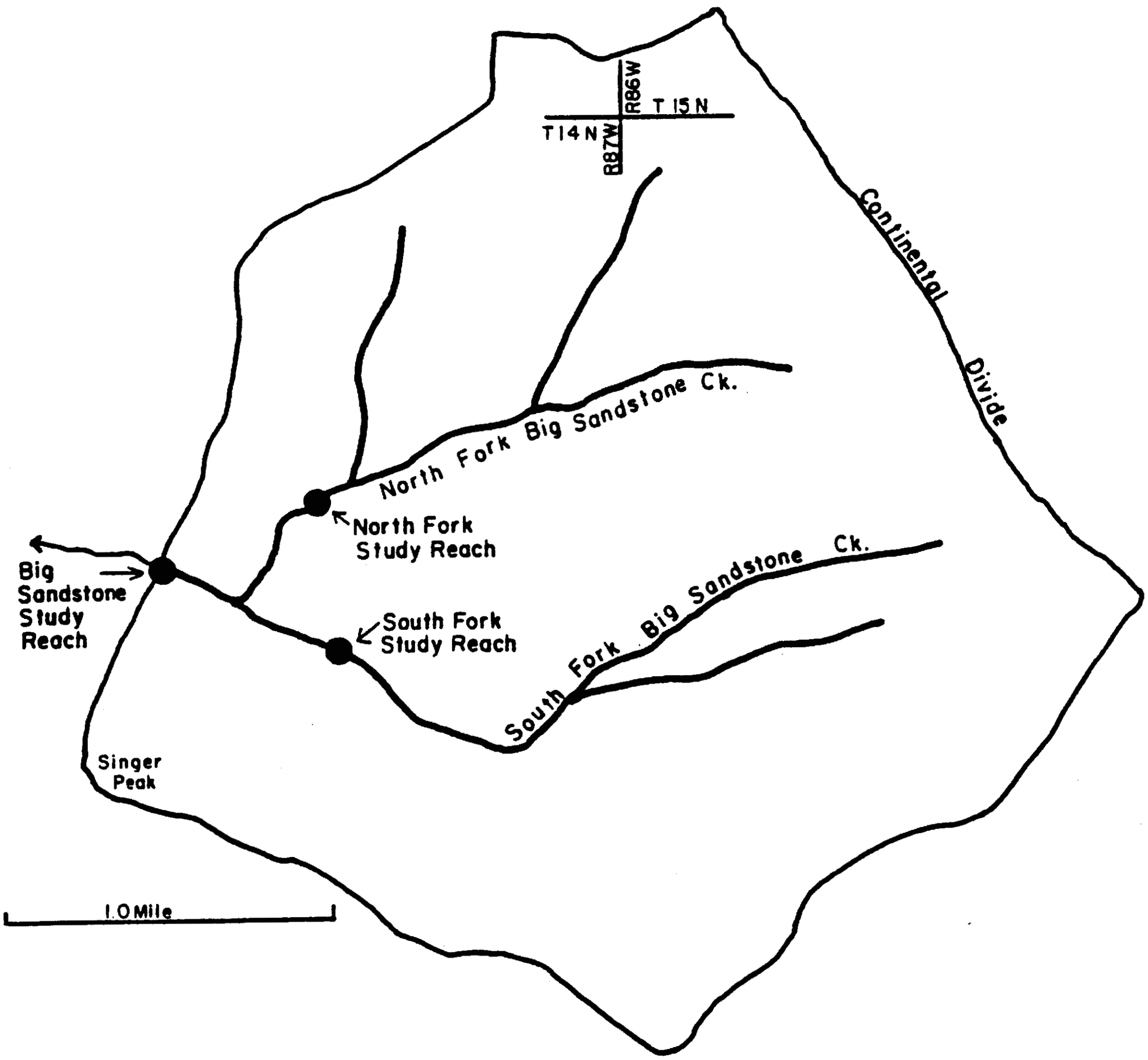


Figure 3. Location map of the three study reaches in the Big Sandstone Creek watershed.

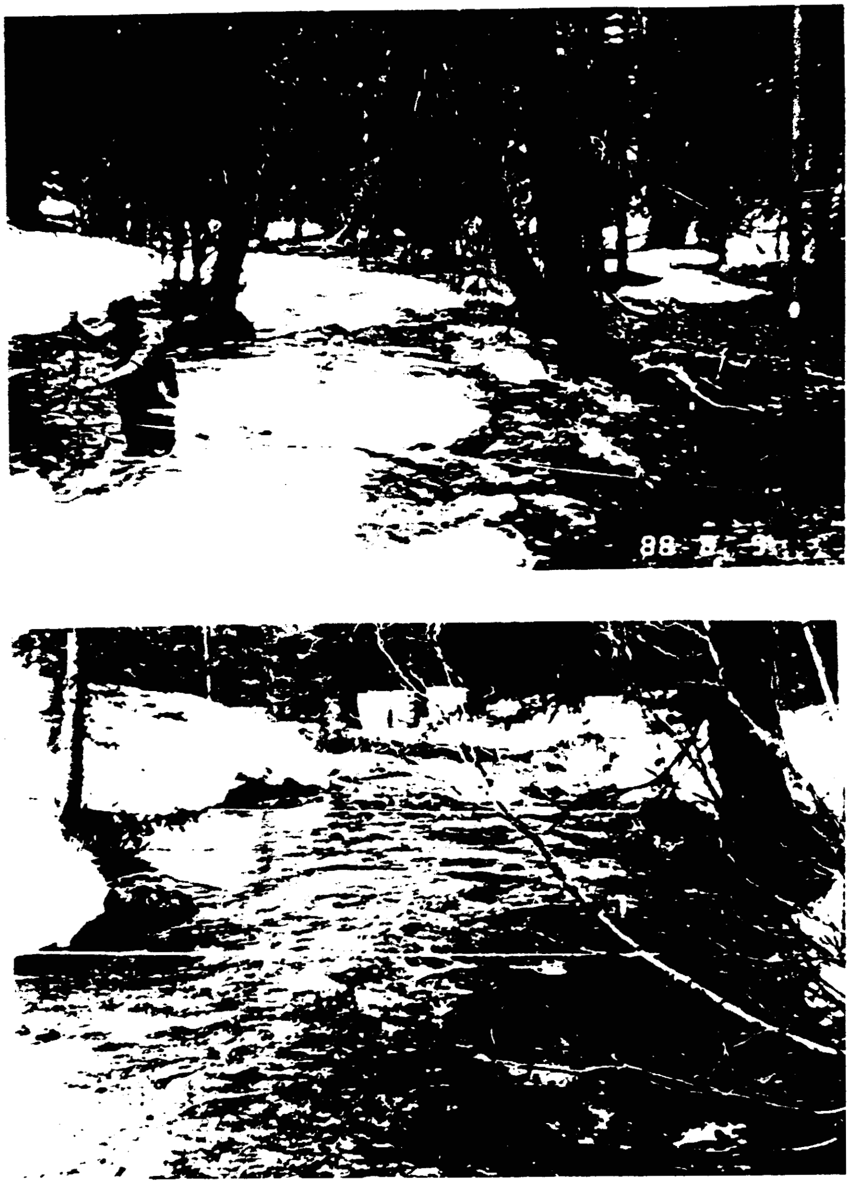


Figure 4. Typical views of Big Sandstone Creek (upper photo) and North Fork of the Little Snake River (lower photo) during snowmelt runoff.

South Forks at an elevation of approximately 8530 feet above msl in the northeast quarter of Section 11, T14N, R87W. At this location, Big Sandstone Creek drains 6.08 sq. miles and has a mean basin elevation of 9455 feet. Average annual flow is estimated to be 9.6 cfs, while the gradient of the reach is 1.6 percent.

Game fish populations in the Big Sandstone Creek study reaches are presently predominated by brook trout (*Salvelinus fontinalis*). Historically these streams served as important habitats for the Colorado River cutthroat trout (*Oncorhynchus clarki pleuriticus* Cope).

North Fork Little Snake River Watershed

The North Fork of the Little Snake River (NFLS) is a steep, rough, regulated tributary of the Little Snake River located in the Green River sub-basin of the Colorado River basin in southwest and south-central Wyoming (Figure 2). The headwaters of the North Fork rise on the west slope of the Continental Divide at an elevation of 10,000 ft. and flow southwesterly 12 miles to the confluence with the Little Snake River at an elevation of 7,000 ft. Average gradient is 4.6 percent. A United States Geological Survey (U.S.G.S.) streamflow gaging station (#09251800) located 1.10 miles below the study area was in operation from 1957 to 1965 and recorded a maximum discharge of 515 cubic feet per second (cfs) on June 7, 1957. Average discharge over the period of record was 26 cfs. Prior to initial water diversion in the mid-1960's, the North Fork hydrograph was typical of unregulated mountain streams in the Central Rocky Mountain region, with the majority of runoff occurring in the May to late-June period, the result of melting snowpack.

The North Fork and its tributaries support the largest known, essentially-pure, naturally-reproducing endemic population of Colorado River cutthroat trout (Binns, 1977). For this reason, management of the population is a high priority for the Wyoming Game and Fish Department.

Transbasin diversion of water from the North Fork drainage has occurred since 1964 when the City of Cheyenne, Wyoming completed Stage I of its water development program. Approximately 8,000 acre-feet per year have been diverted (Banner Associates, Inc., 1976). During 1983, construction began on Stage II collection facilities. When completed, a total of

23,000 acre-feet per year will be conveyed from the upper Little Snake drainage to the east slope of the Continental Divide (U.S.D.A., Forest Service, 1981).

The study area on the North Fork is located in Sections 26, 27, 33 and 34, of Township 13 North, Range 85 West within the boundaries of Medicine Bow National Forest. Within the study reach of 2.0 miles, construction of a bridge and pipeline crossing was underway in the late summer of 1984 when heavy rains precipitated the sediment spill that led to the initiation of this study. Average gradient through this area is 4.2 percent and the predominant natural substrate is boulders, cobbles and gravels. Wesche, et al. (1977) reported a mid-July 1976 water temperature range of 55 to 63°F, a total alkalinity range of 25 to 32 mg/l, a pH of 7.1, and clear water conditions for this section of the North Fork. Instream flow recommendations developed by Wesche et al. (1977) called for a minimum flow of 3.0 cfs or the natural flow, whichever is less, and a three-day annual release of 60 cfs for flushing purposes during the spring runoff period.

Seven study reaches were sampled within the NFLS study area (Figure 5). Reach 0, the uppermost reach at an elevation of 8960 ft, was located just upstream from the diversion structure, while Reach 6 served as the lowermost study site at an elevation of 8515 ft. A typical view of the NFLS during spring runoff is presented in Figure 4.

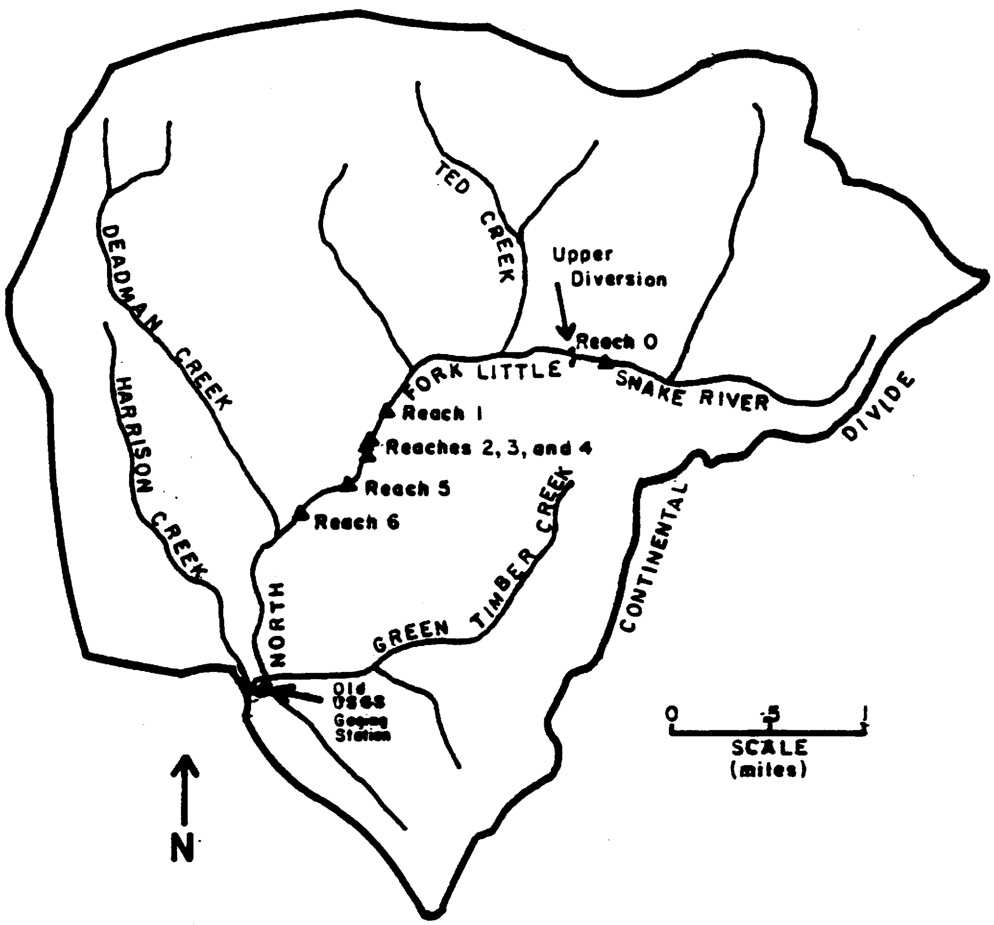


Figure 5. Location map of the North Fork Little Snake River study reaches.

CHAPTER FOUR

METHODS

Stream Channel Response

Preliminary mountain study stream selection was based on the presence of water diversion structures and the availability of streamflow and/or diversion records. Final selection was made in the field to assure that localized land use (e.g., highway construction, channelization, timbering) had not directly affected channel morphology. The study reach on each stream consisted of two study sites, one immediately above and one immediately below a diversion structure. Sites generally ranged from five to seven channel widths in length and were located in straight stream sections.

Data were collected along ten equally spaced cross-sections at each study site and included mean bankfull width and depth, and channel slope. Based on these field data, bankfull cross-sectional area, conveyance capacity and width-depth ratio were calculated for each site. Conveyance capacity was determined by the slope-area method described by Dalrymple and Benson (1968). Density and species composition of the riparian zone vegetation were also recorded. Each stream reach was classified by channel type as an A (slope > 4%), B (slope 1.5 to 4%), or C (slope < 1.5%) following Rosgen (1985).

The hydrologic record for each study reach was developed by one of two methods. For those study reaches where suitable streamflow records were available, flood frequency analysis using the log-Pearson Type III method (Linsley et al, 1975) was performed to determine the peak discharge having a recurrence interval of two years. This discharge, termed Q_{P2}, is often considered to be an indicator of channel forming flow based upon its magnitude and availability. Q_{P2} was also selected because for reaches where flow records were unavailable, the basin characteristics method of Lowham (1976) could be applied. This method is widely accepted in Wyoming and predicts only peak flood events. Diversion records, provided by the Wyoming State Engineer's Office, the Denver Water Board, and the City of Cheyenne, were analyzed to determine the percent of flow reduction experienced at the downstream site within each reach.

Following preliminary analysis of the mountain stream reaches, additional low gradient (C type channel) reaches on several foothill and basin streams in Wyoming were selected for study and measured. Measurements made were the same as for the mountain streams. Where larger diversion structures were present, measurements were made at sites immediately upstream and downstream. Where numerous small diversions were present through a longer reach, sites were selected beginning at the upper end of the reach and progressed downstream to assess cumulative effects of flow depletion.

Sediment Dynamics

Big Sandstone Creek

The three Big Sandstone Creek study reaches were selected in early July 1986 based upon 1) their representation of general channel geometry, hydrologic, hydraulic, and sediment characteristics, 2) their location in relation to the proposed diversion system, 3) the presence of a diversity of fish habitat types, and 4) the absence of significant land use effects.

Hydrology

Two recording streamflow gaging stations were installed during early July, 1986, one at the North Fork study reach and one on the South Fork. Each station consisted of a stilling well constructed from perforated plastic pipe, a Leopold and Stevens Type F water stage recorder, a steel recorder platform and an outside staff gage. A rating curve for each gage station was developed following standard U.S. Geological Survey procedures (Buchanan and Somers, 1969). The gage stations were operated from July to September, 1986; April to September, 1987; and May through June, 1988. No attempt was made to operate the stations through the winter months due to their remote locations. A staff gage was installed at a rated cross-section in the Big Sandstone reach and daily records were developed by correlation analysis with the recording stations. All streamflow records are entered onto the Water Resources Data System (WRDS) maintained by the Wyoming Water Research Center at the University of Wyoming.

As no long-term streamgage records are available for Big Sandstone Creek, it was necessary to estimate the average annual discharge (Q_{AA}) at each reach following the procedures of Lowham (1976). Application of the channel geometry method resulted in exceptionally high estimates while the basin characteristics estimates were felt to be too low based upon our limited gage record. As a result, the two estimates for each reach were averaged. As these average values agreed quite closely with the model estimates of average annual flow reported by Stone and Webster (1986), they were selected for use.

Hydraulic Geometry

Four cross-channel transects were established in the North Fork and South Fork study reaches to evaluate hydraulic characteristics over a wide range of streamflow conditions. Five such transects were established at the Big Sandstone reach. Measurements of water depth and mean velocity were made at approximately 20 locations along each transect at a series of low, moderate and high discharges. These data, in conjunction with measurements of top width (W), were then used to develop power function relationships with stream discharge (Q_w) for the following hydraulic variables:

D (mean water depth, feet)

V (mean water velocity, ft/sec)

W (wetted top width, feet)

W/D (width to depth ratio, ft/ft)

All mean velocity measurements were made at 0.6 of depth with Marsh-Birney current meters. Water surface slope was measured with a surveyor's level and rod over each transect for a range of flow conditions.

Sediment

The primary sampling units for sediment transport and storage were the 13 transects described above. Suspended sediment samples were taken with USDH-48 samplers using the Equal Transit Rate (ETR) technique described by Guy and Norman (1970). Bedload transport was measured using a Helley-Smith sampler, with each sample being composed of at least 20 subsamples, each of one minute duration. While sediment transport samples were taken at each transect over a range of discharges and locations on the runoff hydrograph during the spring and summer of 1987 and 1988, sampling emphasis was focused on the uppermost and lowermost transects in each reach to attempt to define sediment import and export from a reach perspective.

The particle size distribution of stored sediment in each reach was sampled four times over the course of the study. Three core samples were taken in the vicinity of each transect at each sampling time using a six-inch diameter McNeil sampler following techniques described by Reiser and Wesche (1977). Coring depth was a maximum of six inches and a minimum of four inches, dependent upon the depth of underlying boulders and bedrock. The quantity of stored sediment in each reach was estimated four times during the study. Depth of deposition was measured at 20 locations along each transect at each sampling time by driving a graduated steel rod into the bed until bedrock or boulder was encountered.

Laboratory analysis of all sediment samples was conducted at the Watershed Laboratory of the Range Management Department, College of Agriculture, University of Wyoming. Suspended sediment samples were analyzed by the filtration method (U.S. Geological Survey, 1977), with results reported in mg/l. Suspended load discharge (Q_{SL}) in tons/day was calculated using the equation:

$$Q_{SL} = .0027\, C_s Q_w$$

where,

C_s = sediment concentration in mg/l

Q_w = water discharge in cfs

and .0027 is a conversion constant

All bedload samples were oven dried for 24 hours at 140°F, dry sieved and weighed. Bedload discharge (Q_{BL}) in tons per day was then calculated directly based upon the weight of the sample, the width of the sampler orifice, the top width of the transect at the time of sampling, the number of subsamples taken across the transect, and the total sampling time.

Bed material core samples were also oven dried for at least 24 hours at 140°F, dry sieved and weighed. Particle size distributions were then plotted on log probability paper to determine the d_{84}, d_{50}, and d_{16} values (those particle diameters for which 84, 50 and 16 percent, respectively, of the sample is finer than by weight) and the gradation coefficient ($G = 1/2\ (d_{84}/d_{50} + d_{50}/d_{16})$), as described by Simons and Senturk (1977).

North Fork of Little Snake River

During the fall of 1984, four reaches were selected for study in cooperation with personnel from the Wyoming Game and Fish Department and the U.S. Forest Service. Reach 1, the uppermost site below the diversion, was located just above the confluence of Second Creek, approximately 1,200 ft. upstream from the North Fork bridge and pipeline crossing. Reach 1 served as the control above the construction area from which much of the sediment spill originated. Reaches 2,3 and 4 were located sequentially below the North Fork crossing area and were within the zone of immediate deposition from the spill. Given the intensive nature of the sampling, study reaches were kept short in length, with Reach 2 being the longest, 50 feet.

During Fall 1985, three additional study reaches were established. Reach 0, located above the diversion, was selected to represent unregulated hydrologic and hydraulic conditions, while Reaches 5 and 6 were added to evaluate migration of the sediment spill downstream. With the addition of Reach 0 to the design, Reach 1 was deleted from further sampling in the spring of 1986.

Hydrology

Three recording streamflow gage stations were installed within the study area in 1985 to monitor the North Fork hydrograph. These stations were of the same design described previously for Big Sandstone Creek and were located at Reaches 0, 3 and 6 (Figure 5). The gages were operated seasonally through June, 1988, with stage-discharge relations updated annually.

Given the brief historic streamflow record available for the NFLS, it was necessary to estimate discharge characteristics for the study reaches following the procedures of Lowham (1976). The channel geometry method showed the best agreement with the available records and was selected for further analysis.

Hydraulic Geometry

Four cross-channel transects were established at each NFLS study reach to evaluate hydraulic characteristics over a wide range of streamflow conditions. Field measurement and analysis followed the procedures previously described for the Big Sandstone Creek reaches.

Sediment

The primary sampling units for sediment transport and storage on the NFLS were the cross-channel transects described above. Sampling and analysis procedures for bedload transport, suspended load transport, and quantity and distribution of stored bed material were the same as those described for the Big Sandstone Creek reaches. Field sampling began in the late fall of 1984 and ended in June, 1988.

CHAPTER FIVE

RESULTS

Stream Channel Response

Field measurements of channel characteristics were made at 39 study sites on 19 streams in southern Wyoming and northern Colorado. From this group, 20 comparisons above and below diversion structures were made. Site elevations ranged from 7,480 to 10,060 feet above sea level. Diversion structures ranged in age from 12 to 106 years and depleted streamflows from 17 to 90 percent. Descriptions of the mountain study sites are provided in Table A-1 of the Appendix.

The responses of 20 mountain stream reaches to flow depletion are summarized in Table 1. For the higher gradient study reaches (A and B types), paired t-tests comparing bankfull channel characteristics above and below diversion structures indicated no significant differences for mean width, depth, width-depth ratio, cross-sectional area and conveyance capacity. These steeper channels had maintained their physical dimensions over an average time of diversion exceeding 35 years and an estimated average flow reduction of 70 percent, as shown on Figure 6.

Low gradient C channels responded more to flow depletion than did the A and B types. Mean channel depth, cross-sectional area and conveyance capacity were significantly reduced below diversion structures that averaged 66 years of age and depleted flow by 46 percent. Aggradation and encroachment by streamside vegetation were observed at most of these study sites. Watershed characteristics undoubtedly contributed to this response. As shown on Table 2, the C channel types were generally located lower within their respective watersheds, the result being a more favorable climate for vegetation establishment, a reduced rate of incoming accretion

Table 1. Comparison of bankfull channel characteristics above and below diversion structures on 20 mountain stream reaches, by channel type, using paired t-tests.

	CHANNEL TYPE					
	A		B		C	
	Above	Below	Above	Below	Above	Below
Number of Pairs Sampled	7		7		6	
Mean Width (ft)	10.5	10.0	15.4	15.5	21.5	18.3
Mean Depth (ft)	1.29	1.31	1.30	1.33	1.90	1.43[1]
Width-Depth Ratio	8.6	7.9	11.0	10.4	11.4	12.4
Mean Cross-Section Area (ft^2)	13.5	13.9	23.9	25.1	43.1	28.0[1]
Conveyance Capacity (ft^3/s)	133	141	166	197	253	83[1]

[1] Significant difference between means at $\alpha = .05$

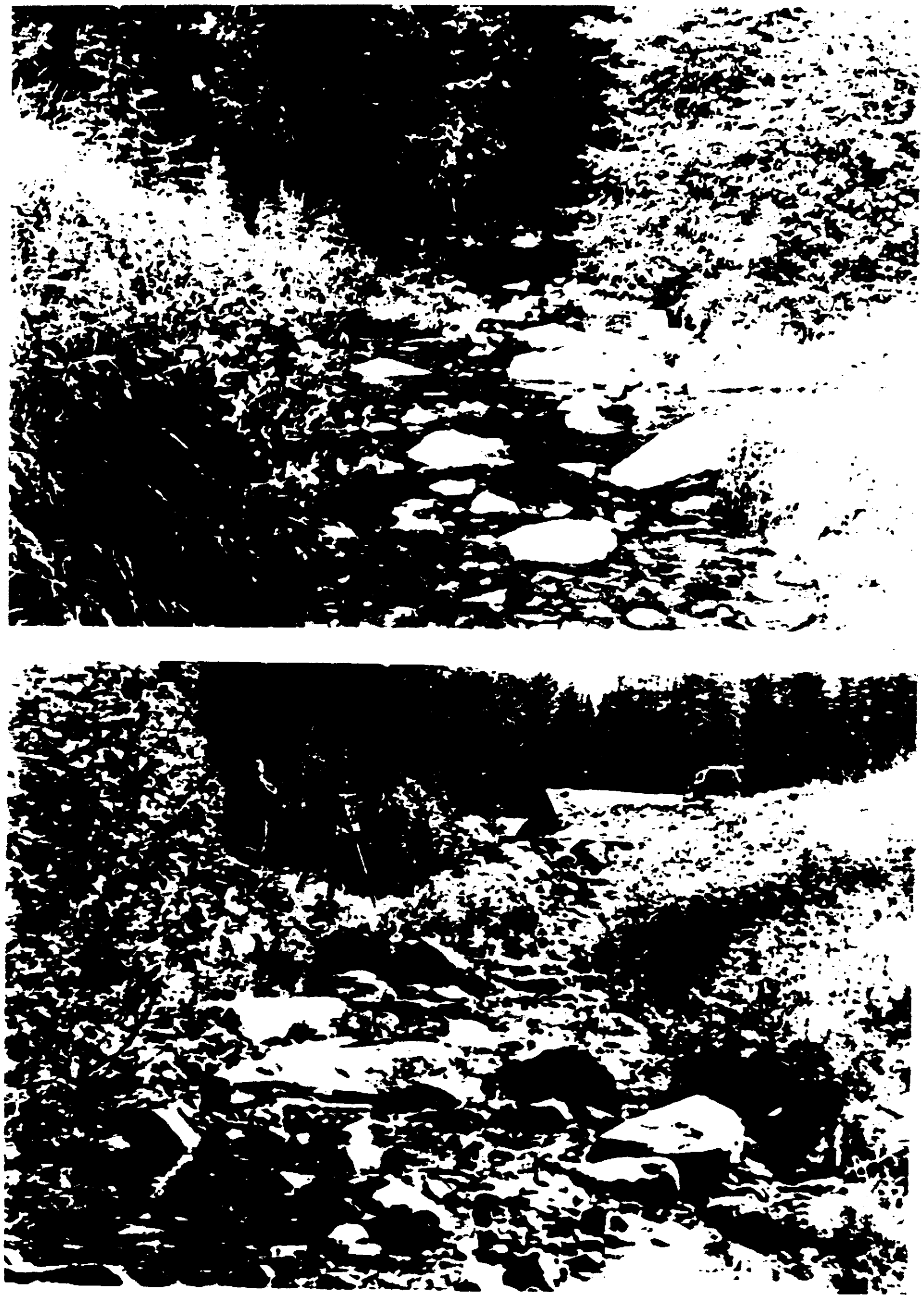


Figure 6. Response of the North Fork Little Snake River to streamflow depletion. Age of the diversion structure is 24 years and flow reduction is 68 percent.
Upper: Moderate gradient (B) channel above diversion (width = 10.1 ft; depth = 1.0ft).
Lower: Moderate gradient (B) channel below diversion (width = 10.5ft; depth = 1.0ft).

Table 2. Watershed characteristics above the 20 mountain stream reaches.

	CHANNEL TYPE A	B	C
Mean Elevation of Sites (ft)	9,566	8,973	8,605
Mean Drainage Area (sq. mile)	3.6	10.9	20.6
Average Main Channel Length (miles)[1]	3.0	4.9	7.0
Mean Basin Elevation (ft)	10,669	9,979	9,968
Average Main Channel Slope (%)[1]	11.3	9.4	5.9

[1] From headwaters downstream to study reaches

flow from snowmelt runoff, an increased sediment supply, and a reduction in sediment transport capability.

Qualitative comparisons of riparian vegetation density and type were made above and below each of the mountain diversion structures. Trends in vegetation response to flow depletion are summarized in Table 3. In 75 percent of the cases, no change or an increasing trend in plant density was observed below diversion structures. Of the 15 cases where a decrease in plant density was noted, 9 (60 percent) occurred in the C channel type where the riparian area was increasing due to channel encroachment.

Low Gradient Streams

Based upon the observations made of mountain stream response to flow depletion, measurements were made on additional low gradient channels. Foothill and basin streams investigated were the Laramie River, New Fork River, Owl Creek and Gooseberry Creek, as described in Table A-2. With the inclusion of these streams, the number of paired observations for C channels was increased to 15. The results of statistical analysis comparing channel characteristics above and below diversion structures are presented in Table 4.

Results using this larger sample were similar to those for the mountain streams. Mean channel width was significantly reduced by 26 percent, mean depth by 14 percent, mean cross-sectional area by 32 percent, and mean conveyance capacity by 55 percent. Flow depleted sites had a reduced width-depth ratio, although this difference was not statistically significant. These results indicate the sample of C channels was responding to flow depletion by reducing channel dimensions, as shown on Figure 7.

Based upon these findings, attempts were made to develop statistical relations that could be used to estimate the response of C channel types to flow depletion. Both multiple and single regression approaches were followed. Best results were obtained using power fit regression with Q_{P2} as the independent variable and the various channel dimensions as the dependent variables. The form of the equation is:

Table 3. Trends in riparian vegetation response to flow depletion in 20 mountain stream reaches.

	Vegetation Type (Number of Streams)		
Vegetation Response[1]	Canopy	Shrub	Grass
+	3	6	2
-	4	5	6
0	13	9	12
Total	20	20	20

[1]

+ indicates increase in plant density below diversion.

- indicates decrease in plant density below diversion.

0 indicates no change in plant density below diversion.

Table 4. Comparison of bankfull channel characteristics above and below diversion structures for C channel types (n = 15).

	LOCATION	
	Above Diversion	Below Diversion
Mean Width (ft)	32.3	23.8[1]
Mean Depth (ft)	2.2	1.9[1]
Width-Depth Ratio	14.4	12.5
Mean Cross-Section Area (ft^2)	86.4	58.4[1]
Conveyance Capacity (ft^3/s)	270.0	122.6[1]

[1] Significant difference between means at α = .05.

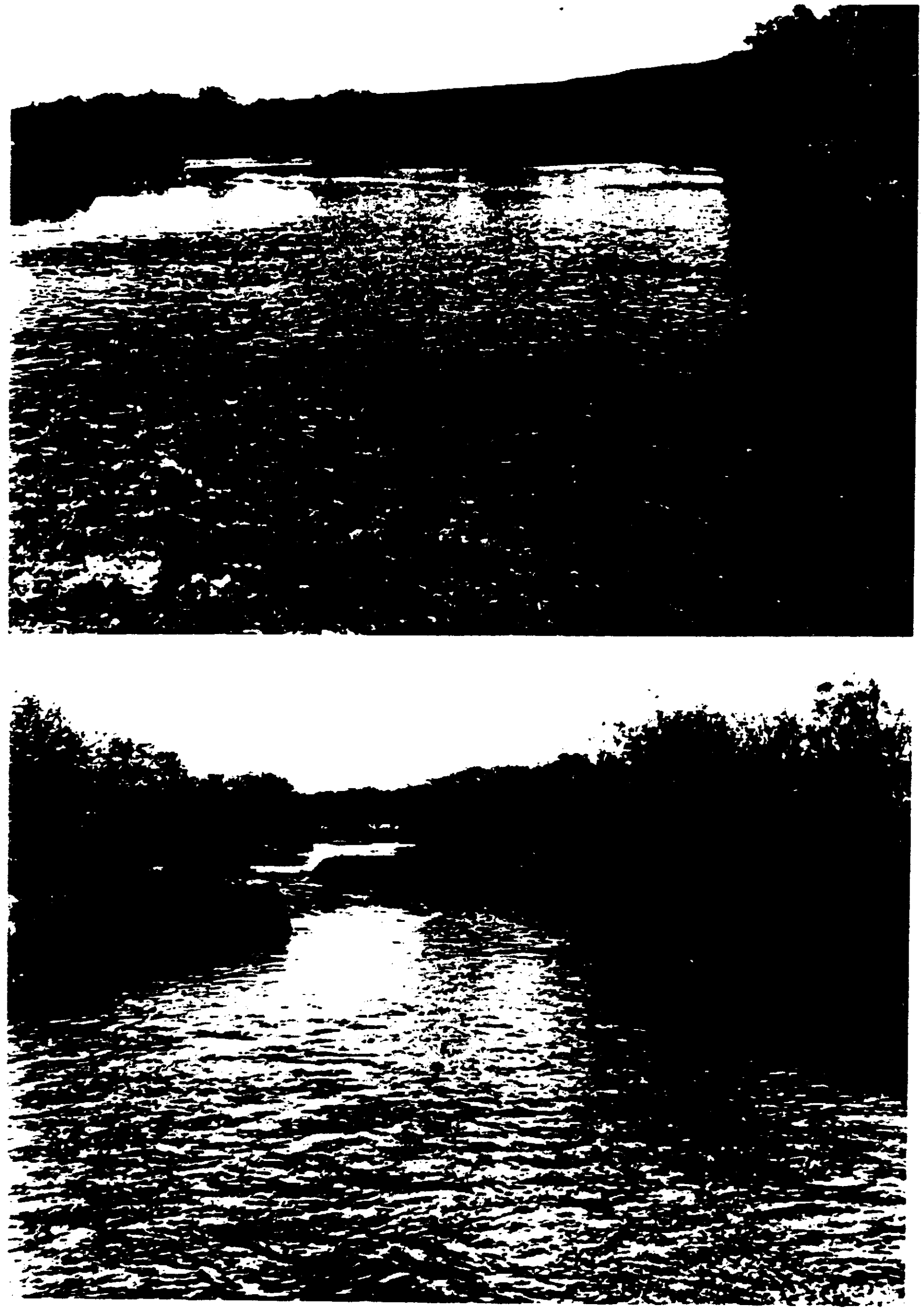


Figure 7. Response of New Fork River to flow depletion.
Upper: Low gradient (C) channel above diversions (width = 45.8ft; depth = 2.3ft).
Lower: Low gradient (C) channel 5 miles below upper photo location. Flow reduced ~ 92% dating back to 1903 (width = 16.5ft; depth = 1.2ft).

$$Y = aQ_{p2}^{b}$$

where,

Y = channel characteristic

a = coefficient

b = exponent

Table 5 summarizes the coefficients, exponents and correlation coefficients for mean width, depth, area and conveyance capacity.

The regression equations presented above can be used to estimate the physical response of a low gradient stream channel in Wyoming to water development. For example, suppose that a planned diversion structure will reduce the Q_{p2} of a stream reach by 75 percent. If we use the subscripts p and a to denote present and altered conditions, the following relationship can be developed for estimating the new channel depth (d_a):

$$d_a/d_p = (Q_a/Q_p)^b$$

$$= 0.75^{0.338}$$

$$d_a = 0.91\ d_p$$

Thus if d_p is 2.0 ft., we would estimate d_a to be 1.81 ft. A similar approach could be followed to estimate relative changes for other channel characteristics.

Multiple regression analysis incorporating age of diversion structure as an independent variable was attempted. The predictive ability of the resultant equations however, was no greater than for the relationships presented above. Stream channels do not respond immediately to flow depletion. A number of years must pass for a new equilibrium condition to be achieved. However, given the age distribution of diversion structures at our study reaches (only 1 diversion was less than 50 years old), we can only assume that most of the depleted sites had reached equilibrium. As a result, the age variable explained little of the variation observed in channel dimensions.

Table 5. Power fit regression relations between channel characteristics and Q_{p2} for C type channels in the Central Rocky Mountain region ($n = 21$).

	Coefficient a	Exponent b	Correlation Coefficient r
Mean Width (ft)	3.015	0.395	0.77[1]
Mean Depth (ft)	0.303	0.338	0.87[1]
Mean Cross-Section Area (ft)	0.914	0.732	0.85[1]
Conveyance Capacity (ft^3/s)	4.999	0.628	0.78[1]

[1] Significant at $\alpha = .05$

Sediment Dynamics

Hydrology

Estimated streamflow characteristics for the NFLS and BSC study reaches are presented in Table 6. Average annual discharge ranges from 3.6 cfs at North Fork BSC to 14.1 cfs at NFLS Reach 6, while estimated two-year peak flow events range from 59 to 193 cfs. Based upon the dimensionless annual flow duration curve developed by Stone and Webster (1986) for the west slope of the Continental Divide within the Medicine Bow National Forest (Figure 8), average annual discharge is equalled or exceeded approximately 18.5 percent of the time for the study streams.

Stream gage stations installed on the NFLS were operated from 1985 to 1987 and on BSC during 1987 and 1988. Typically, gages were placed in operation early in the spring prior to snowmelt runoff and discontinued in the late summer or fall. The mean daily discharge records from the NFLS Reach 3 and the North Fork BSC stations for the study period are presented in Figures 9 and 10, respectively. The NFLS records reflect some upstream water withdrawal by the City of Cheyenne, while the BSC hydrographs represent the natural runoff pattern.

Based upon Soil Conservation Service snowcourse records, snowpacks during 1985 and 1987 were below normal, 1988 was near normal, and 1986 was above normal. These conditions are reflected in the hydrographs presented. During 1985, mean daily flow peaked at 7.1 times the average annual discharge (Q_{AA}) on the NFLS, while in 1986 the mean daily peak of 240 cfs was 21.4 times Q_{AA}. At the North Fork BSC station, peak mean daily discharges were 41 cfs in 1987 and 53 cfs in 1988, 11.4 and 14.7 times Q_{AA}, respectively. Baseflow conditions during the late summer and early fall on the study streams typically ranged from 15 to 25 percent of Q_{AA}.

Hydraulic Geometry and Channel Morphology

As described in Chapter 4, study reaches were selected to represent typical habitat conditions

Table 6. Estimated streamflow characteristics for the Big Sandstone Creek (BSC) and North Fork Little Snake River (NFLS) study reaches.

Study Reach	Q_{AA} (ft^3/s) [1]	Q_{P2} (ft^3/s) [2]
North Fork BSC	3.6	59
South Fork BSC	3.9	64
BSC	9.6	135
NFLS Reach 0	7.5	116
NFLS Reach 2	11.2	160
NFLS Reach 3	11.2	160
NFLS Reach 4	11.2	160
NFLS Reach 5	12.3	173
NFLS Reach 6	14.1	193

[1] Q_{AA} = Average annual discharge

[2] Q_{P2} = Peak flood flow having a two-year recurrence interval

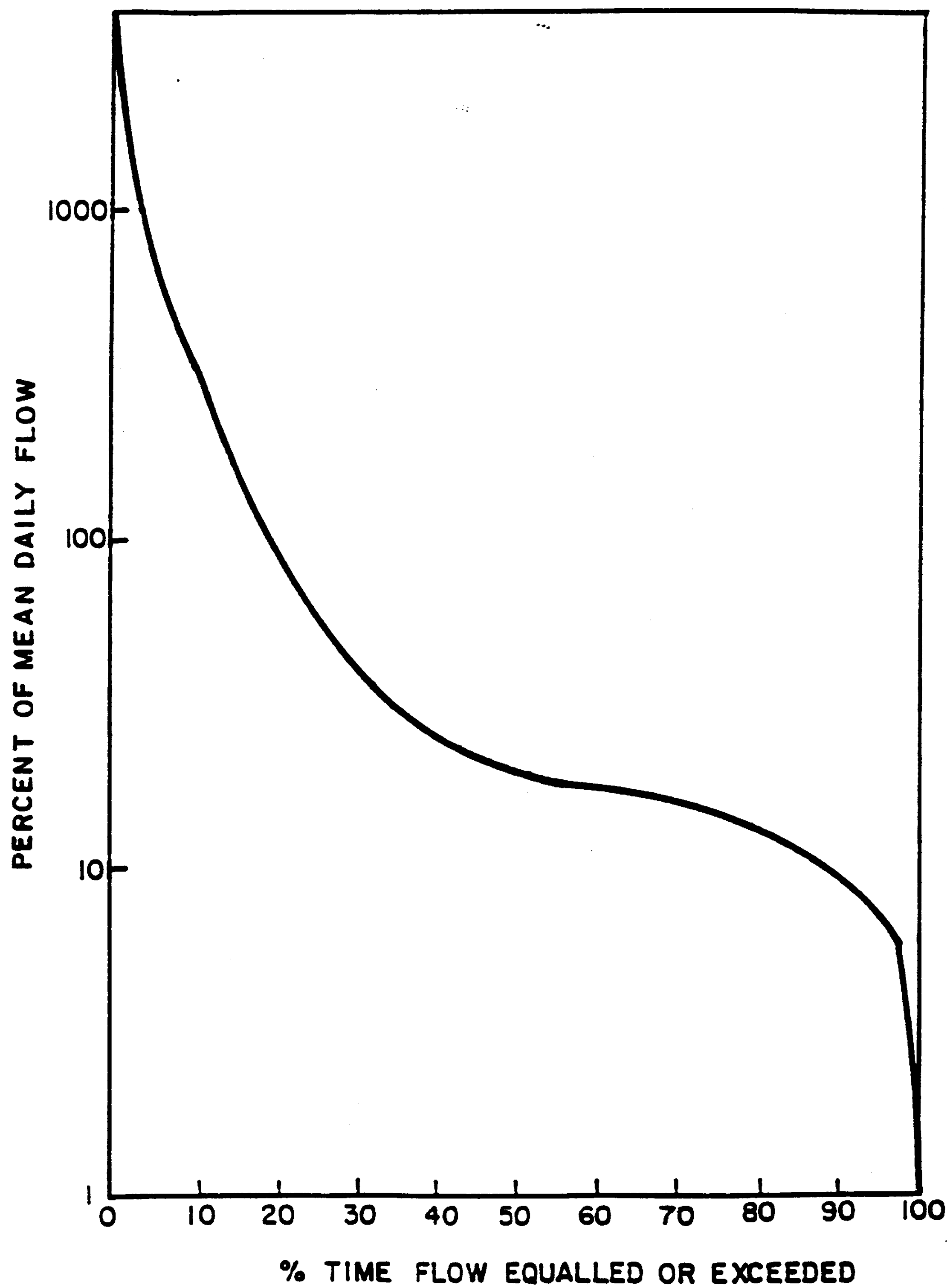


Figure 8. Flow duration curve for west slope streams within Medicine Bow National Forest (from, Stone and Webster, 1986).

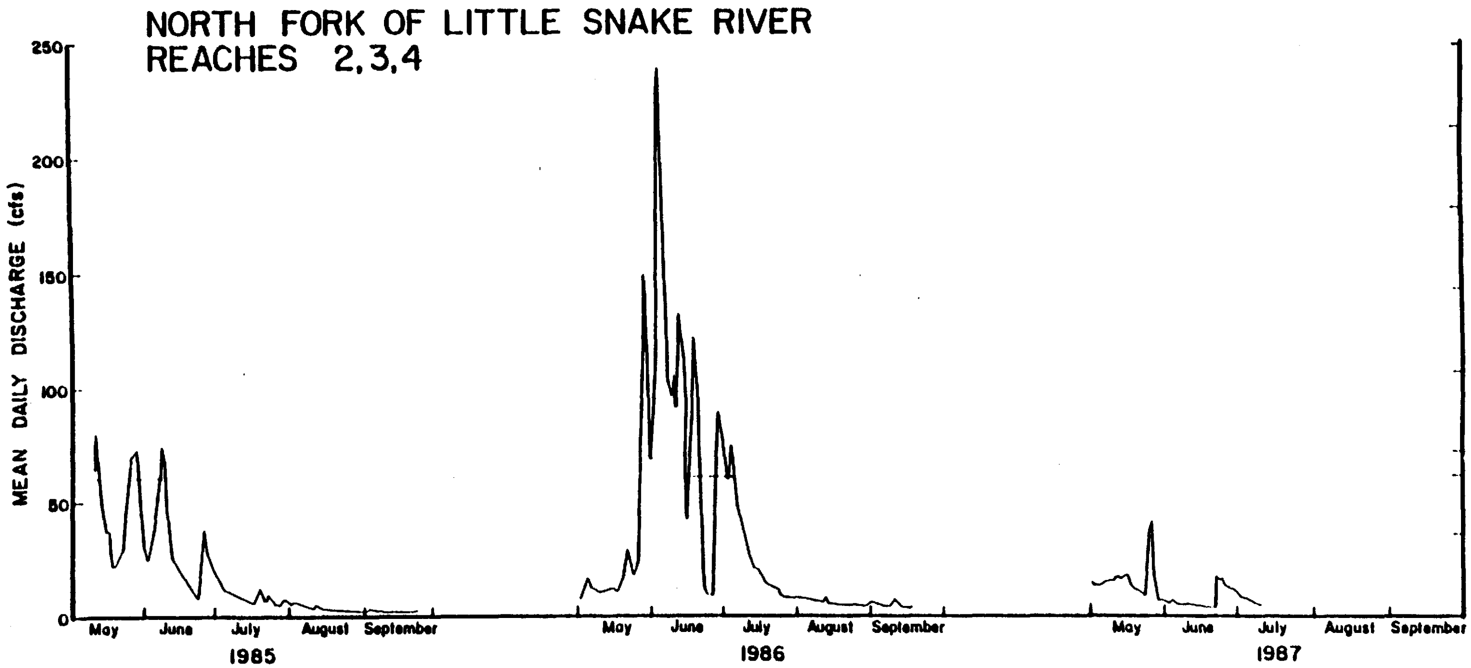


Figure 9. Mean daily hydrograph for Reaches 2, 3, and 4 of North Fork Little Snake River, 1985 to 1987.

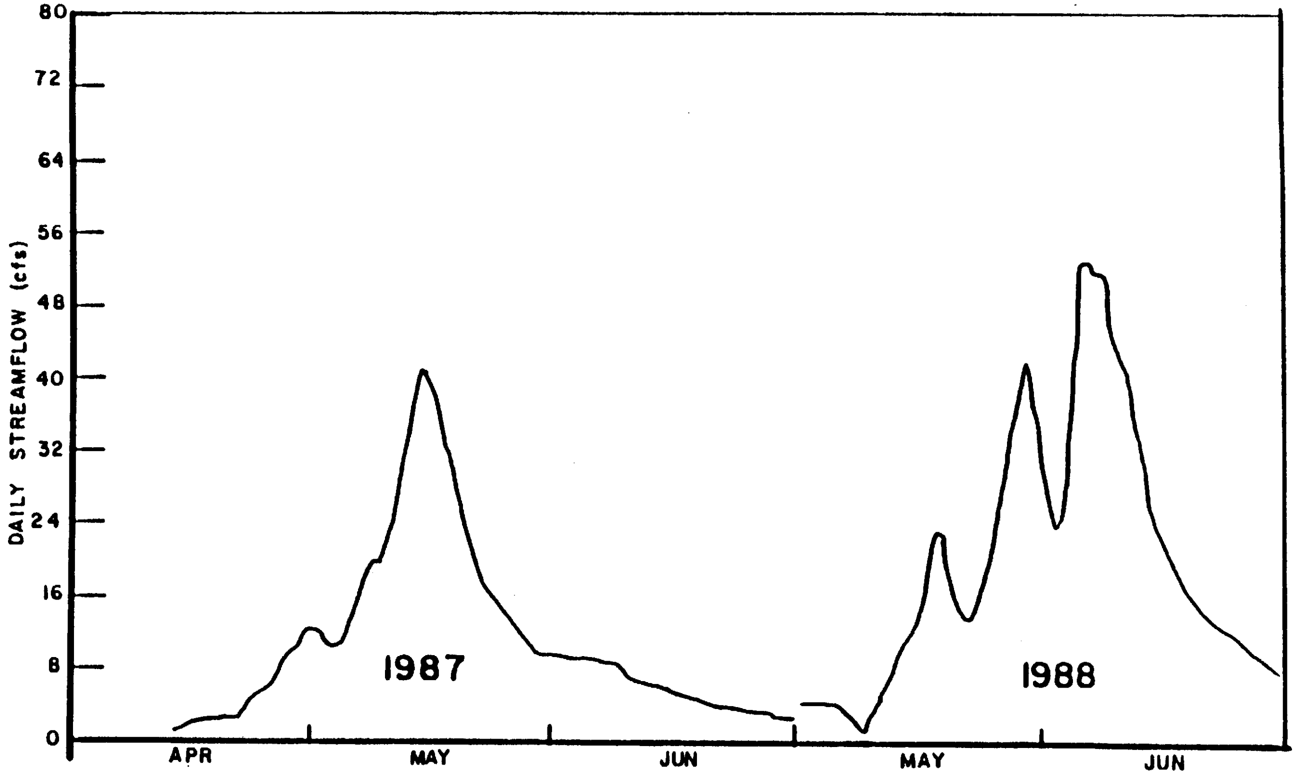


Figure 10. Mean daily hydrograph for the North Fork of Big Sandstone Creek, spring 1987 and 1988.

encountered within the study streams. On the NFLS, Reach 2 represented the steep gradient (greater than 4.0 percent), boulder strewn, riffle-cascade habitat common to the upper Little Snake drainage. Reaches 4, 5, and 6 were lower gradient (less than 1.0 percent), had finer bed material, and contained pool habitat utilized by Colorado cutthroat trout for rearing and spawning. Reach 3 was characterized by a moderate gradient (2.5 percent) and a boulder-cobble bed. Reach 0, located above both the diversion structure and the site of the 1984 sediment spill, was representative of the meadow habitat common in the headwaters of the NFLS and was utilized by cutthroat for spawning and rearing. Gradient through Reach 0 was mild (less than 1.0 percent) and the bed material was primarily gravel with interspersed small boulders and cobble.

The South Fork BSC study reach was similar to NFLS Reach 2, having a steep gradient (3.4 percent) and a rough channel boundary. Both the North Fork BSC and BSC reaches were more moderate in gradient (2.8 and 1.6 percent, respectively) and exhibited greater habitat diversity, including both rearing and spawning habitats. Bed material was composed primarily of gravels interspersed with cobbles and small boulders.

Hydraulic geometry relations were developed to describe the dimensional variation of top width, mean depth, mean velocity, and width to depth ratio with discharge at each transect within each study reach. These relations are presented in Tables 7 to 15 for an upper and a lower transect within each reach. Water surface slope within each reach was typically greater at the upper transects than at the lower, as indicated on Table 16. In general, the channels of the NFLS and BSC can be described as straight, shallow, relatively wide in relation to their depth, and rectangular in shape. Width to depth ratio is inversely related to discharge and directly related to channel gradient. Mean depth and mean velocity show greater variation with discharge than does top width, while depth variation is greater in steeper sections and velocity variation with discharge is greater at locations having more moderate slopes.

Table 7. Hydraulic Geometry Relations for Transects 1 and 4, North Fork Little Snake River (NFLS) Study Reach 0.

Hydraulic Parameter	Units	Equation[1]	Transect
Stream Width (W)	Feet	$W = 9.9\ Qw^{.128}$	1
		$W = 6.7\ Qw^{.214}$	4
Mean Depth (D)	Feet	$D = 0.29\ Qw^{.340}$	1
		$D = 0.22\ Qw^{.444}$	4
Mean Velocity (V)	Ft/sec	$V = 0.35\ Qw^{.532}$	1
		$V = 0.68\ Qw^{.342}$	4
Width to Depth Ratio (W/D)	Ft/Ft	$W/D = 34.3\ Qw^{-.212}$	1
		$W/D = 30.2\ Qw^{-.230}$	4

[1] Qw = streamflow in ft^3/s

Table 8. Hydraulic Geometry Relations for Transects 1 and 4, North Fork Little Snake River (NFLS) Study Reach 2.

Hydraulic Parameter	Units	Equation[1]	Transect
Stream Width (W)	Feet	$W = 16.0\ Qw^{.378}$	1
		$W = 24.4\ Qw^{.328}$	4
Mean Depth (D)	Feet	$D = 0.15\ Qw^{.478}$	1
		$D = 0.07\ Qw^{.501}$	4
Mean Velocity (V)	Ft/sec	$V = 0.42\ Qw^{.144}$	1
		$V = 0.59\ Qw^{.373}$	4
Width to Depth Ratio (W/D)	Ft/Ft	$W/D = 108.1\ Qw^{-.394}$	1
		$W/D = 355.3\ Qw^{-.678}$	4

[1] Qw = streamflow in ft^3/s

Table 9. Hydraulic Geometry Relations for Transects 1 and 4, North Fork Little Snake River (NFLS) Study Reach 3.

Hydraulic Parameter	Units	Equation[1]	Transect
Stream Width (W)	Feet	$W = 20.4\ Qw^{.068}$	1
		$W = 20.0\ Qw^{.016}$	4
Mean Depth (D)	Feet	$D = 0.15\ Qw^{.527}$	1
		$D = 0.26\ Qw^{.364}$	4
Mean Velocity (V)	Ft/sec	$V = 0.33\ Qw^{.405}$	1
		$V = 0.19\ Qw^{.620}$	4
Width to Depth Ratio (W/D)	Ft/Ft	$W/D = 136.1\ Qw^{-.459}$	1
		$W/D = 76.0\ Qw^{-.348}$	4

[1] Qw = streamflow in ft^3/s

Table 10. Hydraulic Geometry relations for Transects 1 and 4, North Fork Little Snake River (NFLS) Study Reach 4.

Hydraulic Parameter	Units	Equation[1]	Transect
Stream Width (W)	Feet	$W = 15.1\ Qw^{.152}$	1
		$W = 18.9\ Qw^{.039}$	4
Mean Depth (D)	Feet	$D = 0.42\ Qw^{.313}$	1
		$D = 0.15\ Qw^{.532}$	4
Mean Velocity (V)	Ft/sec	$V = 0.16\ Qw^{.535}$	1
		$V = 0.35\ Qw^{.429}$	4
Width to Depth Ratio (W/D)	Ft/Ft	$W/D = 35.8\ Qw^{-.161}$	1
		$W/D = 125.1\ Qw^{-.482}$	4

[1] Qw = streamflow in ft^3/s

Table 11. Hydraulic Geometry Relations for Transect 1 and 4, North Fork Little Snake River (NFLS) Study Reach 5.

Hydraulic Parameter	Units	Equation[1]	Transect
Stream Width (W)	Feet	$W = 16.4\ Qw^{.103}$	1
		$W = 13.9\ Qw^{.165}$	4
Mean Depth (D)	Feet	$D = 0.30\ Qw^{.400}$	1
		$D = 0.10\ Qw^{.727}$	4
Mean Velocity (V)	Ft/sec	$V = 0.20\ Qw^{.497}$	1
		$V = 0.72\ Qw^{.108}$	4
Width to Depth Ration (W/D)	Ft/Ft	$W/D = 54.2\ Qw^{-.297}$	1
		$W/D = 139.0\ Qw^{-.562}$	4

[1] Qw = streamflow in ft^3/s

Table 12. Hydraulic Geometry Relations for Transects 1 and 4, North Fork Little Snake River (NFLS) Study Reach 6.

Hydraulic Parameter	Units	Equation[1]	Transect
Stream Width (W)	Feet	$W = 15.7\ Qw^{.051}$	1
		$W = 14.5\ Qw^{.068}$	4
Mean Depth (D)	Feet	$D = 0.26\ Qw^{.405}$	1
		$D = 0.16\ Qw^{.501}$	4
Mean Velocity (V)	Ft/sec	$V = 0.25\ Qw^{.544}$	1
		$V = 0.43\ Qw^{.430}$	4
Width to Depth Ratio (W/D)	Ft/Ft	$W/D = 60.1\ Qw^{-.354}$	1
		$W/D = 92.8\ Qw^{-.450}$	4

[1] Qw = streamflow in ft^3/s

Table 13. Hydraulic Geometry Relations for Transects 1 and 3, North Fork of Big Sandstone Creek Study Reach.

Hydraulic Parameter	Units	Equation[1]	Transect
Stream Width (W)	Feet	$W = 11.8\ Qw^{.381}$	1
		$W = 10.8\ Qw^{.322}$	3
Mean Depth (D)	Feet	$D = 0.21\ Qw^{.305}$	1
		$D = 0.26\ Qw^{.320}$	3
Mean Velocity (V)	Feet/sec	$V = 0.40\ Qw^{.338}$	1
		$V = 0.36\ Qw^{.358}$	3
Width to Depth Ratio (W/D)	Ft/Ft	$W/D = 56.0\ Qw^{-.244}$	1
		$W/D = 41.4\ Qw^{-.300}$	3

[1] Qw = streamflow in ft^3/s

Table 14. Hydraulic Geometry Relations for Transects 1 and 4, South Fork of Big Sandstone Creek Study Reach.

Hydraulic Parameter	Units	Equation[1]	Transect
Stream Width (W)	Feet	$W = 14.0\ Qw^{.300}$	1
		$W = 7.7\ Qw^{.346}$	4
Mean Depth (D)	Feet	$D = 0.31\ Qw^{.348}$	1
		$D = 0.26\ Qw^{.408}$	4
Mean Velocity (V)	Ft/sec	$V = 0.23\ Qw^{.354}$	1
		$V = 0.50\ Qw^{.346}$	4
Width to Depth Ratio (W/D)	Ft/Ft	$W/D = 45.6\ Qw^{-.349}$	1
		$W/D = 29.4\ Qw^{-.363}$	4

[1] Qw = streamflow in ft^3/s

Table 15. Hydraulic Geometry Relations for Transects 1 and 4, Big Sandstone Creek Study Reach.

Hydraulic Parameter	Units	Equation[1]	Transect
Stream Width (W)	Feet	$W = 18.5\ Qw^{.301}$	
		$W = 23.0\ Qw^{.314}$	4
Mean Depth (D)	Feet	$D = 0.17\ Qw^{.507}$	1
		$D = 0.25\ Qw^{.421}$	4
Mean Velocity (V)	Ft/sec	$V = 0.31\ Qw^{.498}$	1
		$V = 0.17\ Qw^{.589}$	4
Width to Depth Ratio (W/D)	Ft/Ft	$W/D = 108.9\ Qw^{-.510}$	1
		$W/D = 93.0\ Qw^{-.408}$	4

[1] Qw = streamflow in ft^3/s

Table 16. Mean water surface slope by transect and reach on the North Fork Little Snake River (NFLS) and Big Sandstone Creek (BSC).

Stream	Reach	Transects	Water Surface Slope (%)
NFLS	0	1,2,3,4	0.85
NFLS	2	1,2	3.7
NFLS	2	3,4	6.0
NFLS	3	1,2	1.5
NFLS	3	3,4	3.4
NFLS	4	1,2	0.11
NFLS	4	3,4	0.98
NFLS	5	1,2	0.27
NFLS	5	3,4	1.7
NFLS	6	1,2	0.42
NFLS	6	3,4	1.0
BSC	North Fork	1,2	0.58
BSC	North Fork	3	2.4
BSC	North Fork	4	4.6
BSC	South Fork	1,2,3,4	3.4
BSC	Mainstem	1,2,3,4	1.4
BSC	Mainstem	5	2.7

Bed Material Characteristics

Bed material characteristics were evaluated spatially and temporally between and within study reaches by the measurement of stored material quantity (deposition depth) and its particle size distribution (from core sample analysis). Stored material is here considered the sand, gravel and small cobble particles (as defined by the sediment grade scale proposed by the American Geophysical Union and described by Chang, 1988) which were in temporary storage within the study reaches and subject to transport. These particles are differentiated from the large cobbles, boulders and bedrock which underlay the channel and are not subject to frequent transport. Trends in the quantity of stored material for the study streams and reaches are presented in Figures 11, 12 and 13 and summarized in Table 17. Trends in the median particle size at each reach over the course of the study are presented in Figures 14, 15, and 16 and summarized in Table 18. The particle size distributions for three sampling dates at NFLS Reaches 0, 4, 5, and 6, and the three BSC reaches are presented in Figures A-1 to A-7 of the Appendix.

The quantity of stored sediment in the study reaches generally varied inversely with channel slope and was relatively stable over time. NFLS Reach 2 and South Fork BSC, the steepest sections, averaged 38 and 59 mm of deposited material with coefficients of variation of 24 and 22 percent, respectively. On the NFLS, Reaches 4 and 5 consistently stored the largest amounts of finer material due to their low gradients and location just below the site of the 1984 sediment spill. Quantities in storage were similar to those within the unimpacted North Fork BSC and BSC reaches. Variability over time was also quite similar between these reaches. Deposition quantity at NFLS Reaches 0 and 6 compared favorably, averaging 60 mm at the upstream site and 64 mm at the downstream site over the three year sampling period. These similarities suggest the sediment wave resulting from the 1984 spill had not yet migrated downstream to Reach 6 and that approximately 60 mm may be the natural stable depth of stored material in such NFLS pool habitats. The fall 1984 deposition depth in Reach 4, 53 mm, measured prior to the redistribution of

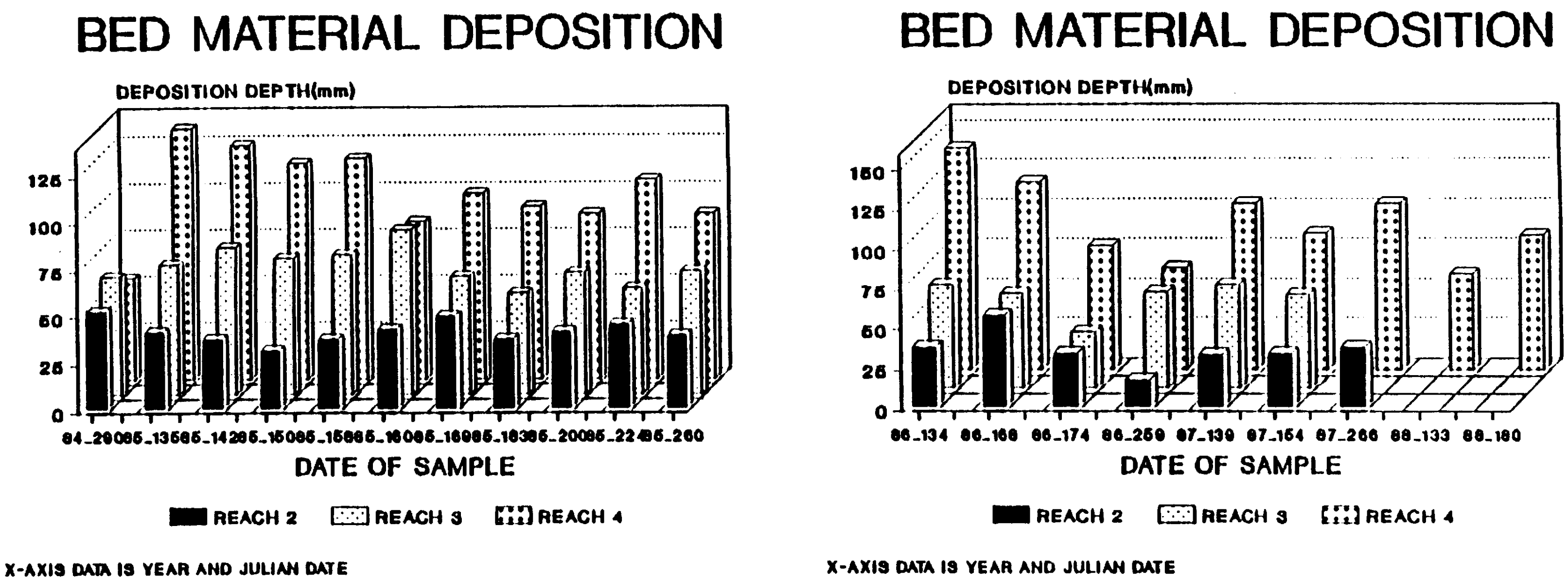


Figure 11. Depth of stored sediment at Reaches 2, 3, and 4, North Fork Little Snake River, 1984 to 1988.

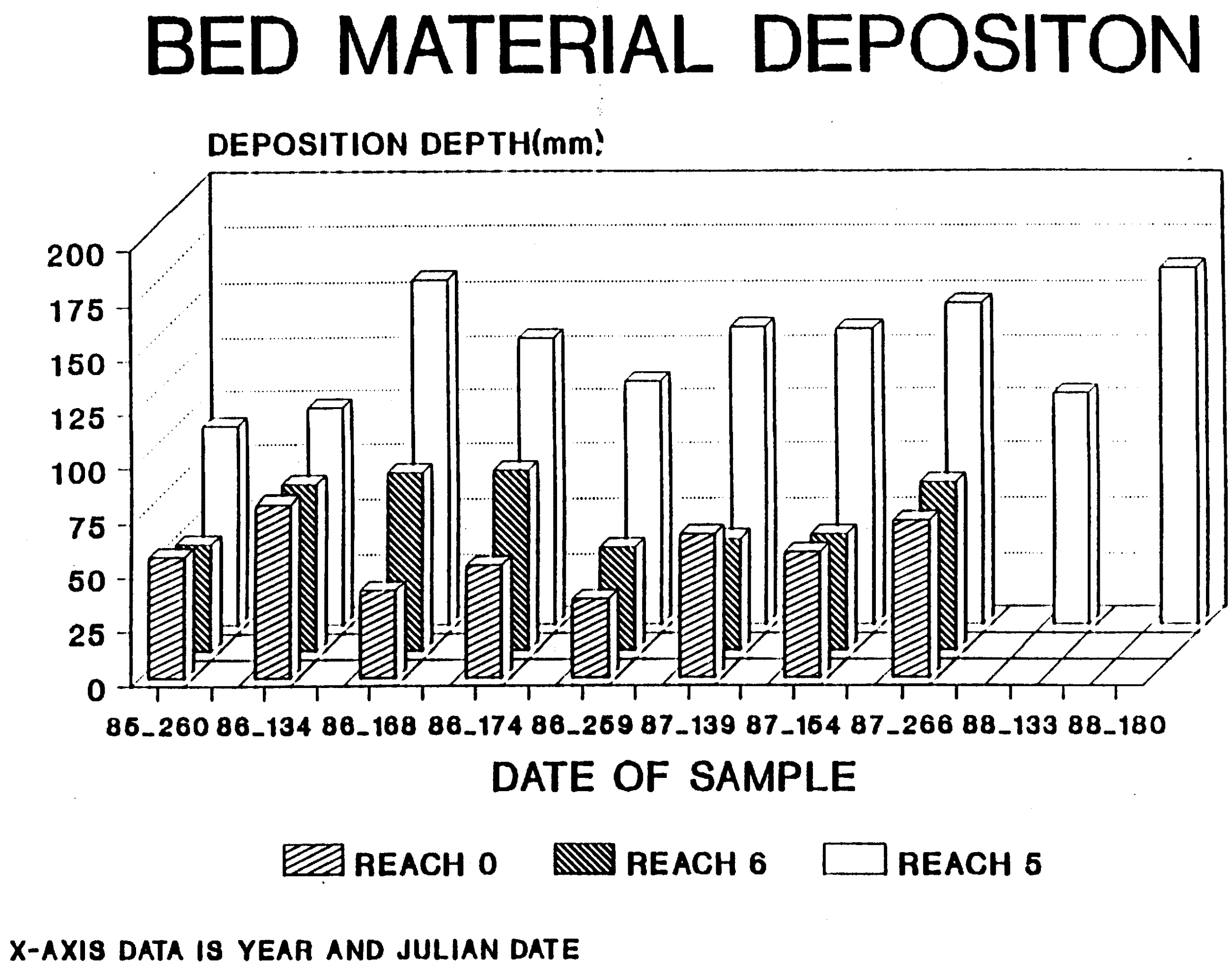
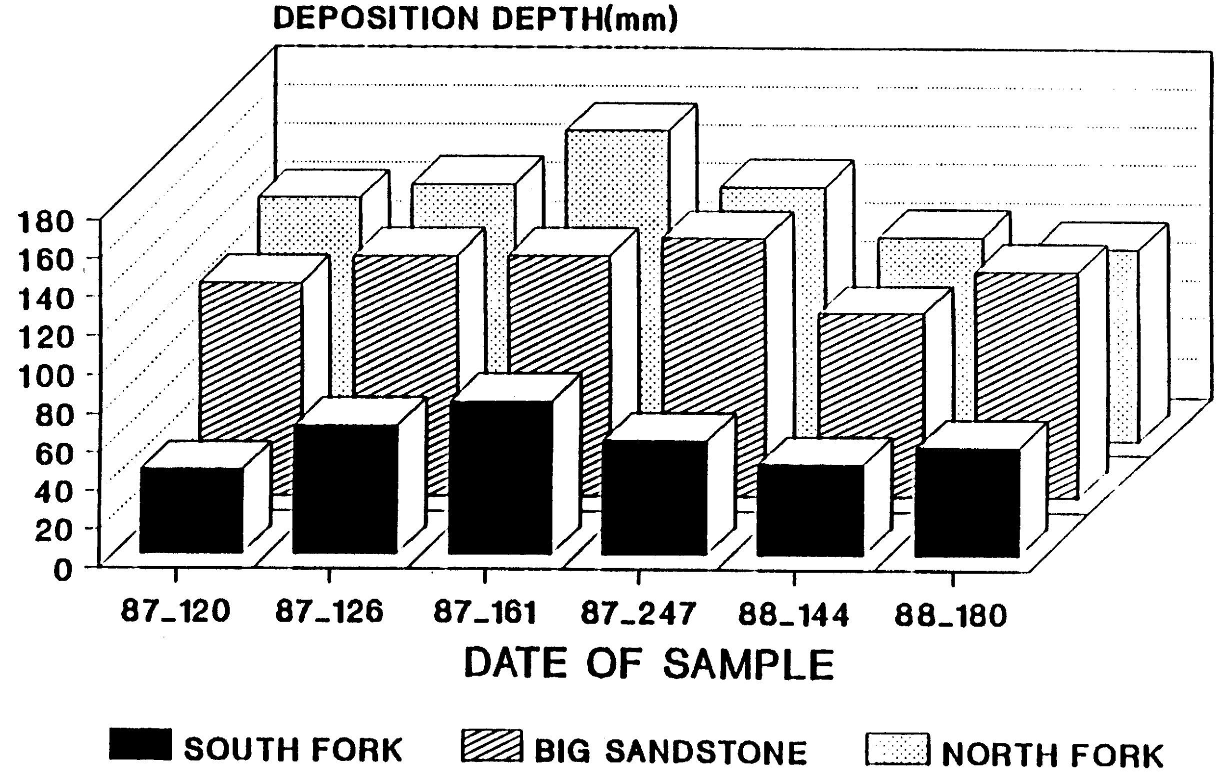


Figure 12. Depth of stored sediment at Reaches 0, 5, and 6, North Fork Little Snake River, 1985 to 1988.

BED MATERIAL DEPOSITION



X-AXIS DATA IS YEAR AND JULIAN DATE

Figure13. Depth of stored sediment in the Big Sandstone Creek study reaches, 1987 and 1988.

Table 17. Comparison of means, standard deviations and coefficients of variation for deposition depth (mm) at the North Fork Little Snake River (NFLS) and Big Sandstone Creek (BSC) study reaches.

Stream Reach	Sample Size [1]	Mean (mm)	St. Deviation (mm)	Coefficient of Variation (%)
NFLS-R0	7	60.0	14.4	24
NFLS-R2	18	37.7	8.9	24
NFLS-R3	18	63.1	11.2	18
NFLS-R4	20	97.1	23.9	25
NFLS-R5	10	128.5	25.0	19
NFLS-R6	8	64.4	15.6	24
NFBSC	6	126.0	22.7	18
SFBSC	6	58.7	13.1	22
BSC	6	119.0	11.1	9

[1] Each sample represents 80 measurements

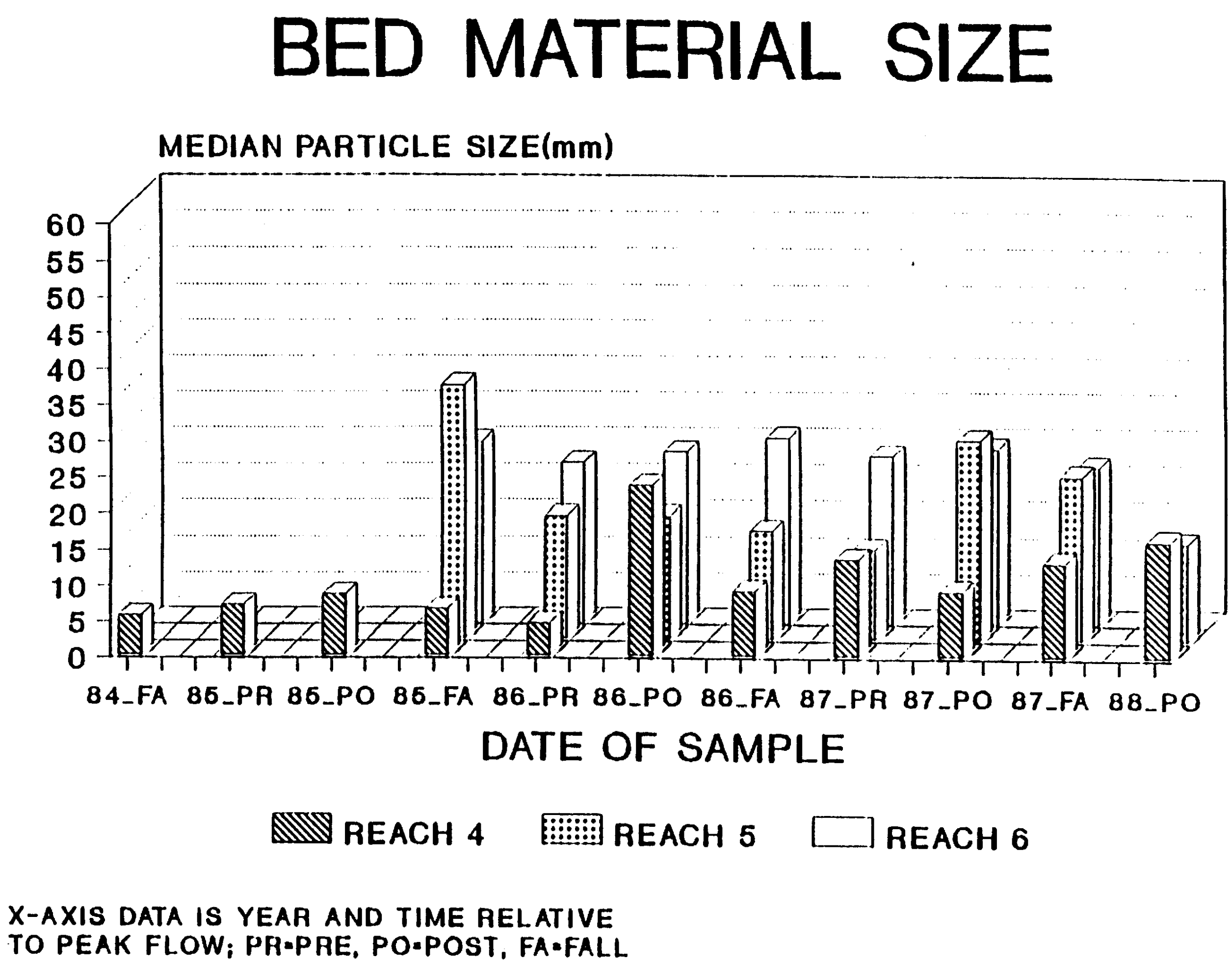
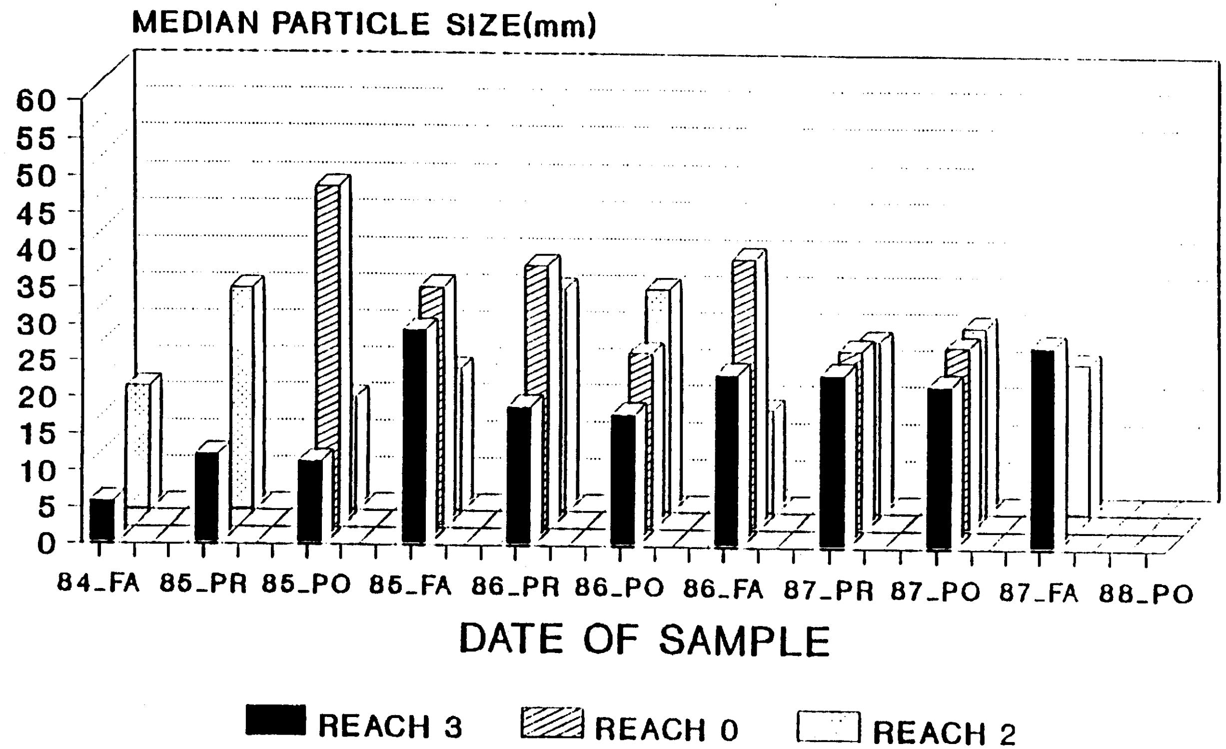


Figure 14. Median particle size of stored sediment at Reaches 4, 5, and 6, North Fork Little Snake River, 1984 to 1988.

BED MATERIAL SIZE



X-AXIS DATA IS YEAR AND TIME RELATIVE
TO PEAK FLOW; PR=PRE, PO=POST, FA=FALL

Figure 15. Median particle size of stored sediment at Reaches 0, 2, and 3, North Fork Little Snake River, 1984 to 1987.

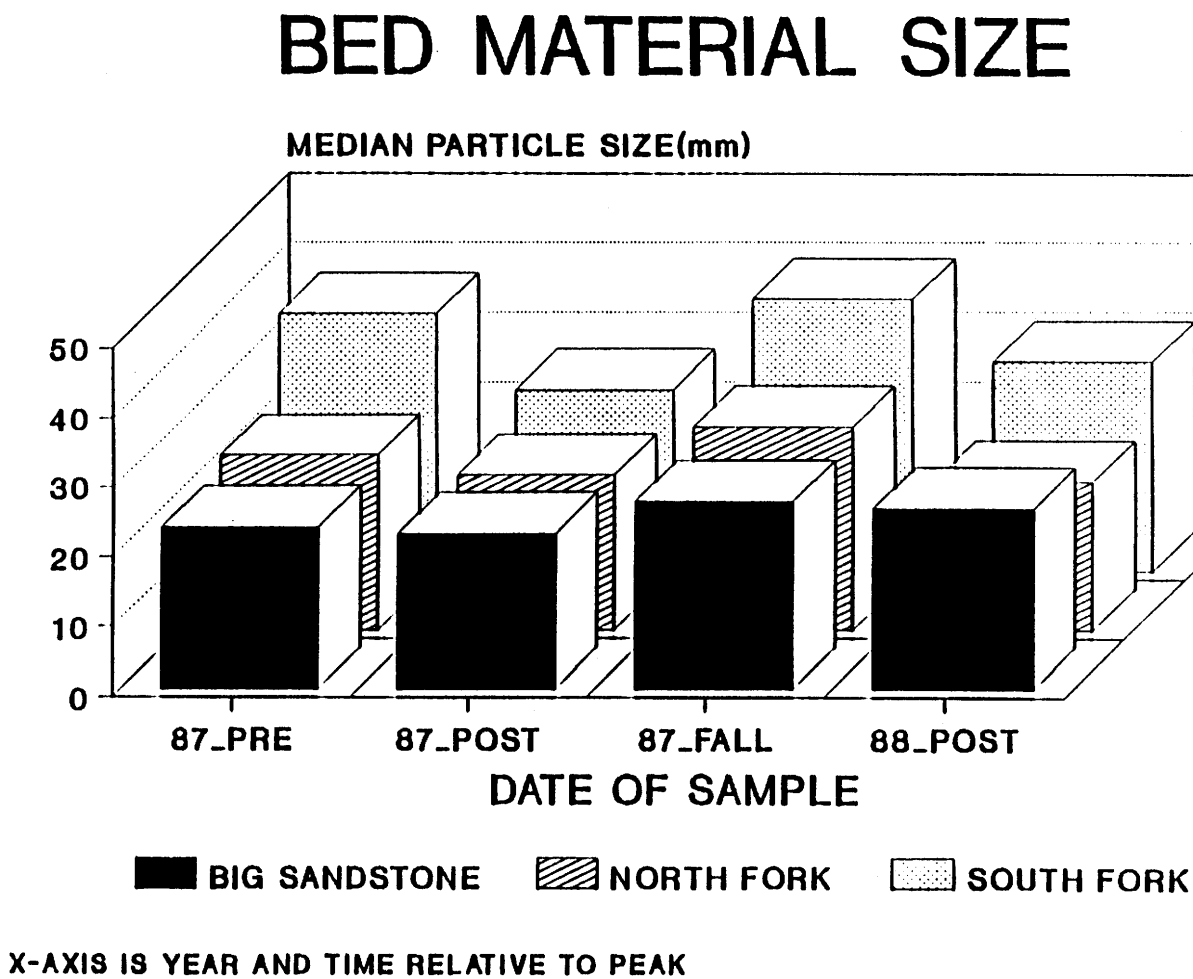


Figure 16. Median particle size of stored sediment at the Big Sandstone Creek study reaches, 1987 and 1988.

Table 18. Comparison of means, standard deviations and coefficients of variation for median bed material particle size (mm) at the North Fork Little Snake River (NFLS) and Big Sandstone Creek (BSC) study reaches.

Stream Reach	Sample Size [1]	Mean (mm)	St. Deviation (mm)	Coefficient of Variation (%)
NFLS-R0	7	31.9	8.7	27
NFLS-R2	10	22.2	6.4	29
NFLS-R3	10	18.8	7.6	40
NFLS-R4	11	10.5	5.9	56
NFLS-R5	8	20.0	7.9	40
NFLS-R6	7	23.5	1.5	6
NFBSC	4	24.5	4.0	16
SFBSC	4	33.0	6.1	18
BSC	4	24.2	2.1	9

[1] Each sample represents 12 McNeil core samples

the spill material by spring runoff discharges, also supports this hypothesis.

As summarized in Table 18, the median particle size of stored sediment was largest and coefficients of variation were smallest in the unimpacted study reaches. These included NFLS Reaches 0 and 6, and the three BSC reaches. Within the impacted reaches, median particle size was directly related to gradient. Comparison of the particle size distributions presented in Figures A-1 to A-7 reinforces these findings. The proportion of sand particles (less than 2.0 mm diameter) in the bed material was consistently higher in NFLS Reaches 4 and 5 than in the unimpacted reaches, ranging up to 38 percent by weight in Reach 4. Overall, the particle size distributions of stored material at the unimpacted reaches compared favorably with the distributions used by trout for spawning elsewhere on the Medicine Bow National Forest (Figure A-8, Appendix), as determined by Reiser and Wesche (1977).

Trial flushing flow releases were made on the NFLS during 1985 and 1986 to mitigate the effects of the 1984 sediment spill. As the City of Cheyenne does not have storage capacity in association with their west slope collection system, the releases entailed allowing the natural peak runoff flows to bypass the diversion structure. The 1985 hydrograph was of sufficient magnitude and duration to move the spill material into Reach 4, and initiate transport downstream. Deposition depth varied from 136 mm in mid-May down to a post-flush low of 88 mm in early July. Median particle size remained constant during this period. As shown on Figure 11, late season baseflows during the fall and winter of 1985-86 appeared to serve an important role in pool filling. By May 1986, deposition depth had again increased to 139 mm at Reach 4. The large spring runoff of 1986 was of sufficient magnitude and duration to scour 75 mm of material from the streambed at Reach 4 and increase median particle size. However, the duration was not sufficient to move the spill completely through Reach 5, as indicated by the observed increase in stored material and the reduction in particle size. Wesche et al (1987) provides a detailed description of these flow releases and the bed material response.

The above observations point out several aspects of stream behavior which should be considered in flushing flow studies. First, the greatest variability in bed material characteristics occurred within low gradient impacted reaches. Such stream sections are critical in the design and conduct of maintenance flow studies. Steeper reaches are more stable in regard to bed material characteristics. Second, while the magnitude of the flow event is important in the mobilization of stored material, the duration of the event must be given careful consideration to assure transport out of critical habitat reaches. Multiple study reaches are needed to confirm this. Third, baseflow contributes to pool aggradation and should not be overlooked in the development of recommendations. Fourth, the bed material needs to be evaluated not only from the standpoint of quantity, but also particle size distribution. Depth of stored material alone may not reflect habitat quality. Finally, short-term sampling, which determines immediate responses, may lead to erroneous conclusions regarding the degree of success achieved by a particular flow event. In the case of mitigative flow releases, several years may be necessary to assure objectives are met.

Sediment Transport

A major thrust of this study has been to investigate sediment transport processes in steep, rough mountain stream channels. During the four-year field study period, 642 bedload and 735 suspended load sediment transport samples were taken at the NFLS and BSC study reaches. Stream conditions varied widely during sampling. Discharge varied from approximately 0.6 to 162 cfs (0.15 to 18.1Q_{AA}) and channel gradients at sampling cross-sections ranged from 0.11 to 6.0 percent. Sampling times were from early spring (April) prior to peak snowmelt runoff through the late fall (October). As previously mentioned, sampling effort focused on one upstream and one downstream transect within each reach, although numerous samples were collected at intermediate transects and are included as appropriate in the analysis.

The power function relations developed between bedload and suspended load discharge and streamflow for an upper and a lower transect at each study reach are presented in Tables 19 and 20. Regression statistics are also included. Scatter plots of the data, including the best-fit lines and 95 percent confidence belts about this line, are presented on Figures A-9 to A-82 of the Appendix

Table 19. Relations of bedload (Q_{BL}) and suspended load (Q_{SL}) transport (tons/day) to discharge (Q_w, ft³/s) at the six North Fork Little Snake River (NFLS) study reaches.

Reach - Transect	Sample Size	Equation	St.Error of Regr. Coeff.	Coeff. of Deter. (R^2)	Corr. Coeff.(r)	F[1]	Prob>F
RO - 1	20	$Q_{BL} = .022Qw^{1.80}$	0.18	0.85	0.92	101.3	.0001
	20	$Q_{SL} = .005Qw^{1.47}$	0.12	0.89	0.94	146.5	.0001
RO - 4	17	$Q_{BL} = .001Qw^{1.91}$	0.14	0.93	0.96	186.1	.0001
	17	$Q_{SL} = .003Qw^{1.86}$	0.16	0.88	0.94	112.9	.0001
R2 - 1	15	$Q_{BL} = .0001Qw^{2.57}$	0.42	0.75	0.86	38.3	.0001
	12	$Q_{SL} = .010Qw^{1.04}$	0.19	0.75	0.87	30.0	.0003
R2 - 4	14	$Q_{BL} = .0001Qw^{2.48}$	0.28	0.87	0.93	80.1	.0001
	26	$Q_{SL} = .003Qw^{1.53}$	0.13	0.87	0.93	145.7	.0001
R3 - 1	13	$Q_{BL} = .001Qw^{1.84}$	0.30	0.78	0.88	38.8	.0001
	14	$Q_{SL} = .009Qw^{1.13}$	0.18	0.77	0.88	39.7	.0001
R3 - 4	13	$Q_{BL} = .00003Qw^{2.81}$	0.29	0.90	0.95	94.2	.0001
	13	$Q_{SL} = .006Qw^{1.28}$	0.18	0.82	0.91	51.7	.0001
R4 - 1	45	$Q_{BL} = .0001Qw^{2.19}$	0.18	0.78	0.88	150.2	.0001
	59	$Q_{SL} = .012Qw^{1.29}$	0.09	0.79	0.89	208.5	.0001
R4 - 4	25	$Q_{BL} = .007Qw^{1.36}$	0.31	0.45	0.67	18.7	.0002
	21	$Q_{SL} = .005Qw^{1.62}$	0.18	0.79	0.89	71.7	.0001
R5 - 1	35	$Q_{BL} = .0001Qw^{2.33}$	0.16	0.87	0.93	222.7	.0001
	42	$Q_{SL} = .013Qw^{1.27}$	0.11	0.78	0.89	146.0	.0001

Table 19 Continued.

Reach-Transect	Sample Size	Equation	St. Error of Regr. Coeff.	Coeff. of Deter.(R^2)	Corr. Coeff.(r)	F[1]	Prob > F
R5 - 4	15	$Q_{BL} = .019Qw^{1.26}$	0.36	0.64	0.80	14.2	.0024
	13	$Q_{SL} = .010Qw^{1.17}$	0.23	0.71	0.84	27.0	.0003
R6 - 1	21	$Q_{BL} = .0001Qw^{1.97}$	0.22	0.80	0.90	77.4	.0001
	29	$Q_{SL} = .006Qw^{1.46}$	0.14	0.81	0.90	113.3	.0001
R6 - 4	13	$Q_{BL} = .0003Qw^{1.80}$	0.28	0.79	0.89	41.9	.0001
	14	$Q_{SL} = .002Qw^{1.66}$	0.21	0.84	0.91	61.6	.0001

[1] Ho: B = O

Table 20. Relations of bedload (Q_{BL}) and suspended load (Q_{SL}) transport (tons/day) to discharge (Q_w, ft^3/s) at the North Fork (NF), South Fork (SF) and Big Sandstone Creek (BSC) study reaches.

Reach-Transect	Sample Size	Equation	St. Error of Regr. Coeff.	Coeff. of Deter. (R^2)	Corr. Coeff.(r)	F[1]	Prob>F
NFBSC - 1	26	$Q_{BL} = .0007Qw^{2.07}$	0.21	0.80	0.90	96.7	.0001
	24	$Q_{SL} = .010Qw^{1.21}$	0.21	0.59	0.77	31.7	.0001
NFBSC - 3	20	$Q_{BL} = .0005Qw^{2.12}$	0.30	0.74	0.86	51.4	.0001
	16	$Q_{SL} = .007Qw^{1.36}$	0.30	0.65	0.81	25.9	.0002
SFBSC - 1	23	$Q_{BL} = .008Qw^{0.74}$	0.36	0.17	0.41	4.2	.0527
	26	$Q_{SL} = .013QW^{1.03}$	0.10	0.82	0.91	112.8	.0001
SFBSC - 4	17	$Q_{BL} = .002Qw^{0.81}$	0.48	0.16	0.40	2.8	.1136
	23	$Q_{SL} = .010Qw^{1.14}$	0.16	0.72	0.85	54.0	.0001
BSC - 1	27	$Q_{BL} = .022Qw^{1.63}$	0.15	0.80	0.90	101.2	.0001
	30	$Q_{SL} = .008Qw^{1.19}$	0.14	0.73	0.85	75.9	.0001
BSC - 4	23	$Q_{BL} = .0009Qw^{1.76}$	0.33	0.58	0.76	28.5	.0001
	27	$Q_{SL} = .005Qw^{1.32}$	0.15	0.76	0.87	78.8	.0001

[1] Ho: B = O

for each transect sampled.

In all cases, the relationship between sediment discharge and streamflow was positive. With the exception of two transects, all correlation coefficients were statistically significant and the slopes of the best-fit lines were significantly different than 0 ($P <= 0.05$). The two exceptions were for bedload discharge at Transects 1 and 4 within the steep, rough South Fork BSC study reach. Within reaches, exponents were typically higher for bedload discharge than for suspended load discharge (15 of 16 cases, excluding South Fork BSC), while coefficients were higher for suspended load (15 of 16 cases). These results indicate bedload predominates total load at higher streamflows, while the suspended fraction predominates at lower discharges.

The concept of channel maintenance implies a balance should exist between the sediment supplied to a stream reach and the sediment transported through that reach. To evaluate this concept, annual sediment budgets were developed for the critical lower gradient study reaches based upon the sediment transport relations presented in Tables 19 and 20, the estimated average annual discharges contained in Table 6, and the flow duration curve shown in Figure 8. These budgets are presented in Tables 21 to 26 for NFLS Reaches 0, 4, 5, and 6, and the North Fork BSC and BSC Reaches, respectively. With the exception of NFLS Reach 4, the estimated differences between sediment imported to a reach and exported from that reach ranged from 0.3 to 7.5 percent. These results indicate that given a natural flow regime, the reaches would remain in balance and thus in a condition of quasi-equilibrium. The import-export difference at Reach 4 was 20.4 percent, indicating a trend toward aggradation and suggesting that transport capability is less than sediment supply, likely a result of the excess sediment loading which occurred.

The concept of effective discharge discussed in Chapter 2 is germane to an understanding of channel maintenance requirements. The results presented in Tables 21 to 26 indicate that the effective discharges for the two mountain streams investigated consistently range from about 8 to 10 times the average annual discharge. While the transport rates for this range of flows is less than for higher discharges, their availability over a water year enhances their contribution to total sediment transport. The distribution of bedload and suspended load transport, expressed as percent

Table 21. Total Annual Bedload (BL) and Suspended Load (SL) sediment budget for Reach 0, North Fork Little Snake River (NFLS).

	Transect 1			Transect 4	
Qw (ft^3/s)	#Days Qw Present	Total BL (tons)	Total SL (tons)	Total BL (tons)	Total SL (tons)
186.0	.0365	1.10	0.43	1.06	0.68
171.0	.1095	2.83	1.15	2.70	1.78
156.0	.1825	4.00	1.67	3.77	2.55
141.0	.365	6.66	2.88	6.22	4.31
126.8	1.095	16.51	7.39	15.25	10.84
96	1.825	16.65	8.19	14.94	11.40
74.2	3.65	20.90	11.22	18.28	14.89
57.8	10.95	40.00	23.32	34.05	29.56
21.8	36.5	22.60	18.56	17.66	19.64
6.4	36.5	2.51	3.07	1.70	2.59
2.8	36.5	0.56	0.91	0.35	0.66
1.9	36.5	0.28	0.52	0.17	0.35
1.4	36.5	0.16	0.33	0.09	0.21
1.3	36.5	0.14	0.30	0.08	0.18
<1.3	127	0.22	0.51	0.12	0.30
	365	135.1	80.5	116.4	99.9
Total Annual Load:	215.6 tons			216.3 tons	

Table 22. Total annual bedload (BL) and suspended load (SL) sediment budget for Reach 4, North Fork Little Snake River (NFLS).

	Transect 1			Transect 4	
Qw (ft^3/s)	# Days Qw Present	Total BL (tons)	Total SL (tons)	Total BL (tons)	Total SL (tons)
278.0	.0365	0.95	0.62	0.51	1.01
255.0	.1095	2.35	1.67	1.37	2.66
233.0	.1825	3.22	2.48	2.03	3.86
210.6	.365	5.16	4.35	3.53	6.62
189.3	1.095	12.30	11.40	9.17	16.90
143.4	1.825	11.10	13.30	10.49	18.48
110.9	3.65	12.70	19.00	14.80	25.03
86.2	10.95	21.90	41.20	31.54	51.24
32.5	36.5	8.60	39.10	27.98	38.89
9.5	36.5	0.58	8.00	5.27	6.02
4.3	36.5	0.10	2.88	1.80	1.81
2.8	36.5	0.04	1.65	1.00	0.94
2.1	36.5	0.02	1.14	0.68	0.61
1.9	36.5	0.02	1.00	0.59	0.52
<1.9	127	0.02	1.94	1.14	0.94
	365	79.1	149.7	111.9	175.5
Total Annual Load:	228.8 tons			287.4 tons	

Table 23. Total annual bedload (BL) and suspended load (SL) sediment budget for Reach 5, North Fork Little Snake River (NFLS).

		Transect 1		Transect 4	
Qw (ft^3/s)	# Days Qw Present	Total BL(tons)	Total SL (tons)	Total BL (tons)	Total SL (tons)
305.0	.0365	2.24	0.66	0.87	0.29
280.4	.1095	5.53	1.78	2.34	0.80
255.8	.1825	7.44	2.64	3.47	1.20
231.2	.365	11.76	4.64	6.12	2.13
207.9	1.095	27.50	12.16	16.10	5.64
157.4	1.825	24.00	14.23	18.90	6.80
121.8	3.65	26.40	20.56	27.10	10.10
94.7	10.95	44.10	44.81	60.20	22.50
35.7	36.5	15.10	43.31	59.20	24.00
10.5	36.5	0.87	9.17	12.80	5.72
4.7	36.5	0.13	3.30	4.70	2.23
3.1	36.5	0.05	1.33	2.80	1.37
2.3	36.5	0.03	1.19	1.90	0.97
2.1	36.5	0.02	0.91	1.70	0.87
<2.1	127	0.03	1.44	3.41	1.78
	365	165.2	162.1	221.6	86.4
Total Annual Load:	327.3 tons			308.0 tons	

Table 24. Total annual bedload (BL) and suspended load (SL) sediment budget for Reach 6, North Fork Little Snake River (NFLS).

		Transect 1		Transect 4	
Qw (ft^3/s)	#Days Qw Present	Total BL (tons)	Total SL (tons)	Total BL (tons)	Total SL (tons)
347.2	.0365	0.52	1.02	0.46	1.22
321.5	.1095	1.35	2.75	1.21	3.22
293.3	.1825	1.88	4.01	1.71	4.60
265.1	.365	3.08	6.92	2.86	7.79
238.3	1.095	7.49	17.76	7.06	19.57
180.5	1.825	7.22	19.76	7.13	20.58
139.6	3.65	8.71	27.18	8.97	26.88
108.6	10.95	15.92	56.57	17.10	53.19
40.9	36.5	7.74	45.50	9.78	35.12
12.0	36.5	0.69	7.63	1.07	4.60
5.4	36.5	0.14	2.39	0.25	1.22
3.5	36.5	0.06	1.27	0.12	0.60
2.7	36.5	0.04	0.87	0.07	0.39
2.4	36.5	0.03	0.73	0.06	0.32
<2.4	127	0.04	1.37	0.10	0.56
	365	54.9	197.5	58.0	179.9
Total Annual Load:		250.6 tons		237.9 tons	

Table 25. Total annual bedload (BL) and suspended load (SL) sediment budget for the North Fork Big Sandstone Creek study reach.

		Transect 1		Transect 3	
Qw (ft^3/s)	# Days Qw Present	Total BL (tons)	Total SL (tons)	Total BL (tons)	Total SL (tons)
89.3	.0365	0.28	0.08	0.23	0.11
82.1	.1095	0.71	0.22	0.58	0.30
75.0	.1825	0.98	0.32	0.80	0.44
67.8	.365	1.60	0.57	1.28	0.76
60.7	1.095	3.81	1.50	3.04	1.96
46.1	1.825	3.59	1.79	2.83	2.25
35.7	3.65	4.23	2.63	3.29	3.18
27.7	10.95	7.52	5.81	5.77	6.76
10.4	36.5	3.30	5.93	2.41	5.96
3.0	36.5	0.25	1.32	0.17	1.10
1.4	36.5	0.05	0.53	0.03	0.39
0.89	36.5	0.02	0.30	0.01	0.21
0.68	36.5	0.01	0.22	0.01	0.15
0.61	36.5	0.01	0.19	0.01	0.13
<0.61	127	0.01	0.40	0	0.25
	365	26.37	21.81	20.46	24.12
Total Annual Load:	48.2 tons			44.6 tons	

Table 26. Total annual bedload (BL) and suspended load (SL) sediment budget for the Big Sandstone Creek study reach.

		Transect 1		Transect 4	
Qw (ft^3/s)	# Days Qw Present	Total BL (tons)	Total SL (tons)	Total BL (tons)	Total SL (tons)
238.0	.0365	0.33	0.20	0.48	0.26
219.0	.1095	0.88	0.55	1.25	0.71
200.0	.1825	1.28	0.82	1.78	1.04
180.9	.365	2.19	1.46	2.98	1.83
161.9	1.095	5.55	3.83	7.36	4.74
122.8	1.825	6.06	4.60	7.57	5.48
95.2	3.65	8.22	6.81	9.70	7.84
73.8	10.95	16.69	15.10	18.66	16.79
27.6	36.5	12.36	15.70	11.16	15.25
8.1	36.5	1.89	3.67	1.31	3.01
3.7	36.5	0.57	1.46	0.34	1.07
2.4	36.5	0.29	0.86	0.15	0.60
1.8	36.5	0.19	0.63	0.10	0.42
1.6	36.5	0.16	0.55	0.08	0.36
<1.6	127	0.29	1.12	0.15	0.70
	365	56.95	57.36	63.07	60.10
Total Annual Load:	114.3			123.2 tons	

of total annual load, over a range of streamflows, normalized by average annual discharge, at a series of cross-sections are presented in Figures 17 to 24. These plots, similar to flow duration curves, indicate the Q_{50} (that flow above which 50 percent of the sediment load is transported) ranges from 8.5 to 14.5 times Q_{AA} for bedload and from 8.0 to 10.0 times Q_{AA} for suspended load. At steep gradient cross-sections (greater than 3.0 percent) 90 percent of the bedload is transported by flows of a magnitude 8.0 Q_{AA} or larger, while for moderate and low gradient transects (less than 3.0 percent gradient), Q_{90} varied from 3.0 to 7.5 Q_{AA}. For suspended load, Q_{90} typically was lower than for bedload, ranging from about 1 to 4 times Q_{AA}. These findings suggest the importance of a range of flow conditions for channel maintenance purposes, the need to consider development project effects on the total hydrograph, and the greater streamflow requirements necessary to maintain bedload transport processes.

The maintenance of stream channel conditions and the quality of the available spawning and rearing habitat for salmonids depends in large measure on the ability of the streamflow to mobilize and transport stored bed material. The process of gravel recruitment to spawning bars must be maintained and finer sediments which may impact survival-to-emergence of developing embryos and reduce habitat diversity within pools need to be periodically flushed. To evaluate these aspects of channel (and habitat) maintenance, bedload transport relations entering and exiting the NFLS and BSC study were compared. As presented in Figures 25 to 28, several mechanisms appear to be involved. Statistical comparison of the regression exponents within NFLS Reaches 0, 2, 3, and 6 and the two BSC reaches indicates no significant differences between the slopes of the best-fit lines ($P <= 0.05$). These results suggest that bedload transport occurs at similar rates through the reaches over the entire range of flows and the supply of sediment limits transport. For NFLS Reaches 4 and 5 however, the exponents are significantly different. Within these impacted pool habitats, aggradation occurs at lower discharges and scour at higher flows. The crossover point of the two lines indicates the initiation of net pool scour, or threshold of pool flushing. Within each of these reaches, the crossover occurs at approximately 12 times Q_{AA}, or 85 percent of the estimated peak flood flow having a two-year recurrence interval.

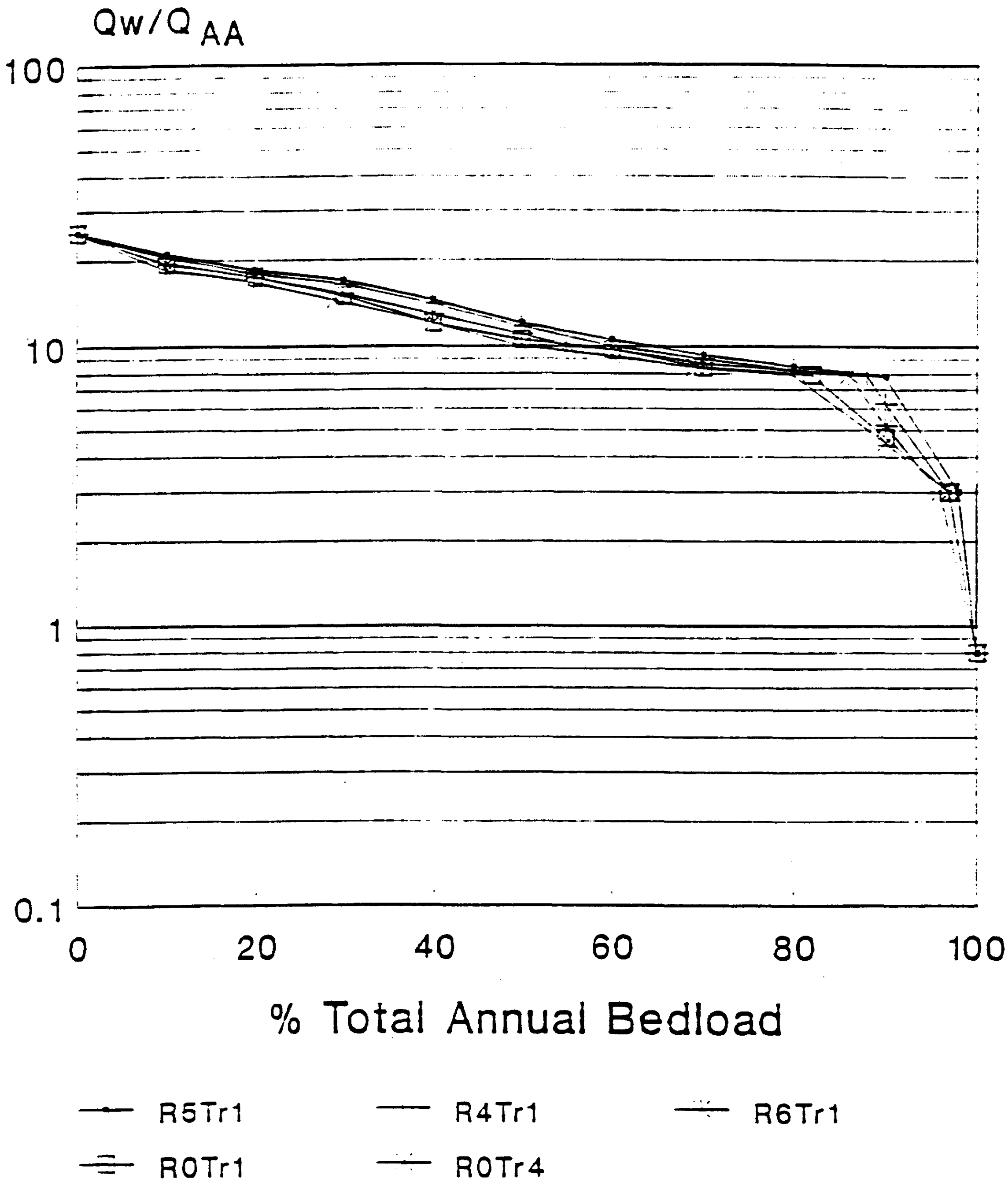


Figure 17. Percent total annual bedload versus normalized streamflow for low gradient transects, North Fork Little Snake River.

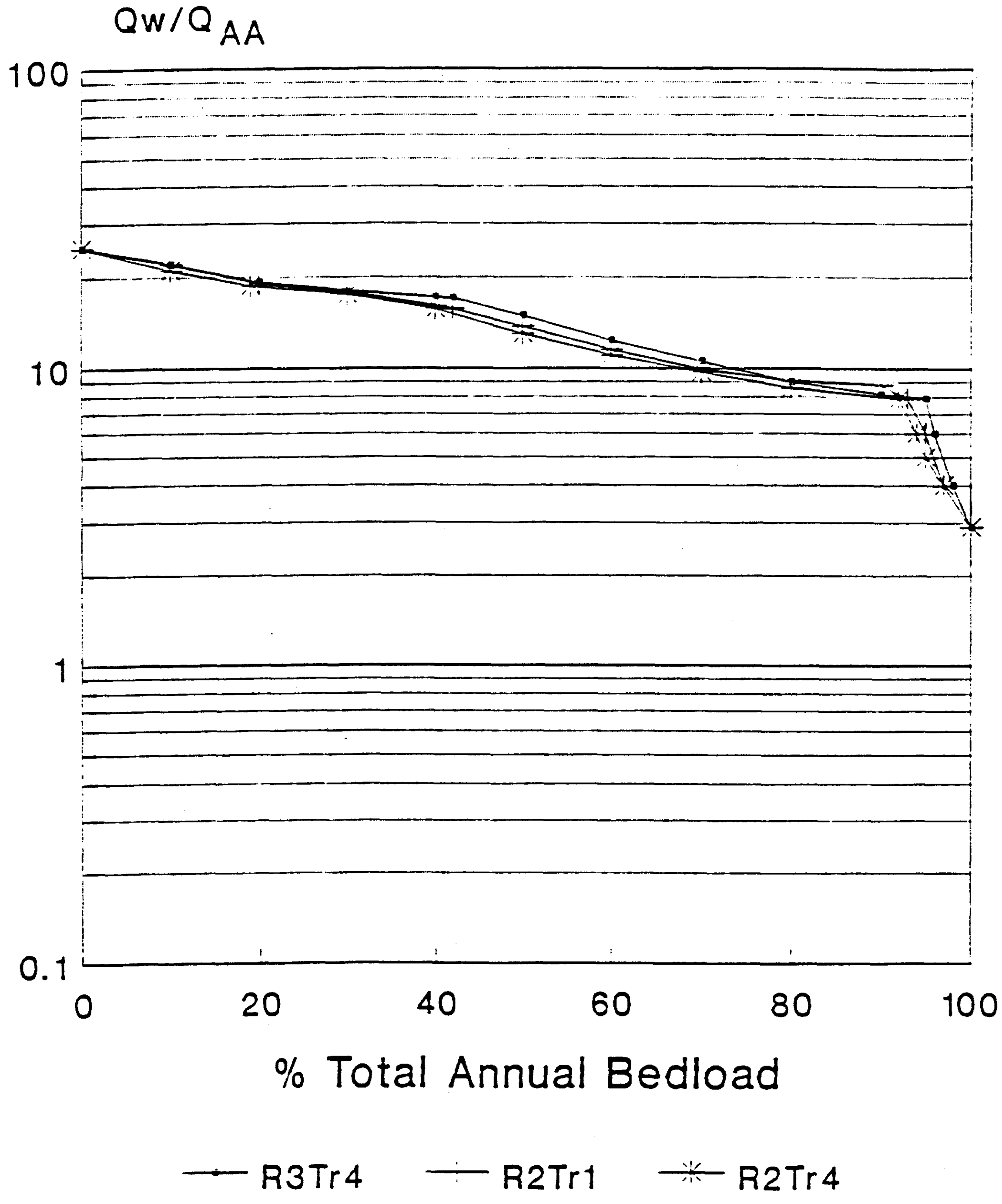


Figure 18. Percent total annual bedload versus normalized streamflow for moderate gradient transects, North Fork Little Snake River.

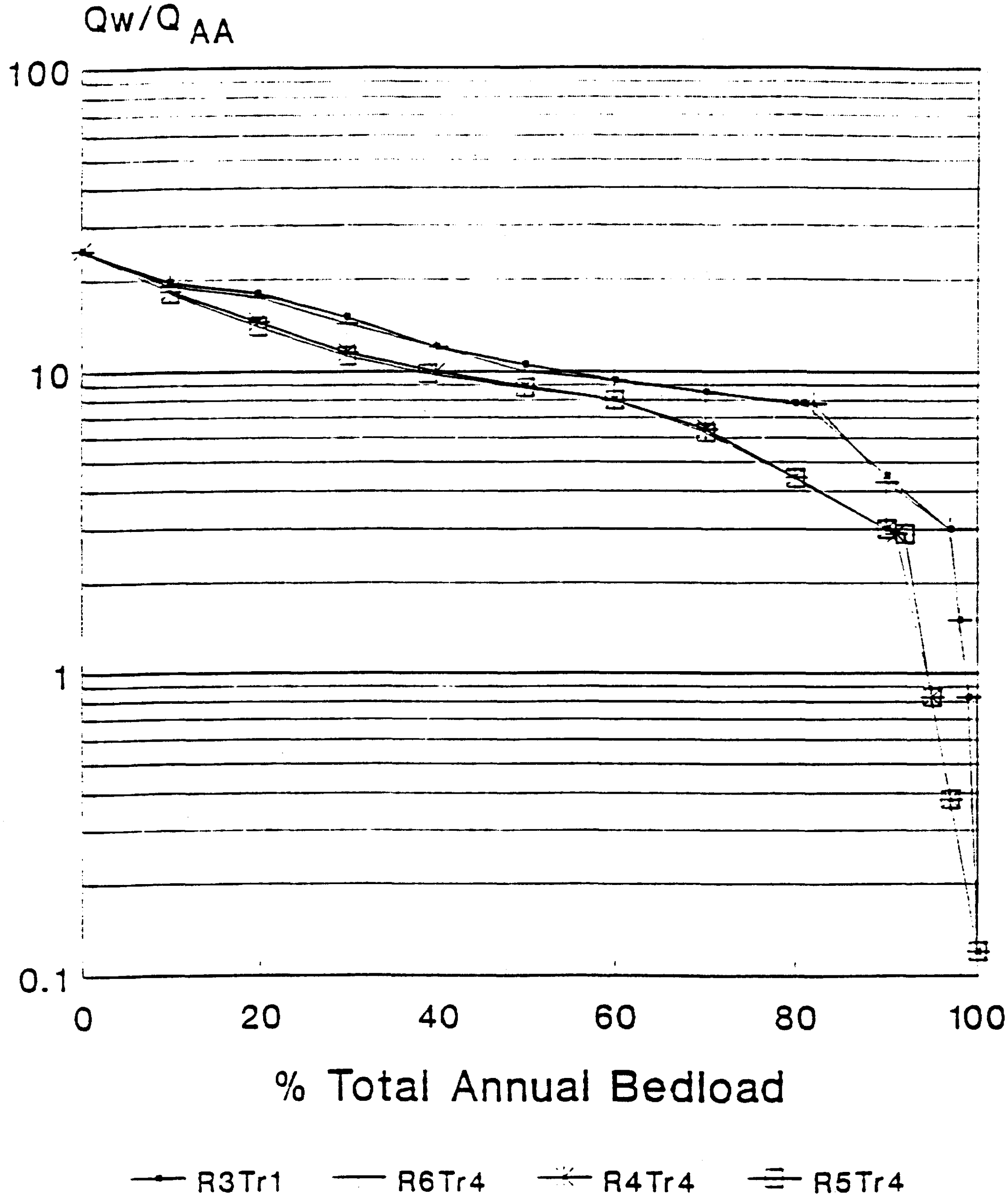


Figure 19. Percent total annual bedload versus normalized streamflow for steep gradient transects, North Fork Little Snake River.

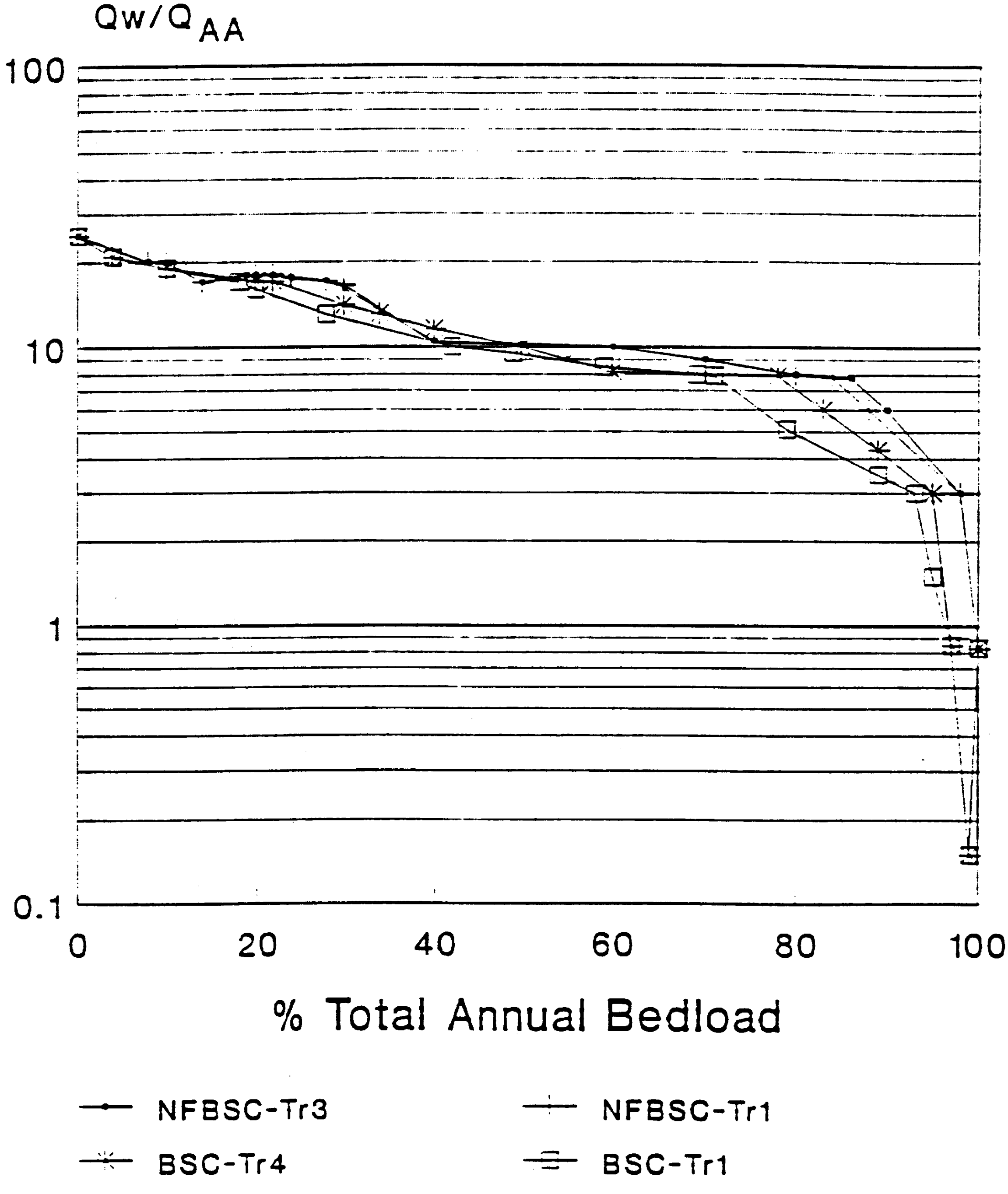


Figure 20. Percent total annual bedload versus normalized streamflow for North Fork and Big Sandstone Creek study reaches.

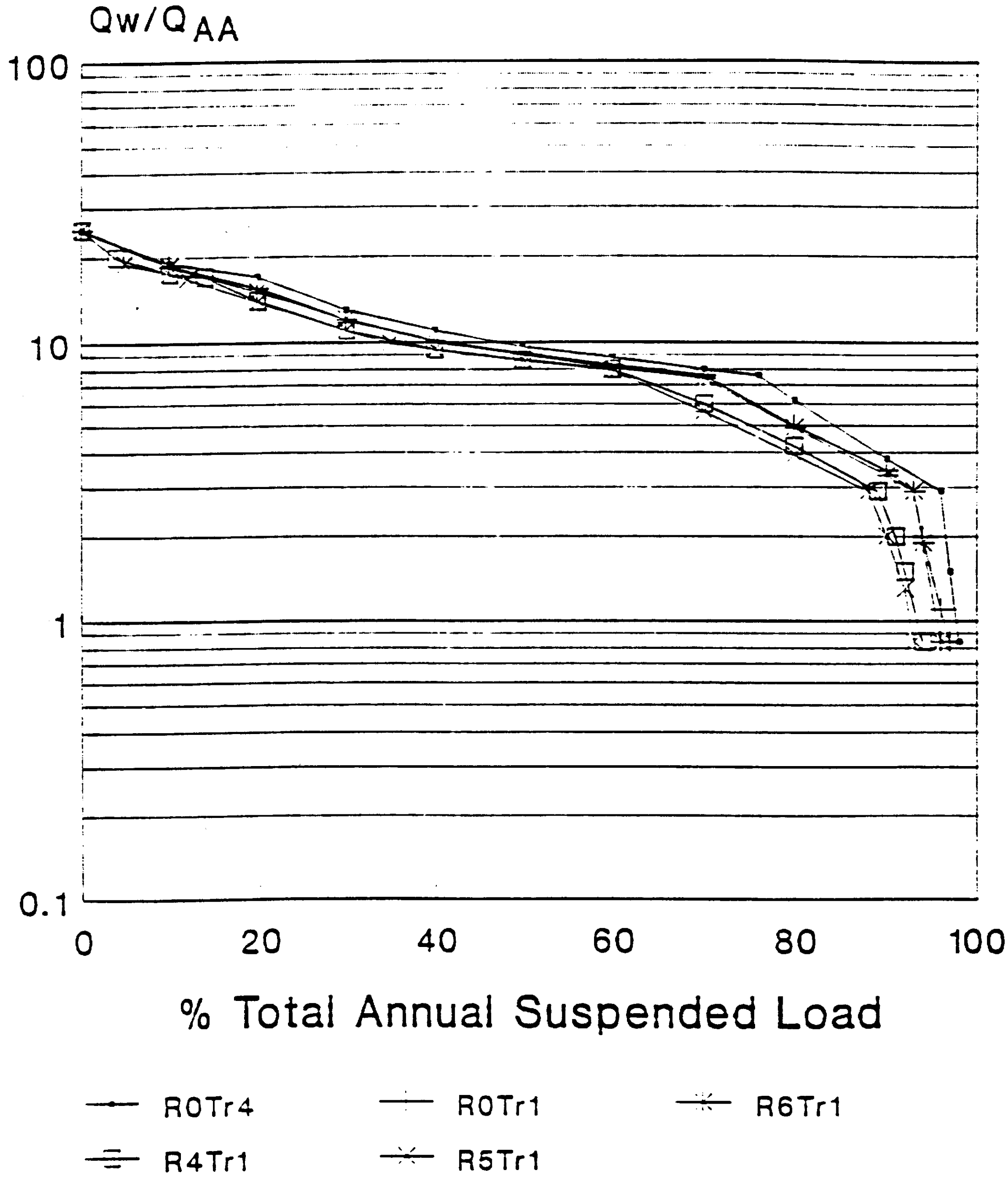


Figure 21. Percent total annual suspended load versus normalized streamflow for low gradient transects, North Fork Little Snake River.

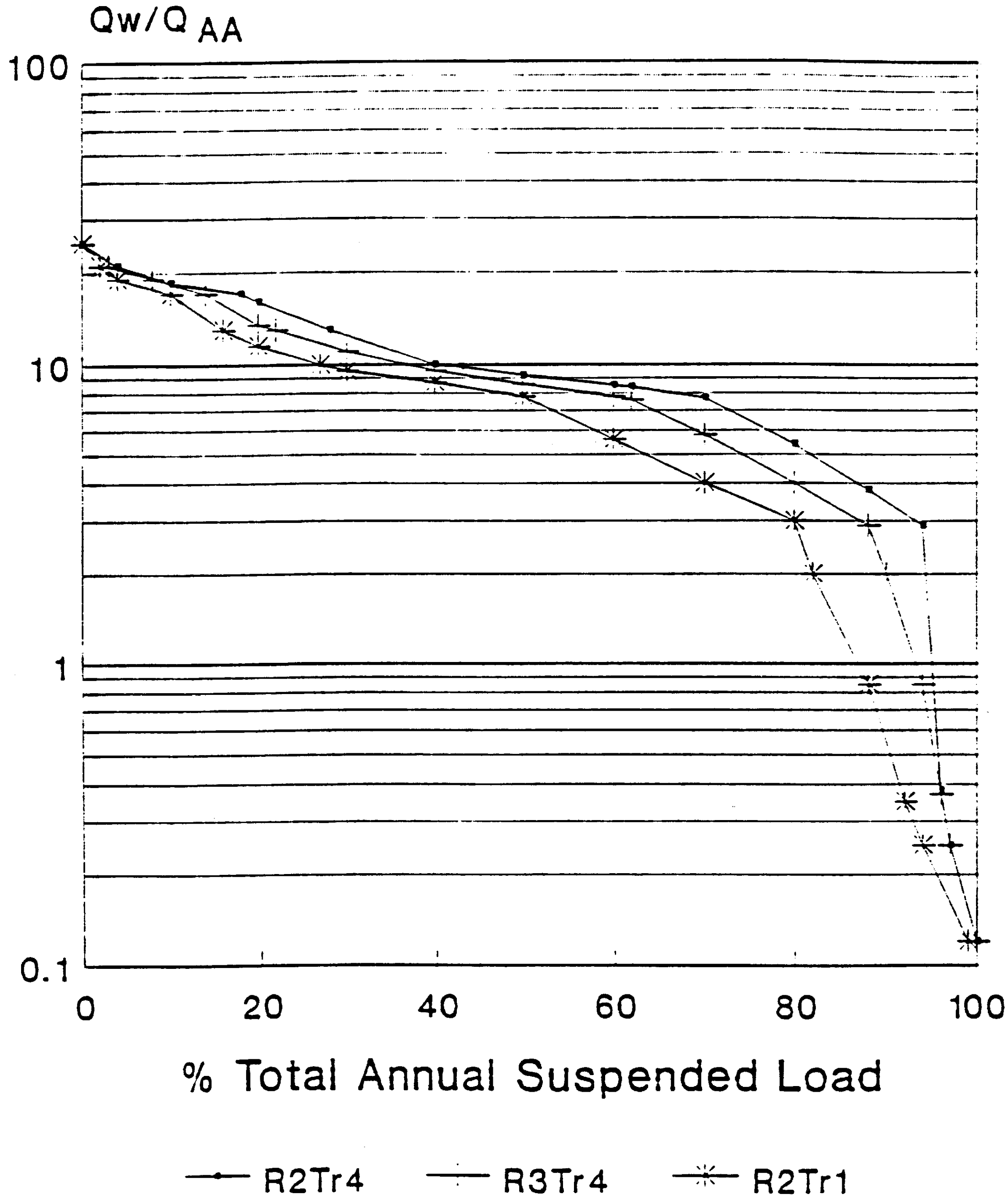


Figure 22. Percent total annual suspended load versus normalized streamflow for moderate gradient transects, North Fork Little Snake River.

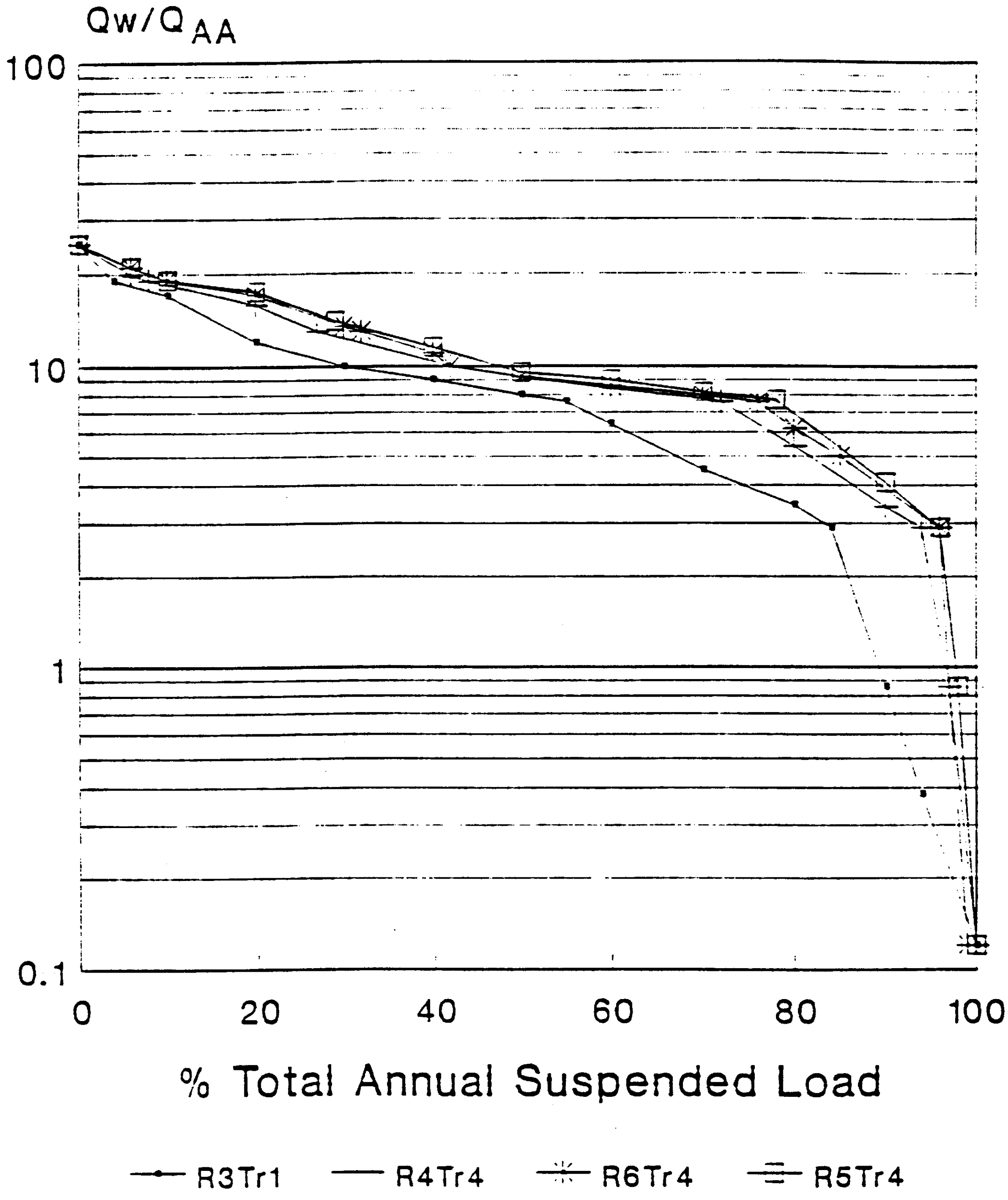


Figure 23. Percent total annual suspended load versus normalized streamflow for steep gradient transects, North Fork Little Snake River.

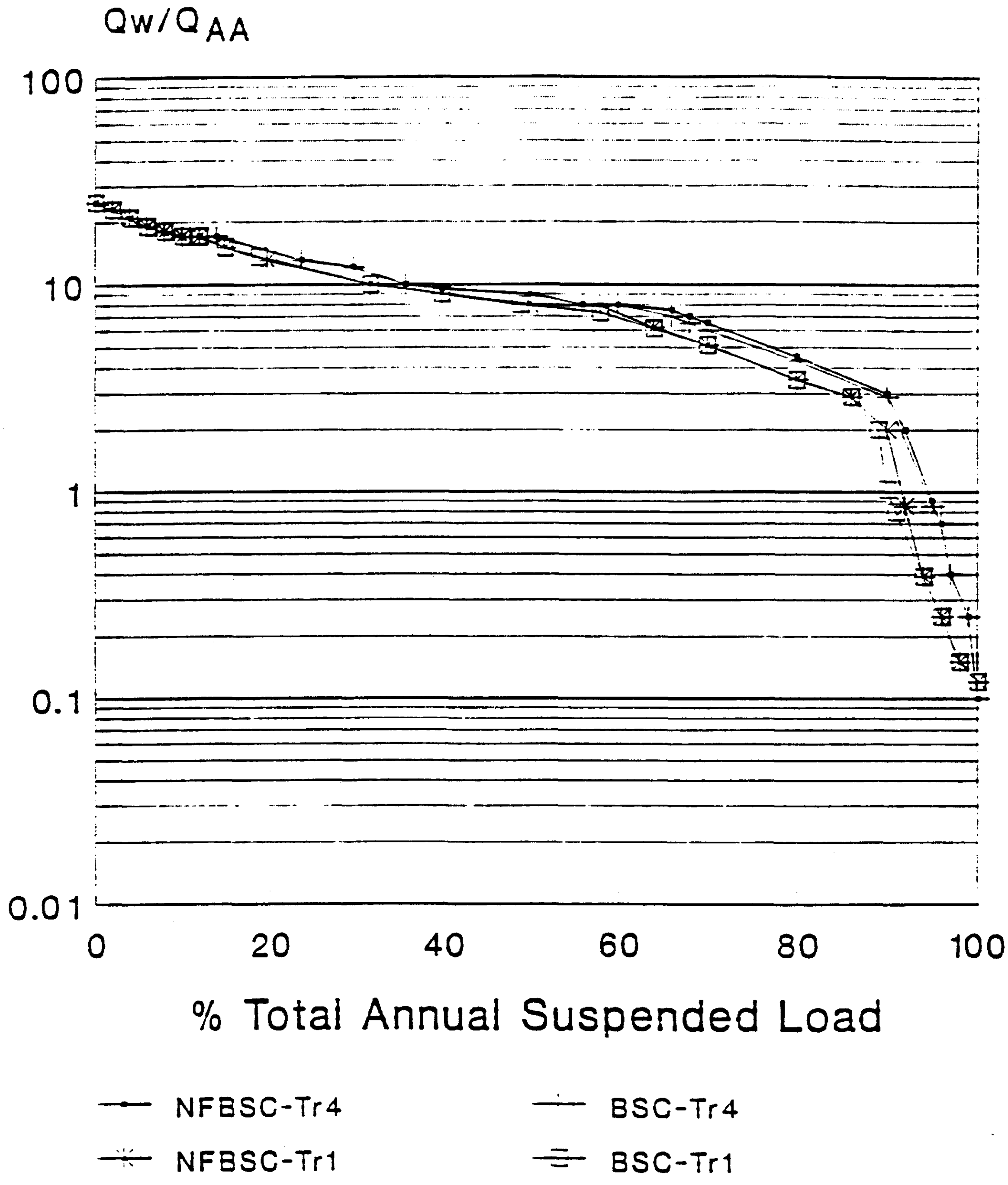


Figure 24. Percent total annual suspended load versus normalized streamflow for North Fork and Big Sandstone Creek study reaches.

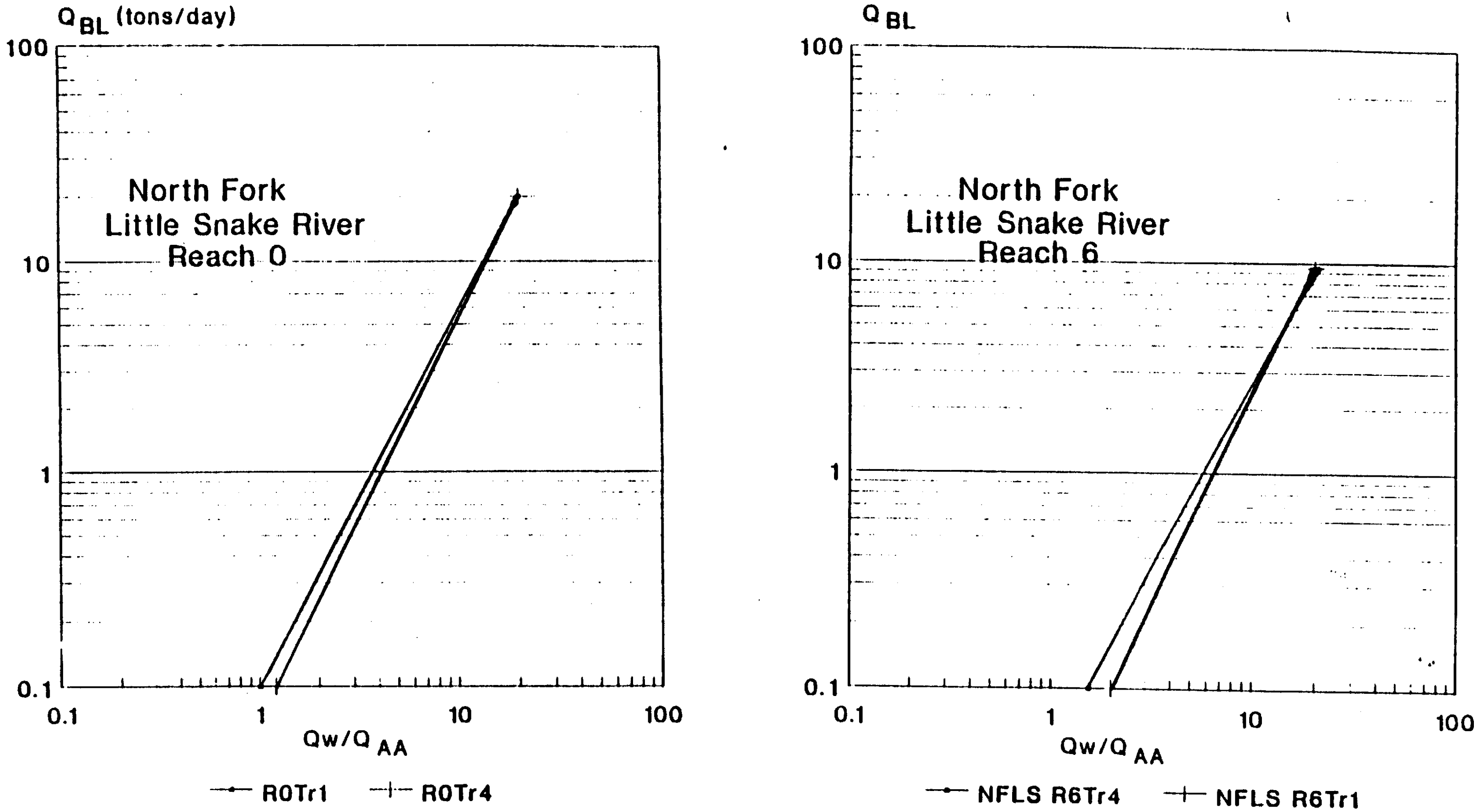


Figure 25. **Bedload transport relations entering and exitting Reaches 0 and 6, North Fork Little Snake River.**

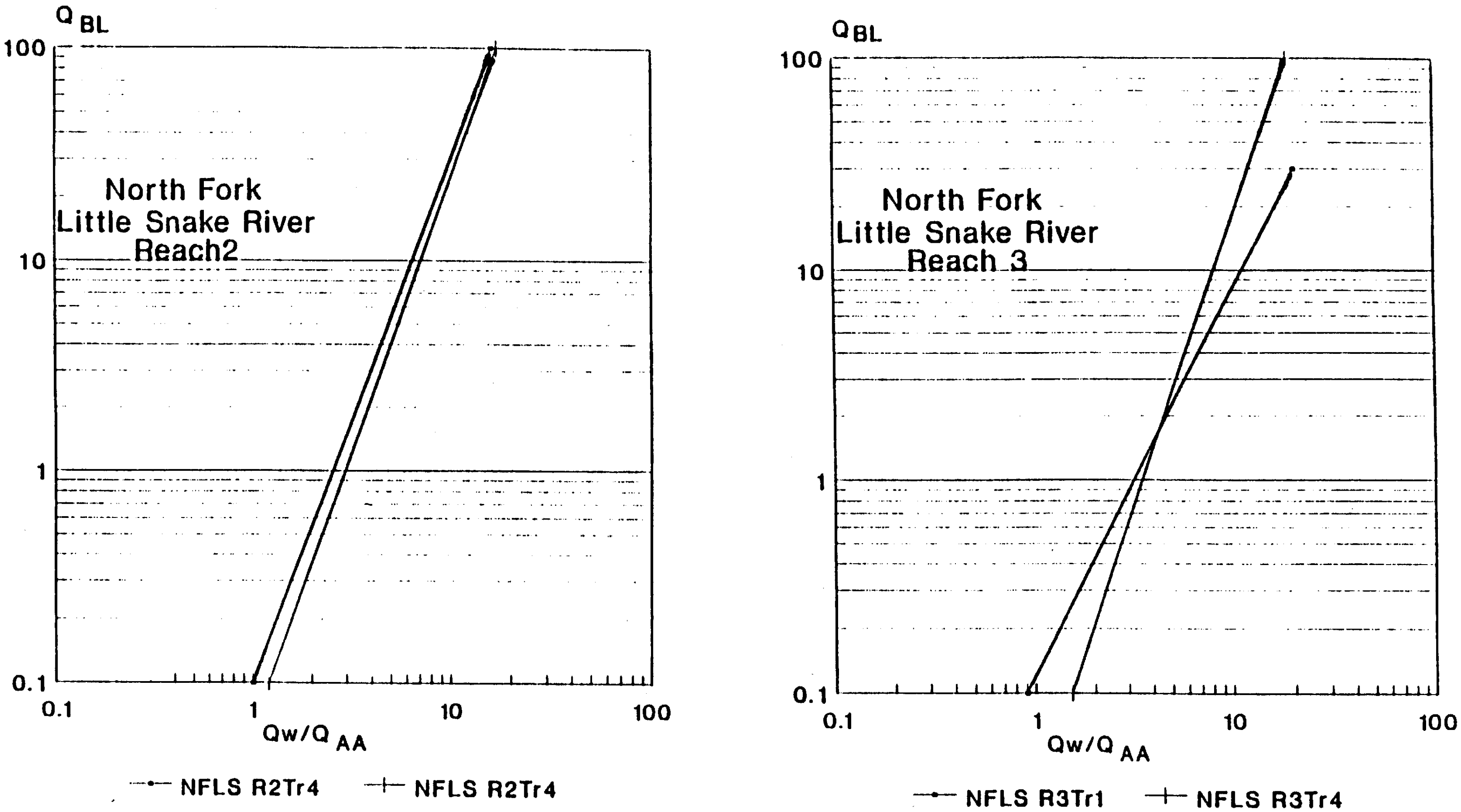


Figure 26. Bedload transport relations entering and exitting Reaches 2 and 3, North Fork Little Snake River.

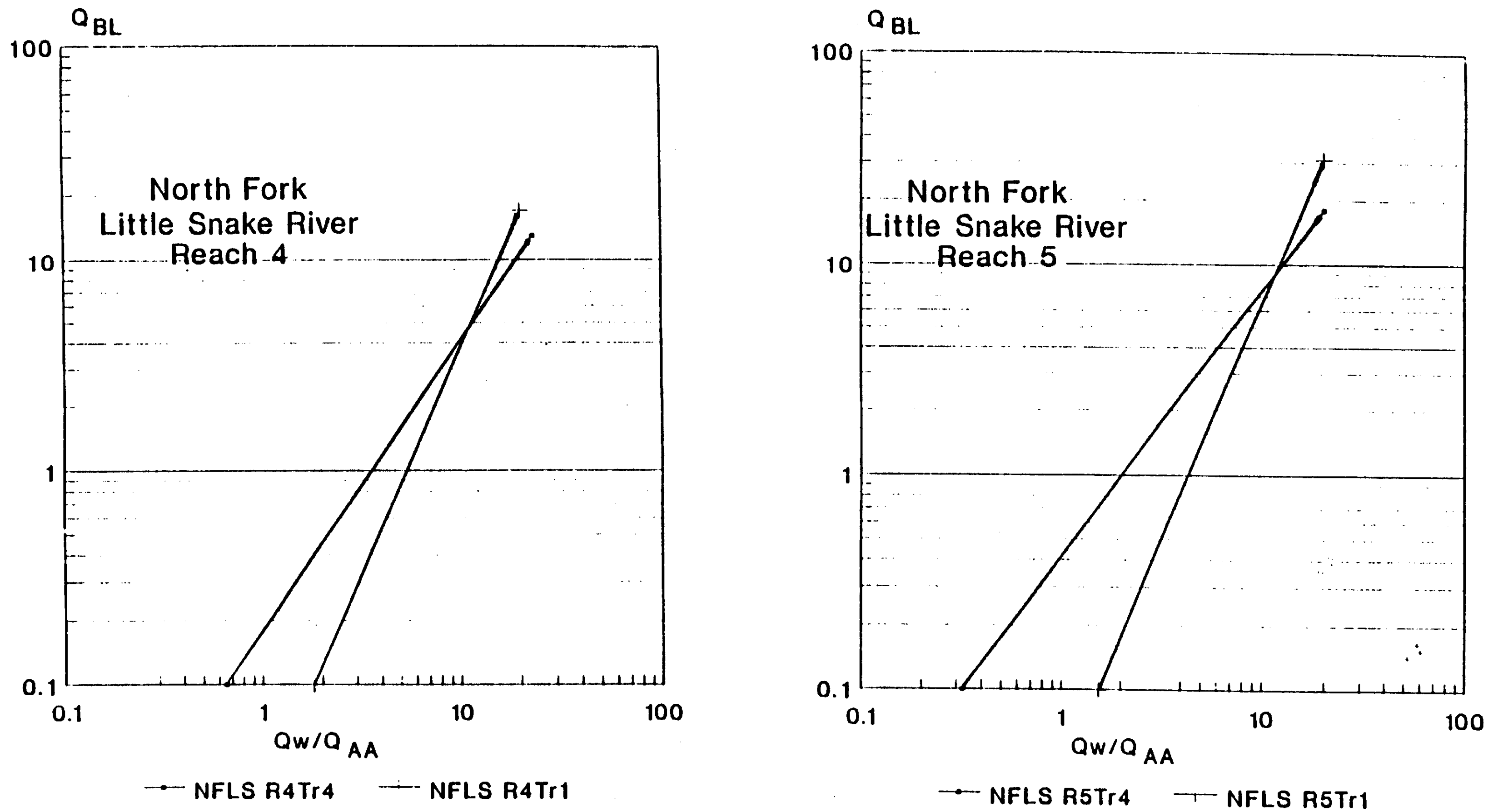


Figure 27. Bedload transport relations entering and exitting Reaches 4 and 5, North Fork Little Snake River.

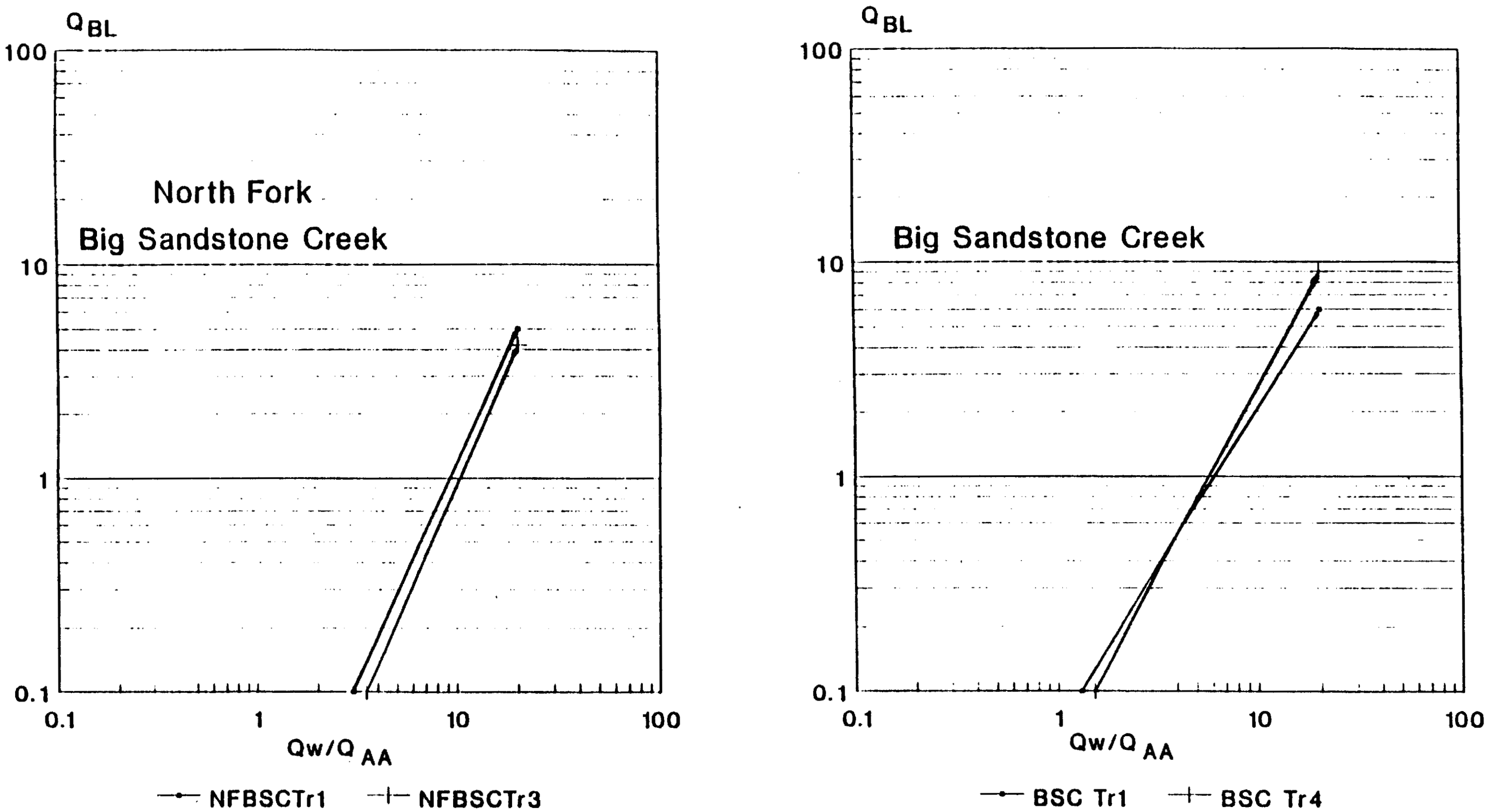


Figure 28. Bedload transport relations entering and exitting the North Fork and Big Sandstone Creek study reaches.

The particle size distribution of the bedload is also relevant to the maintenance of habitat quality. The median particle size in the bedload has been plotted against streamflow normalized by average annual discharge for cross-sections of differing water surface slopes, as shown in Figure 29. The correlation coefficients for these power function relations were statistically significant at $P <= 0.05$ and F-tests indicated the slopes of the best-fit lines were significantly different than 0. The relations for BSC represent natural conditions, with only slight differences observed over the gradient ranges. Fine gravels (greater than 2 mm diameter) began to predominate the bedload as discharge exceeded $4Q_{AA}$. The d_{50} began to approach 10 mm when flow exceeded $13Q_{AA}$. The influence of the sediment spill is reflected in the NFLS data, especially at the lower gradient transects. The relationship representing the steep gradient cross-sections was similar to those for BSC, suggesting that fine sediments from the spill were rapidly flushed. In the lower gradient sections, fine gravels did not predominate the bedload until flow exceeded $10Q_{AA}$, suggesting significant flow events would be required to transport large amounts of gravel through these reaches.

Bedload Transport Modelling

A bedload transport model was developed for steep, rough mountain stream channels utilizing the data derived from the intensive field studies described previously in Chapters 4 and 5. Model development was based upon three criteria. First, the model had to account for a statistically significant portion of the variation within the field measured bedload discharge values. Second, the model had to consist of easily measured independent variables which could be collected as part of a routine fishery habitat analysis. Finally, from the physical process standpoint, the model variables had to be logical.

Field investigations were designed to incorporate a range of sediment, hydrologic and hydraulic conditions typically encountered in streams of the Central Rocky Mountain region which provide native habitat for Colorado River cutthroat trout. Table 27 presents the range of dependent

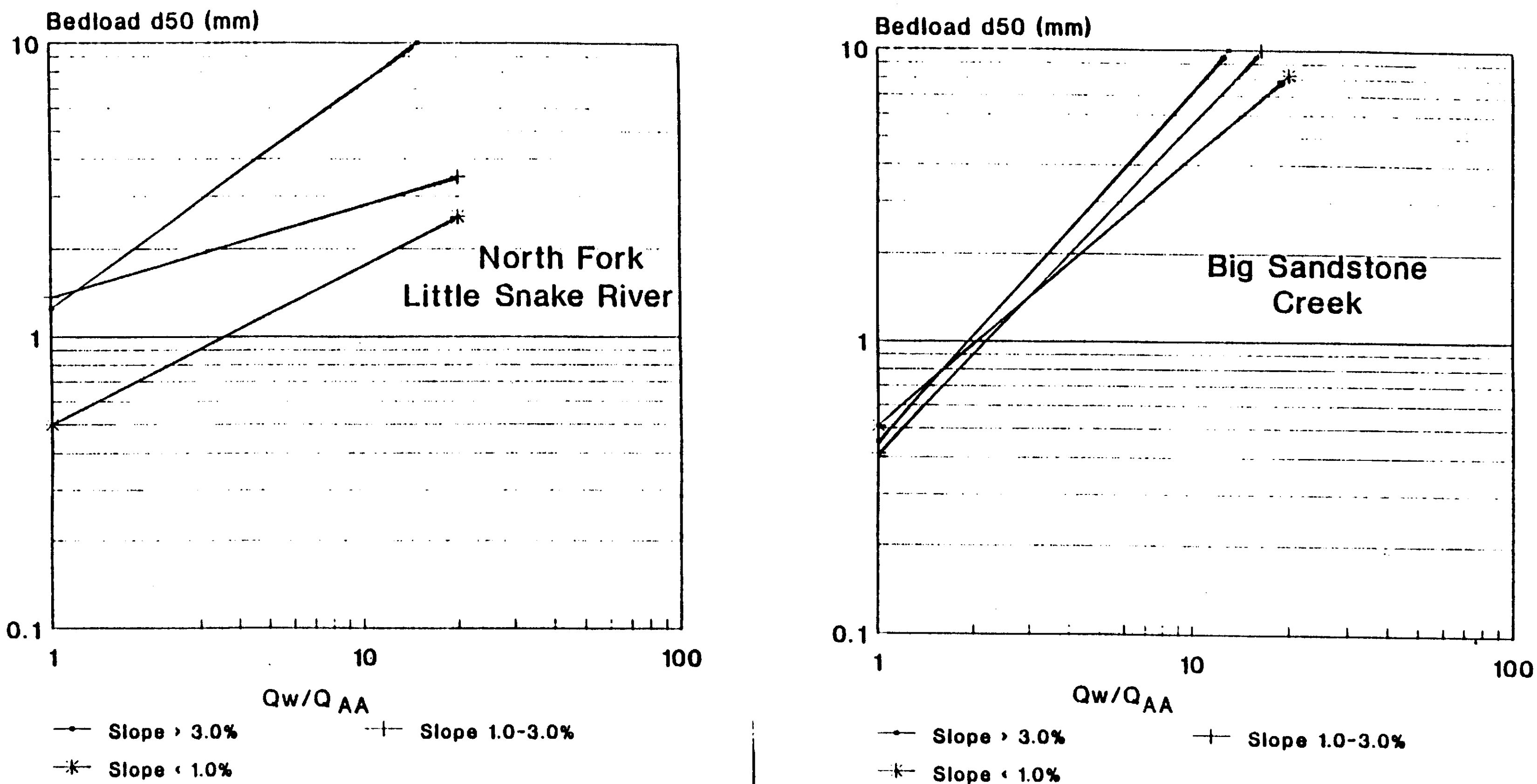


Figure 29. Relations between median bedload particle size and normalized streamflow for steep, moderate, and low gradient transects at the North Fork Little Snake and Big Sandstone study reaches.

Table 27. Range of independent and dependent variables used in the stepwise multiple regression analysis of bedload transport data from the North Fork Little Snake River (NFLS) and Big Sandstone Creek (BSC) watersheds.

Variable	Range
Unit Bedload Discharge (q_{bl}) lbs/ft/day	0.1 - 3240
Water Discharge (Q_w) ft^3/s	0.6 - 162
Unit Water Discharge (Q_w/W) ft^2/s	0.1 - 6.2
Normalized Water Discharge (Q_w/Q_{AA})	0.2 - 18.1
Top Width W(ft)	6.1 - 33.9
Width to Depth Ratio (W/D)	7.9 - 216.4
Deposition Depth (Dd) mm	3 - 232
Median bed material size (d_{50}) mm	0.9 - 79
Transportability Index (T) Dd/d_{50}	0.24 - 223.3
Drainage Density (DD) miles/$miles^2$	1.48 - 2.77
Water Surface Slope (S) %	0.11 - 6.0

and independent variables included in the analysis. As this subspecies inhabits steep, low order, headwater streams on the west slope of the Continental Divide (Baxter and Simon, 1970), conditions encountered in the two study streams are representative of such habitats.

Stepwise multiple linear regression (SAS Institute, Inc., 1985) was the statistical procedure used for model development. All variables underwent logarithmic transformation to increase the accounted for variance following inspection of normal probability and residual plots. The units of bedload discharge, pounds (dry weight) per foot of width per day (lbs/ft/day), were selected for the dependent variable to conform with most other published bedload transport models.

Independent variables were selected, within the limits of the database, to represent the variety of physical parameters typically associated with transport processes. Stream discharge, Q_w, was represented by two variables, unit discharge (Q_w in cfs per foot of width) and the dimensionless flow parameter, Q_w/Q_{AA} (Q_w normalized by average annual discharge). These, as well as other hydraulic parameters such as shear stress, unit stream power, mean cross-section velocity, mean bottom velocity, mean depth, maximum depth, and channel gradient were considered as measures of the stream energy available for sediment transport. Due to strong co-linearity between these variables however, all except Q_w/ft, Q_w/Q_{AA}, and slope (S) were deleted early in the analysis.

Three channel shape parameters were considered in the early stages of analysis, stream width (W), stream depth (D) and the ratio of width to depth (W/D). Because it is two dimensional and therefore unitless, W/D was considered the preferred shape parameter.

The availability of the bed material for transport was considered from the aspect of deposition depth (Dd) and the median particle size (d_{50}). As it was physically impossible to measure these characteristics at the time each bedload sample was taken, they were estimated from bed material data collected on the nearest sampling day. They were combined into one dimensionless variable , Dd/d_{50}, termed a "transportability" index, for model development purposes.

While the water discharge variables reflect the size of the drainage basins, one additional parameter was felt necessary to consider the geology of the watersheds. Based upon the findings of Doehring and Ethridge (1979), drainage density (DD), the ratio of stream channel length to drainage area, was selected to represent the developed stream networks. For the purposes of this study, drainage density was measured from 7.5 minute topographic maps. All stream channels, both perennial and ephemeral, which appeared as "blue lines" on the maps were measured after their headwaters were extended to the drainage divide. High values of DD typically represent areas of highly erodible rock and soil, while low values reflect materials of low erodibility. Drainage density also indicates the length of streambanks along which erosion can occur.

The multiple regression model which explained the greatest amount of variation in unit bedload discharge contained five statistically significant independent variables. These included unit water discharge (Q_w/ft), drainage density (DD), width to depth ratio, the transportability index (T), and slope (S). The equation takes the form:

$$q_{bl} = 0.35\ (Q_w/ft)^{2.11}(DD)^{3.38}(W/D)^{0.66}(T)^{0.48}(S)^{0.37}$$

This model explained 65 percent of the variation within the bedload transport samples (n = 642) collected at 37 cross-sections within 9 study reaches on 4 streams. The correlation coefficient, 0.81, was statistically significant at $P <= 0.0001$ and F-tests indicate all exponents are significantly different than 0. Table 28 summarizes the regression statistics, while Figures 30 and 31 present scatter plots of the predicted and measured values, the best-fit line, and 95 percent confidence belts.

The five-variable model included parameters which represented stream power (Q_w/ftS), channel shape, bed material characteristics, and basin erodibility. While these are all logical from the standpoint of physical processes, it is apparent from Table 28 that the dominant variables are unit water discharge and drainage density. These combined accounted for 62 percent of the observed variation, the equation taking the form:

$$q_{bl} = 1.07\ (Q_w/ft)^{1.88}(DD)^{3.40}$$

Standard errors of these regression coefficients were slightly reduced from the five variable model, 0.06 for Q_w/ft and 0.37 for DD. Considering practical application, the advantages of this latter model are apparent. Drainage density is easily measured from topographic maps, while streamflow

Table 28. Stepwise multiple regression statistics for the analysis of unit bedload discharge (lbs/ft/day) in the North Fork Little Snake River (NFLS) and Big Sandstone Creek (BSC) (n = 642).

Independent Variable	Regression Coefficient (b)	St. Error of Regr. Coeff.	Partial R^2	Model R^2	F[1]	Prob>F
Unit Water Discharge (Q_w/W, ft^2/s)	2.11	0.10	0.57	0.57	845.4	.0001
Drainage Density (DD, $miles/miles^2$)	3.36	0.44	0.05	0.62	84.5	.0001
Width to Depth Ratio (W/D, ft/ft)	0.65	0.21	0.01	0.63	16.4	.001
Transportability Index (T, Dd/d_{60})	0.48	0.08	0.01	0.64	16.8	.0001
Water Surface Slope (S, ft/ft)	0.37	0.09	0.01	0.65	18.5	.0001

[1] Ho: B = 0

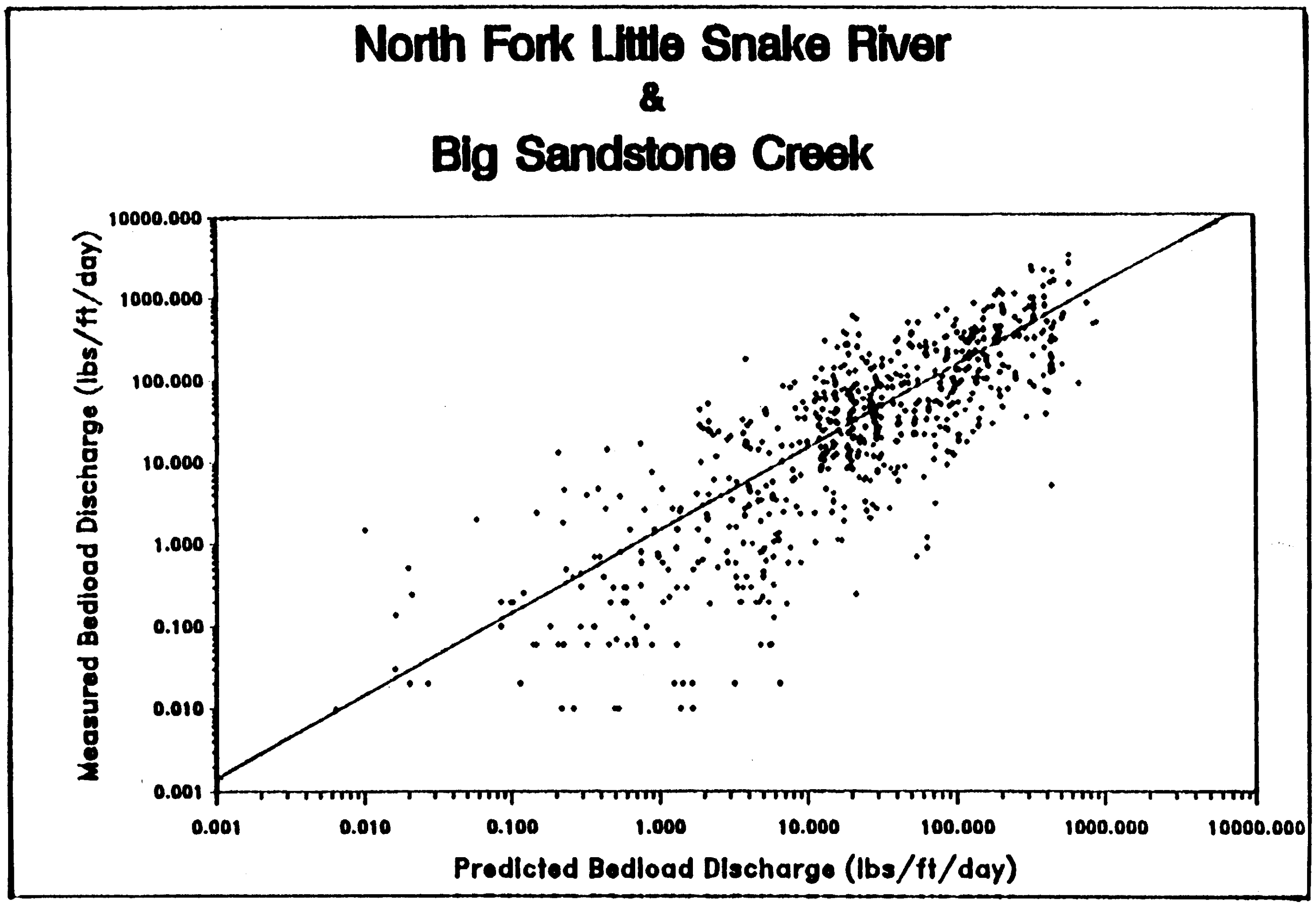


Figure 30. Scatter plot of predicted versus measured bedload discharge applying the five-variable regression model (n = 642; r = 0.81).

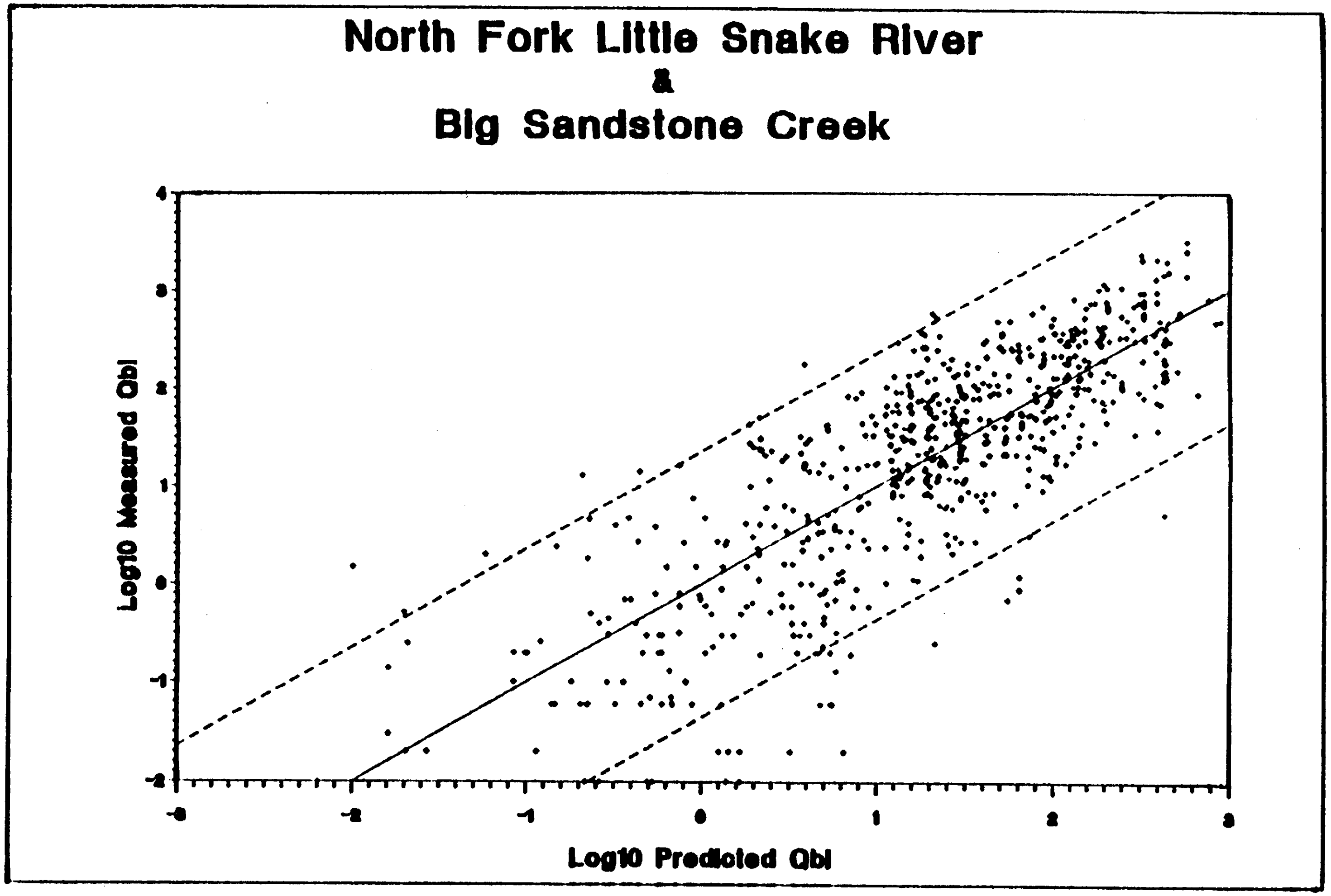


Figure 31. 95 percent confidence belts about the regression line for the 5 variable bedload transport model (n = 642; r = 0.81).

and width are routinely measured habitat characteristics. Given the wide prediction belts associated with both models, it is unlikely the increased effort required to measure deposition depth, particle size distribution and slope would be cost effective for general applications. However, the five-variable model may be more sensitive for assessing relative transport between cross-sections for flushing flow determinations. Additional testing and refinement of the models will better evaluate these considerations.

CHAPTER SIX

SUMMARY AND CONCLUSIONS

The goals of this research were twofold. The first was to evaluate the need for flushing flow releases through different channel types by investigating morphologic response of mountain streams to flow depletion. The second goal was to develop criteria for establishing flushing flow requirements of mountain stream channels by investigating the dynamics of sediment transport and storage in relation to the hydrologic regime.

Study results indicate that all mountain stream channels do not respond in the same manner to streamflow depletion. No significant differences were observed in bankfull channel width, depth, area, and conveyance capacity when comparing above and below diversion structures on steep (slope > 4 percent) and moderate (slope 1.5 to 4.0 percent) gradient reaches. Average time of diversion was 35 years and mean reduction in peak flood flow was estimated to be 70 percent. Channel dimensions on low gradient reaches, however, responded to streamflow depletion by significantly reducing their depth, area, and conveyance capacity. These latter results support the findings of Williams (1978), Gregory and Park (1976) and Bray and Kellerhals (1979) on larger, alluvial rivers.

The results from this broad scale study suggest that high elevation, steep gradient channels, where stream power is high, sediment loadings low and growing seasons short, are better able to maintain their channel dimensions with reduced flow regimes over extended time periods. In such sediment-limited conditions, available stream power appears to be sufficient, even under depleted flow conditions, to maintain a relative sediment transport balance through reaches of moderate gradient. Wesche (1989) developed sediment mass curves for the Big Sandstone study reach based upon the 1987 and 1988 spring runoff hydrographs and a simulated water development scenario. As shown in Figures 32 and 33, sand transport was maintained in below normal and near normal water years, suggesting aggradation, channel encroachment by riparian vegetation, and reduction in habitat quality by fine sediment intrusion likely would not occur. This assumes that construction-related erosion control is effective, sediment loadings remain constant, and streamflow accretion below the diversion structures is not otherwise affected.

The results of the sediment dynamics portion of the study provide support for and allow refinement of the findings discussed above. Bed material characteristics were most favorable from a fisheries habitat perspective in the unimpacted and the steeper impacted reaches. NFLS Reaches 0 and 6 provide a comparison of conditions in lower gradient reaches (less than 1.0 percent), neither of which were impacted by the sediment spill. However, the flow regime through Reach 6 had been influenced by the City of Cheyenne's Stage I project since the early 1960's. Stored bed material quantity and composition were quite stable and very similar between the reaches. Sediment transport and budget analyses indicated both reaches were stable, passing through about the same amount of material delivered to them. Despite the long period of streamflow depletion during which about 8000 acre-ft per year were removed from the upper NFLS, Reach 6 showed no signs of aggradation and channel encroachment, despite its low gradient. These findings suggest that the 1.5 percent slope criterion indicated above may be too high for a C type channel located within a much longer section of higher gradient B channel.

The critical reaches for determining flushing flow requirements within steep, rough mountain channels such as NFLS and BSC are those having very low water surface slopes. The log-step pool habitats within NFLS Reaches 4 and 5, where gradients are less than 0.30 percent, act as sediment traps within the system and are most affected by development activities which increase loadings and reduce streamflow. As discussed in Chapter 5, a threshold of flushing was identified within these reaches at which net pool scour is initiated. Below this crossover point, sand predominates the bedload transport from the steeper reaches into the pools up to a flow range of about $3Q_{AA}$. From $3Q_{AA}$ up to about $12Q_{AA}$, finer gravels predominate the pool inflow. Above $12Q_{AA}$, coarser gravels (> 8 mm) comprise over 50 percent of the bedload entering the pool. At

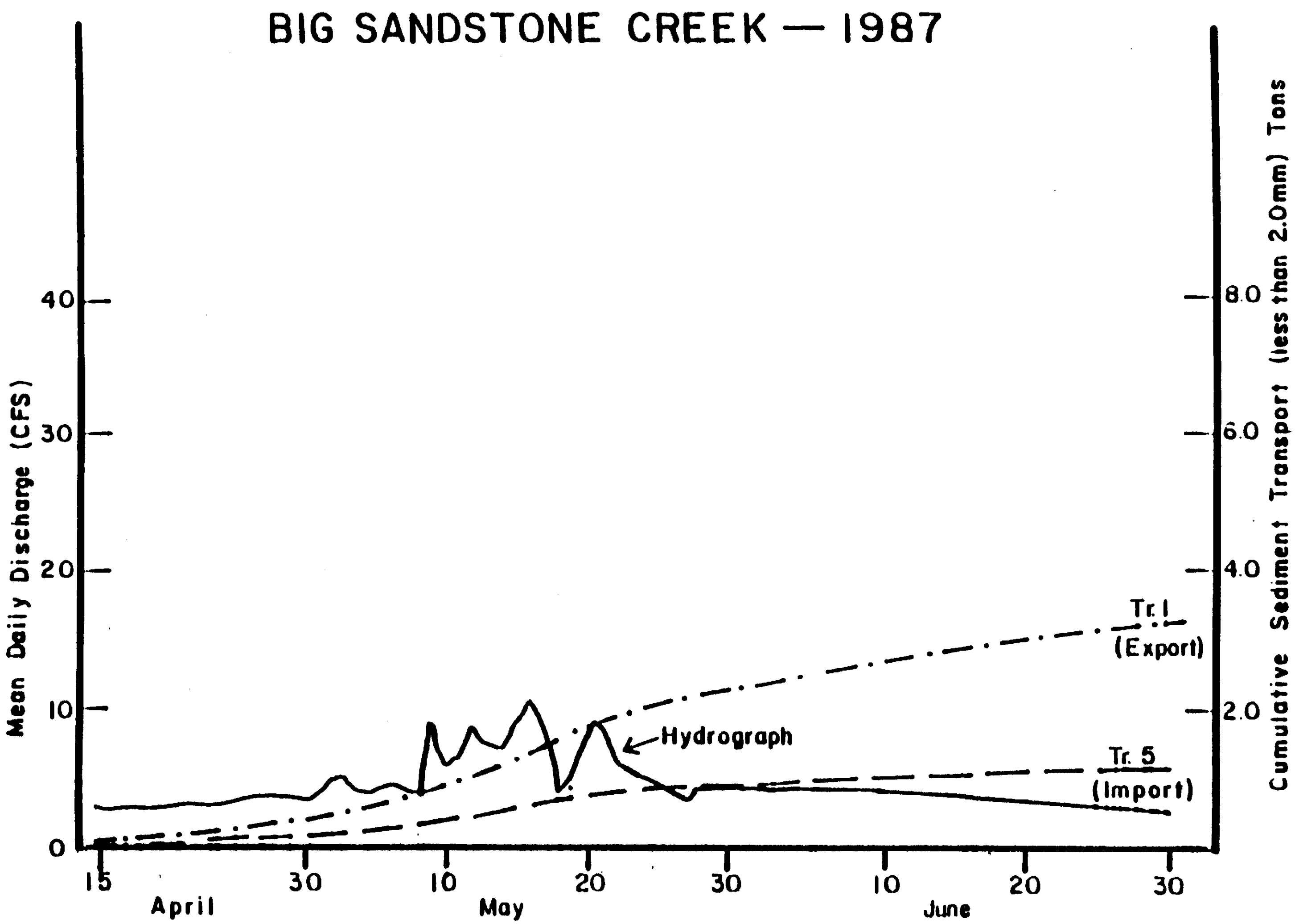


Figure 32. Sediment mass curves for Transects 1 and 5, Big Sandstone Creek, for 1987 spring runoff with simulated water development.

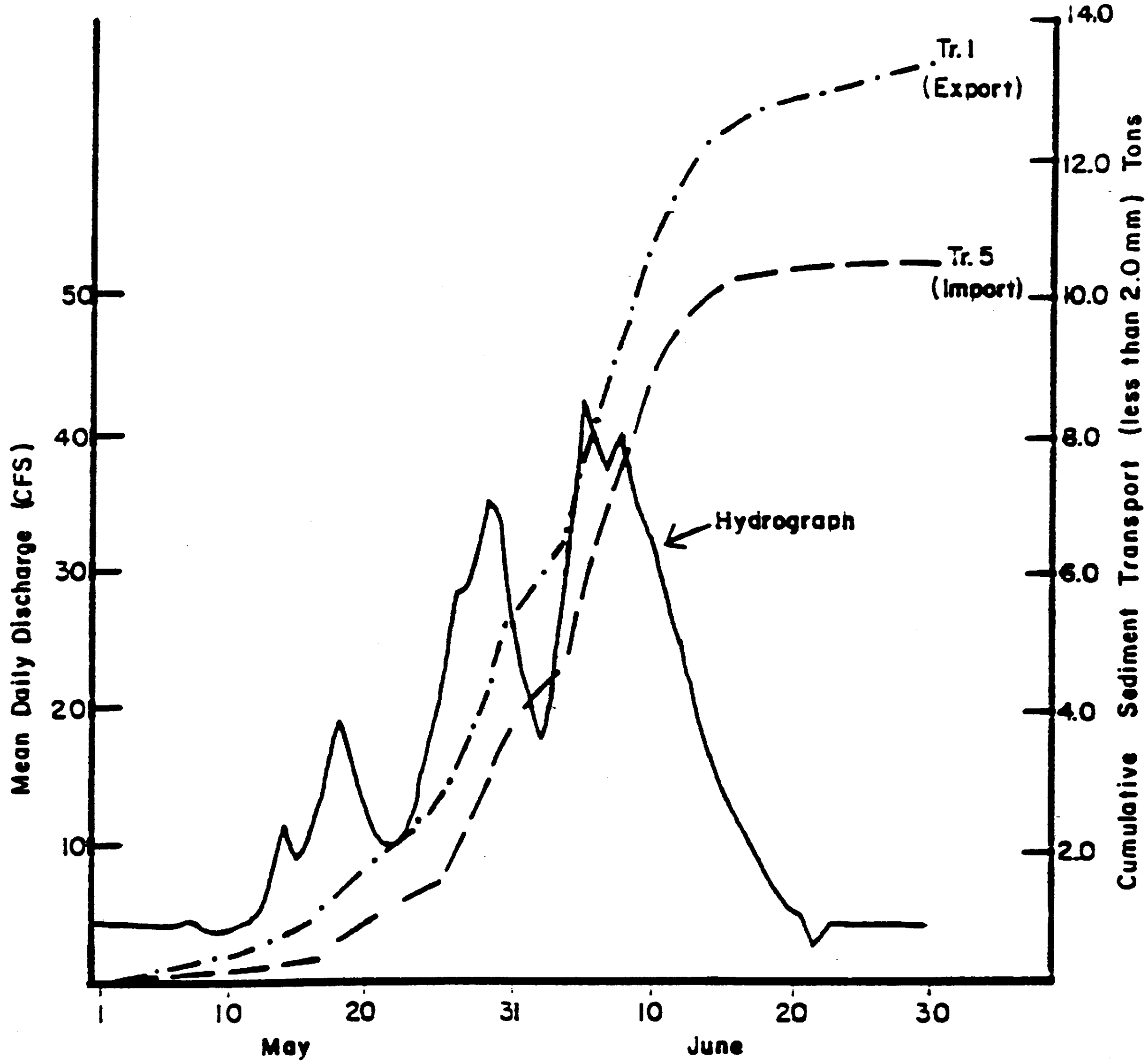


Figure 33. Sediment mass curves for Transects 1 and 5, Big Sandstone Creek, for 1988 spring runoff with simulated water development.

the pool exit, sand predominates the bedload for flows under $10Q_{AA}$, with fine gravels comprising a more significant portion at higher flow ranges. Above $12Q_{AA}$, net pool scour occurs, with coarser gravels replacing the sand and finer gravels which are exiting. These findings suggest a phased bedload transport process, such as that proposed by Jackson and Beschta (1982), wherein transport does not always involve the full range of particle sizes available.

As discussed in Chapter 5, the maintenance of spawning gravel recruitment processes can be an important requirement of a flushing flow regime. Sidle (1988), based upon research in a riffle-pool-riffle sequence of a small Alaskan stream, estimated that a flood equal to or exceeding the event having a 5-year recurrence interval was needed to trigger the scour of coarse gravel (> 8 mm). If the assumption is made that a median spawning particle size of about 12.5 mm is adequate for the small Colorado River cutthroat which inhabit the study streams, Figure 29 indicates this particle size does not begin to predominate the bedload in steeper reaches until flow approaches $20Q_{AA}$. Based upon nine samples collected at NFLS Reach 4, Transect 1, at flows ranging from 12 to $15Q_{AA}$, only about 10 percent of the bedload leaving the pool was greater than 12.5 mm, suggesting higher discharges are required for significant spawning gravel transport through the pool. The instantaneous QP5 for this section of the NFLS estimated by the Lowham (1976) procedure is 249 cfs. The peak mean daily discharge recorded at the NFLS Reach 3 gage station during 1986 was 240 cfs ($21.4Q_{AA}$), a flow likely in excess of the 5-year flood event and one which just began to spill out of the active channel banks. In response to this event, median particle size in Reach 4 increased from 5 to 23 mm, as presented on Figure 14. These results, coupled with the findings of Sidle (1988), suggest periodic flow events in this range are likely necessary for longterm spawning gravel recruitment through such river systems.

Further evidence in support of the threshold concept and the need for periodic large flood events is provided by the flushing flow study undertaken on Deadman Creek (Wesche, 1987 and 1988). Deadman Creek is a major tributary of the NFLS which enters the mainstem approximately 0.1 miles below Reach 6. A diversion structure failure during the spring 1986 resulted in an estimated 261 cubic yards of embankment fill entering the channel. Applying methods and criteria developed on the NFLS and BSC, the critical study reach was identified as a log-step pool similar hydraulically to NFLS Reach 4. Reach gradient was 0.25 percent, deposition depth was 104 mm, and median particle size of stored material was 5.5 mm. Based upon the identified flushing threshold of $12Q_{AA}$ and estimates of flow characteristics developed from the Lowham (1976) procedure, a plot of normalized discharge versus the net sediment export rate from the pool was constructed. This plot then served as the basis for determining the magnitude and duration of the required flushing event. Dye dilution procedures were used to assure the time-of-travel would be sufficient to transport mobilized finer sediments through the important Colorado River cutthroat trout habitats of the upper NFLS. The recommended flow regime released during the spring of 1988 included a peak discharge of 60 cfs, estimated to be the flood event having a 5-year recurrence interval. Following release of the flushing regime, mean deposition depth decreased from 105 mm to 65 mm and median particle size increased from 5.5 to 20.5 mm, conditions similar to the response observed at NFLS Reach 4.

Flushing or channel maintenance flow regimes can be a powerful management tool. However, before studies are undertaken to determine site-specific requirements, management goals need to be clarified. If the objective is only to maintain channel conveyance capacity within steep, rough mountain streams, the results of this study indicate such channels will maintain themselves for extended time periods, assuming sediment loadings remain relatively low and accretion flows below diversion structures are not affected. Studies should focus on critical low gradient reaches where aggradation and encroachment appear more likely to occur. The development of longitudinal profiles from topographic maps for streams to be affected by a particular water development project will rapidly allow identification of reaches most likely to be impacted. The regression equations presented in Chapter 5 can be used to estimate potential channel response, based upon anticipated streamflow depletions. Within these critical reaches, studies should focus on defining inflow and outflow sediment transport capabilities.

Should management goals include the preservation of habitat for important salmonid species within steep, rough mountain channels, critical reaches should include very low gradient pools such as were investigated during this study. To maintain this habitat type, study results suggest flushing flow releases should exceed $12Q_{AA}$ for a sufficient period of time to export accumulated finer sediments and achieve desired net scour. The flushing duration will be dependent on the differential transport rates entering and exiting the pools, based on the magnitude and duration of intermediate and low flow events. The frequency of the flushing event should be based on the rate of pool aggradation and its effect on habitat quality. The five-variable bedload transport model presented in Chapter 5 should be useful for evaluating these transport rates and determining the duration of the flushing flow required above the threshold level. To maintain gravel recruitment processes, diversion structures should allow sediments to be bypassed and a short-term event equivalent to the flood having a 5-year recurrence interval should be released as available.

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APPENDIX

Table A-1. Description of the mountain stream study sites.

Stream & Site	Date of Diversion	Reduction[1] In Q_{r2} %	Mean Width (ft)	Mean Depth (ft)	Mean Cross-Section Area (ft^2)	Estimated Conveyance Capacity (ft^3/s)
Laramie River-Above Poudre Tunnel	1920		25.2	2.5	63.0	266
Laramie River-Below Poudre Tunnel		23	27.3	2.0	54.6	67
North Fork Encampment-Above Wolfard Canal	1890		25.0	2.0	50.0	237
North Fork Encampment-Below Wolfard Canal		44	26.2	2.0	52.4	364
Cow Creek-Above Pilson Ditches	1882		19.8	2.5	49.5	421
Cow Creek-Above Pilson Ditches		17	21.3	1.5	32.0	181
N. Fork Little Snake-Above Cheyenne Div.	1963		10.1	1.0	10.1	36
N. Fork Little Snake-Below Cheyenne Div.		68	10.5	1.0	10.5	59
N. Fork Little Snake-Below Cheyenne Div.		68	6.1	1.0	6.1	22
South Brush Creek-Above Supply Canal	1920		27.9	2.0	55.8	602
South Brush Creek-Below Supply Canal		21	30.4	2.0	60.8	656
North Brush Creek-Above Supply Canal	1888		29.8	2.0	59.6	291
North Brush Creek-Below Supply Canal		72	19.5	1.5	29.2	44
Vasquez Creek-Above Diversion	1936		26.4	1.9	50.2	335
Vasquez Creek-Below Diversion		70	17.6	1.3	22.9	82
Fraser River-Above Diversion	1936		17.6	1.5	26.4	167
Fraser River-Below Diversion		28	18.1	1.3	23.5	102
Fool Creek-Above Diversion	1956		5.0	0.8	4.0	18
Fool Creek-Below Diversion		90	6.2	0.8	5.0	36
St. Louis Creek-Above Diversion	1956		19.2	1.3	25.0	154
St. Louis Creek-Below Diversion		67	21.6	1.4	30.2	193

Table A-1 continued. Description of the mountain stream study sites.

Stream & Site	Date of Diversion	Reduction[1] In Q_{P2} %	Mean Width (ft)	Mean Depth (ft)	Mean Cross Section Area(ft^2)	Estimated Conveyance Capacity Area(ft^3/s)
East St. Louis Creek-Above Diversion	1956		7.6	1.9	14.4	178
East St. Louis Creek-Below Diversion		89	8.2	1.2	9.8	78
West St. Louis Creek-Above Diversion	1956		7.3	0.9	6.6	37
West St. Louis Creek-Below Diversion		90	5.8	0.9	5.2	21
Little Cabin Creek-Above Diversion	1975		2.2	0.8	1.8	10
Little Cabin Creek-Below Diversion		79	2.0	0.7	1.4	6
Cabin Creek-Above Diversion	1975		16.1	1.1	17.7	87
Cabin Creek-Below Diversion		76	11.9	1.3	15.5	82
North Fork Ranch Creek-Above Diversion	1949		10.1	0.9	9.1	28
North Fork Ranch Creek-Below Diversion		66	9.0	0.8	7.2	54
Middle Fork Ranch Creek-Above Diversion	1949		15.7	1.2	18.8	195
Middle Fork Ranch Creek-Below Diversion		66	13.8	2.0	27.6	312
South Fork Ranch Creek-Above Diversion	1949		9.7	1.4	13.6	110
South Fork Ranch Creek-Below Diversion		66	9.4	1.5	14.1	142
Ranch Creek-Above Diversion	1949		11.0	1.6	17.6	262
Ranch Creek-Below Diversion		66	10.0	1.6	16.0	200
Chapman Gulch-Above Diversion	1972		14.1	1.2	16.9	142
Chapman Gulch-Below diversion		90	13.5	1.3	17.6	167

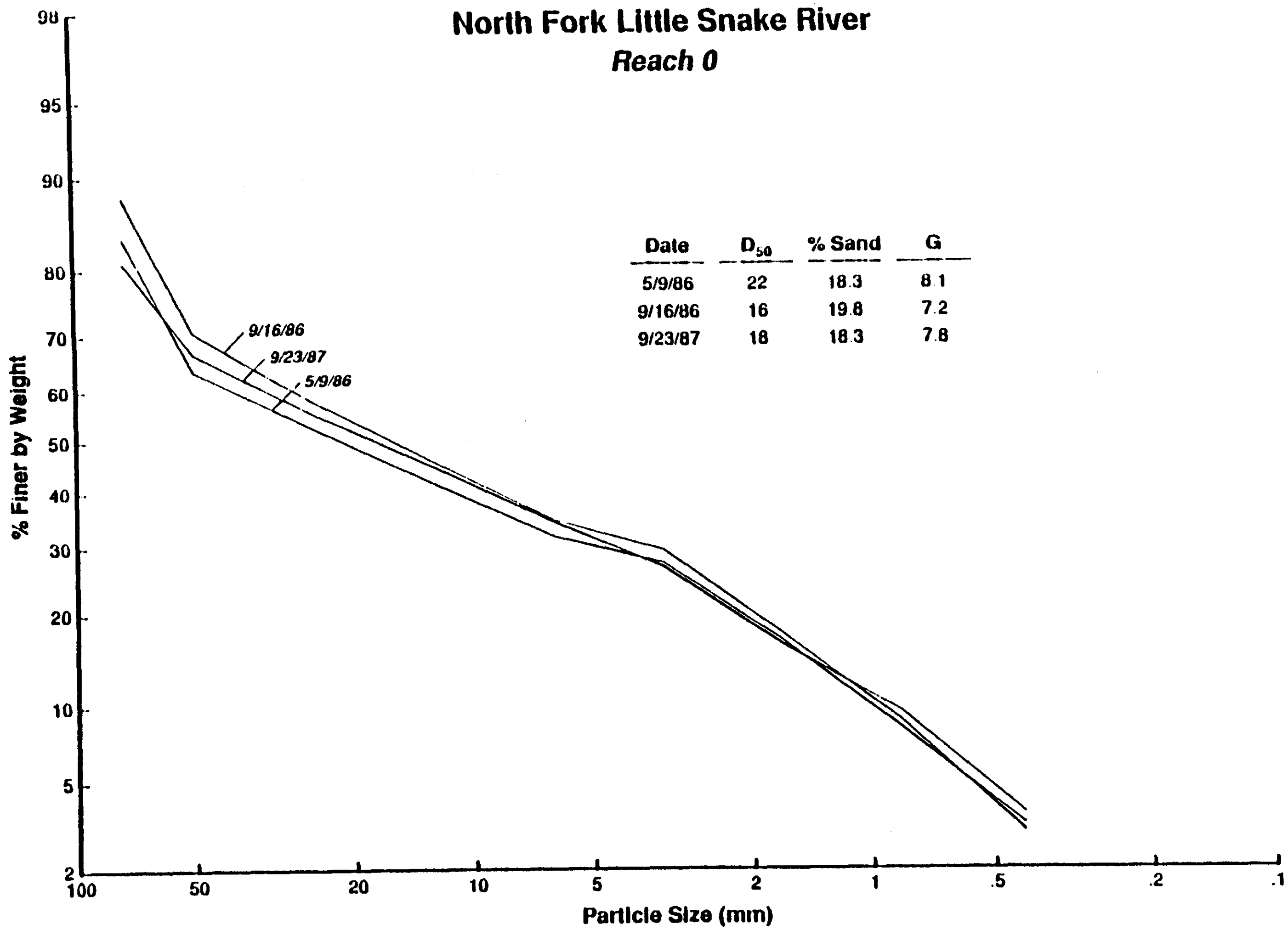
[1]Flood flow having a recurrence interval of two years.

Table A-2. Description of foothill and basin stream study sites.

Stream & Site	Date of Diversion	Reduction[1] In Q_{F2} %	Mean Width (ft)	Mean Depth (ft)	Mean Cross-Section Area (ft^2)	Estimated Conveyance Capacity (ft^3/s)
Laramie River-Above Pioneer Canal	1879		65.6	4.5	295.2	630
Laramie River-Below Pioneer Canal		14	68.4	4.5	307.8	659
Laramie River-Near Laramie, WY		35	48.9	4.0	195.6	190
New Fork River-Barlow Ranch	1903		45.8	2.3	105.3	282
New Fork River-Noble Ranch		27	30.7	2.0	61.4	204
New Fork River-Leopold Cabin		82	16.5	1.2	19.8	67
New Fork River-Murdock Ranch		79	33.5	1.3	43.6	76
New Fork River-Below Duck Creek		+18[2]	42.9	2.4	103.0	287
Owl Creek-Below Confluence of North & South Forks	1900		26.4	1.6	42.2	190
Owl Creek-at County Bridge			16.1	2.0	32.2	84
Owl Creek-near mouth			13.2	1.6	21.1	34
Gooseberry Creek-near Highway 431 Bridge	1910		17.0	1.4	23.8	51
Gooseberry Creek-at Killifish Exclosure			12.3	1.4	17.2	8
Gooseberry Creek-Near Larkin Lane Bridge			7.6	1.4	10.6	20

[1]Flood flow having a two-year recurrence interval.

[2]+ indicates percent increase in Q_{F2} over reference site.



Date	D_{50}	% Sand	G
5/9/86	22	18.3	8.1
9/16/86	16	19.8	7.2
9/23/87	18	18.3	7.8

Figure A - 1. Bed material particle size distribution for Reach 0, North Fork Little Snake River.

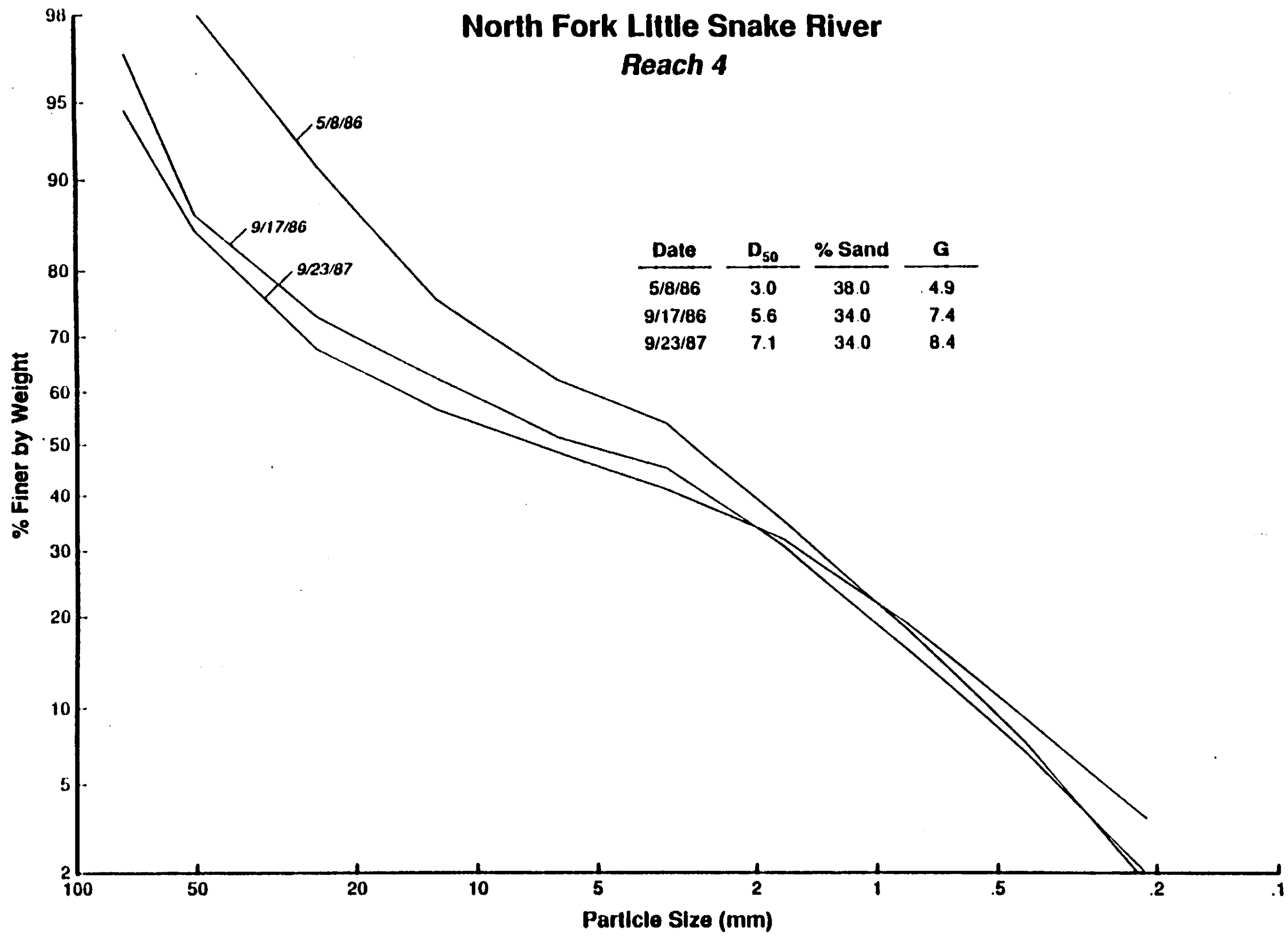


Figure A - 2. Bed material particle size distribution for Reach 4, North Fork Little Snake River.

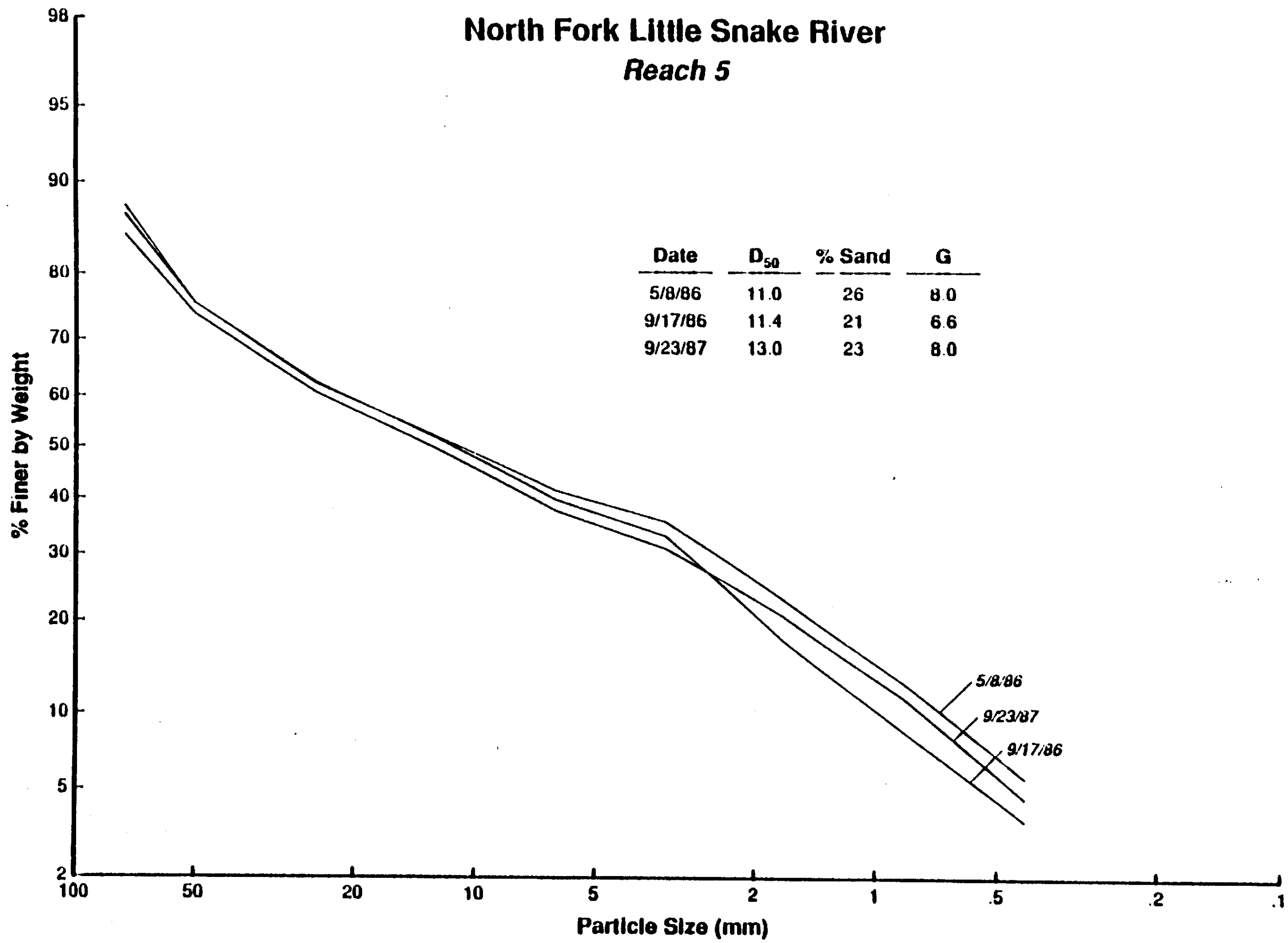


Figure A - 3. Bed material particle size distribution for Reach 5, North Fork Little Snake River.

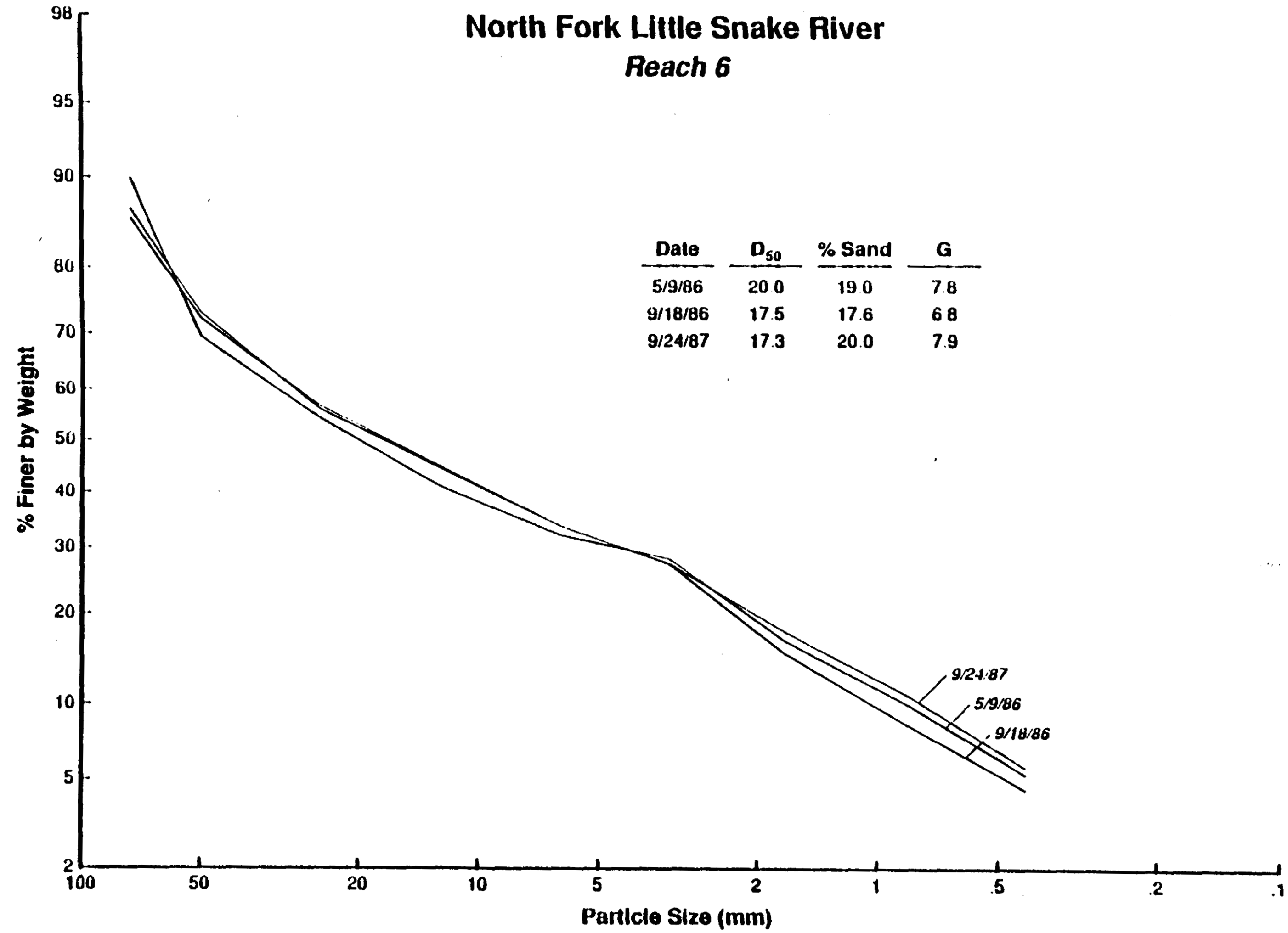


Figure A - 4. Bed material particle size distribution for Reach 6, North Fork Little Snake River.

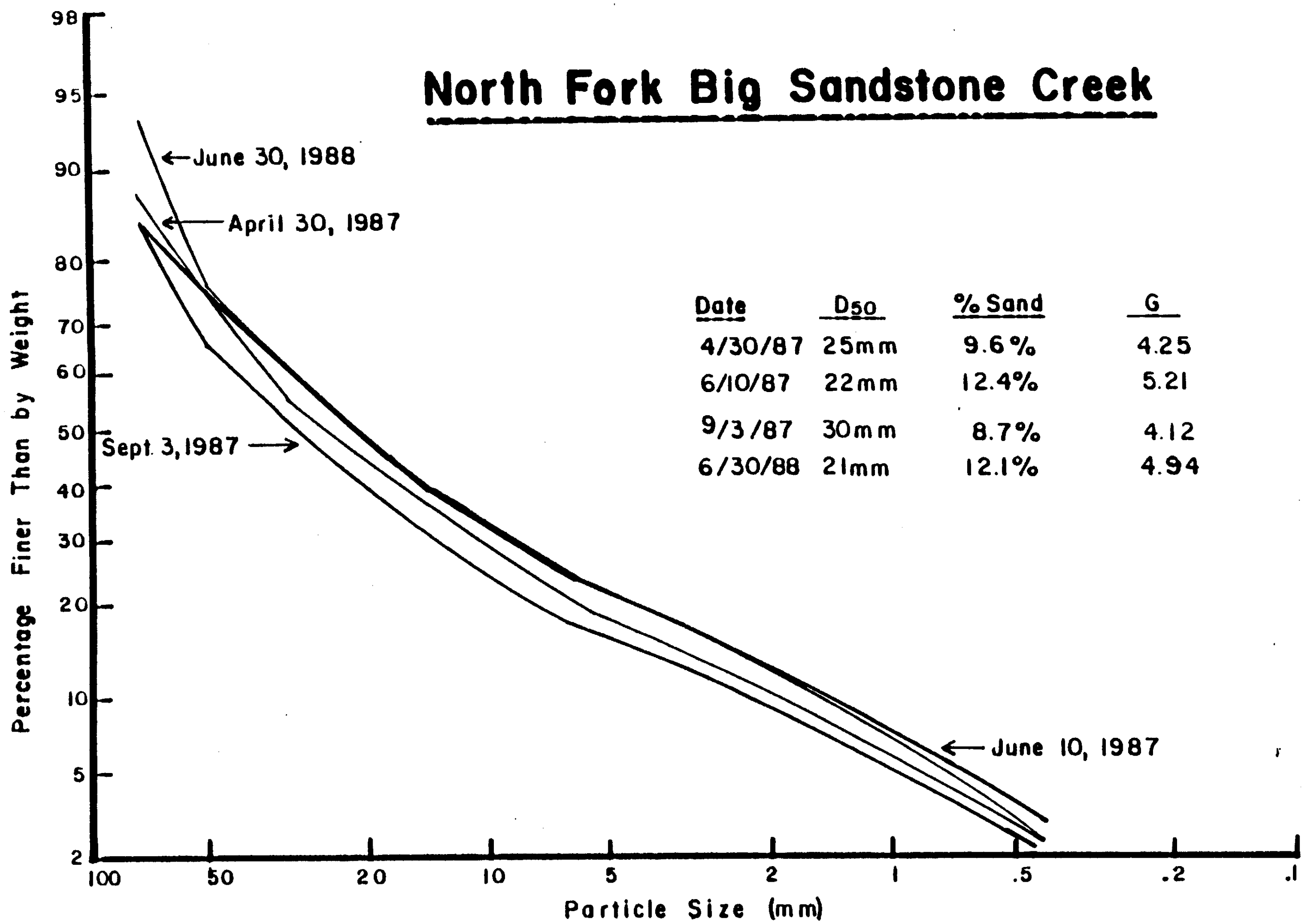


Figure A - 5. Bed material particle size distribution for North Fork Big Sandstone Creek.

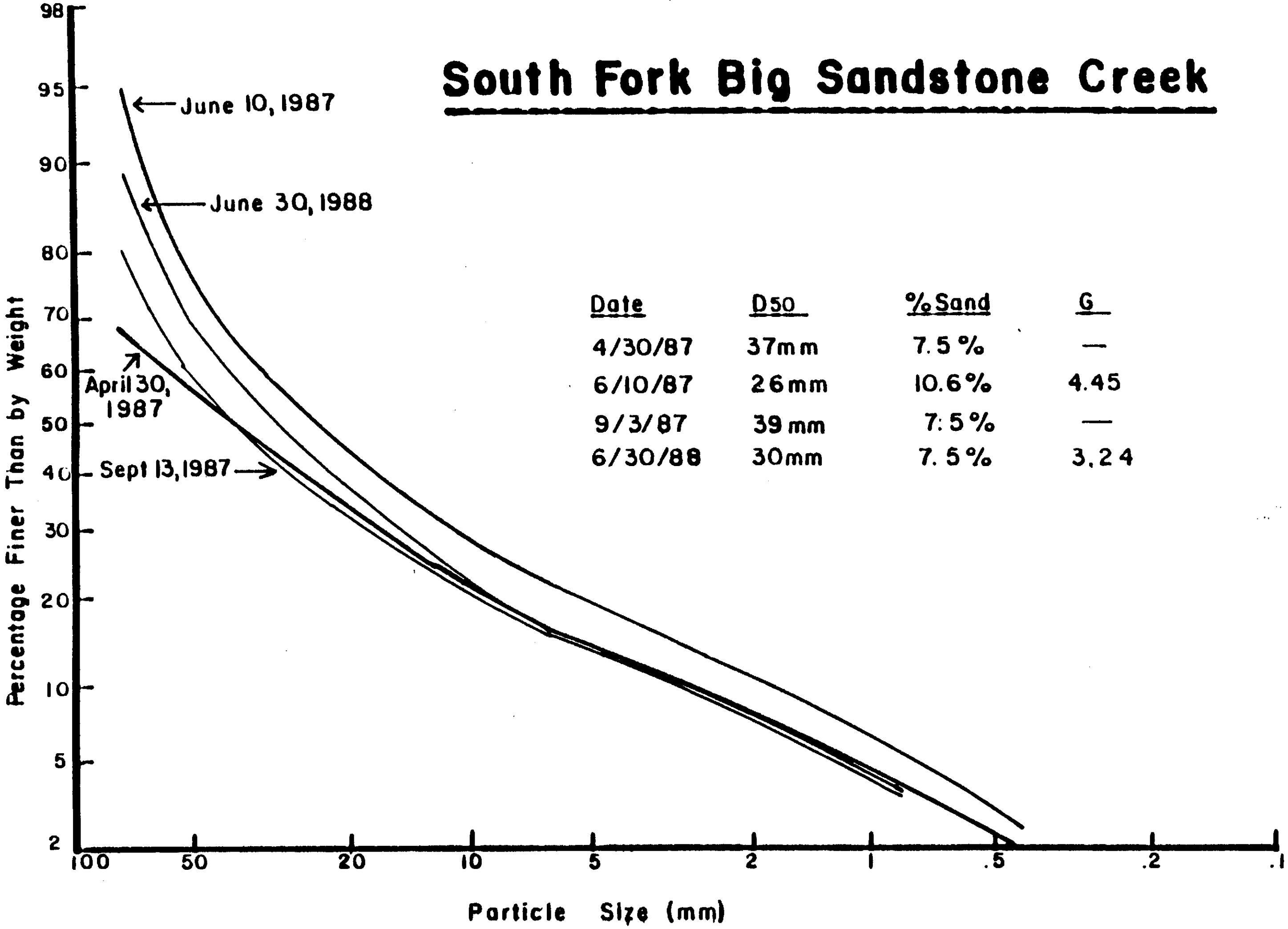
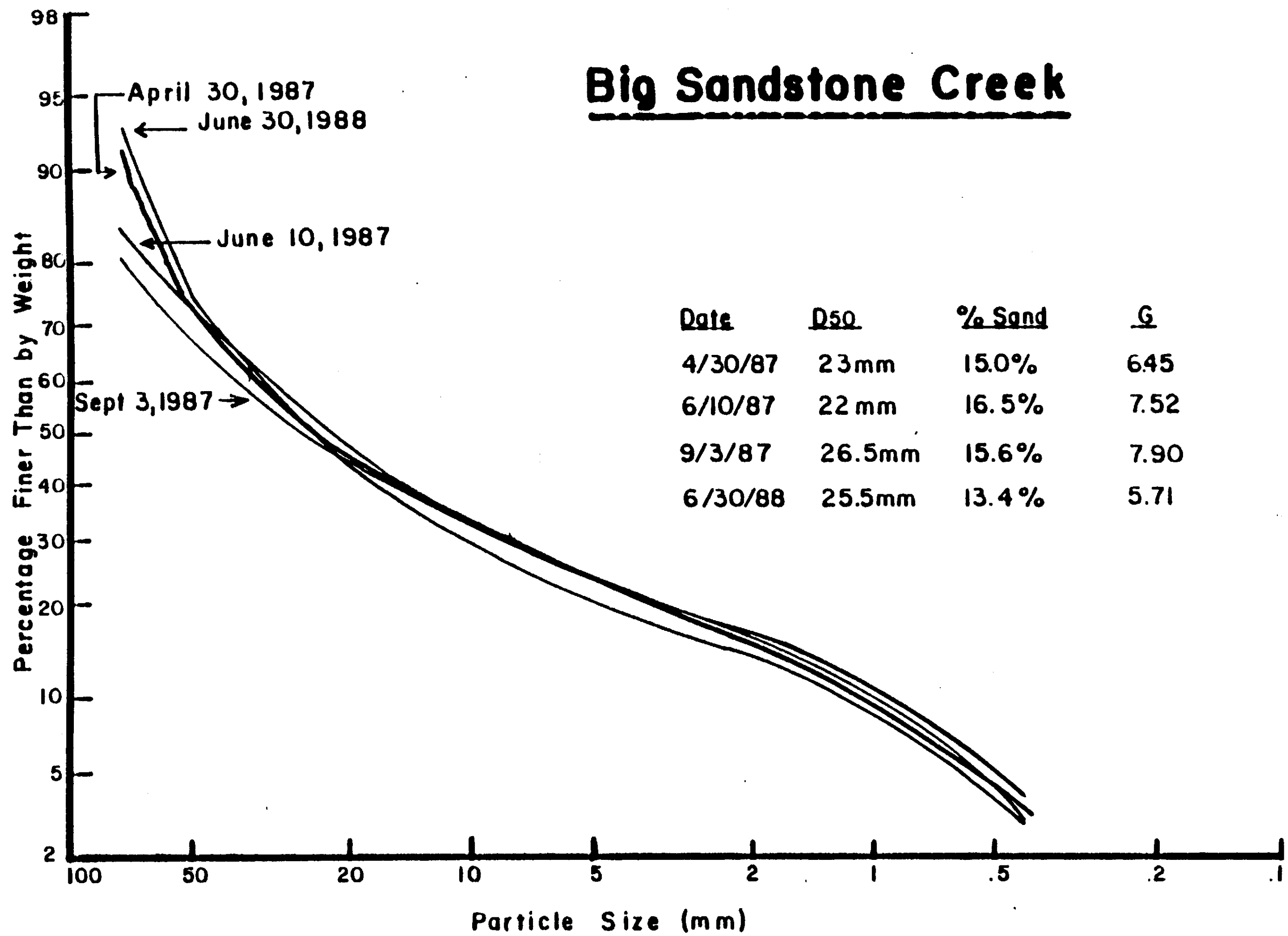


Figure A - 6. Bed material particle size distribution for South Fork Big Sandstone Creek.



Date	D50	% Sand	G
4/30/87	23mm	15.0%	6.45
6/10/87	22 mm	16.5%	7.52
9/3/87	26.5mm	15.6%	7.90
6/30/88	25.5mm	13.4%	5.71

Figure A - 7. Bed material particle distribution for Big Sandstone Creek.

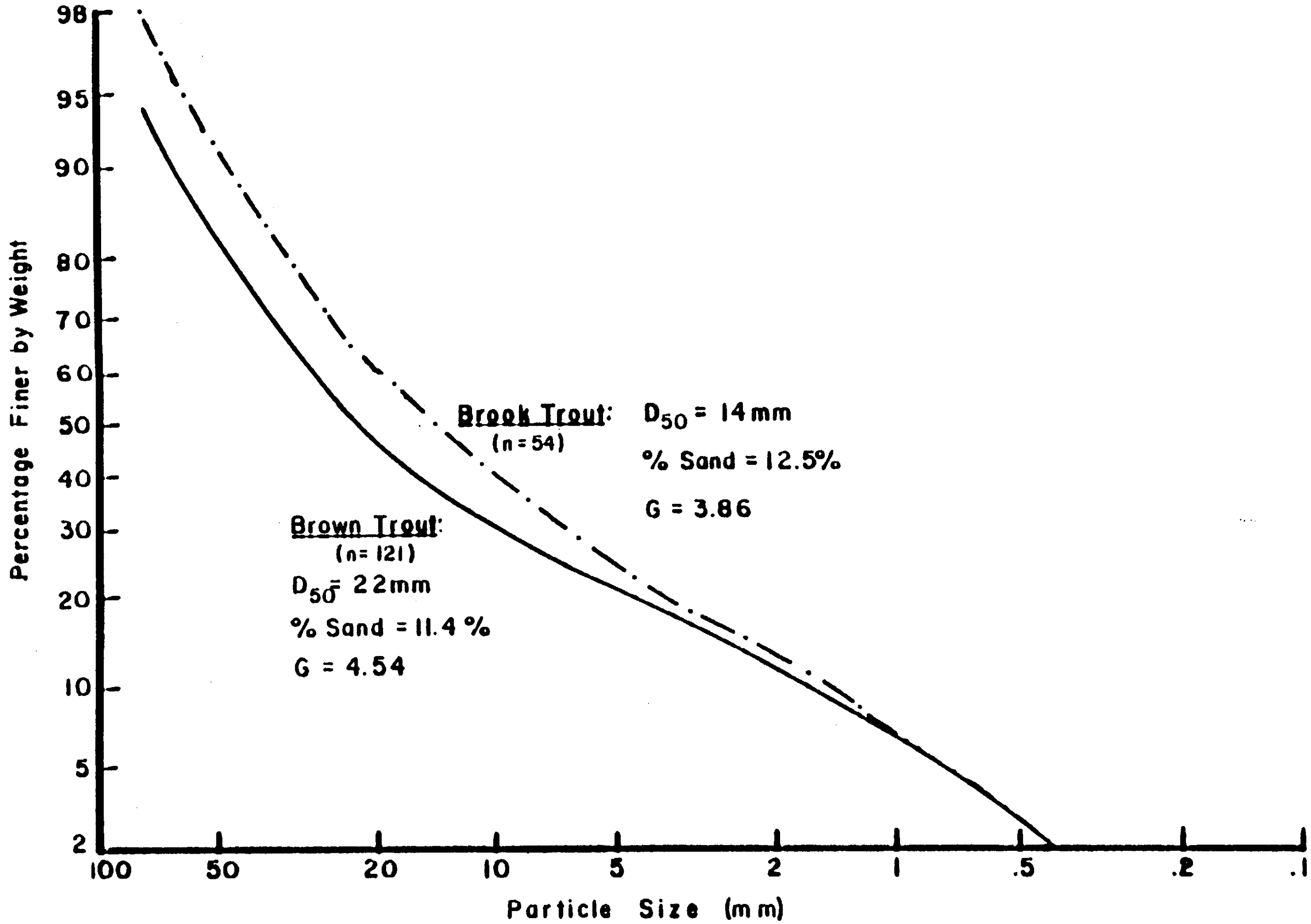


Figure A - 8. Size distribution of bed material particles in Brown Trout and Brook Trout redds, Medicine Bow National Forest, Wyoming.

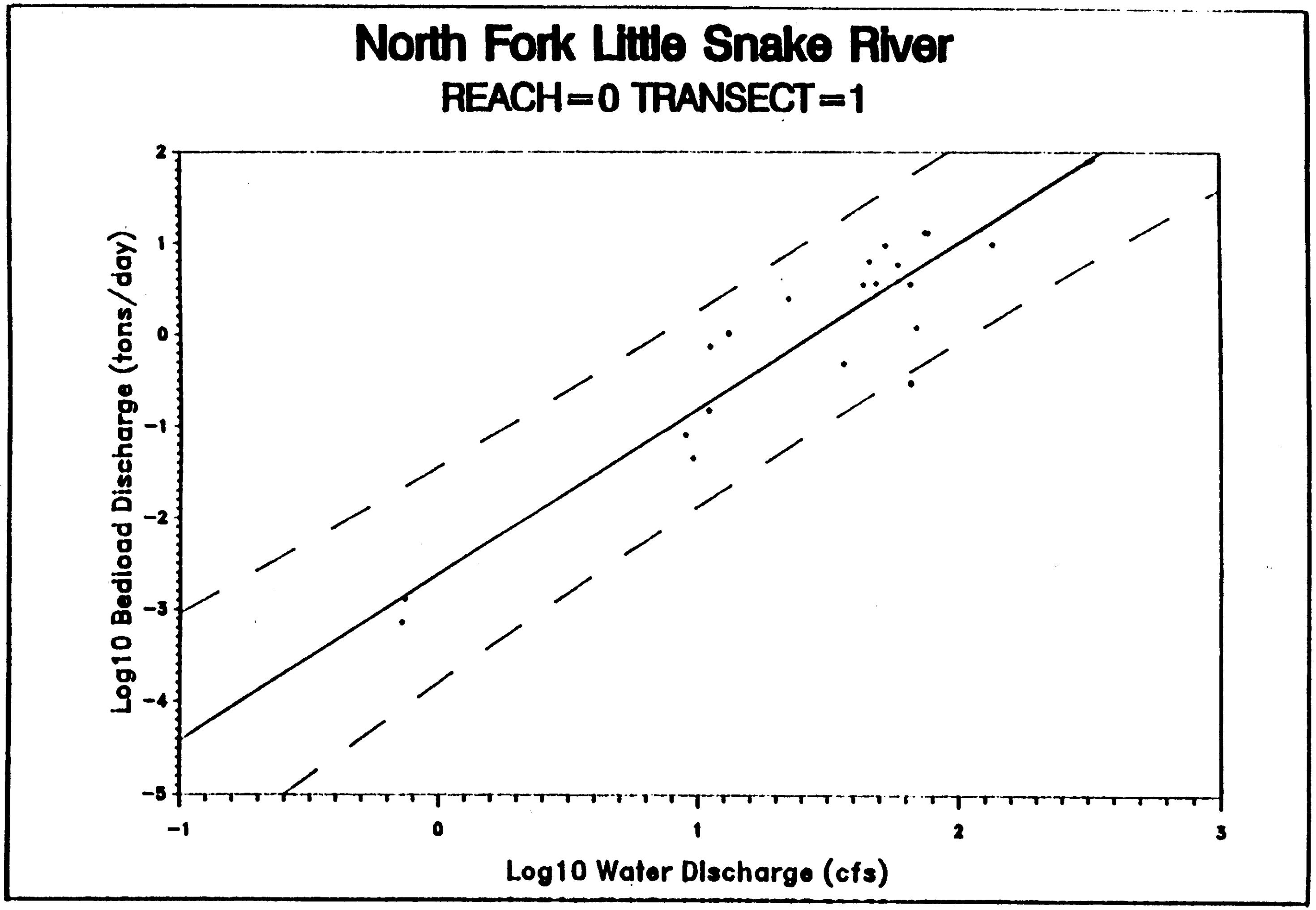


Figure A - 9. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 1, Reach 0, North Fork Little Snake River.

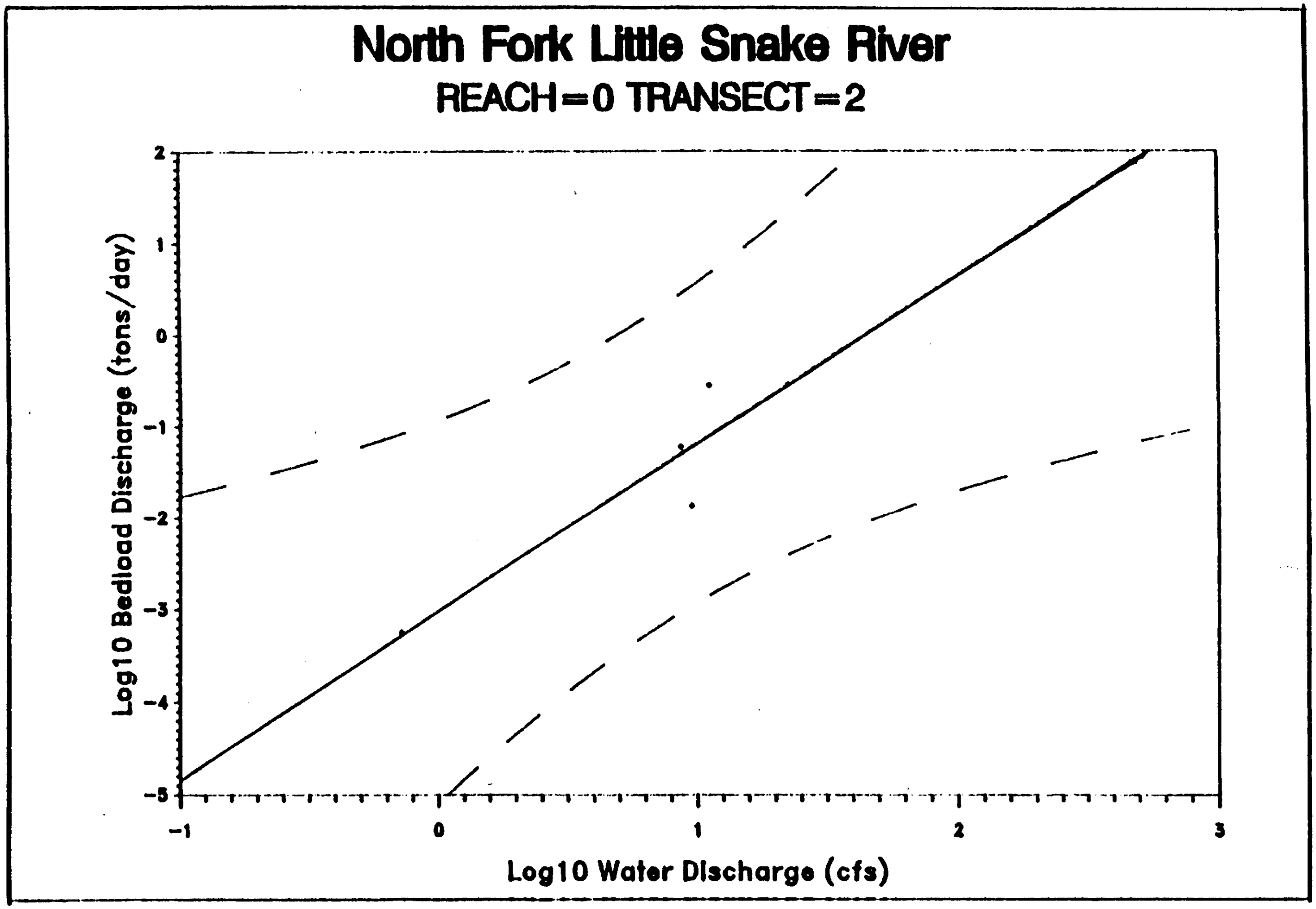


Figure A - 10. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 2, Reach 0, North Fork Little Snake River.

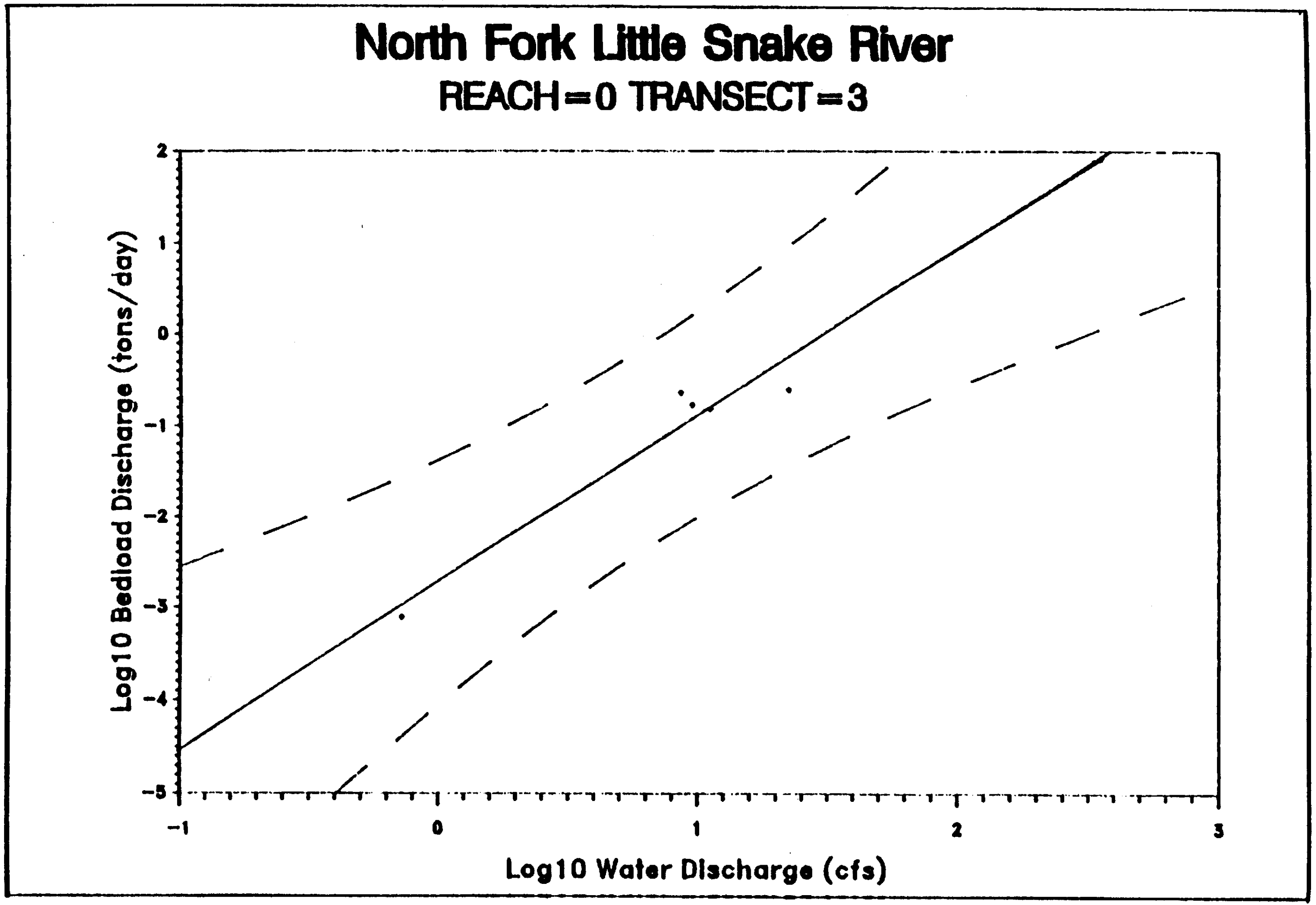


Figure A - 11. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 3, Reach 0, North Fork Little Snake River.

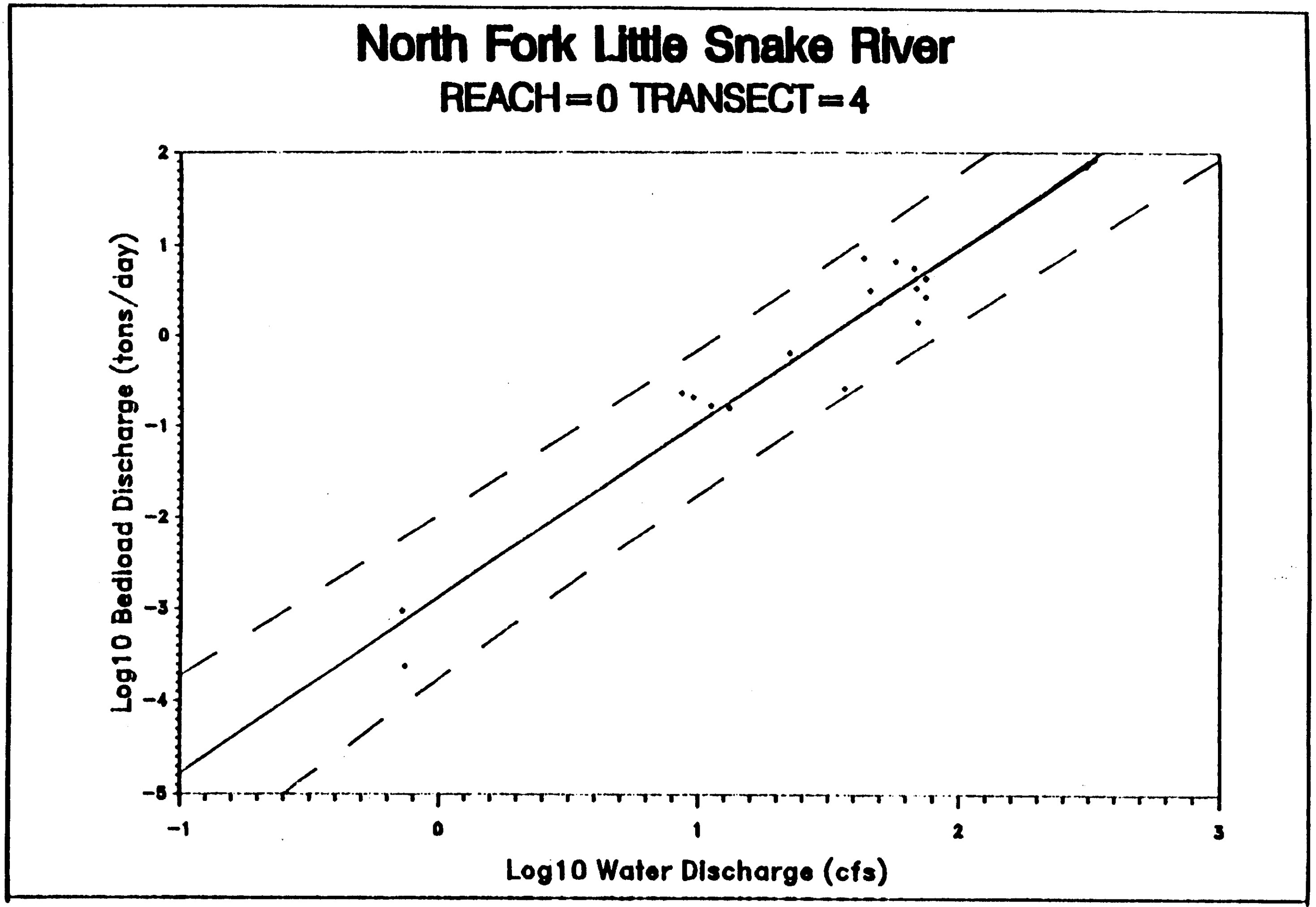


Figure A - 12. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 4, Reach 0, North Fork Little Snake River.

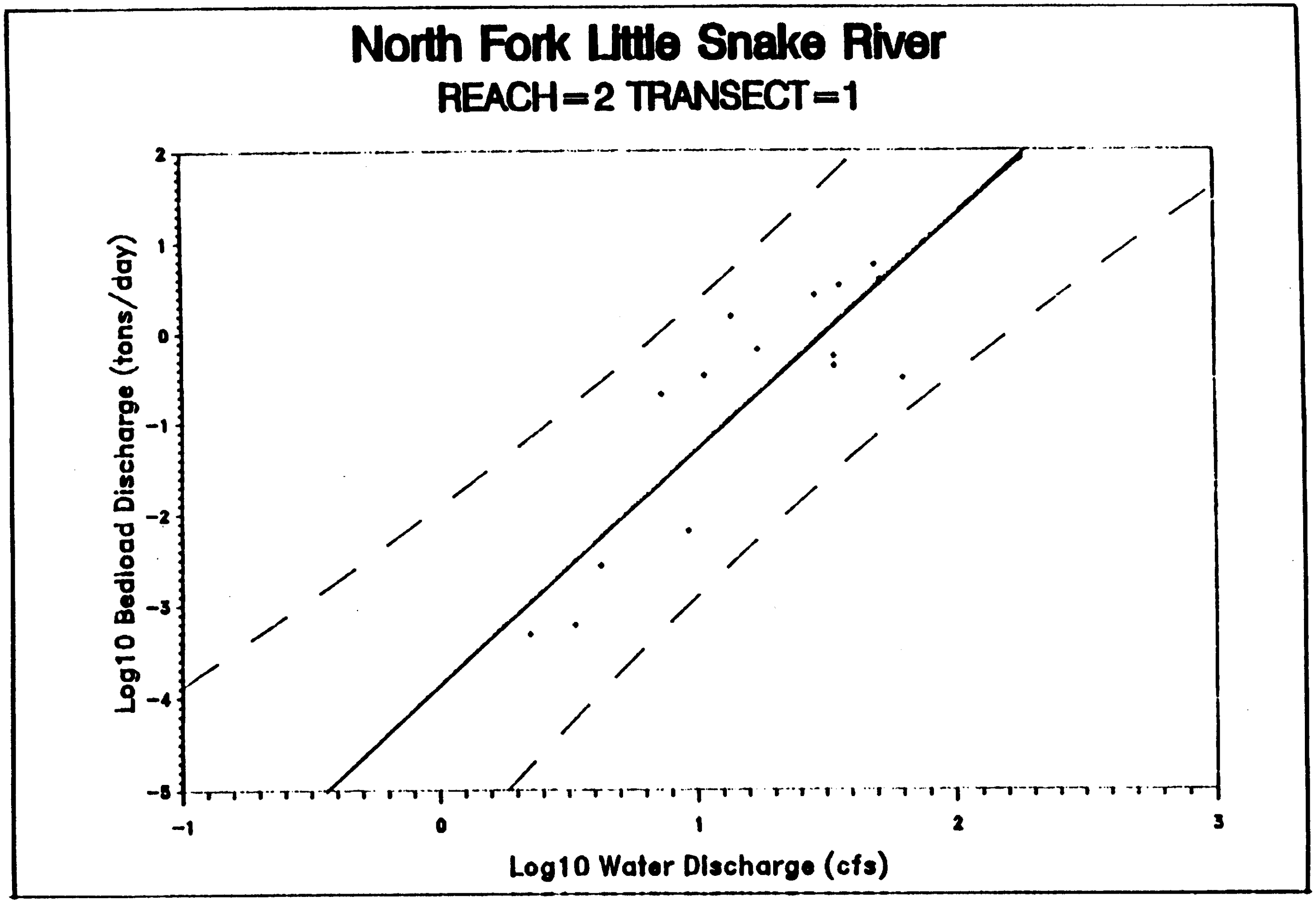


Figure A - 13. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 1, Reach 2, North Fork Little Snake River.

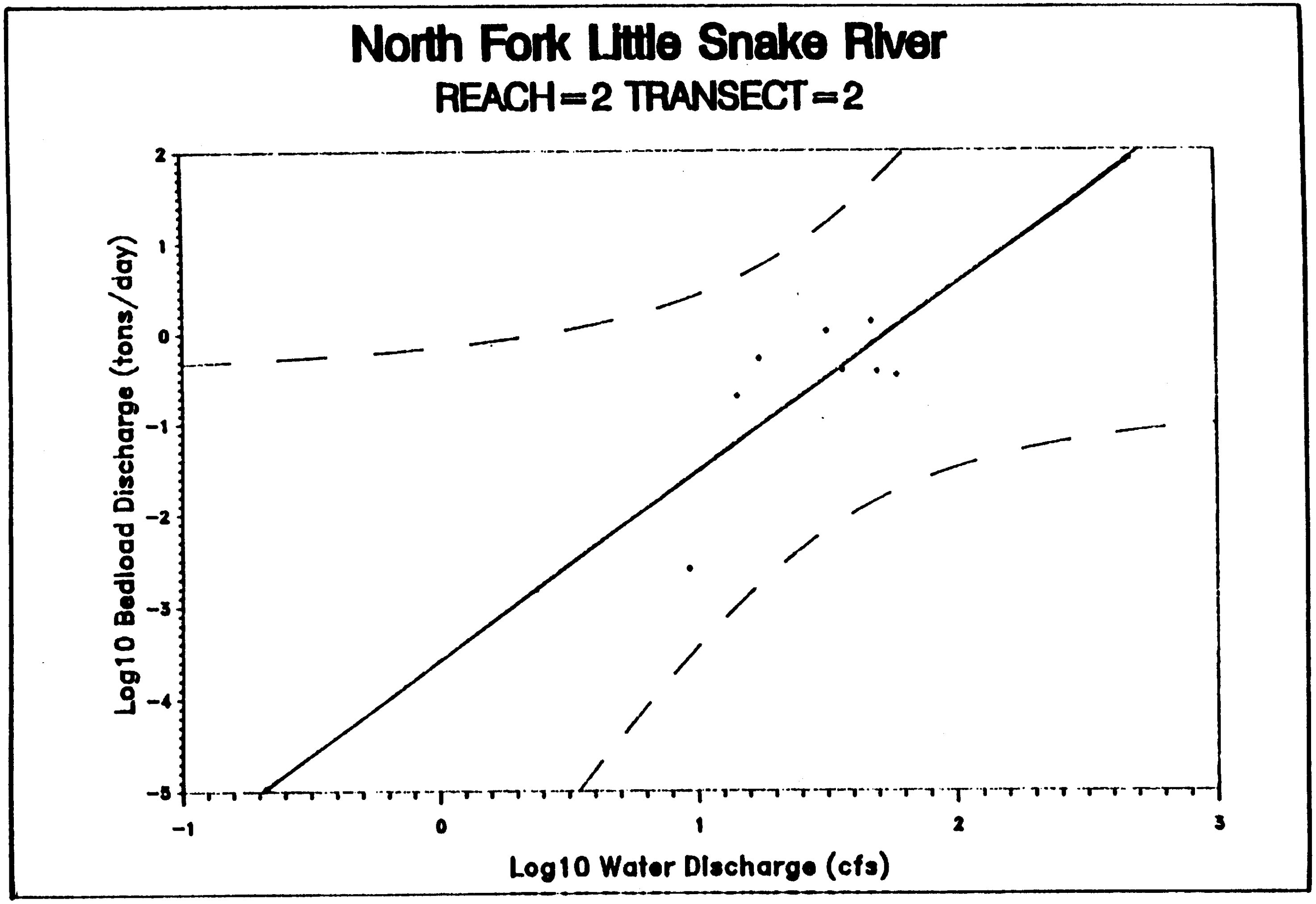


Figure A - 14. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 2, Reach 2, North Fork Little Snake River.

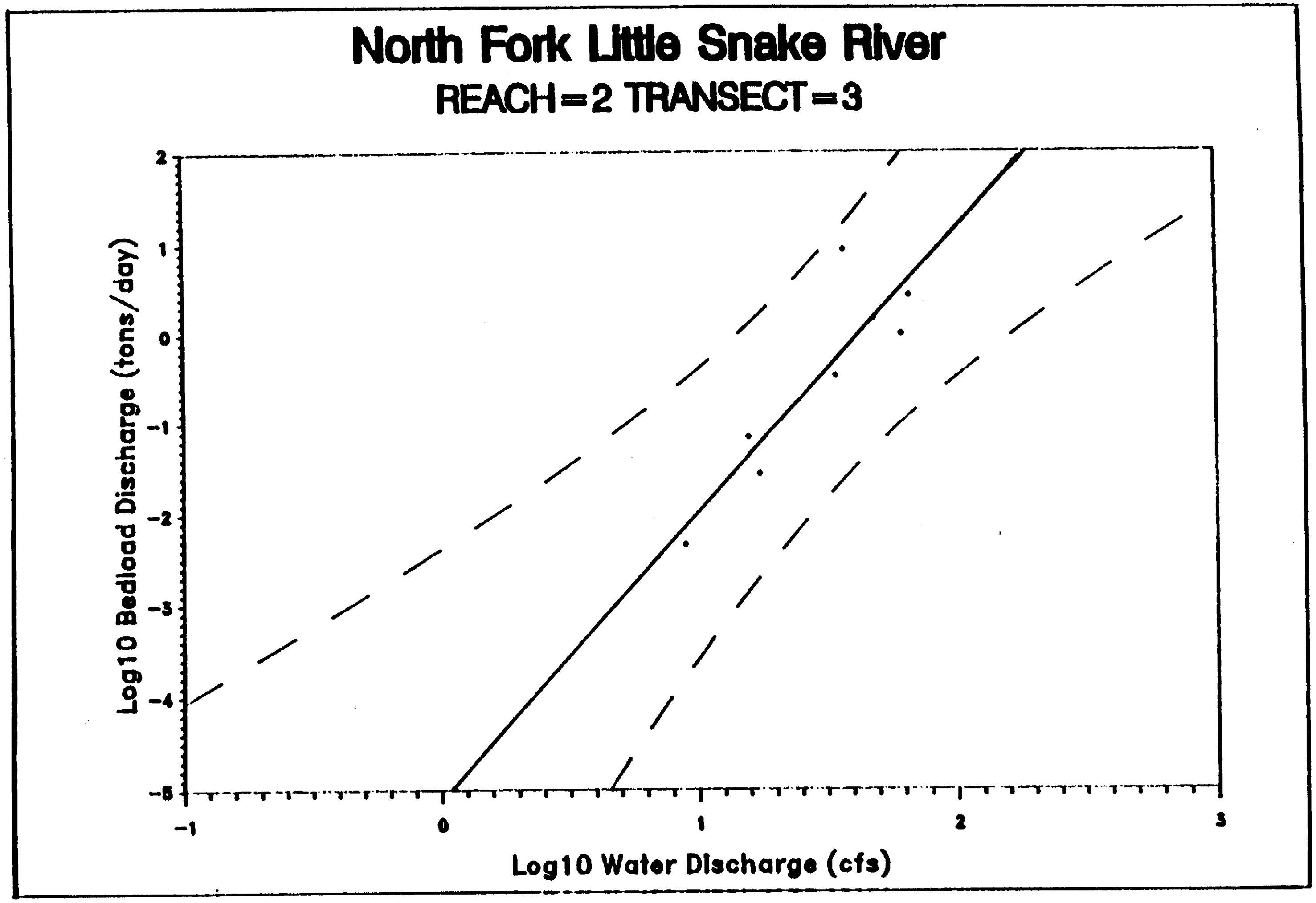


Figure A - 15. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 3, Reach 2, North Fork Little Snake River.

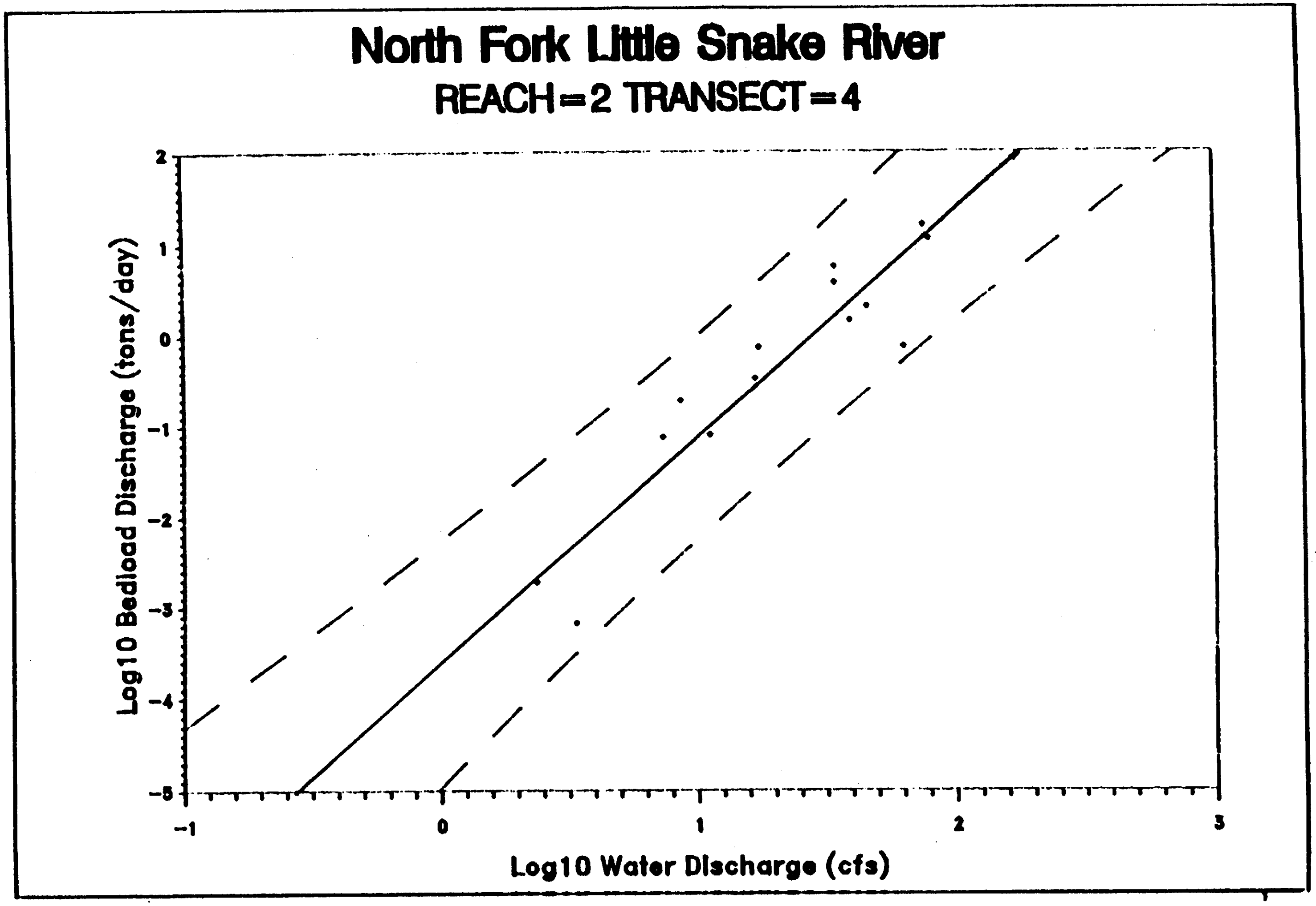


Figure A - 16. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 4, Reach 2, North Fork Little Snake River.

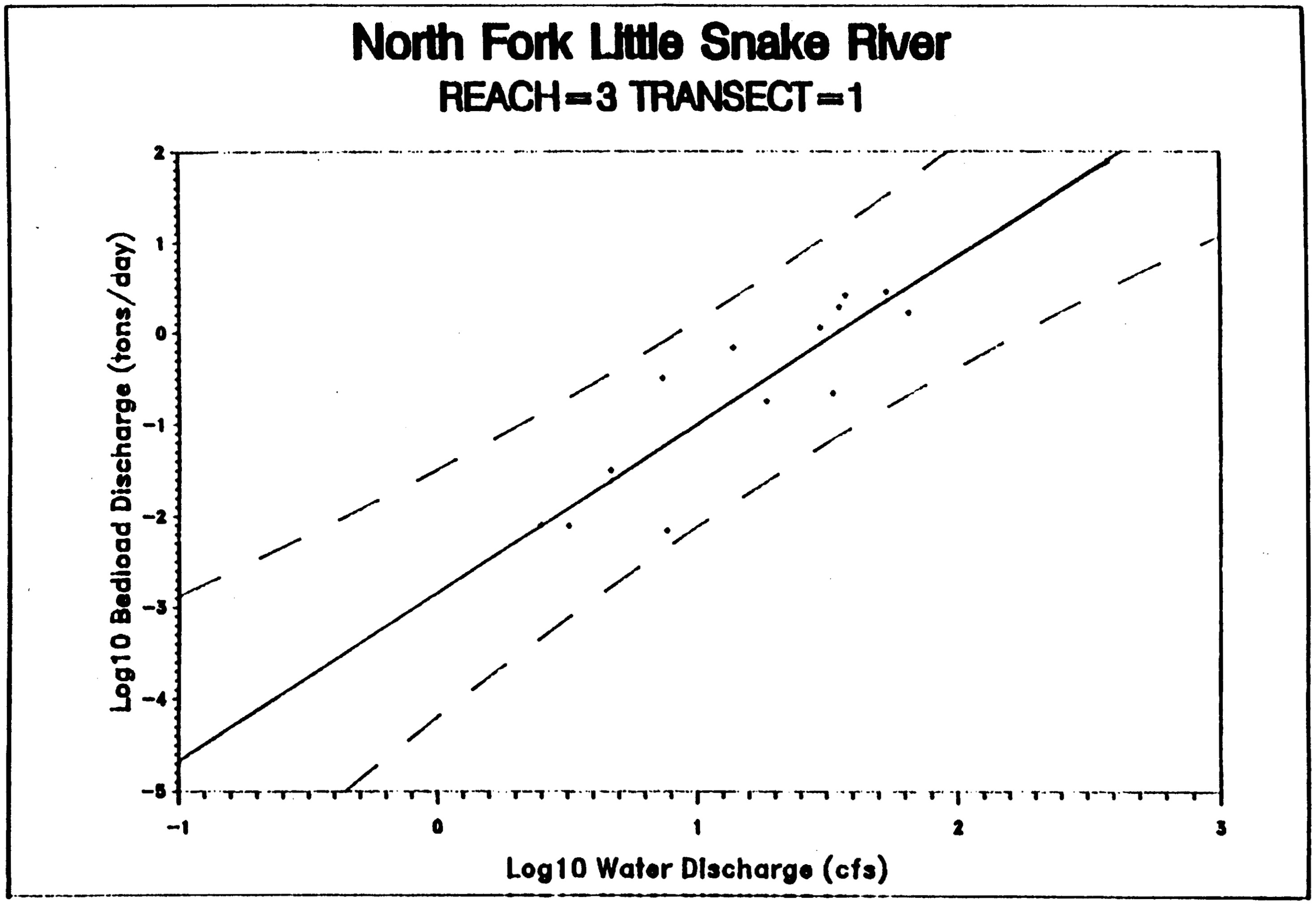


Figure A - 17. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 1, Reach 3, North Fork Little Snake River.

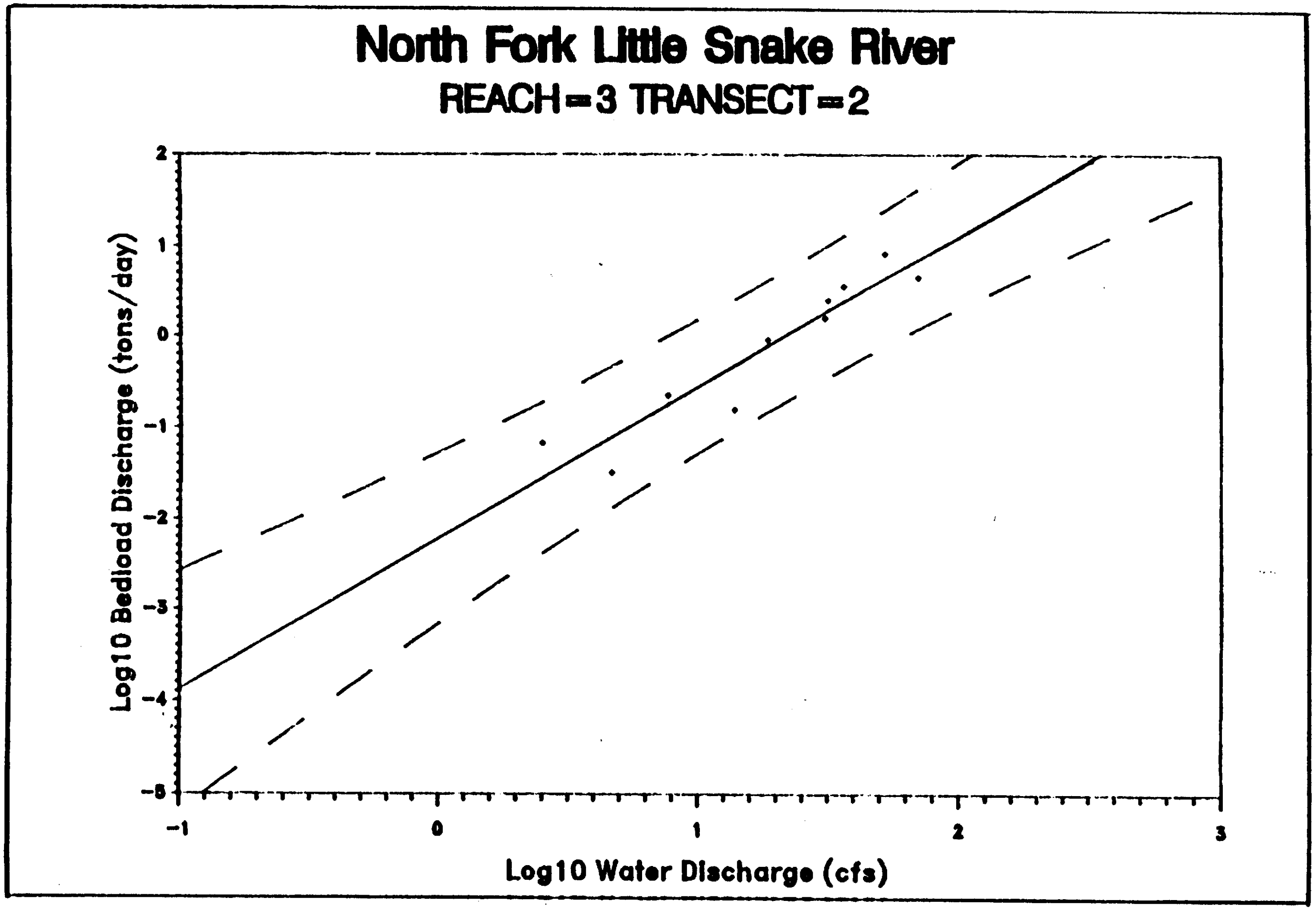


Figure A - 18. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 2, Reach 3, North Fork Little Snake River.

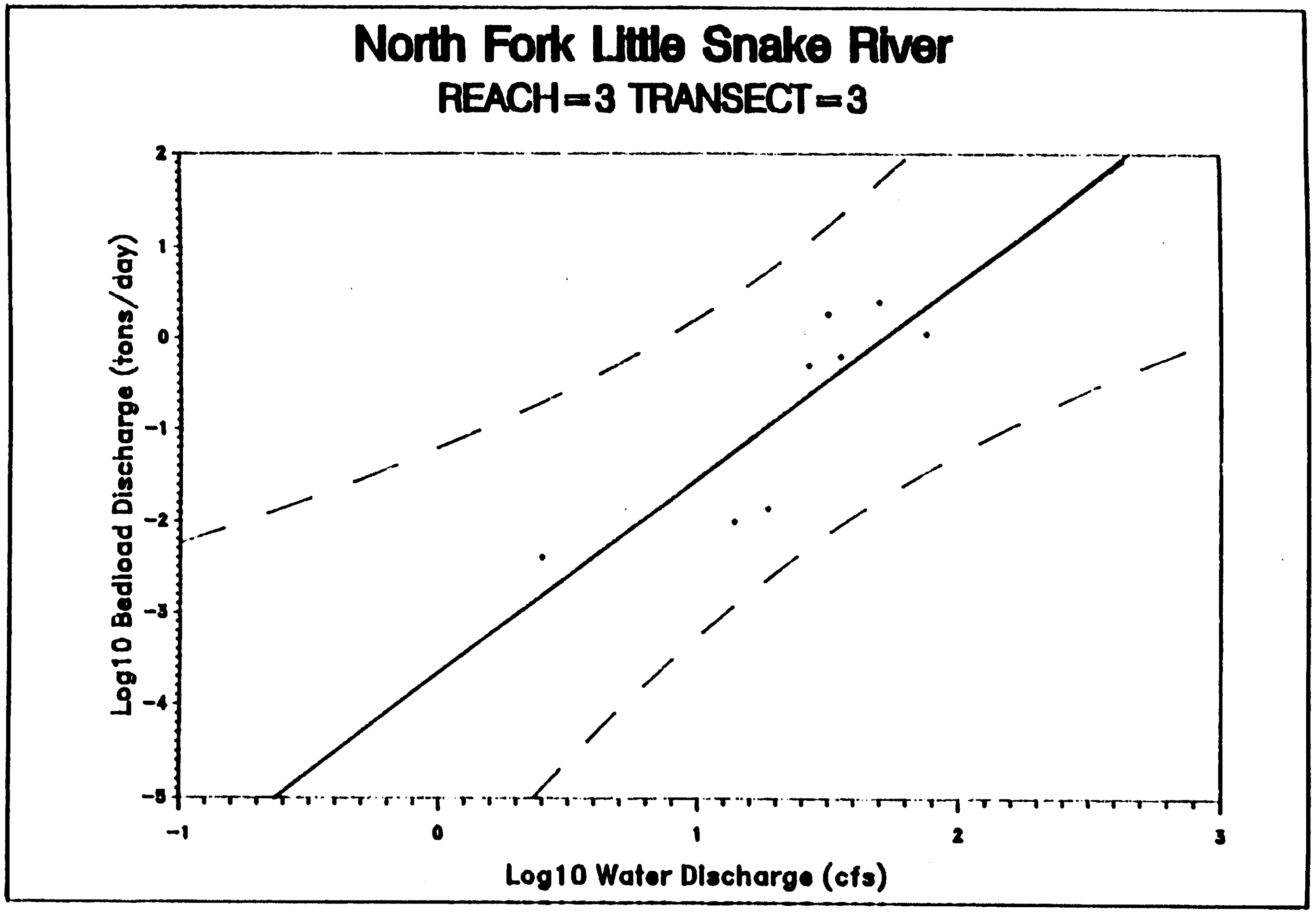


Figure A - 19. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 3, Reach 3, North Fork Little Snake River.

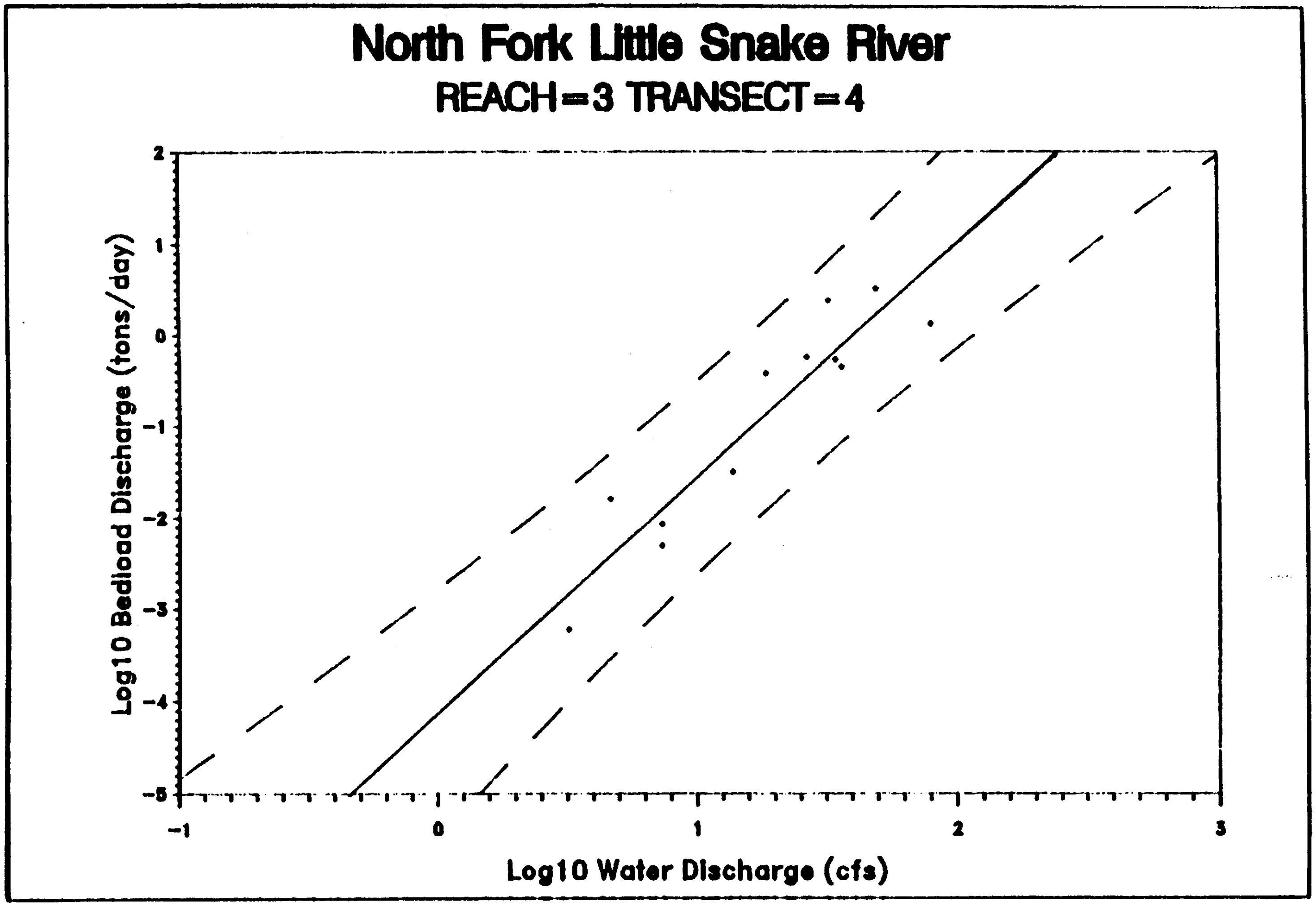


Figure A - 20. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 4, Reach 3, North Fork Little Snake River.

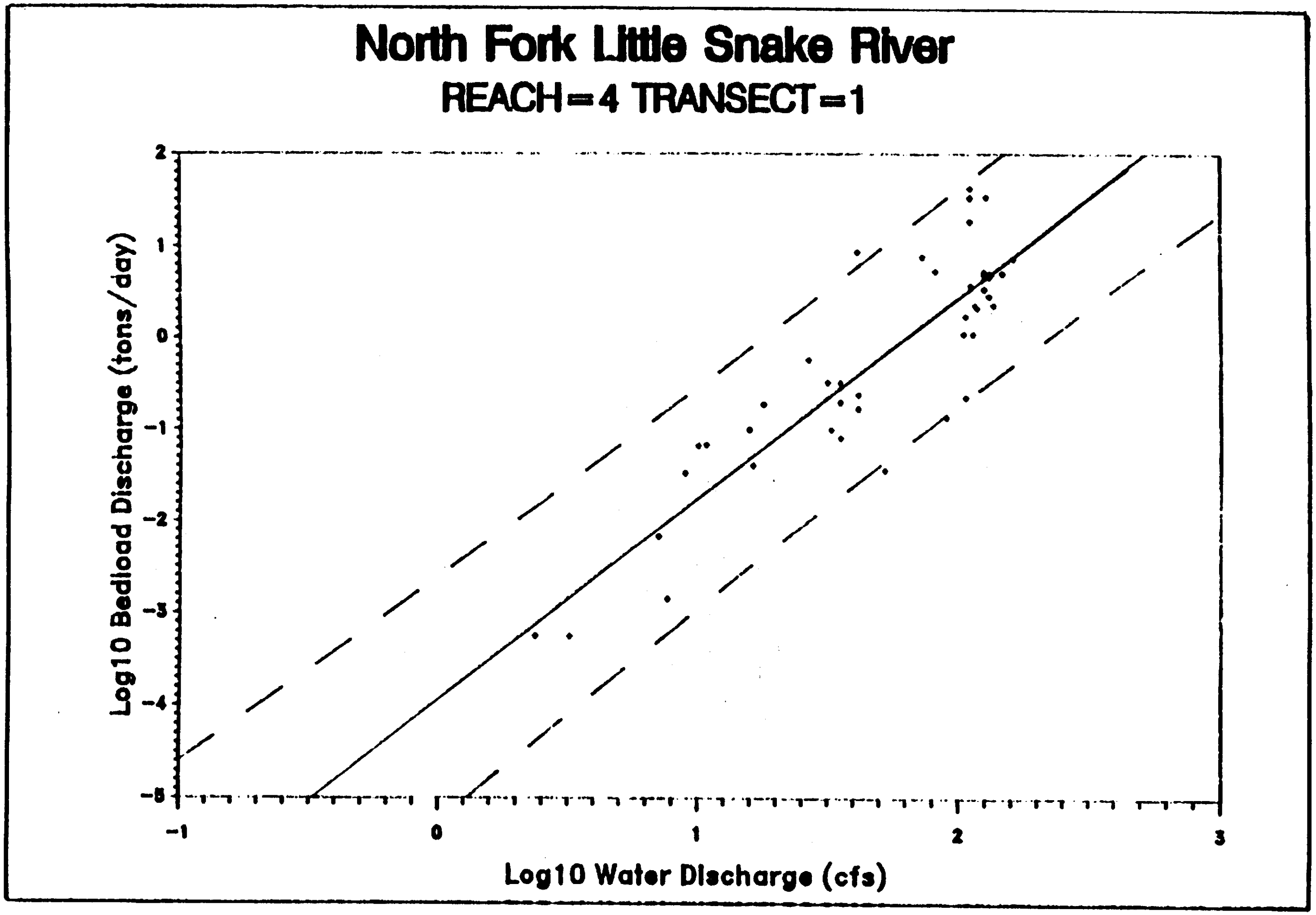


Figure A - 21. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 1, Reach 4, North Fork Little Snake River.

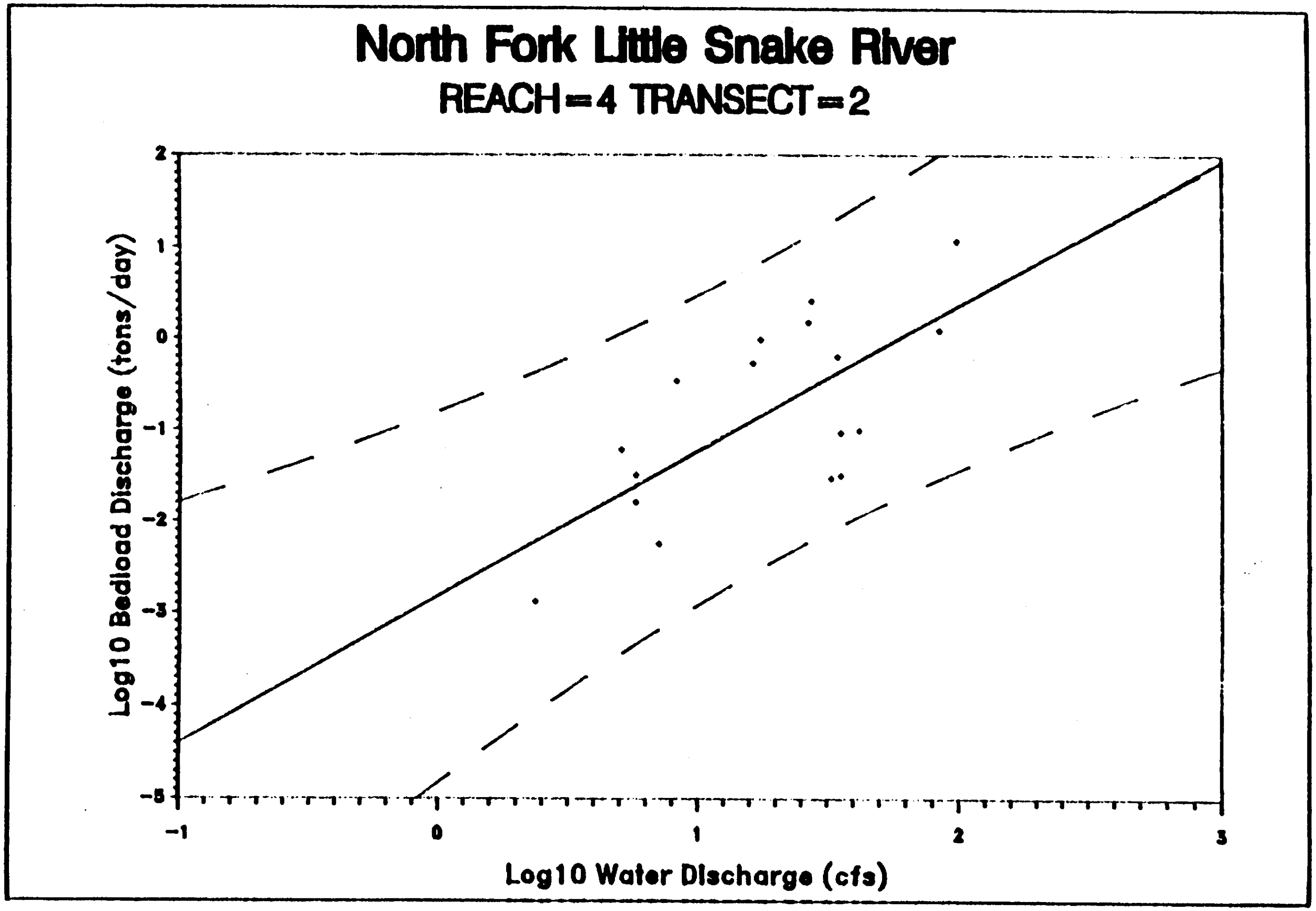


Figure A - 22. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 2, Reach 4, North Fork Little Snake River.

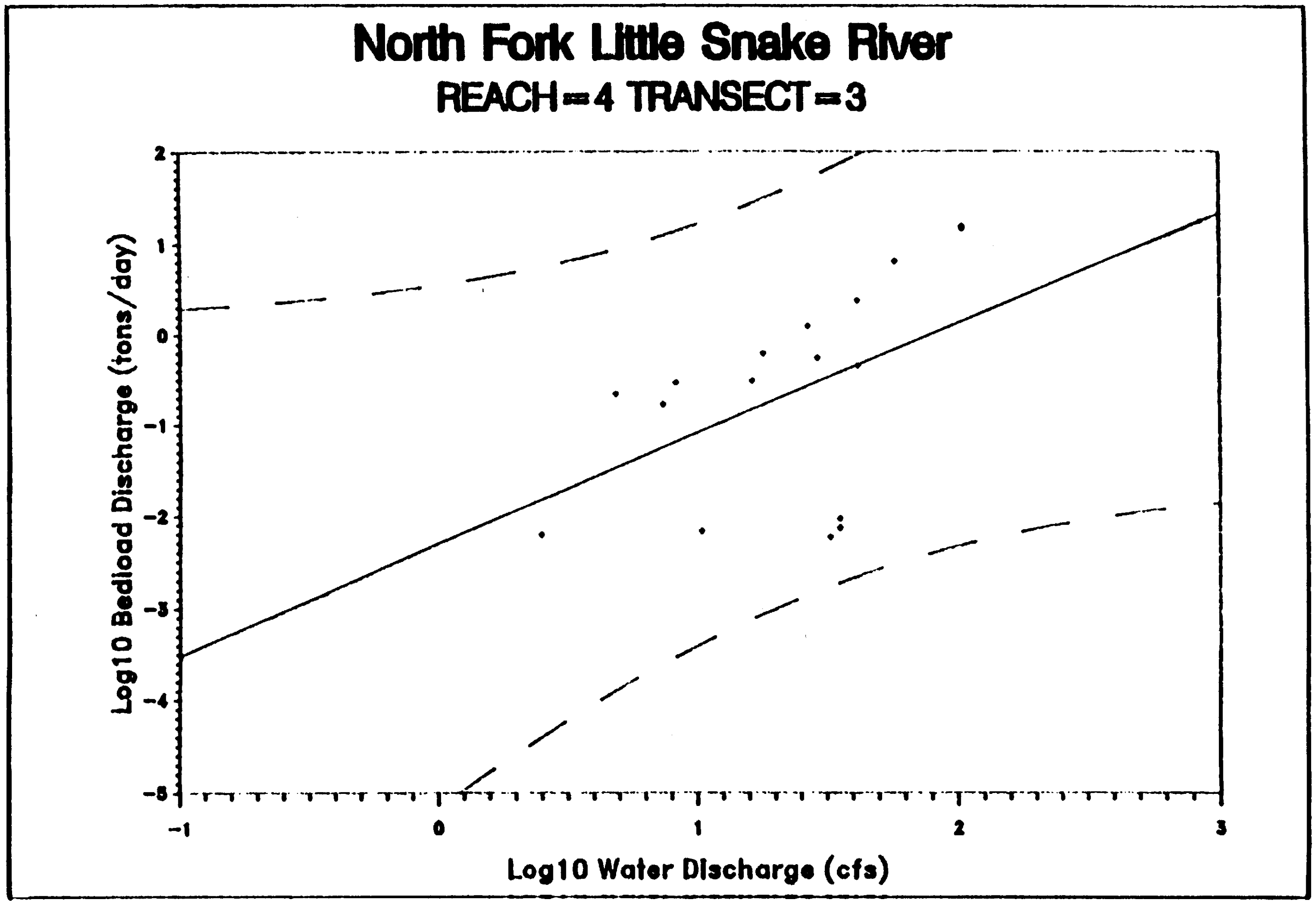


Figure A - 23. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 3, Reach 4, North Fork Little Snake River.

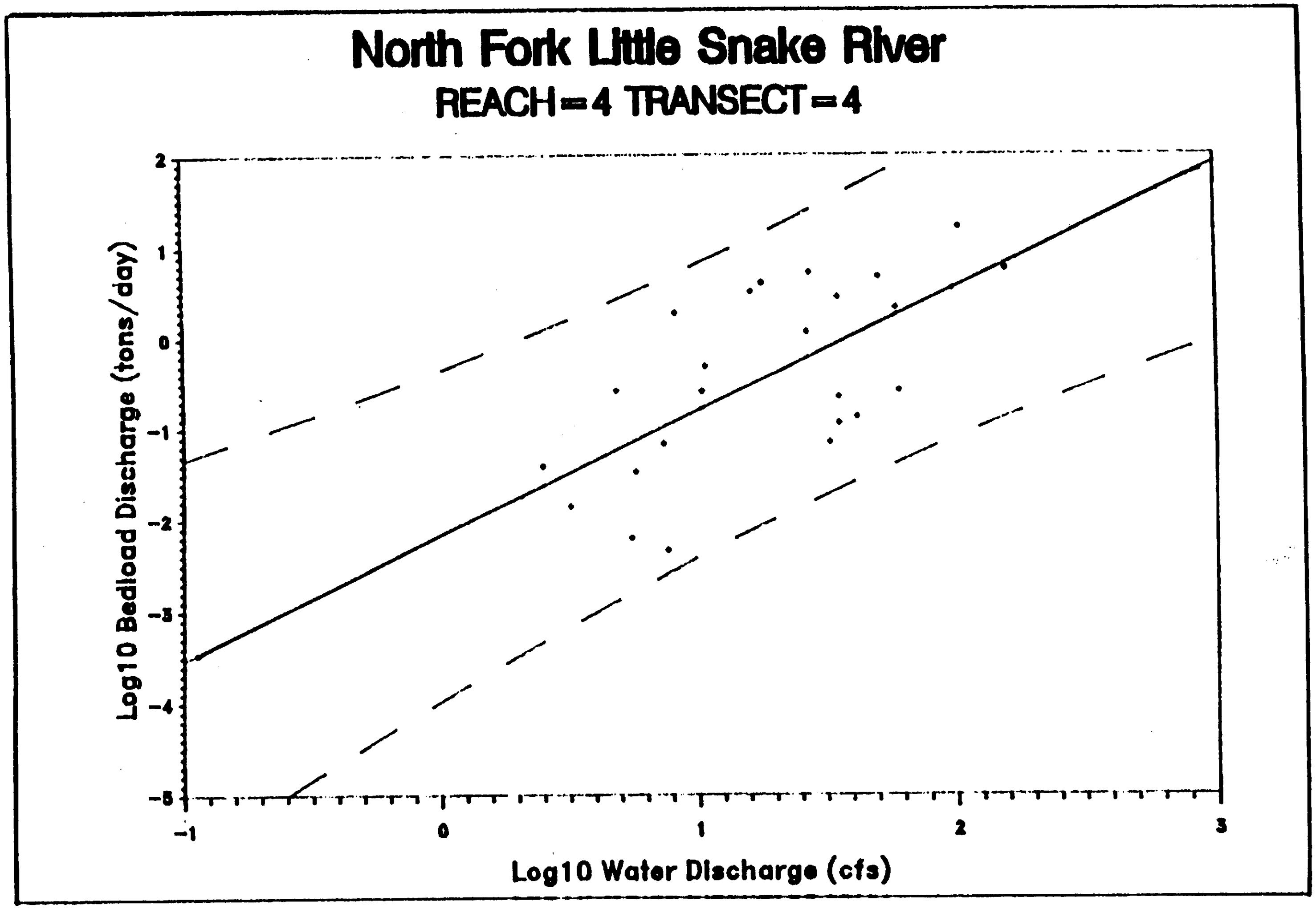


Figure A - 24. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 4, Reach 4, North Fork Little Snake River.

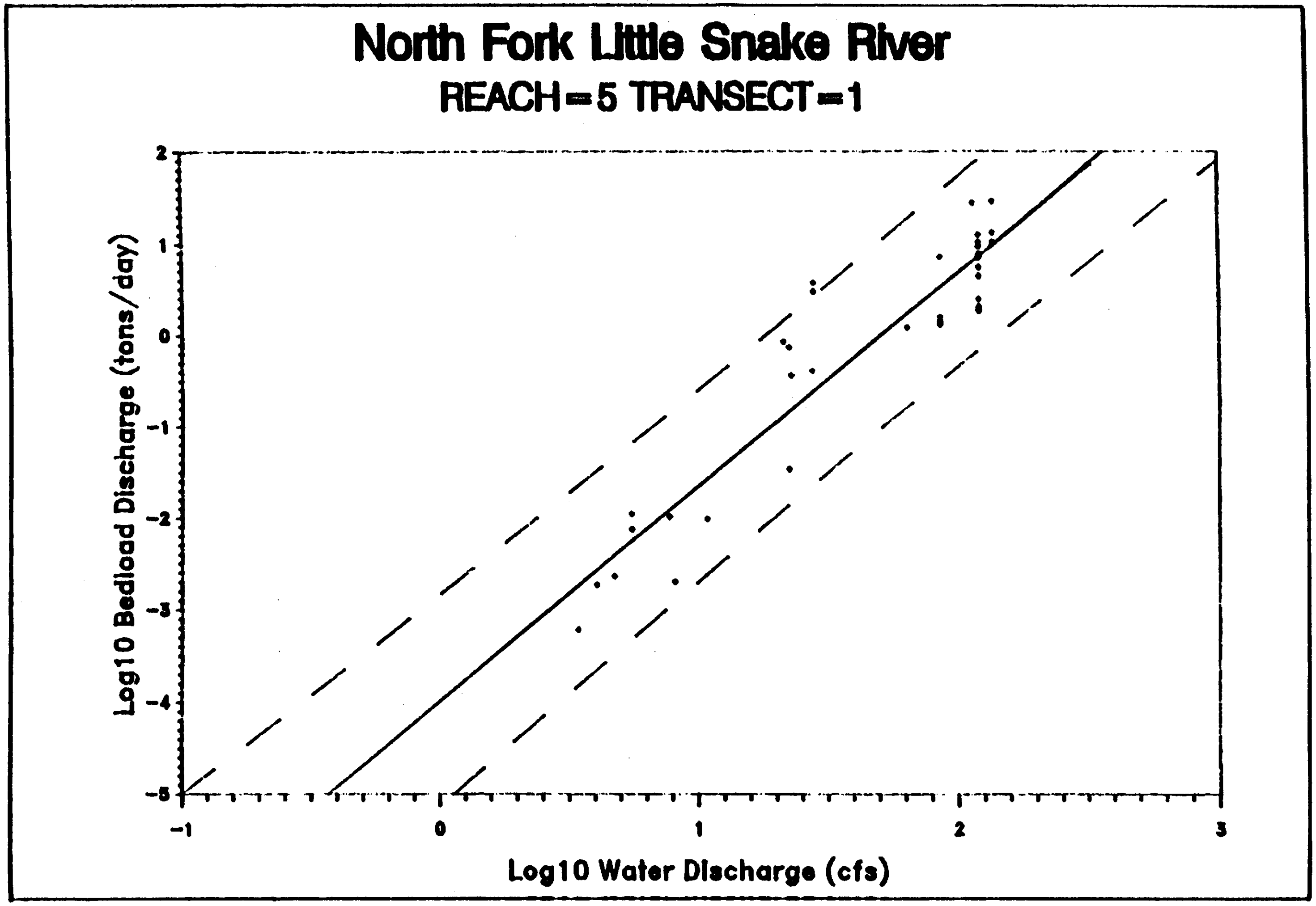


Figure A - 25. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 1, Reach 5, North Fork Little Snake River.

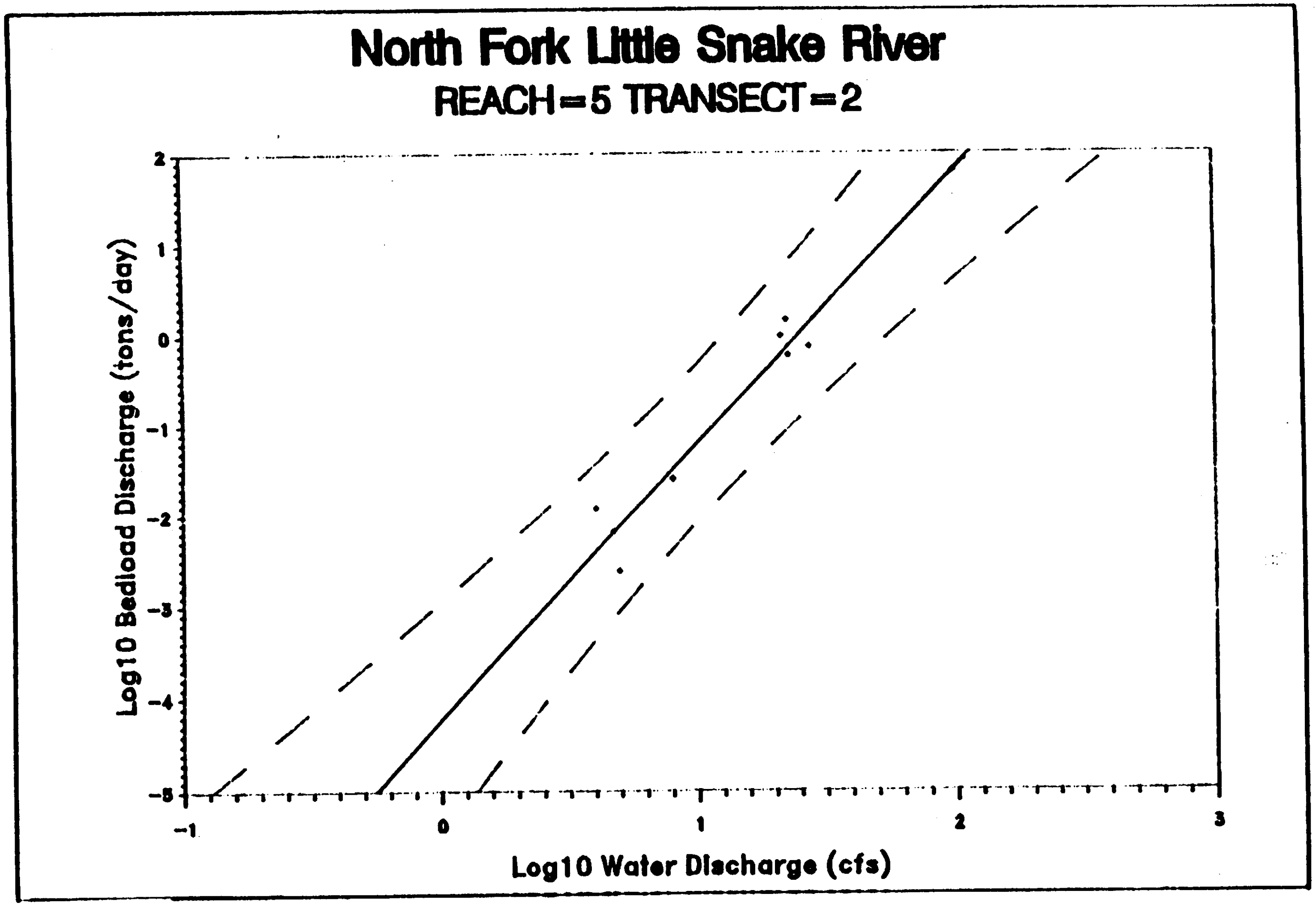


Figure A - 26. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 2, Reach 5, North Fork Little Snake River.

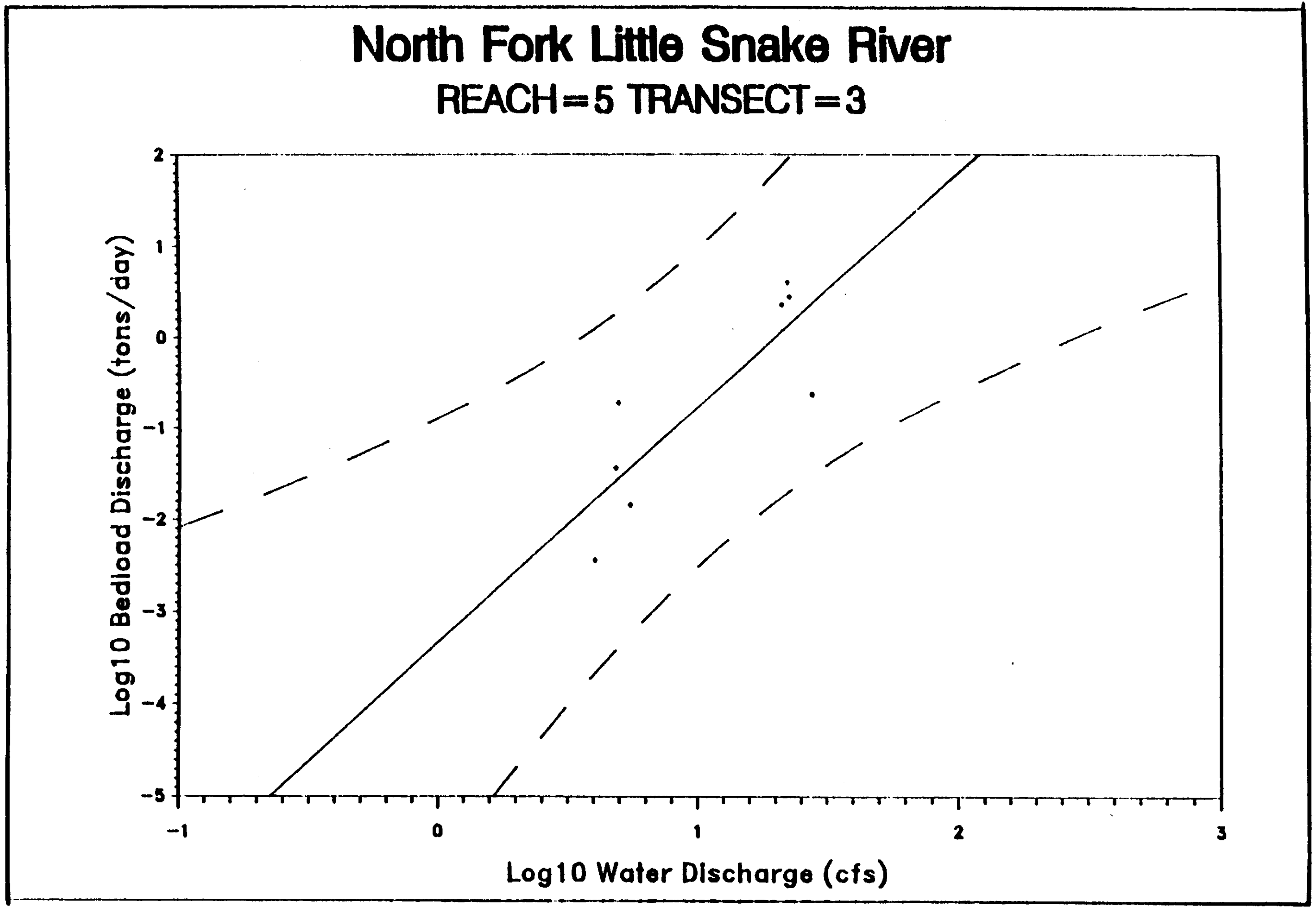


Figure A - 27. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 3, Reach 5, North Fork Little Snake River.

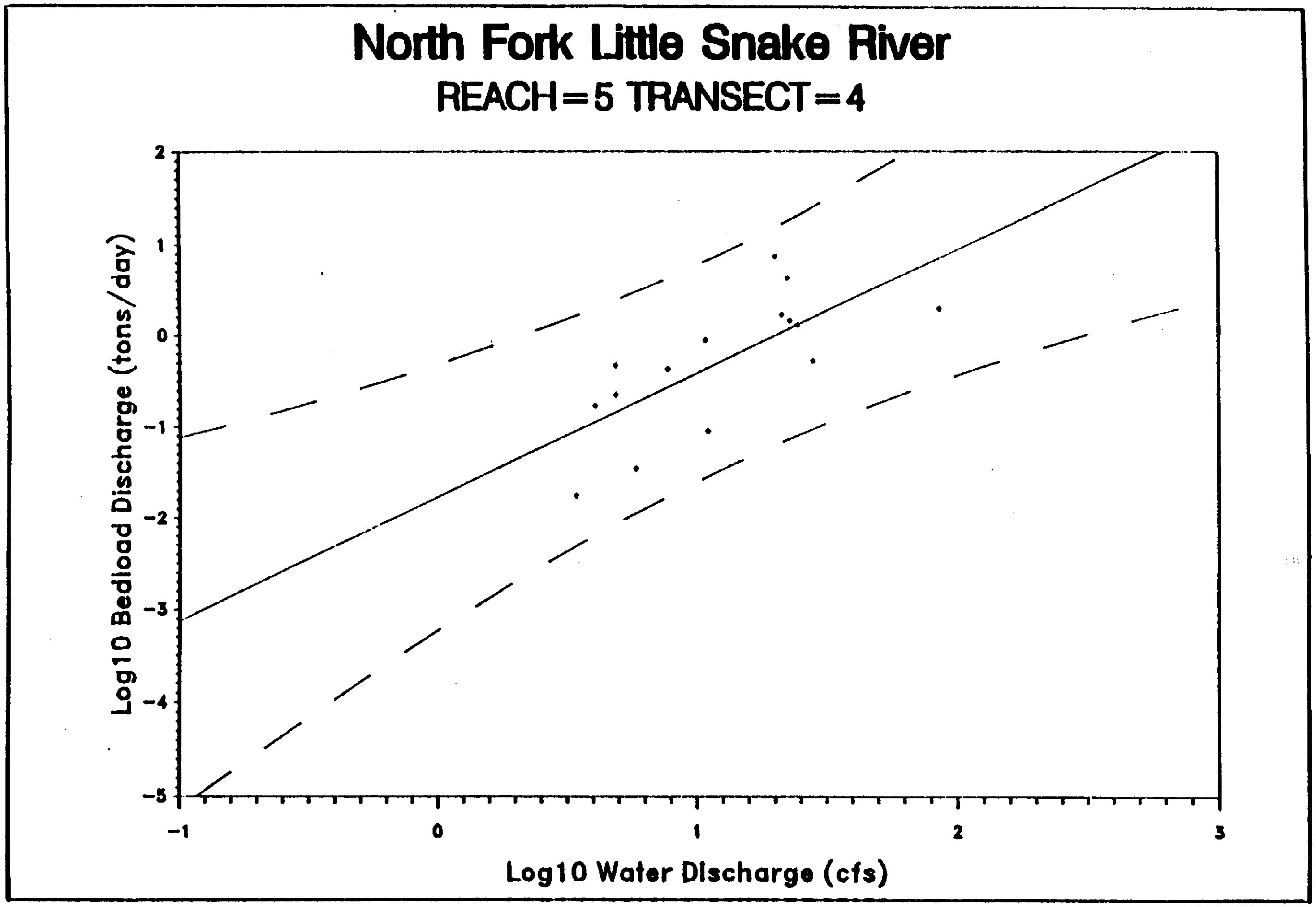


Figure A - 28. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 4, Reach 5, North Fork Little Snake River.

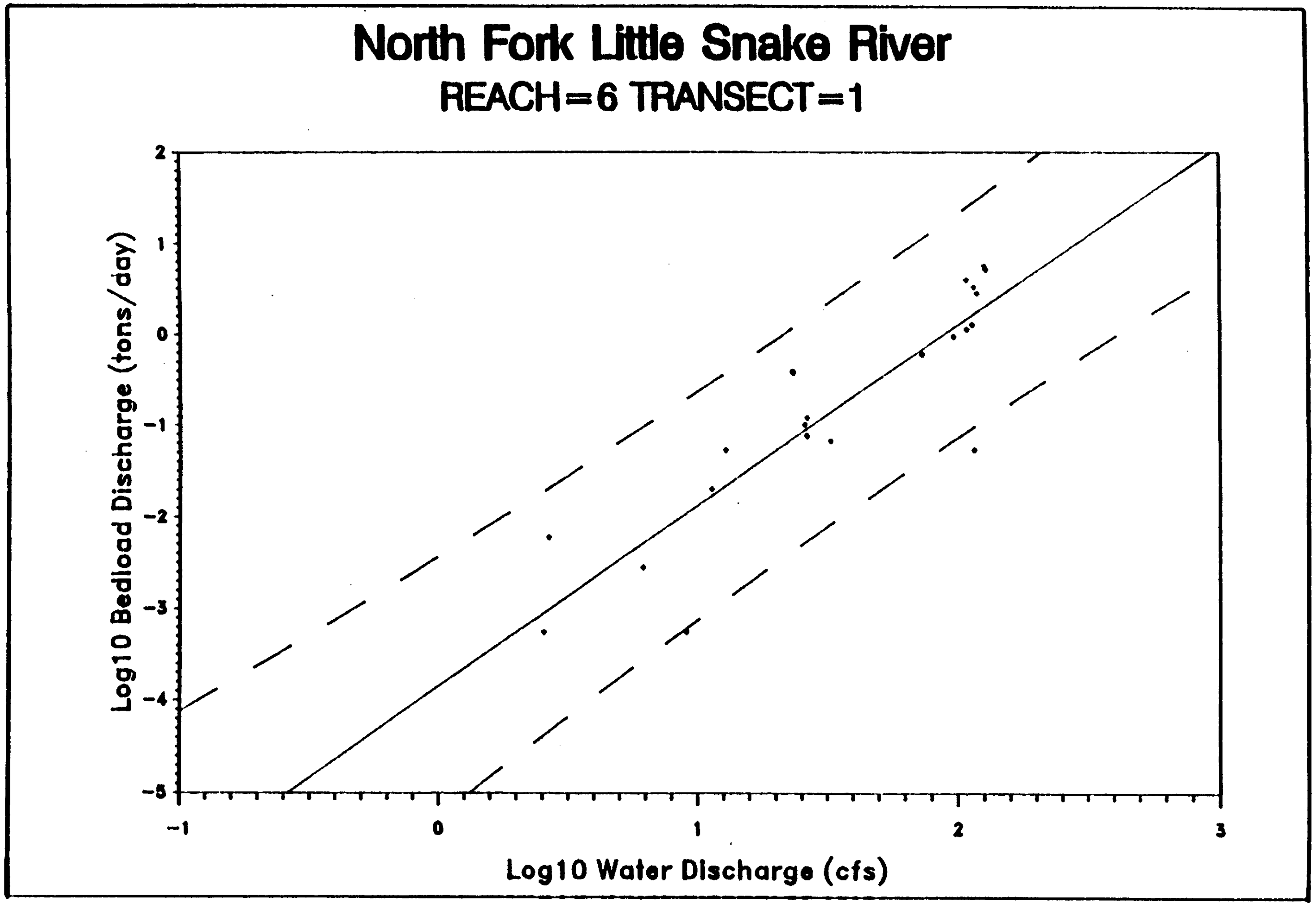


Figure A - 29. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 1, Reach 6, North Fork Little Snake River.

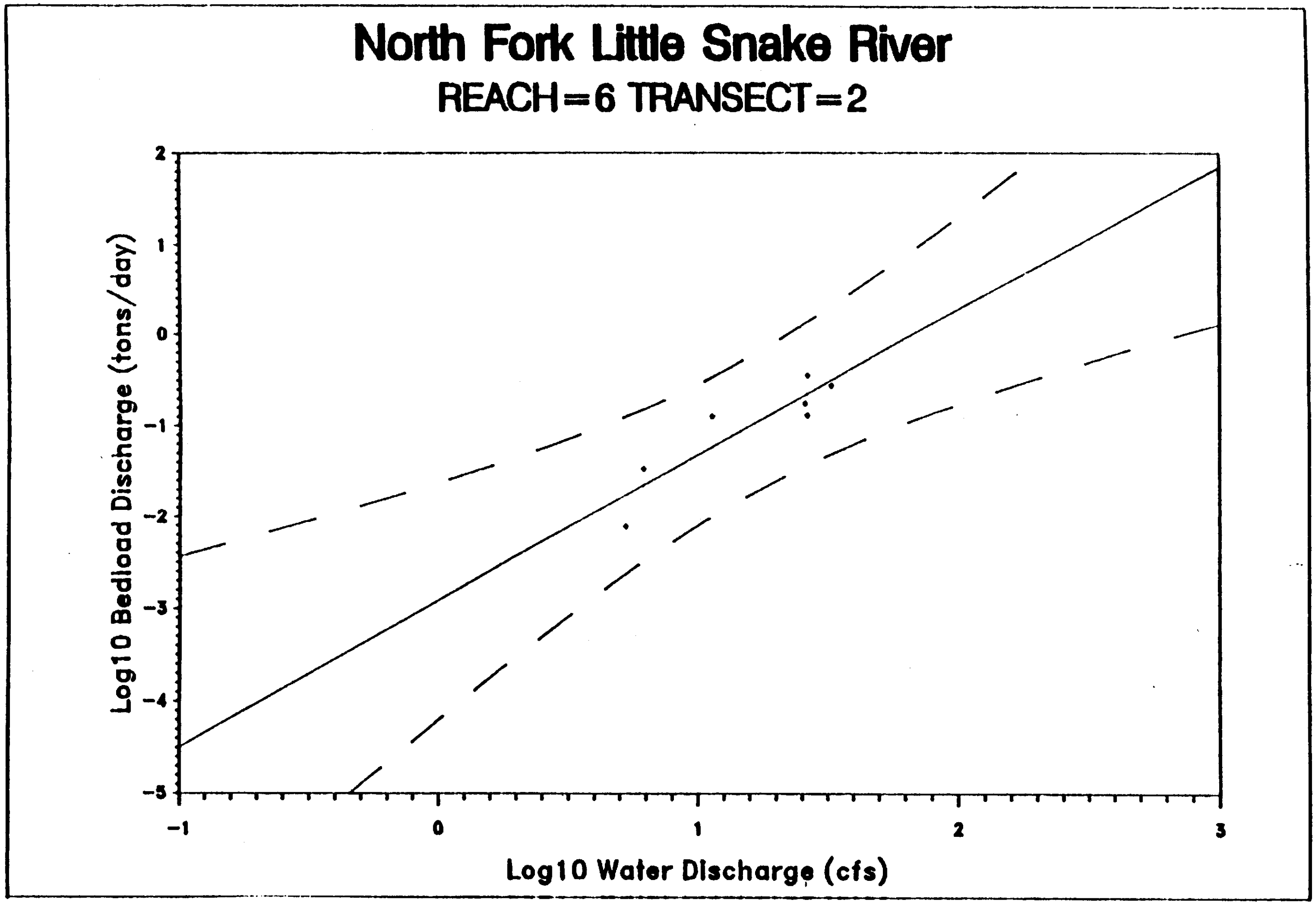


Figure A - 30. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 2, Reach 6, North Fork Little Snake River.

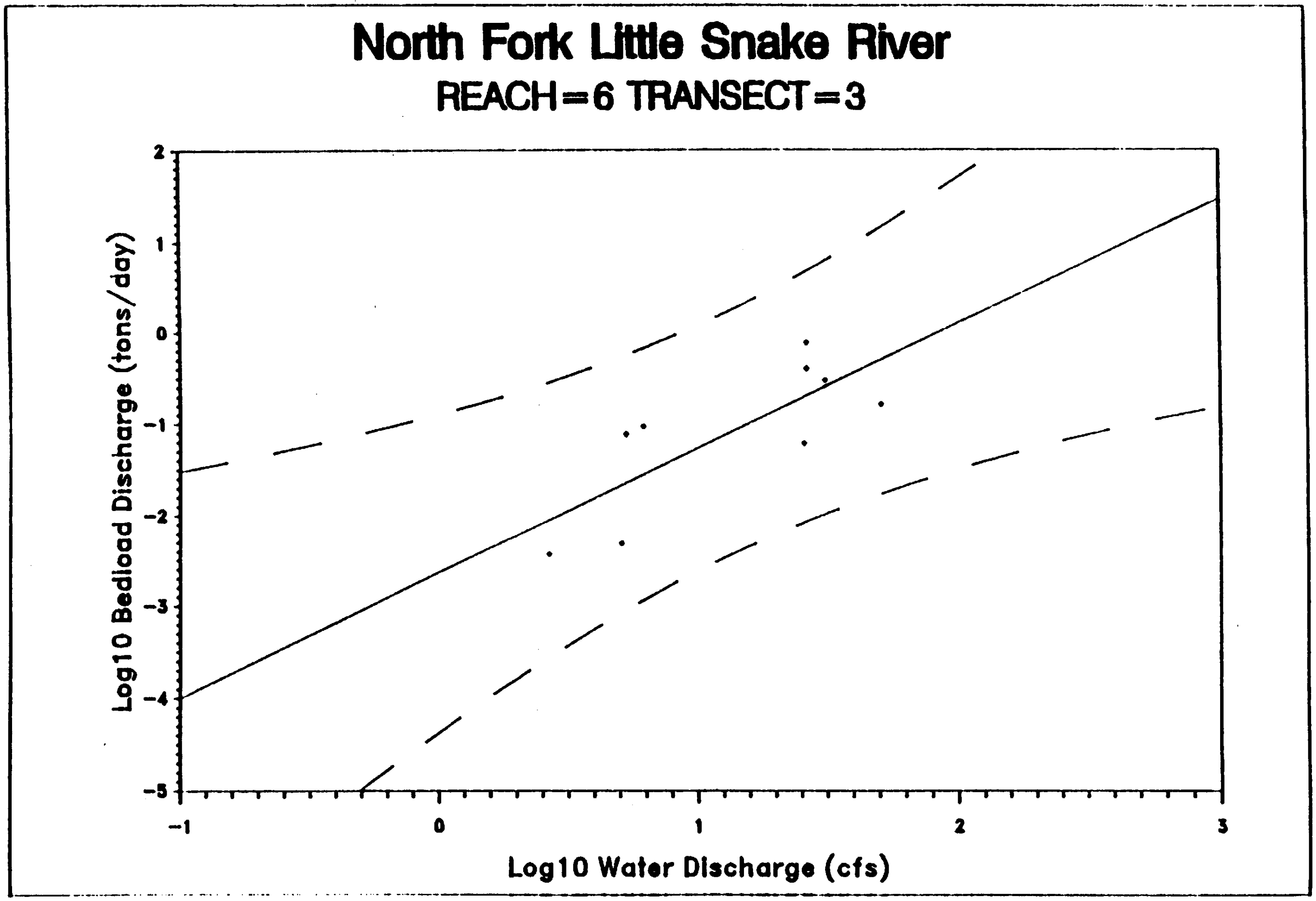


Figure A - 31. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 3, Reach 6, North Fork Little Snake River.

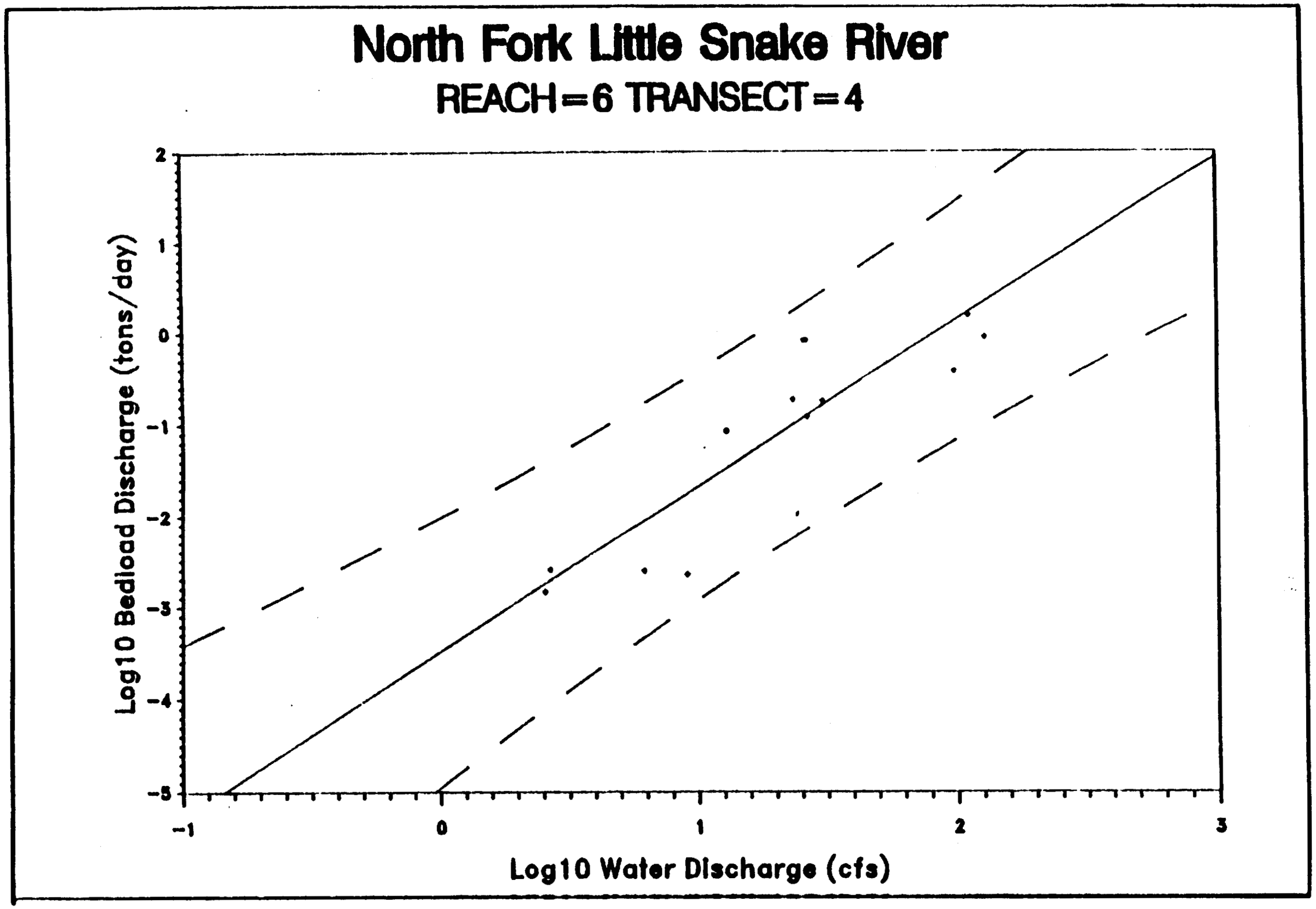


Figure A - 32. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 4, Reach 6, North Fork Little Snake River.

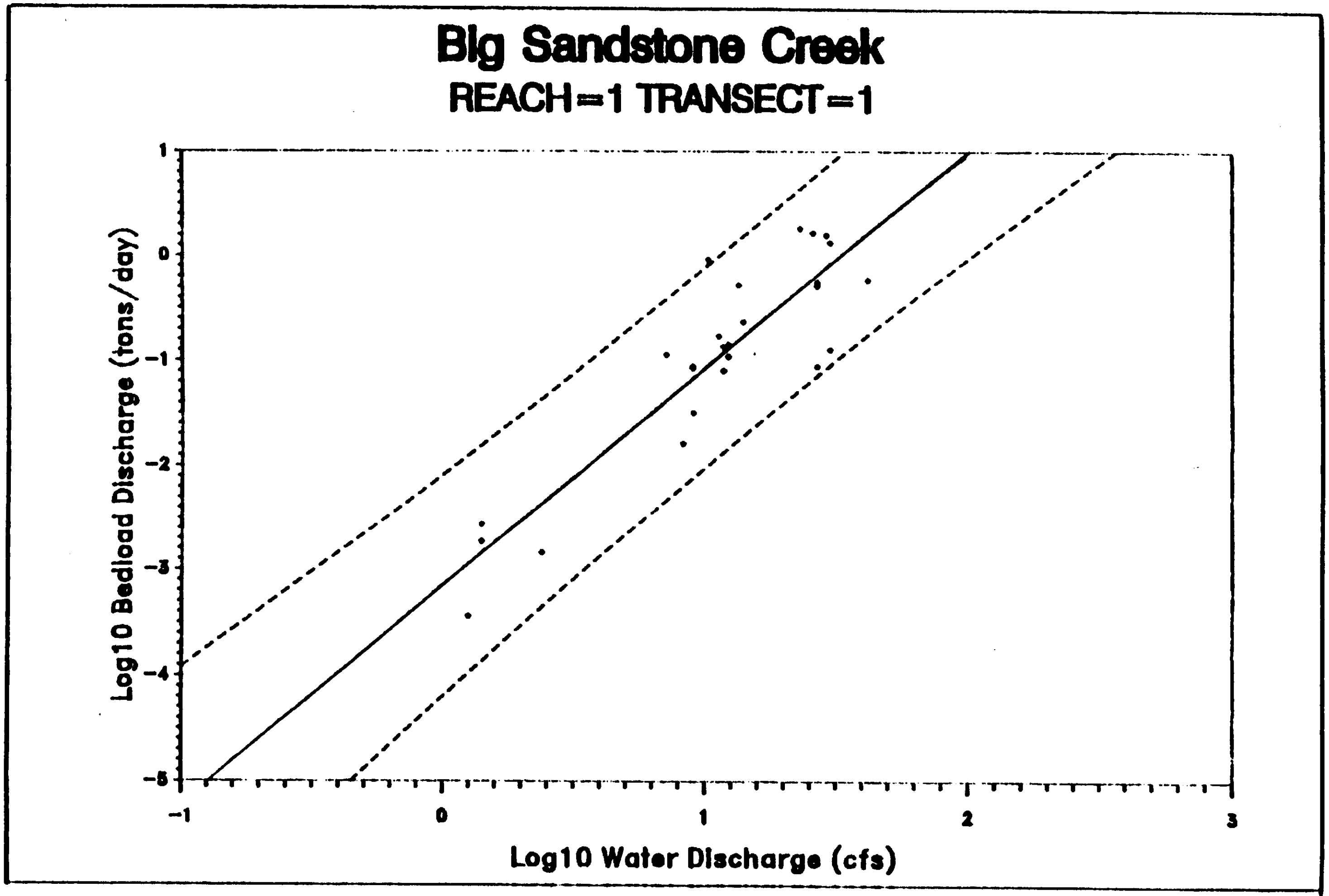


Figure A - 33. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 1, North Fork of Big Sandstone Creek.

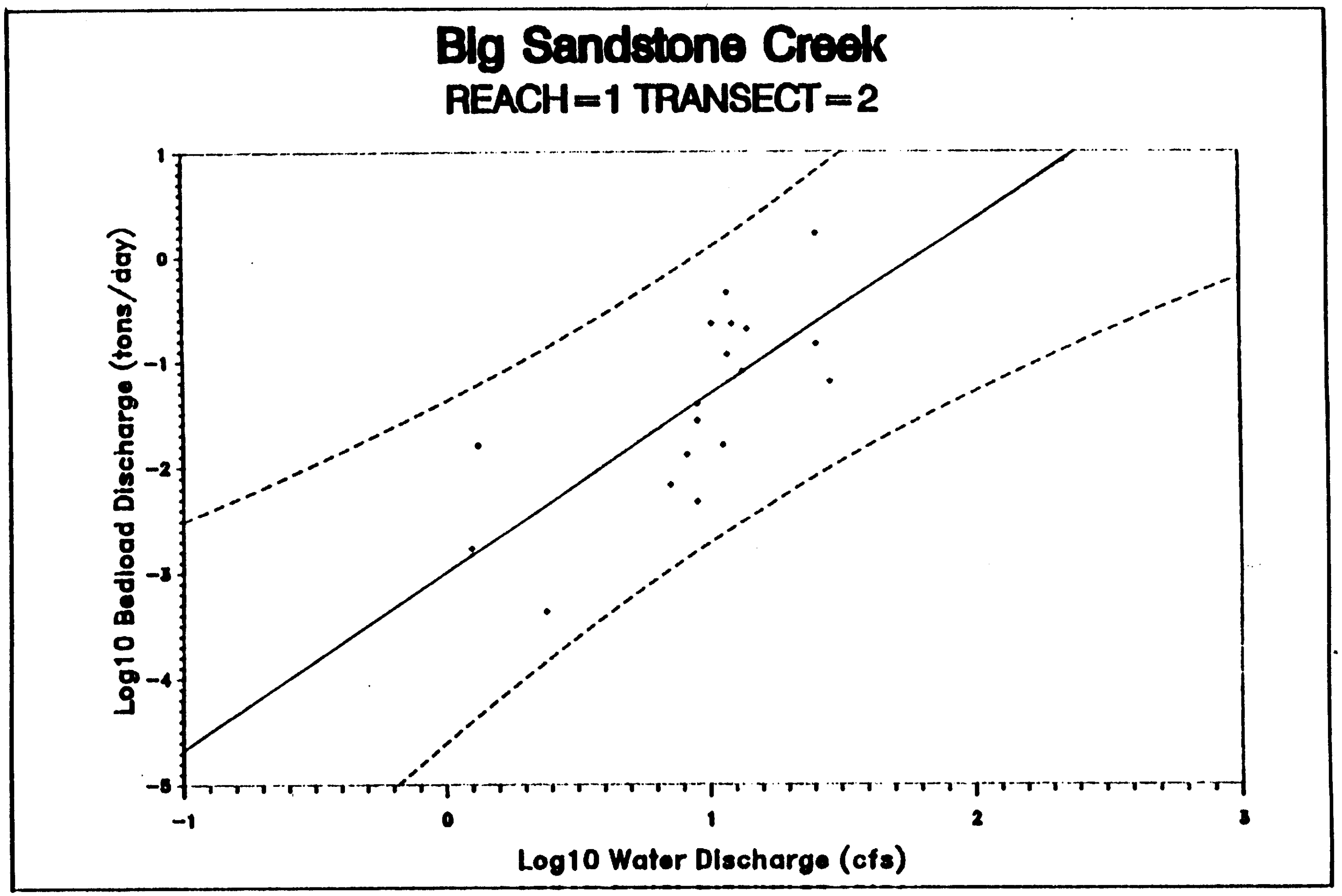


Figure A - 34. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 2, North Fork of Big Sandstone Creek.

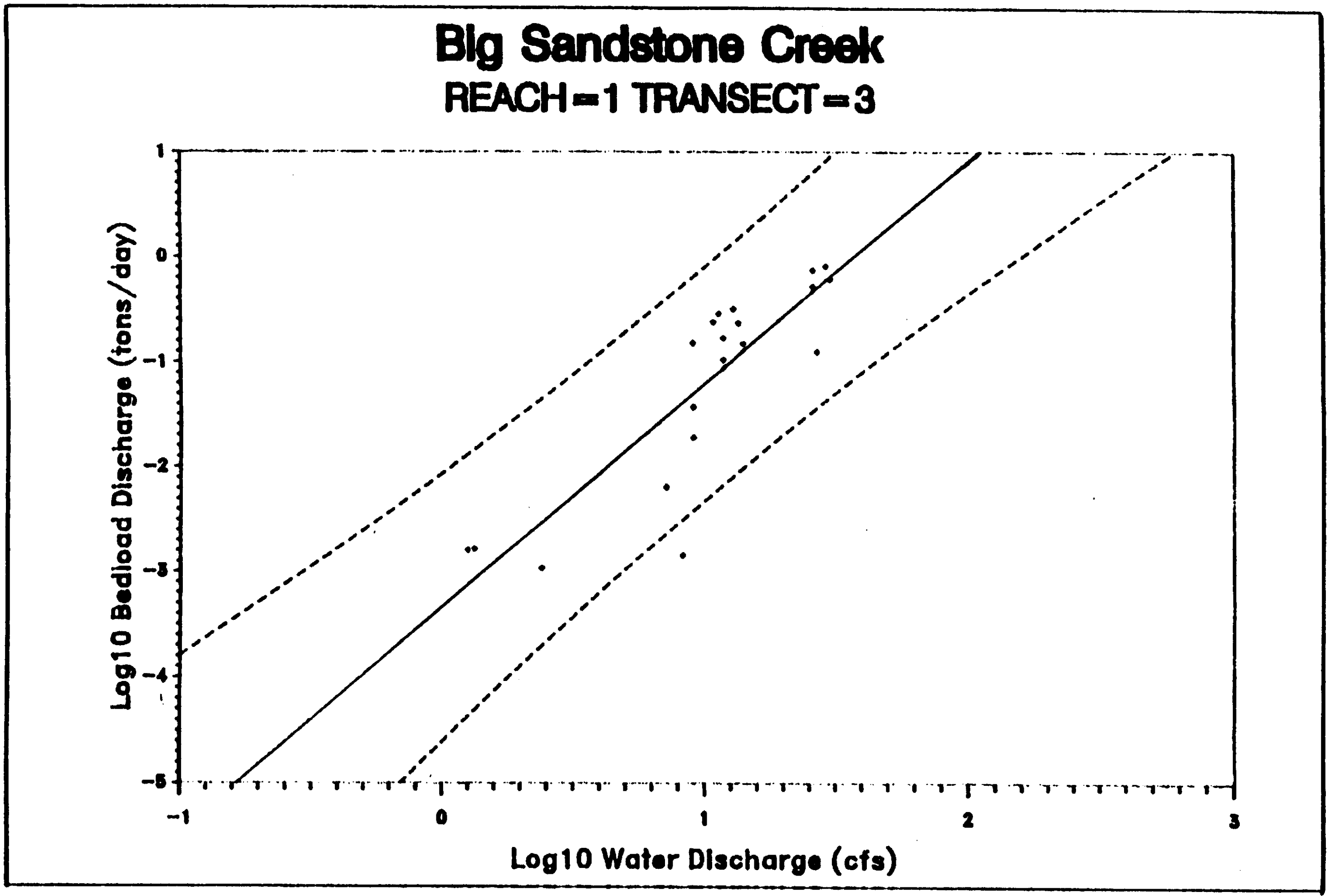


Figure A - 35. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 3, North Fork of Big Sandstone Creek.

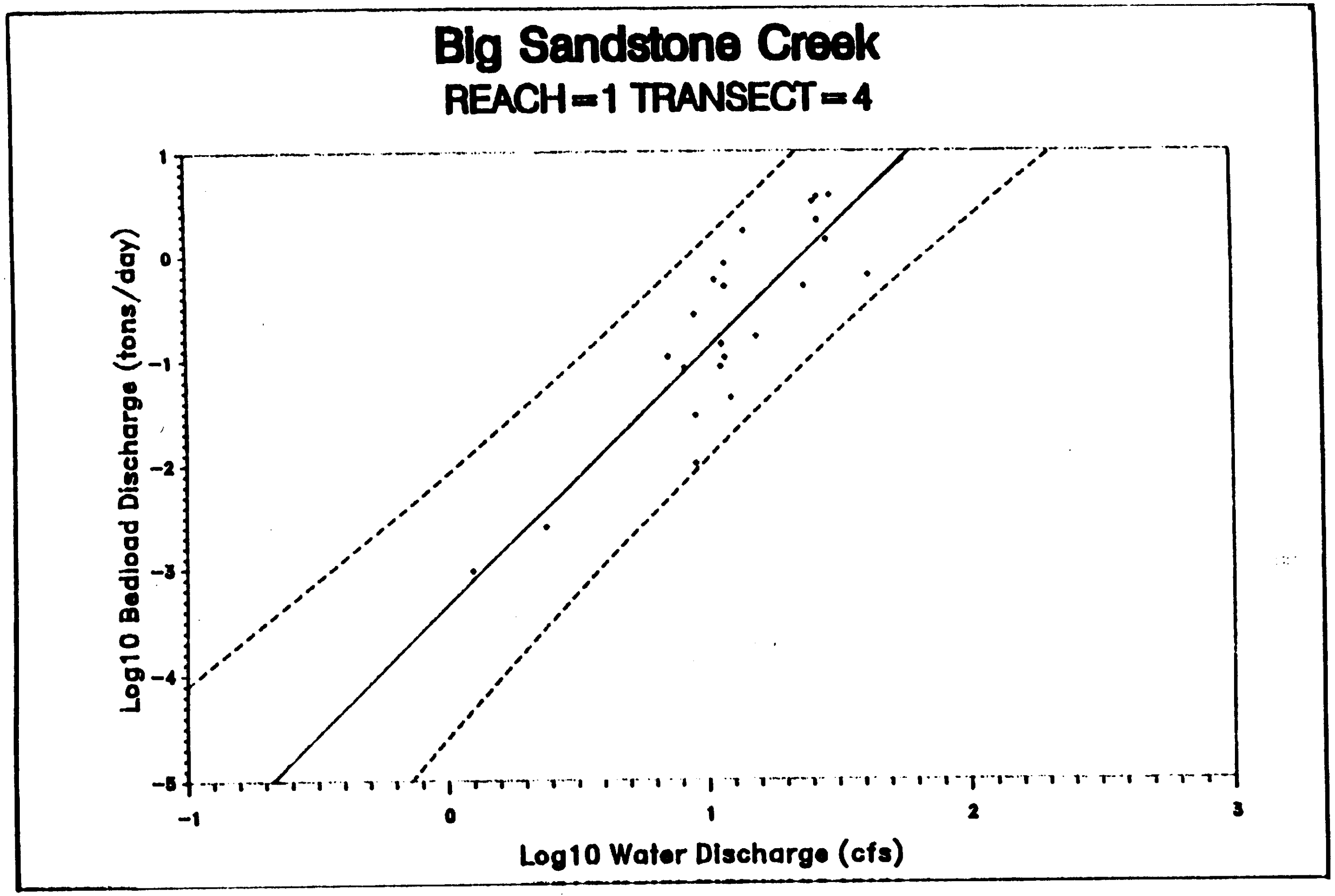


Figure A - 36. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 4, North Fork of Big Sandstone Creek.

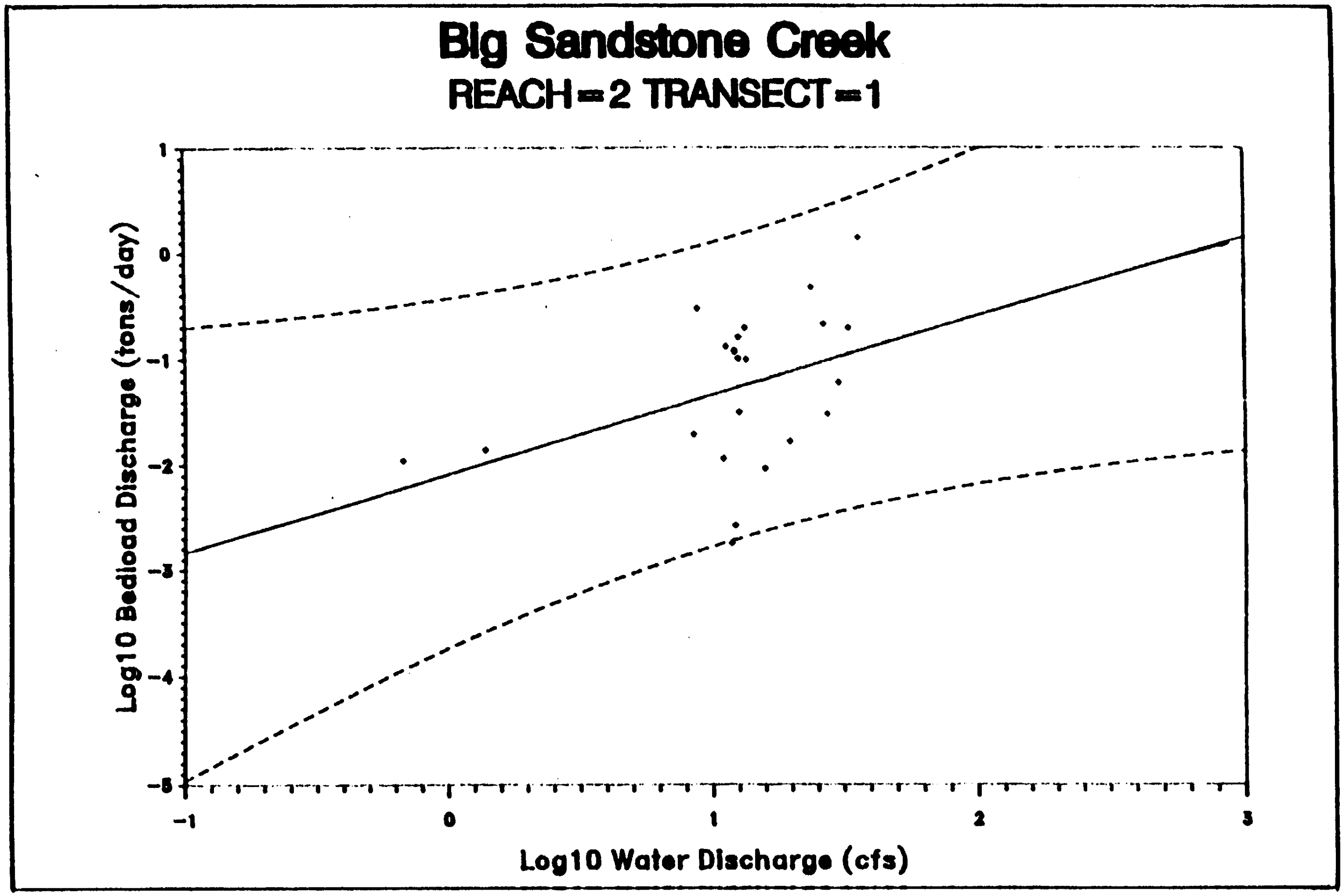


Figure A - 37. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 1, South Fork of Big Sandstone Creek.

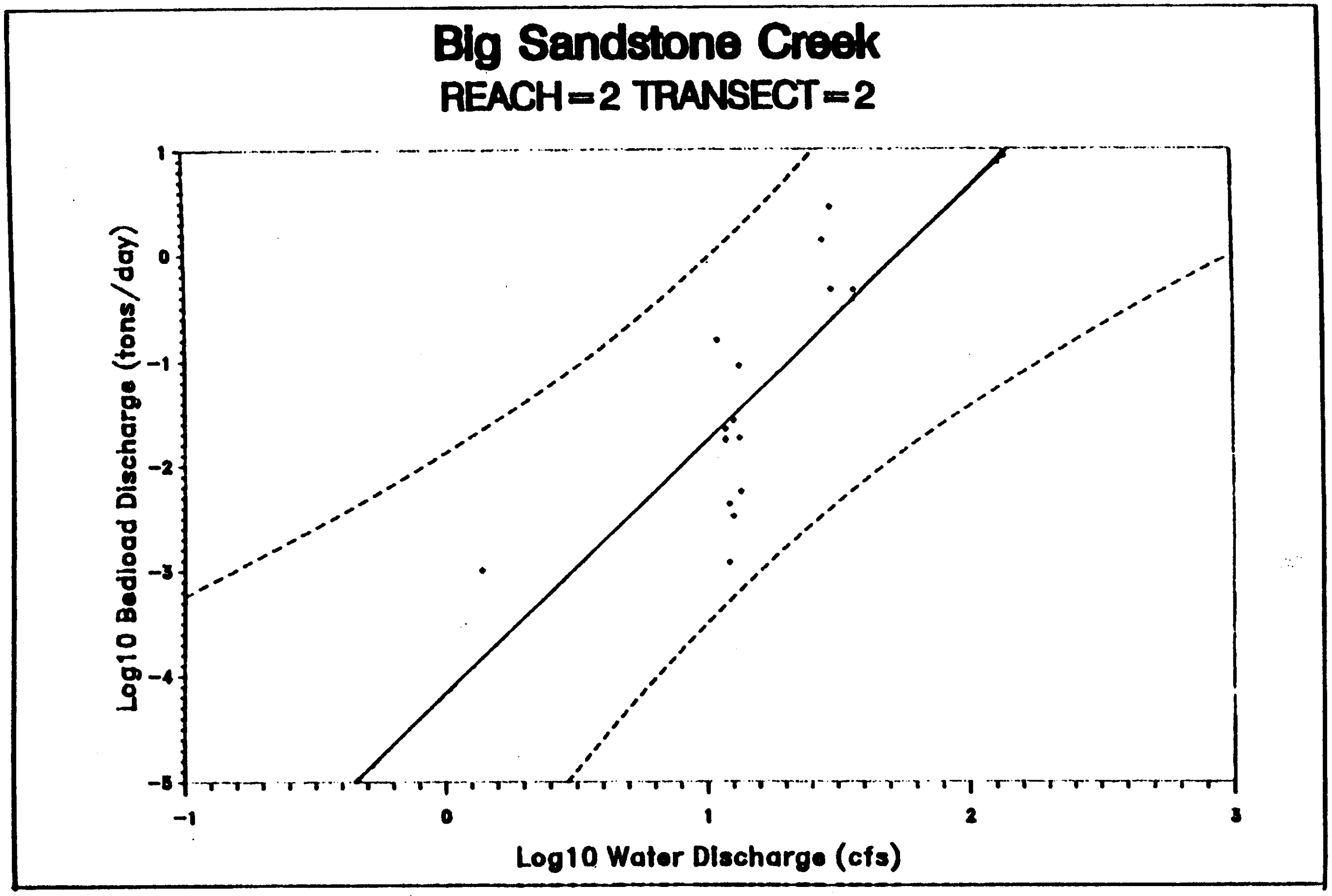


Figure A - 38. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 2, South Fork of Big Sandstone Creek.

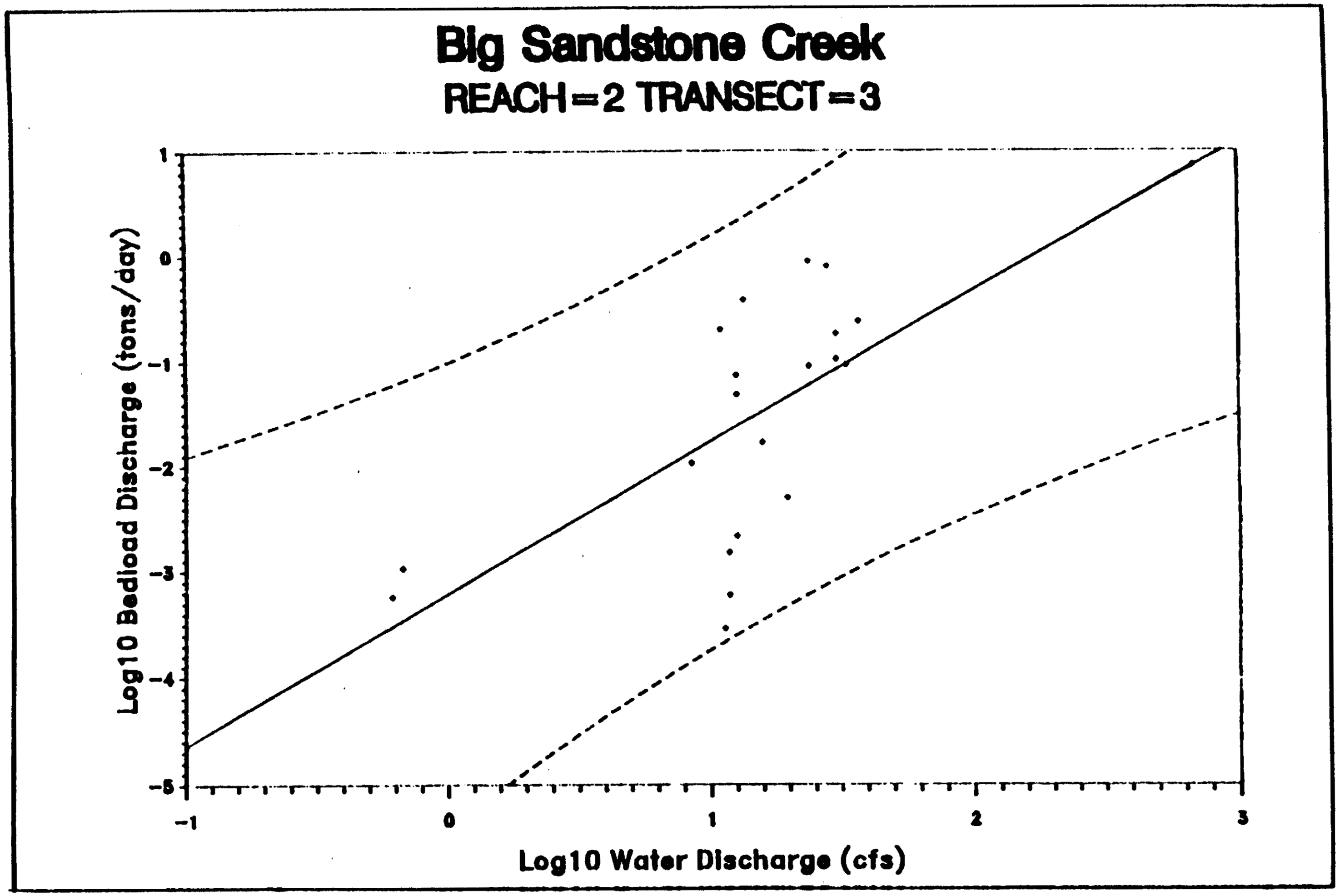


Figure A - 39. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 3, South Fork of Big Sandstone Creek.

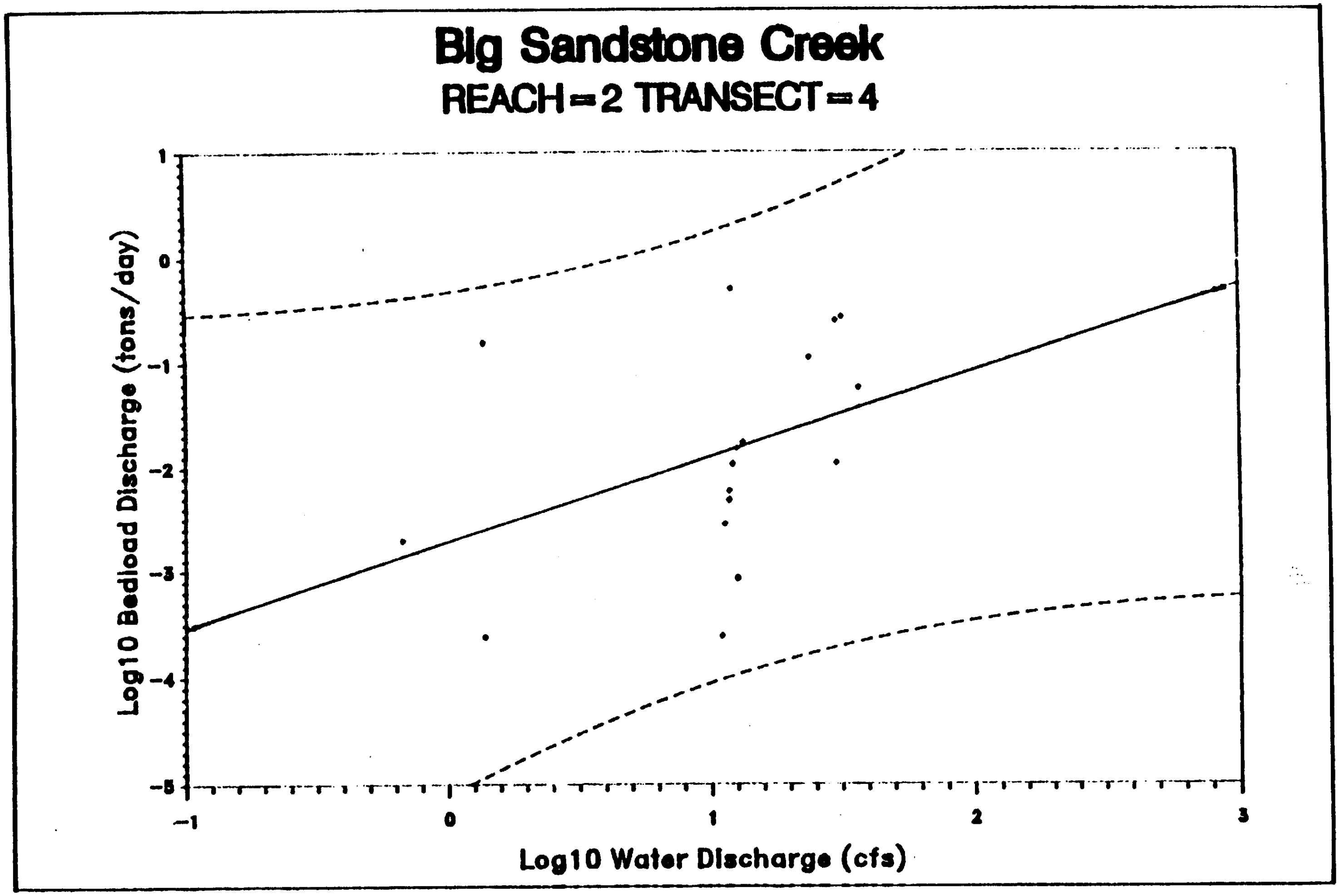


Figure A - 40. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 4, South Fork of Big Sandstone Creek.

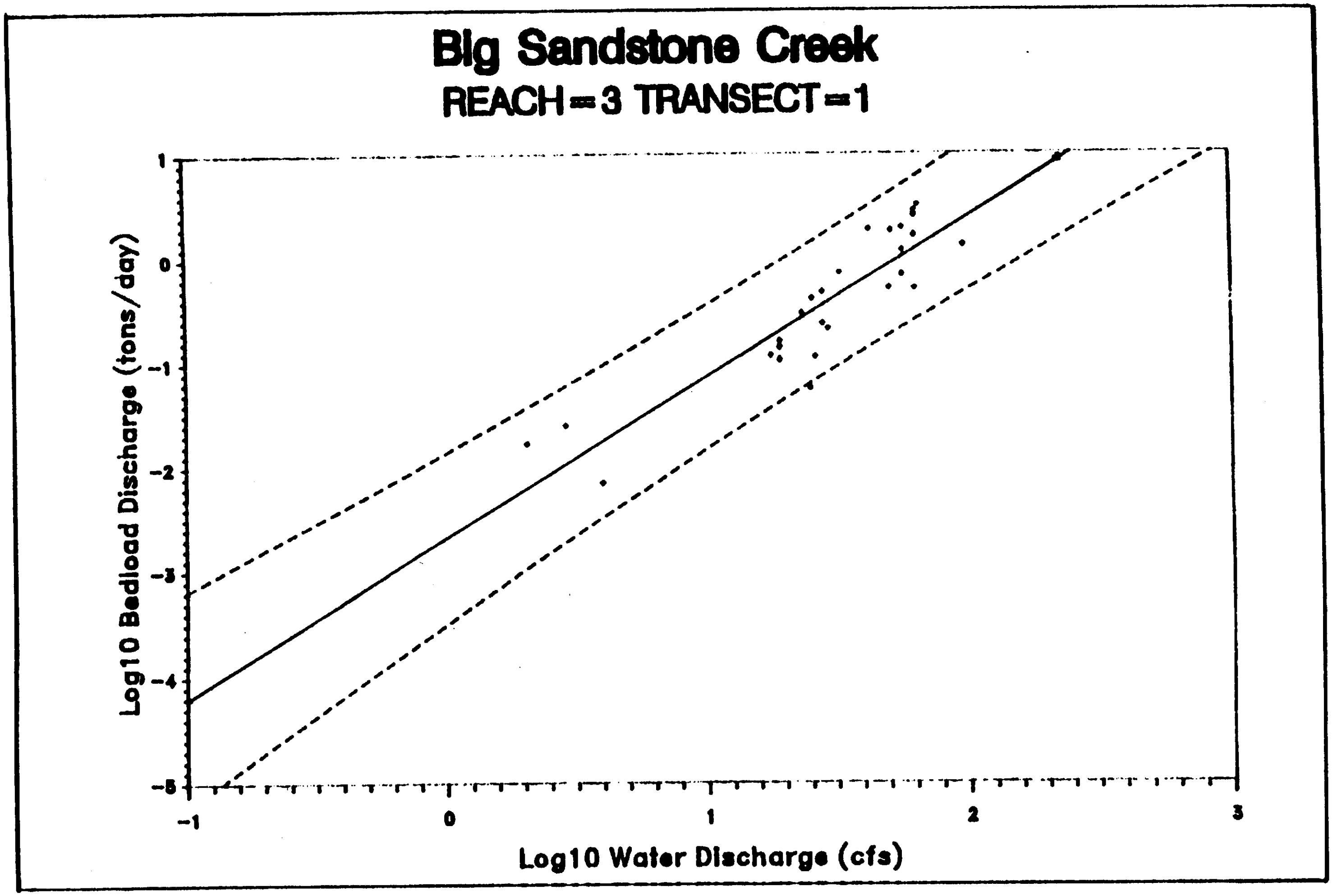


Figure A - 41. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 1, Big Sandstone Creek.

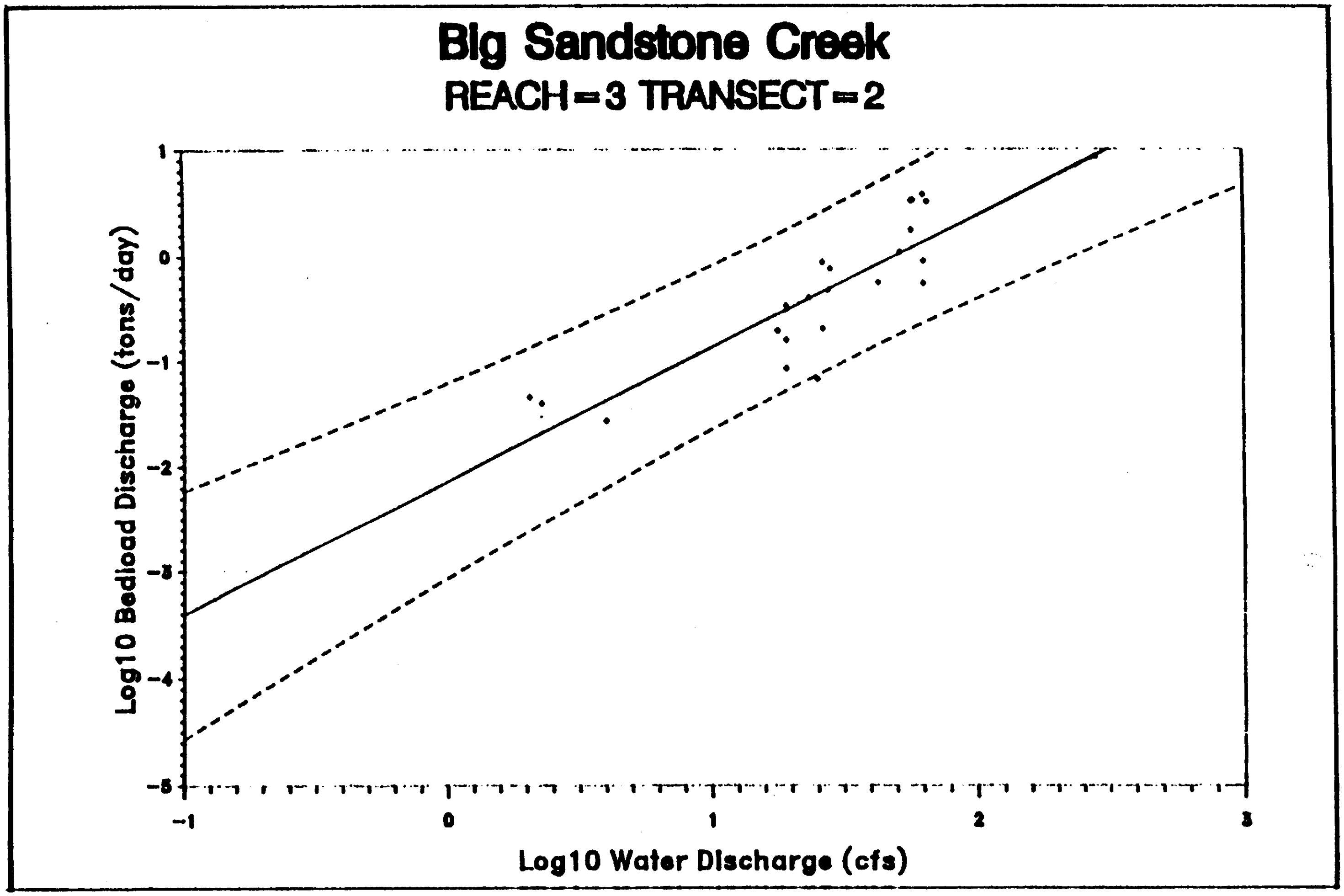


Figure A - 42. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 2, Big Sandstone Creek.

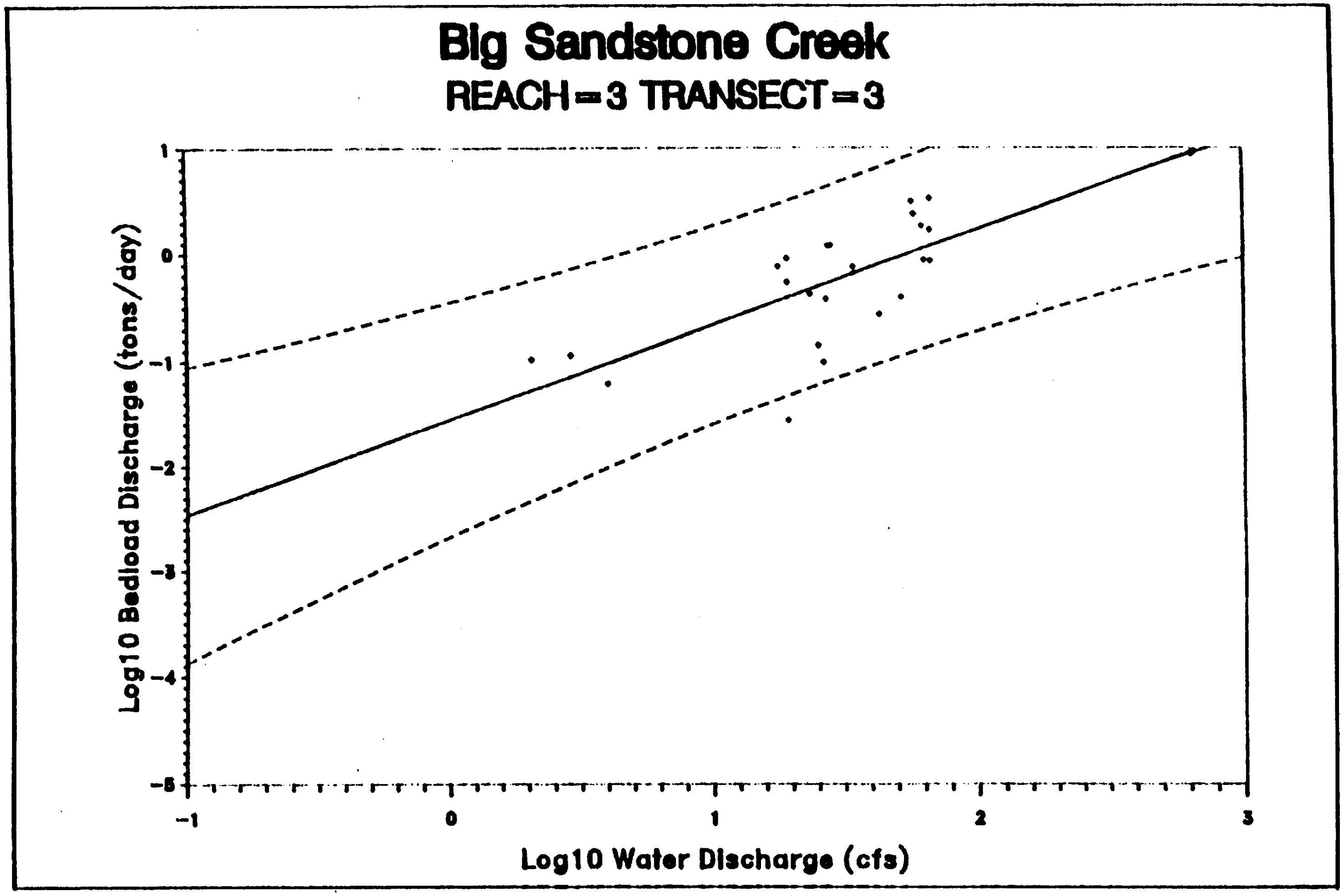


Figure A - 43. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 3, Big Sandstone Creek.

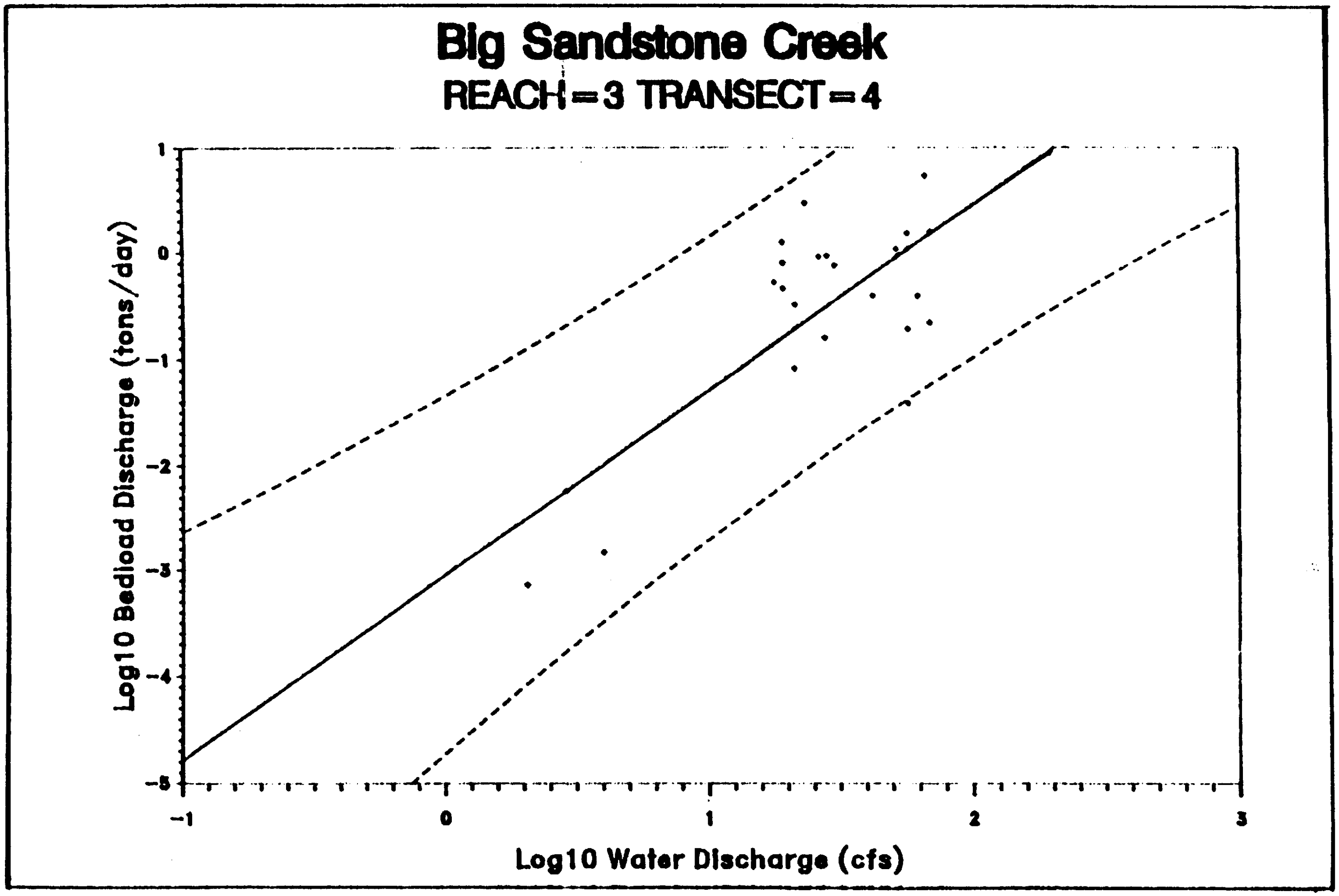


Figure A - 44. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 4, Big Sandstone Creek.

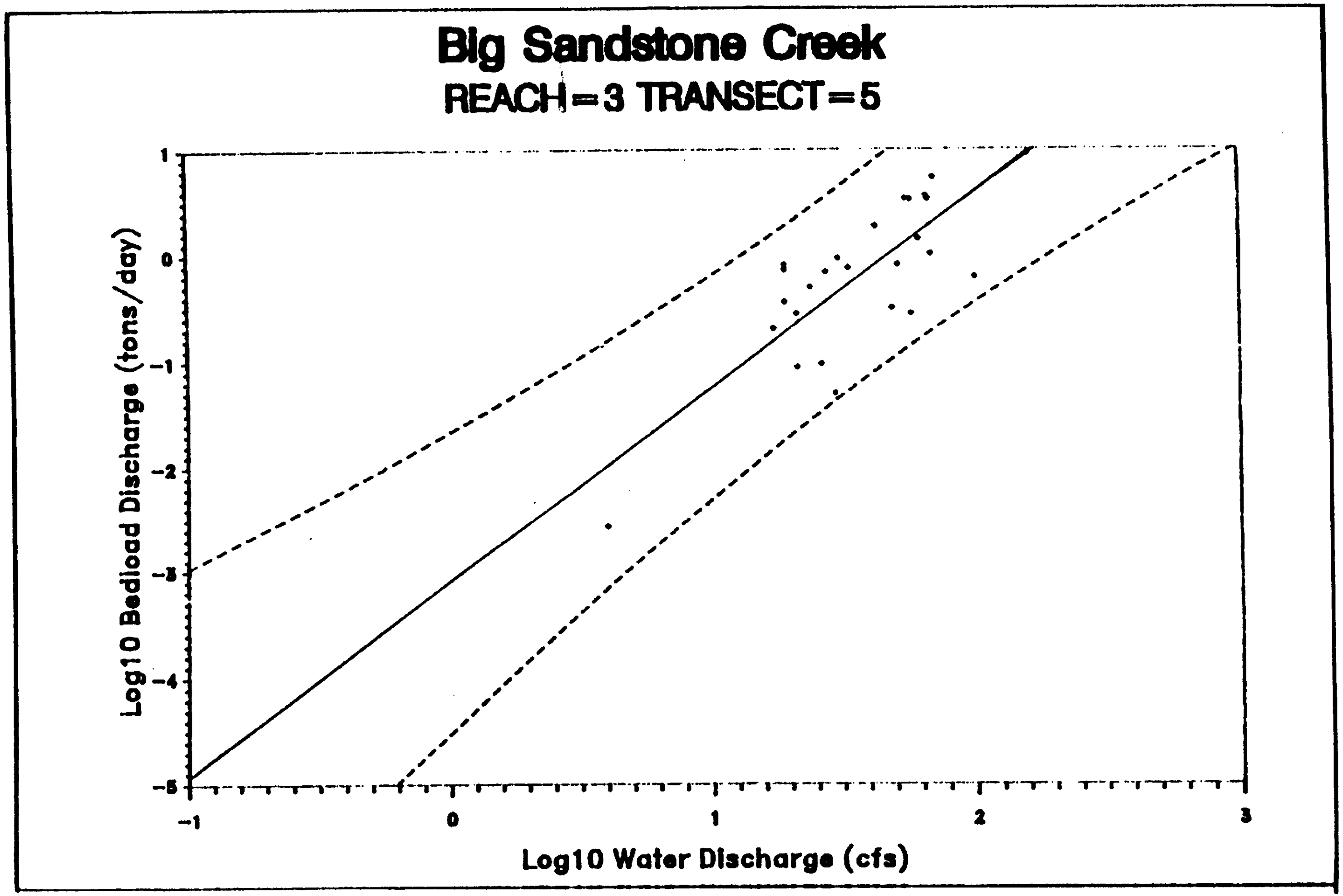


Figure A - 45. Relation of bedload discharge to water discharge, with 95 percent confidence belts, at Transect 5, Big Sandstone Creek.

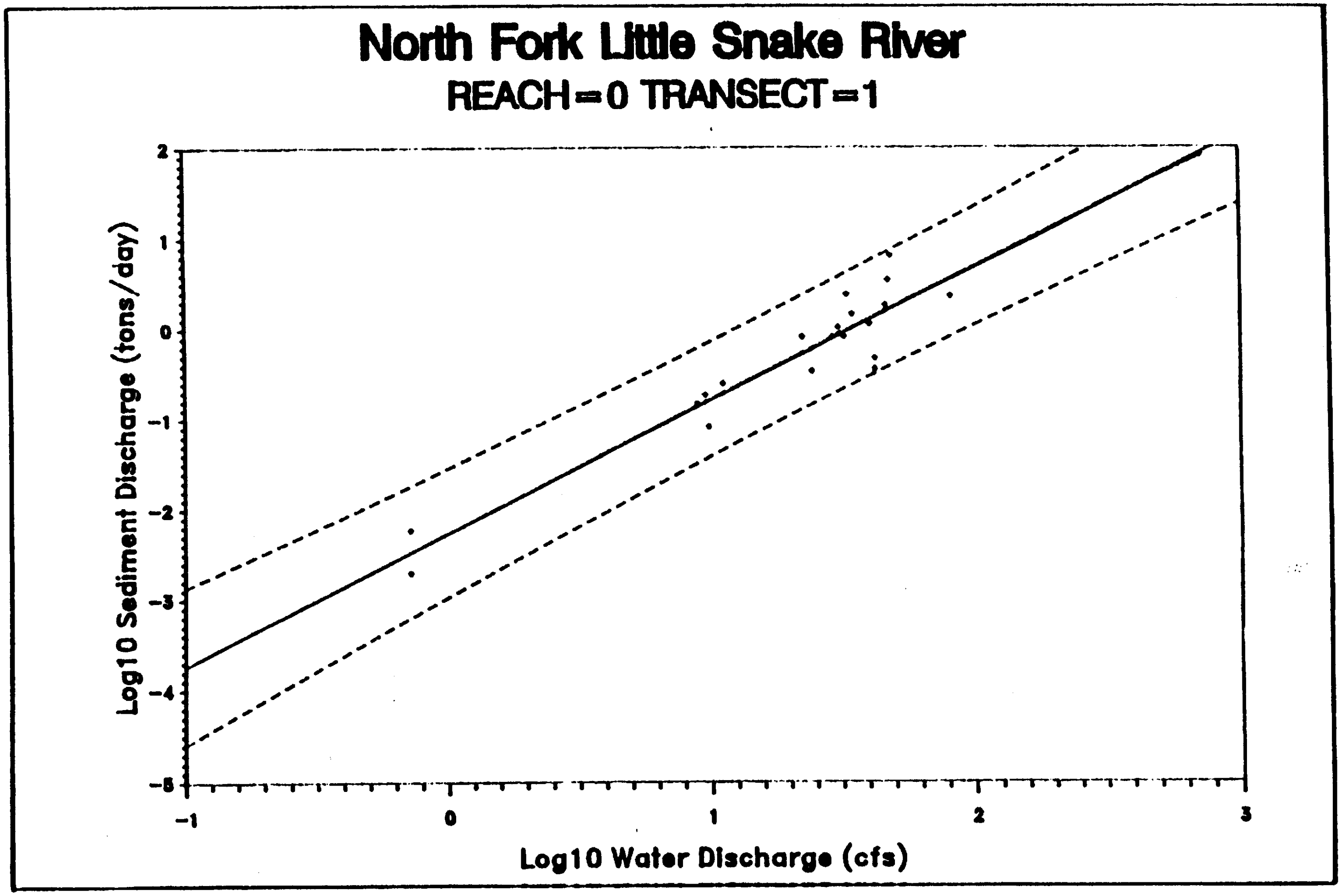


Figure A - 46. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 1, Reach 0, North Fork Little Snake River.

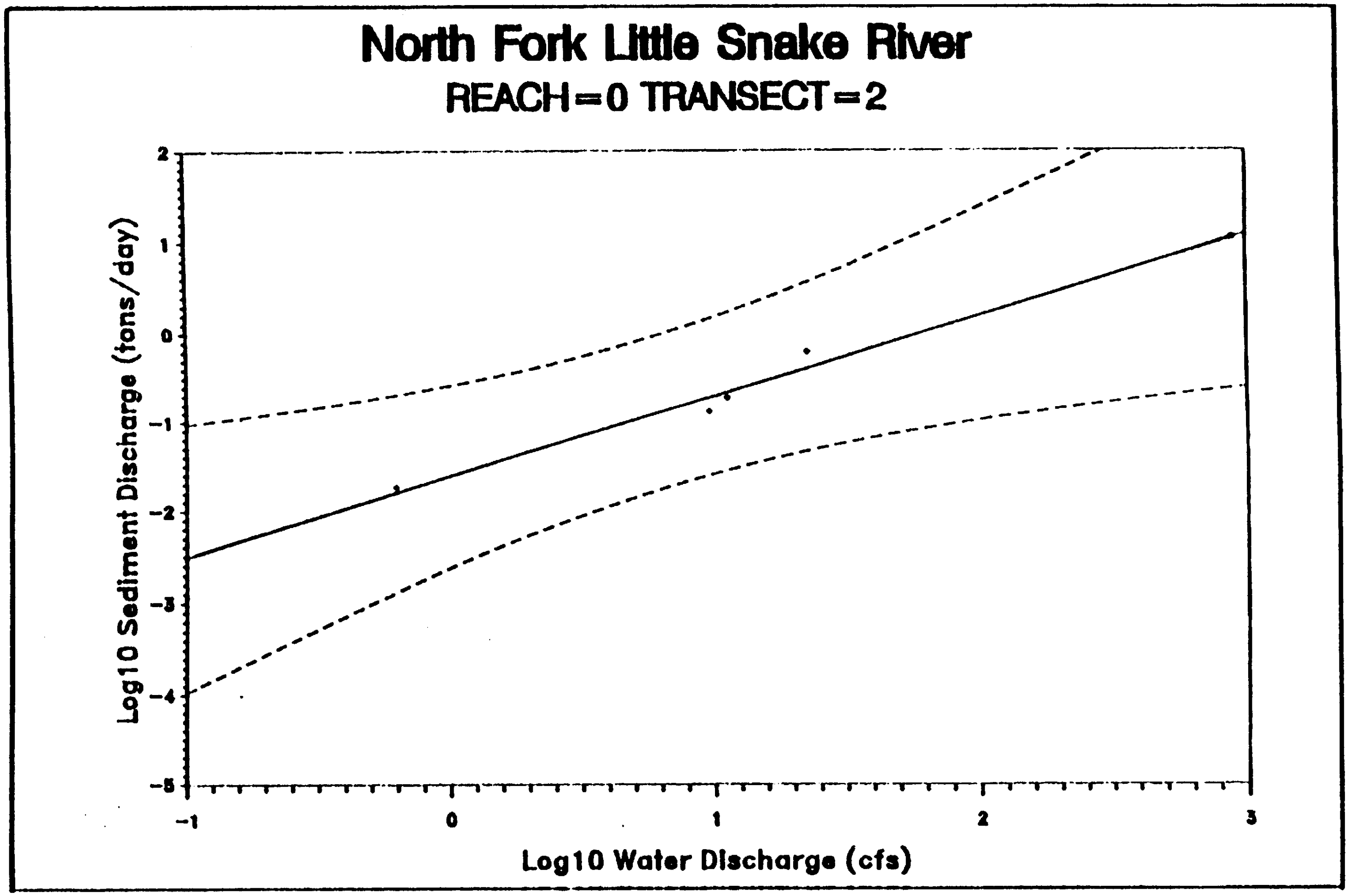


Figure A - 47. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 2, Reach 0, North Fork Little Snake River.

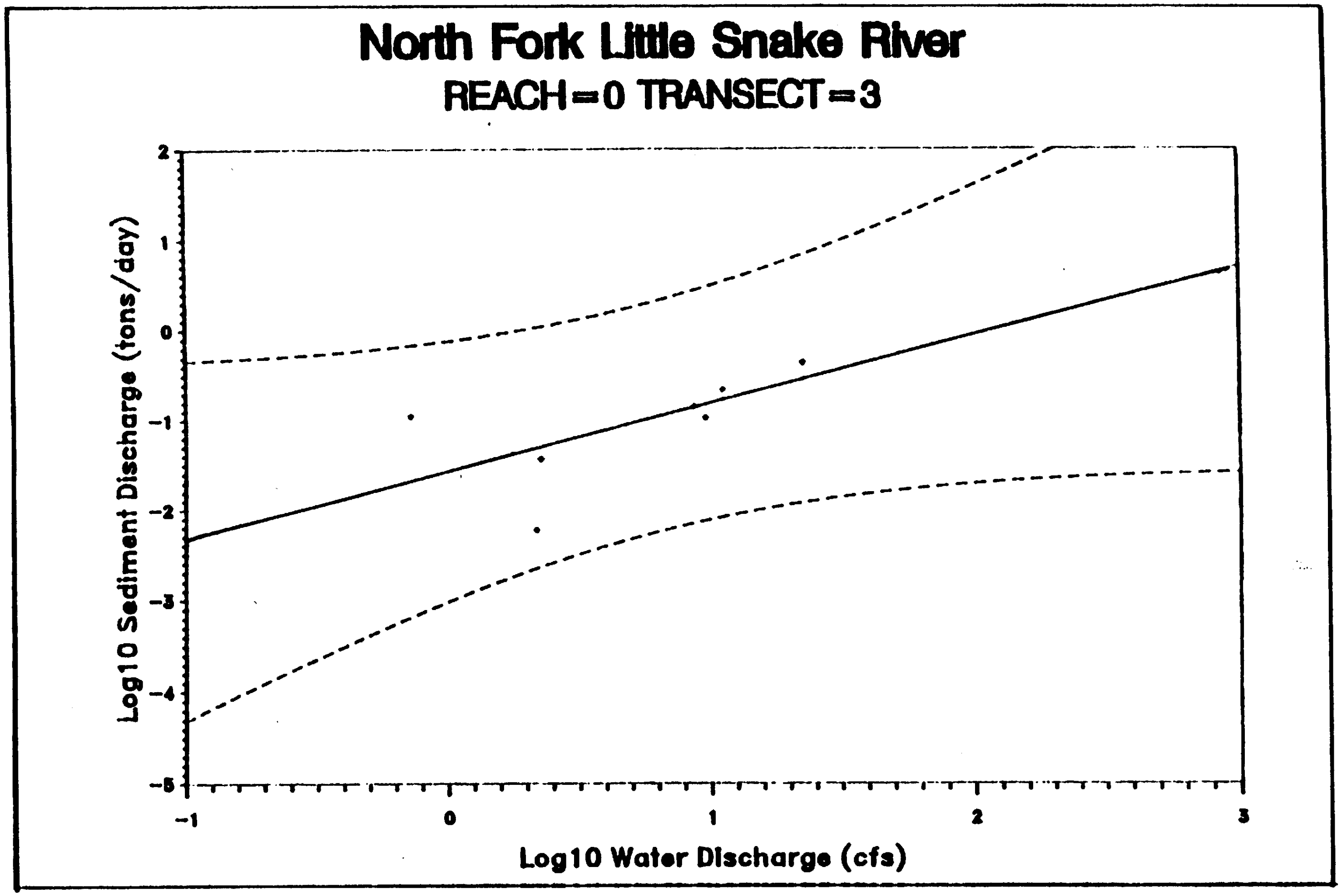


Figure A - 48. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 3, Reach 0, North Fork Little Snake River.

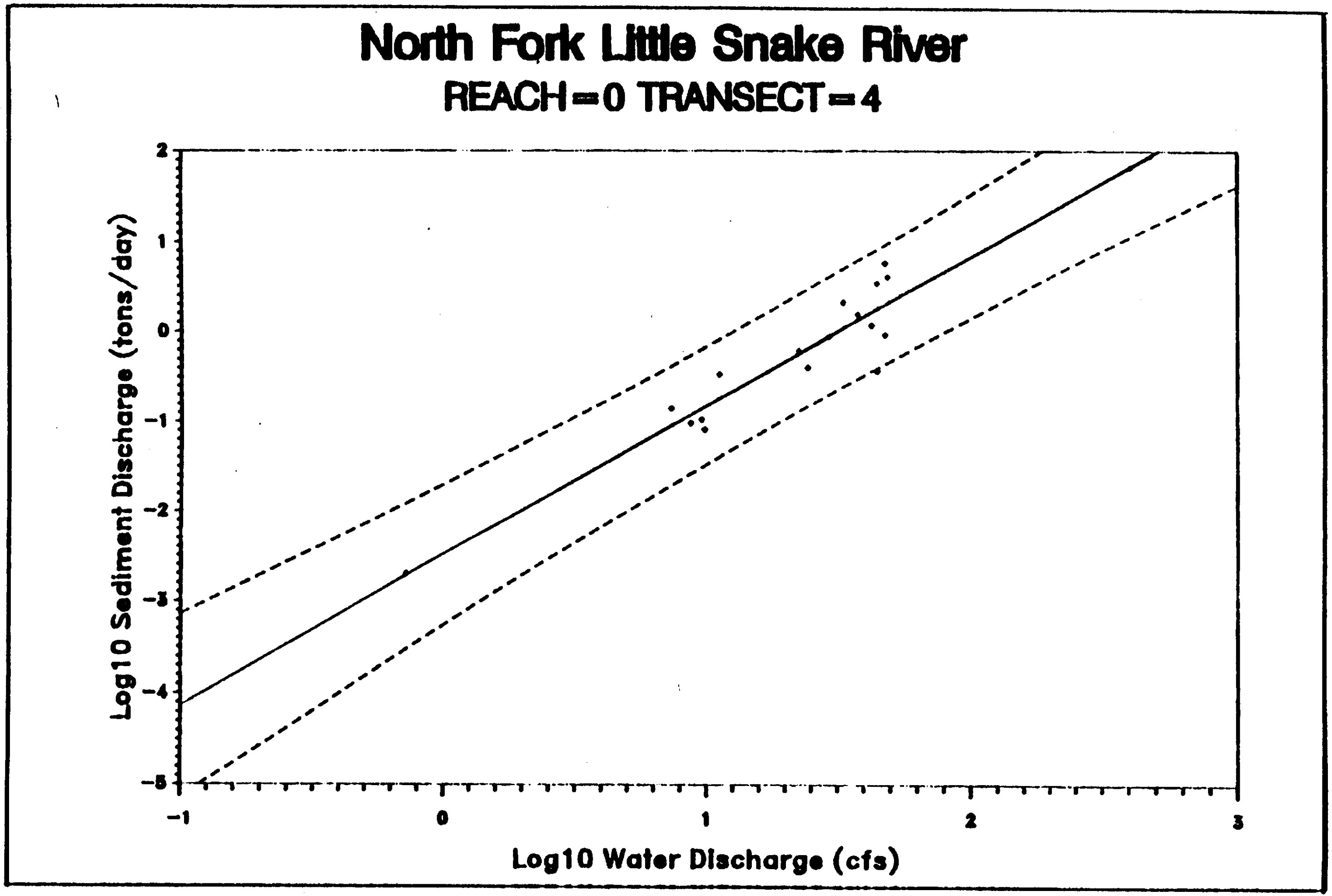


Figure A - 49. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 4, Reach 0, North Fork Little Snake River.

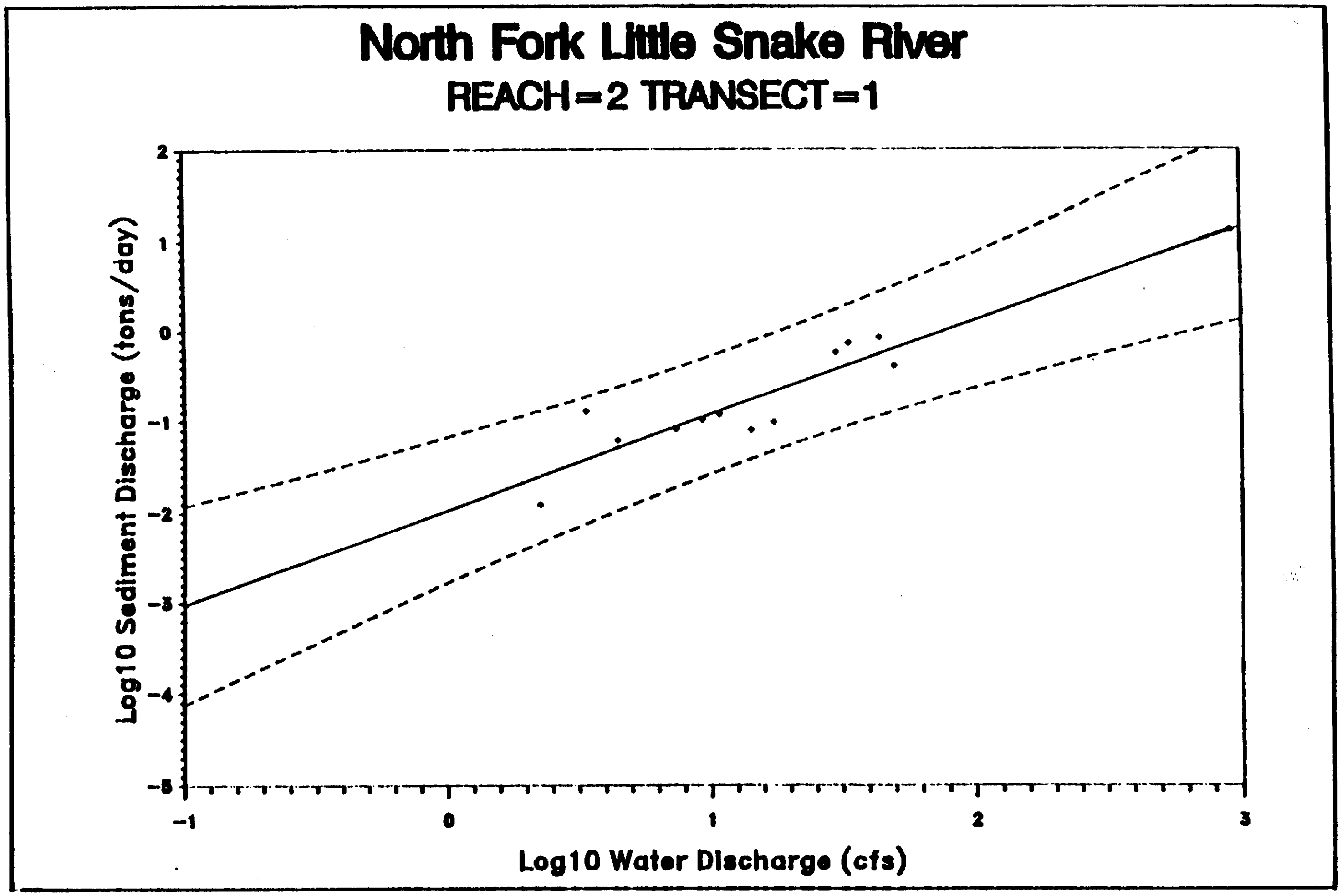


Figure A - 50. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 1, Reach 2, North Fork Little Snake River.

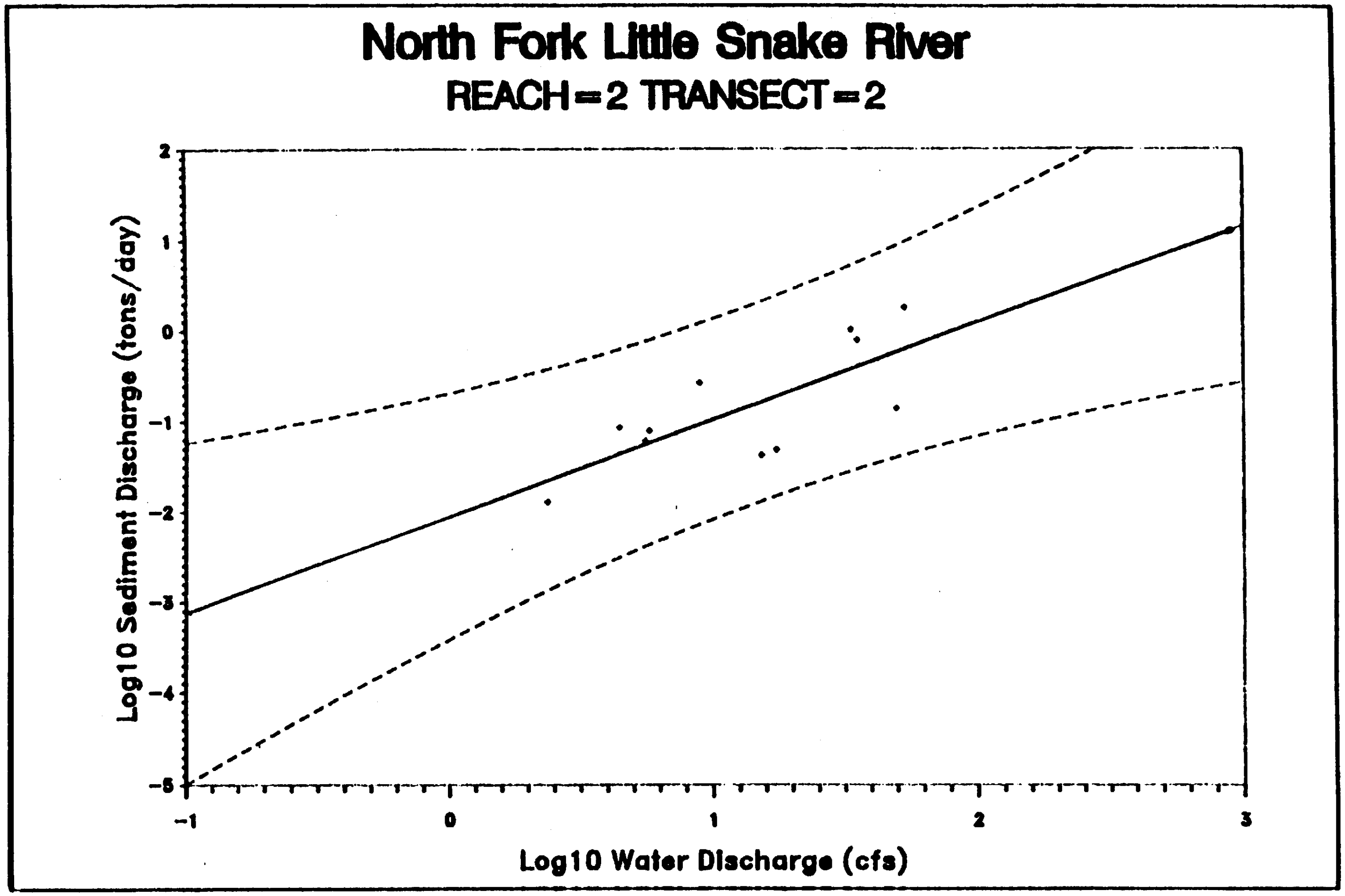


Figure A - 51. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 2, Reach 2, North Fork Little Snake River.

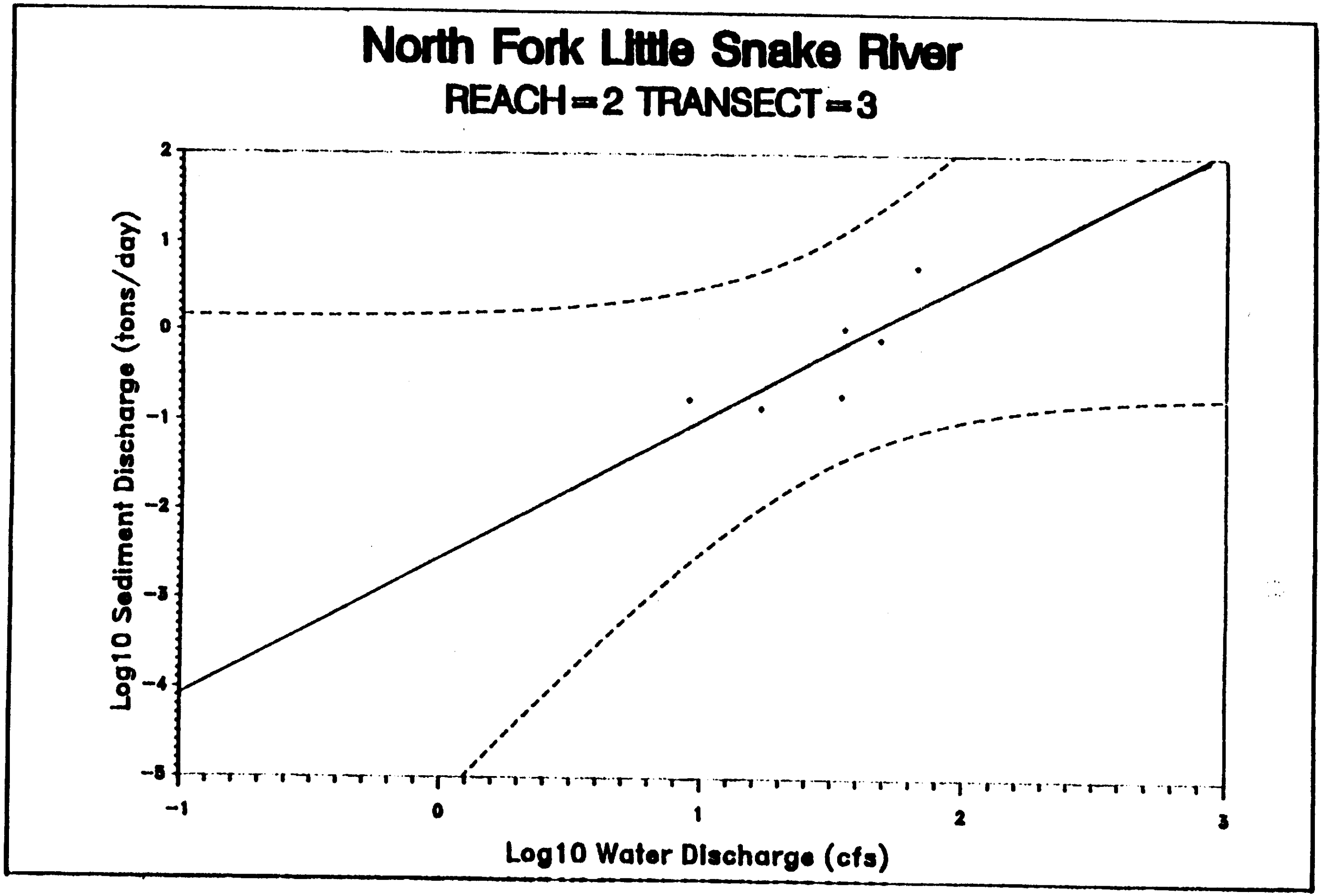


Figure A - 52. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 3, Reach 2, North Fork Little Snake River.

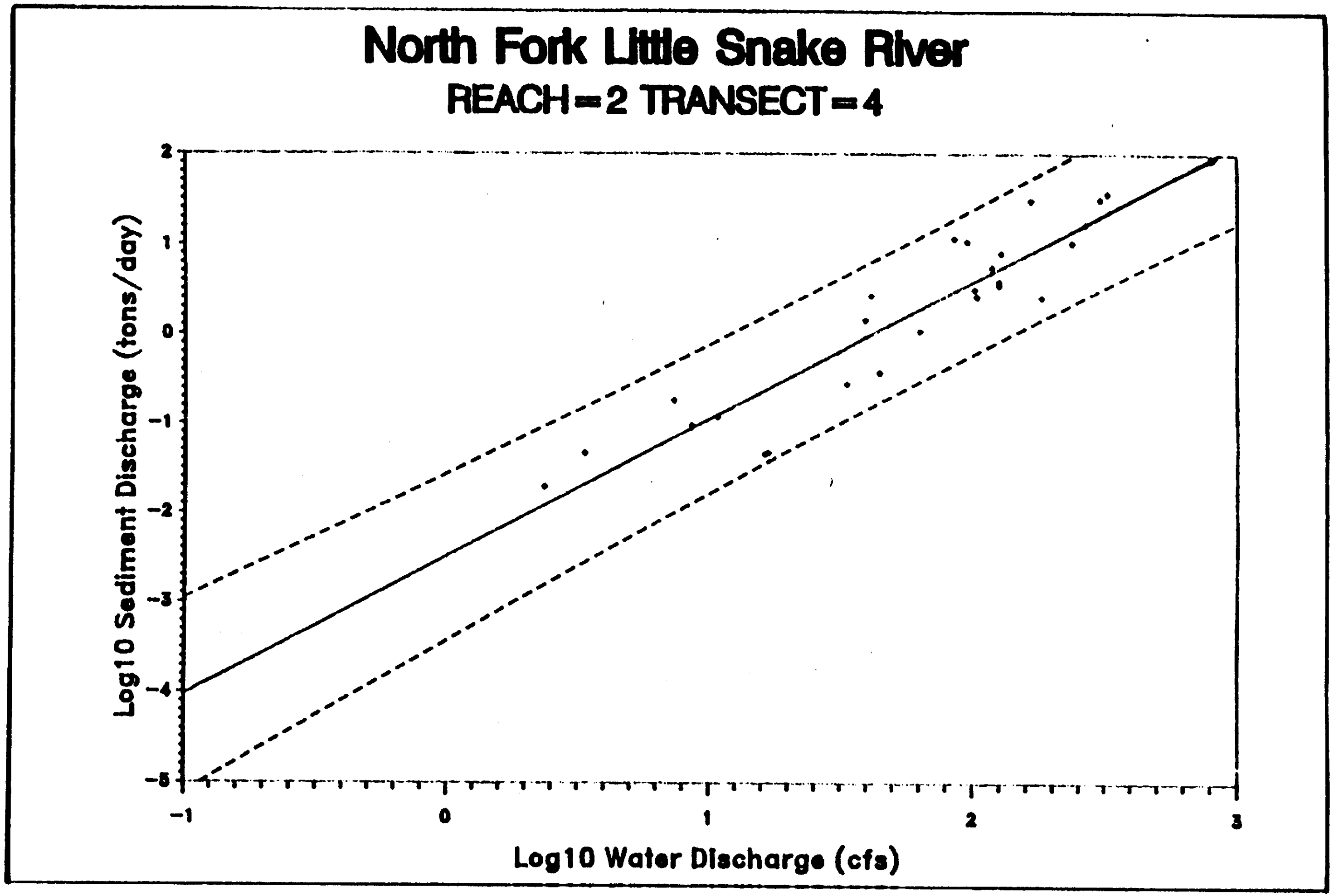


Figure A - 53. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 4, Reach 2, North Fork Little Snake River.

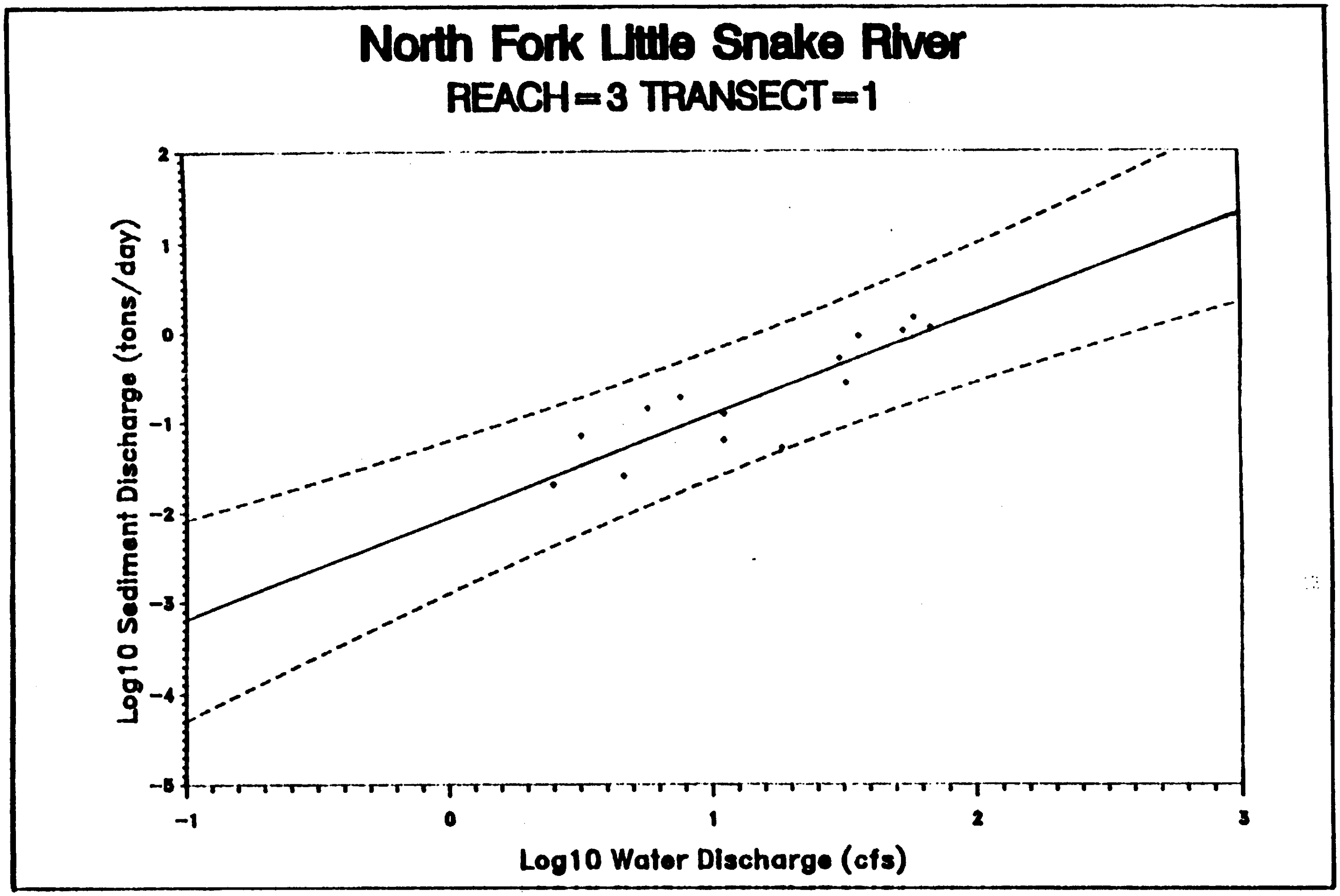


Figure A - 54. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 1, Reach 3, North Fork Little Snake River.

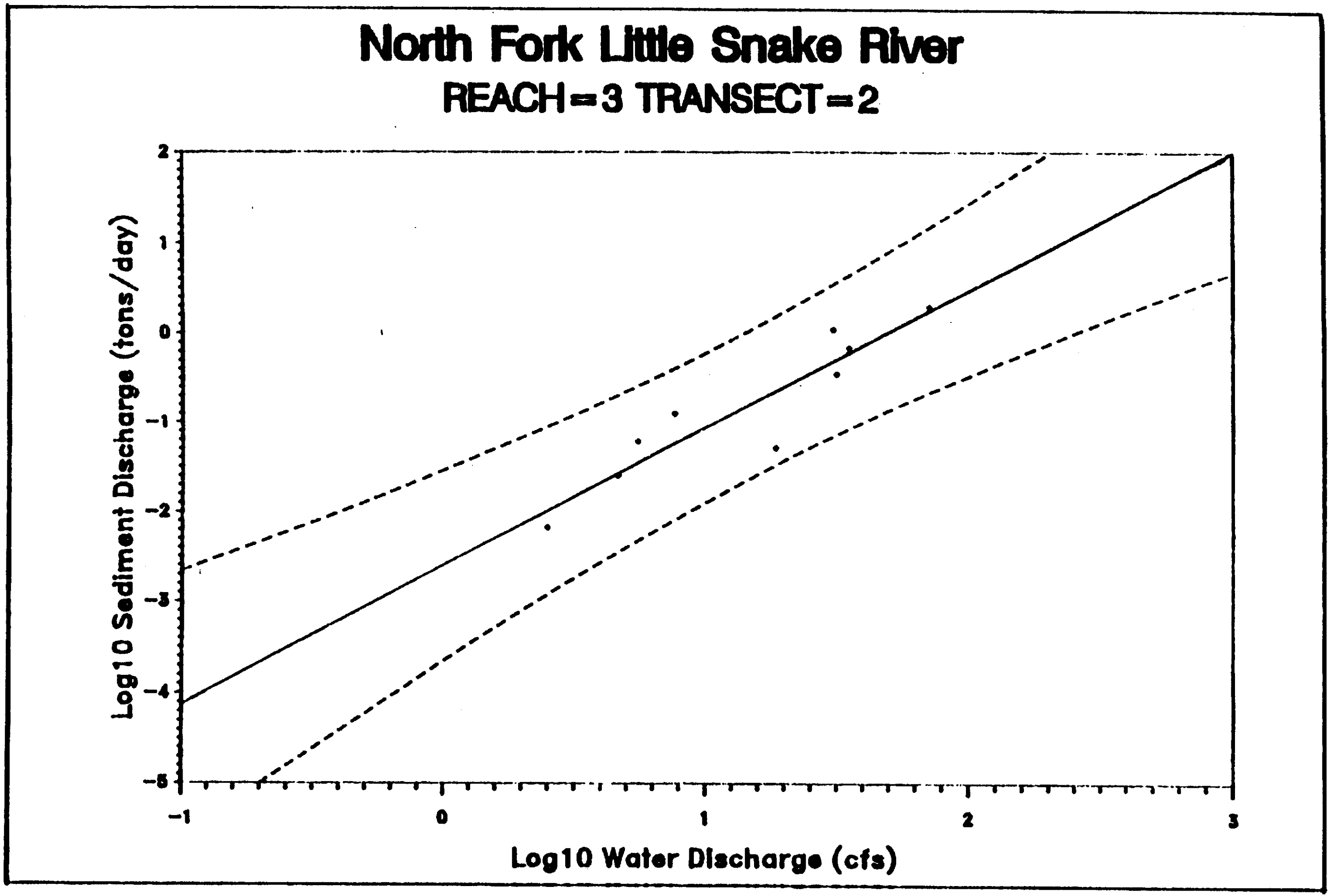


Figure A - 55. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 2, Reach 3, North Fork Little Snake River.

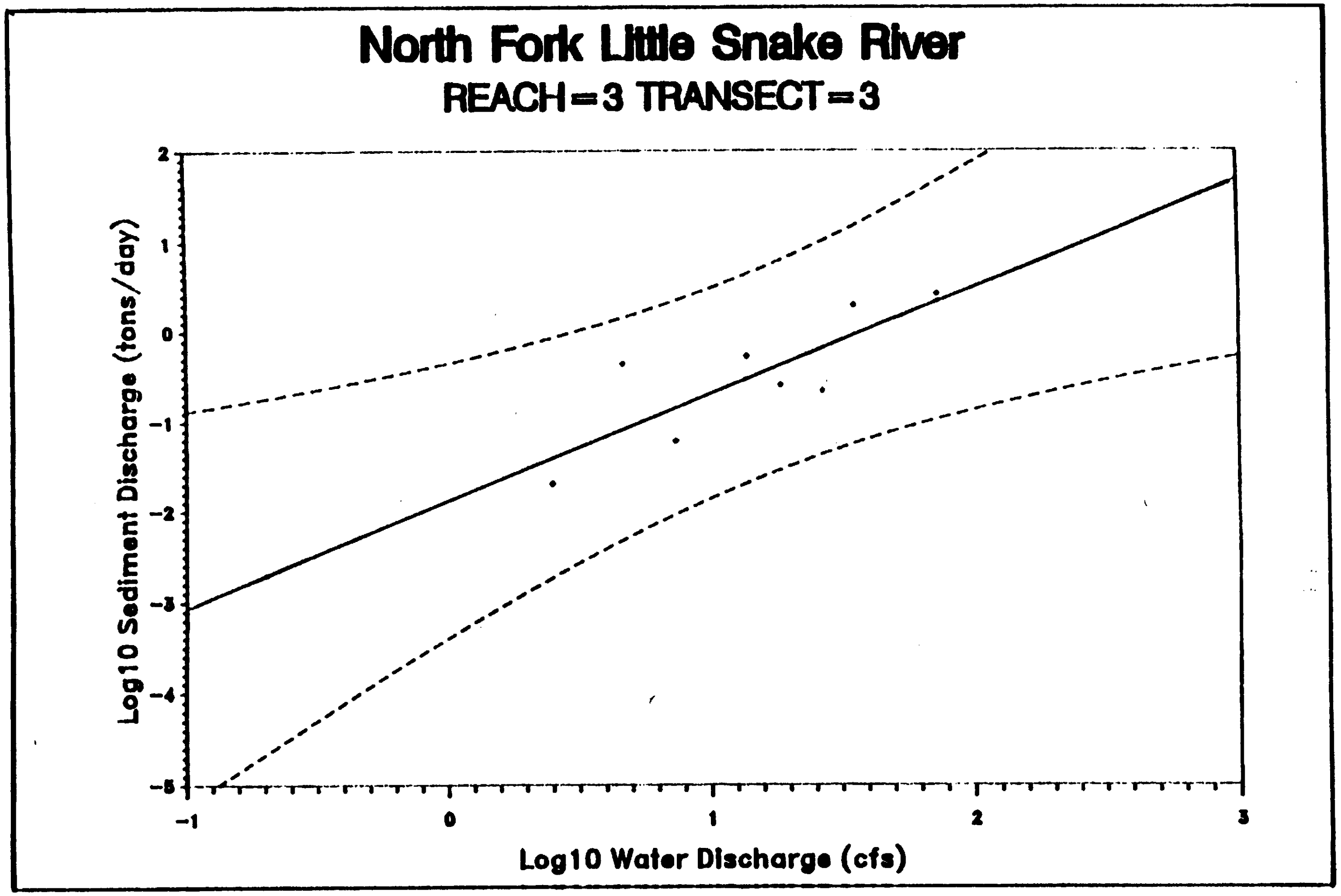


Figure A - 56. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 3, Reach 3, North Fork Little Snake River.

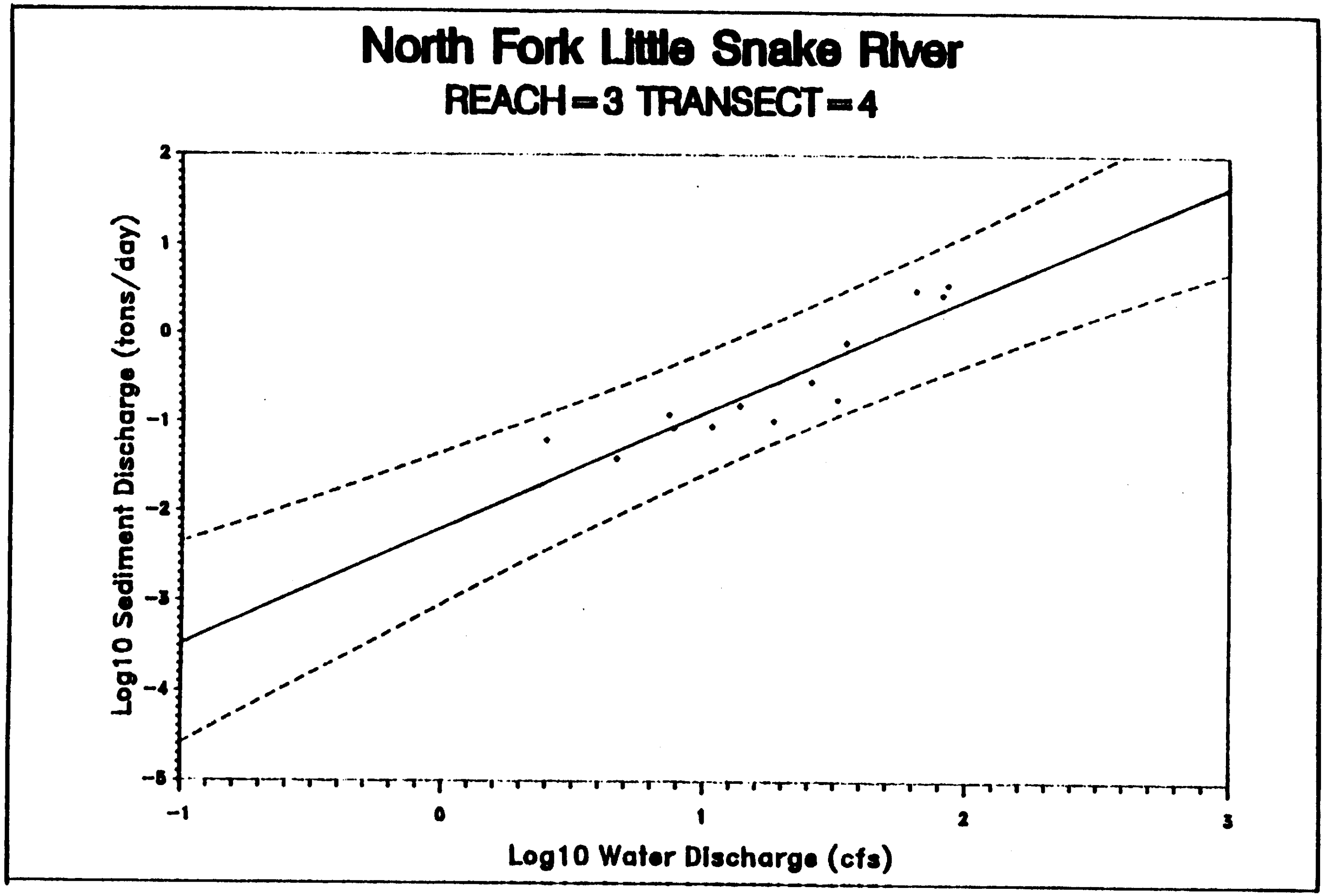


Figure A - 57. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 4, Reach 3, North Fork Little Snake River.

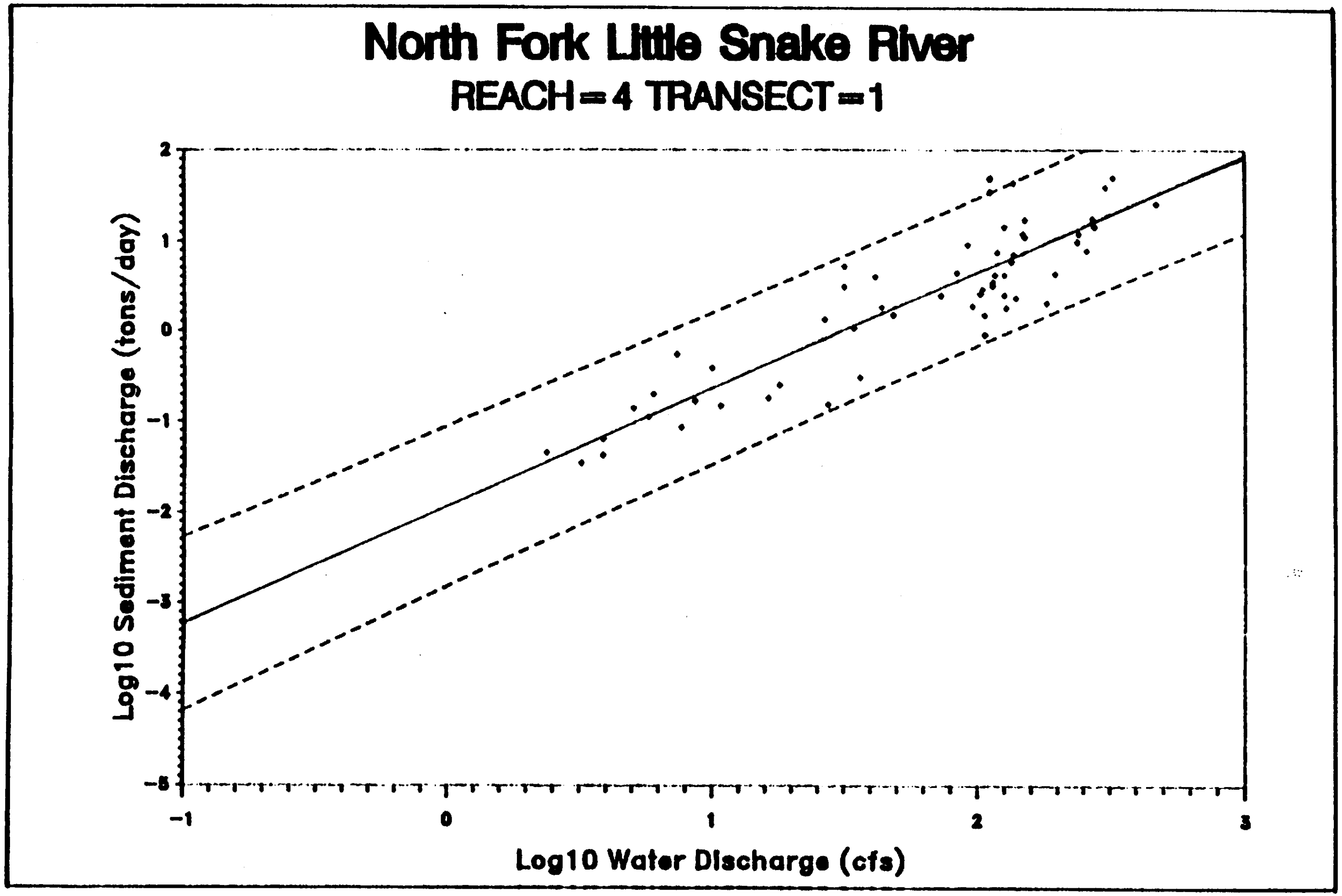


Figure A - 58. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 1, Reach 4, North Fork Little Snake River.

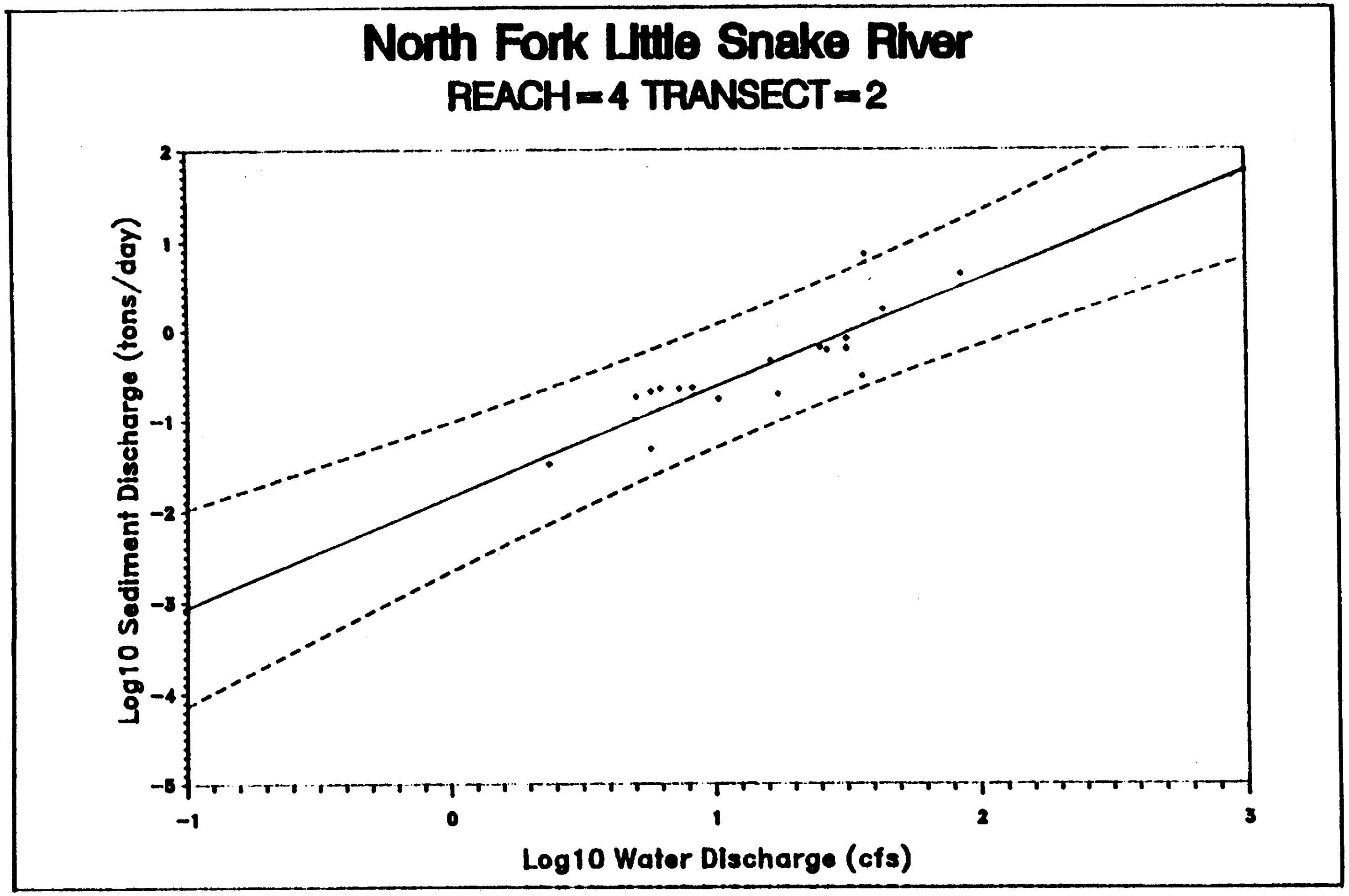


Figure A - 59. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 2, Reach 4, North Fork Little Snake River.

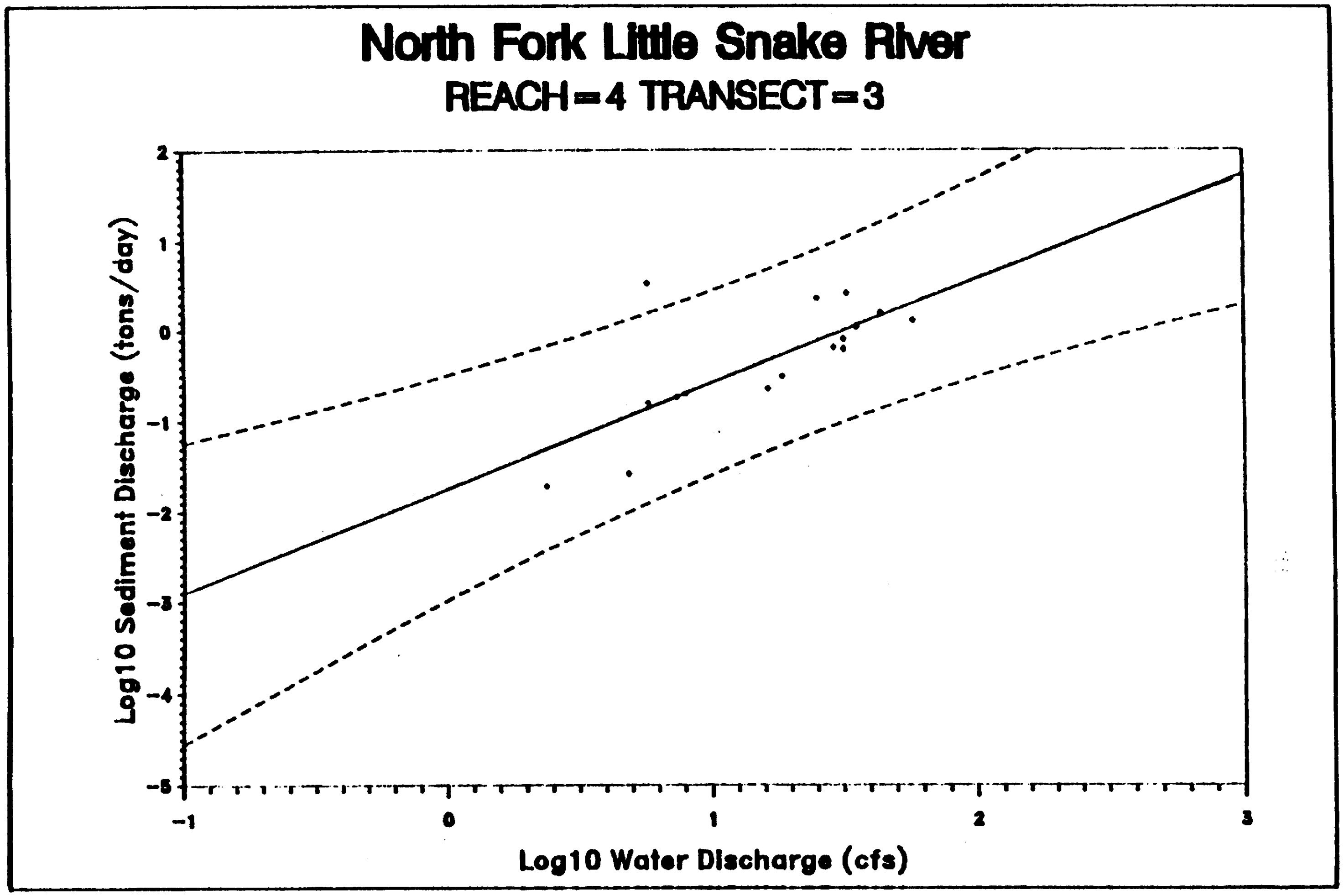


Figure A - 60. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 3, Reach 4, North Fork Little Snake River.

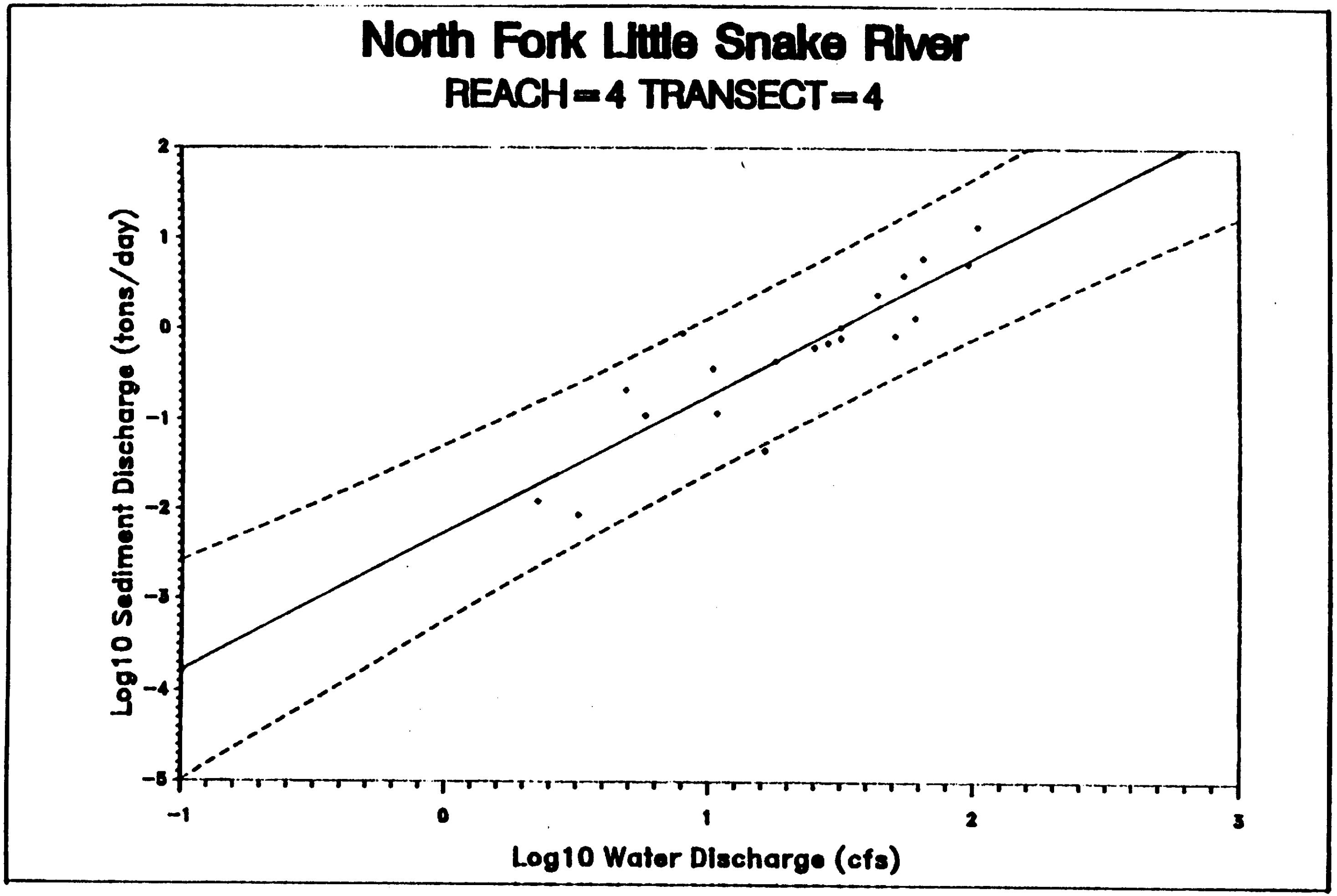


Figure A - 61. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 4, Reach 4, North Fork Little Snake River.

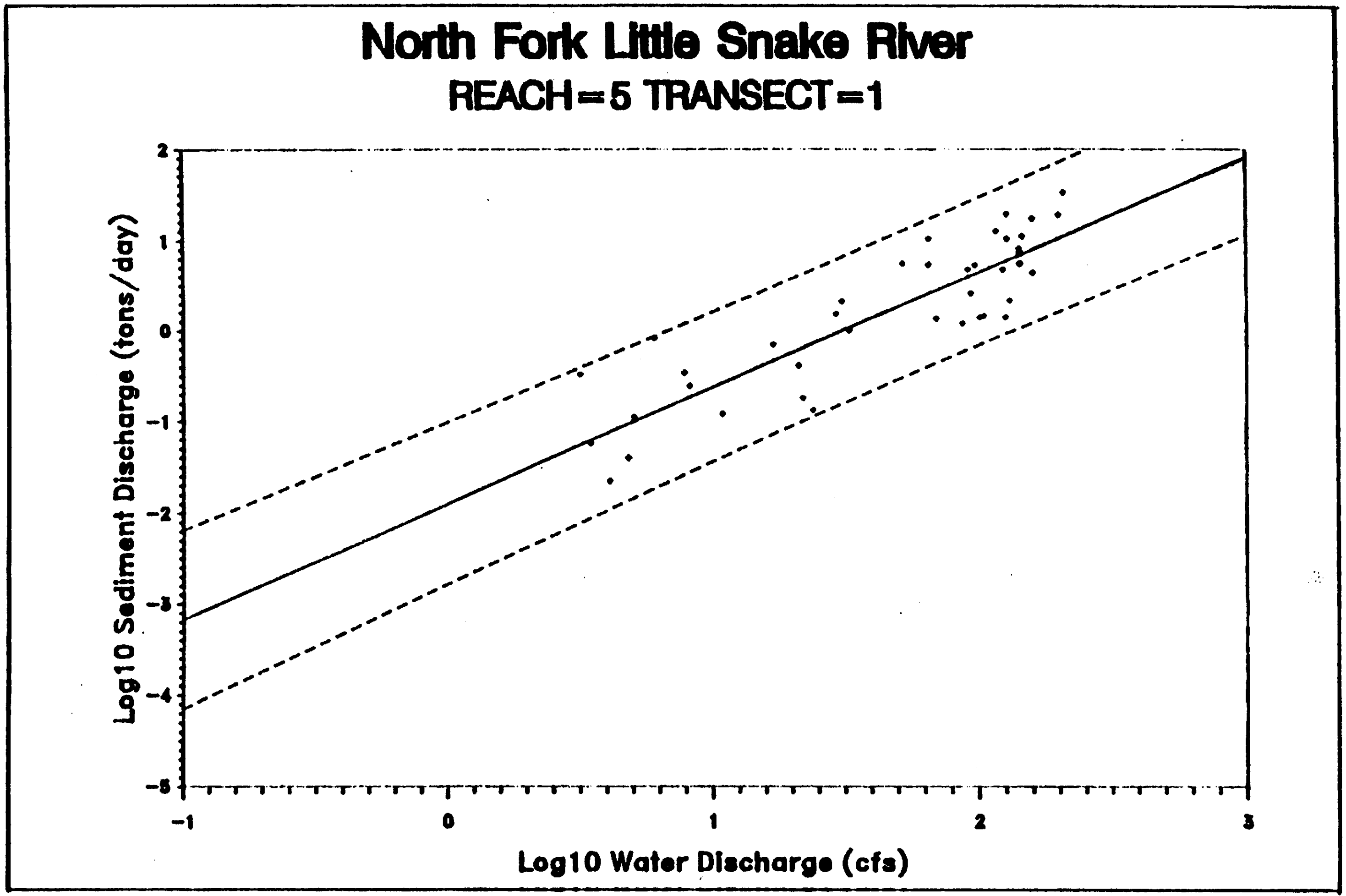


Figure A - 62. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 1, Reach 5, North Fork Little Snake River.

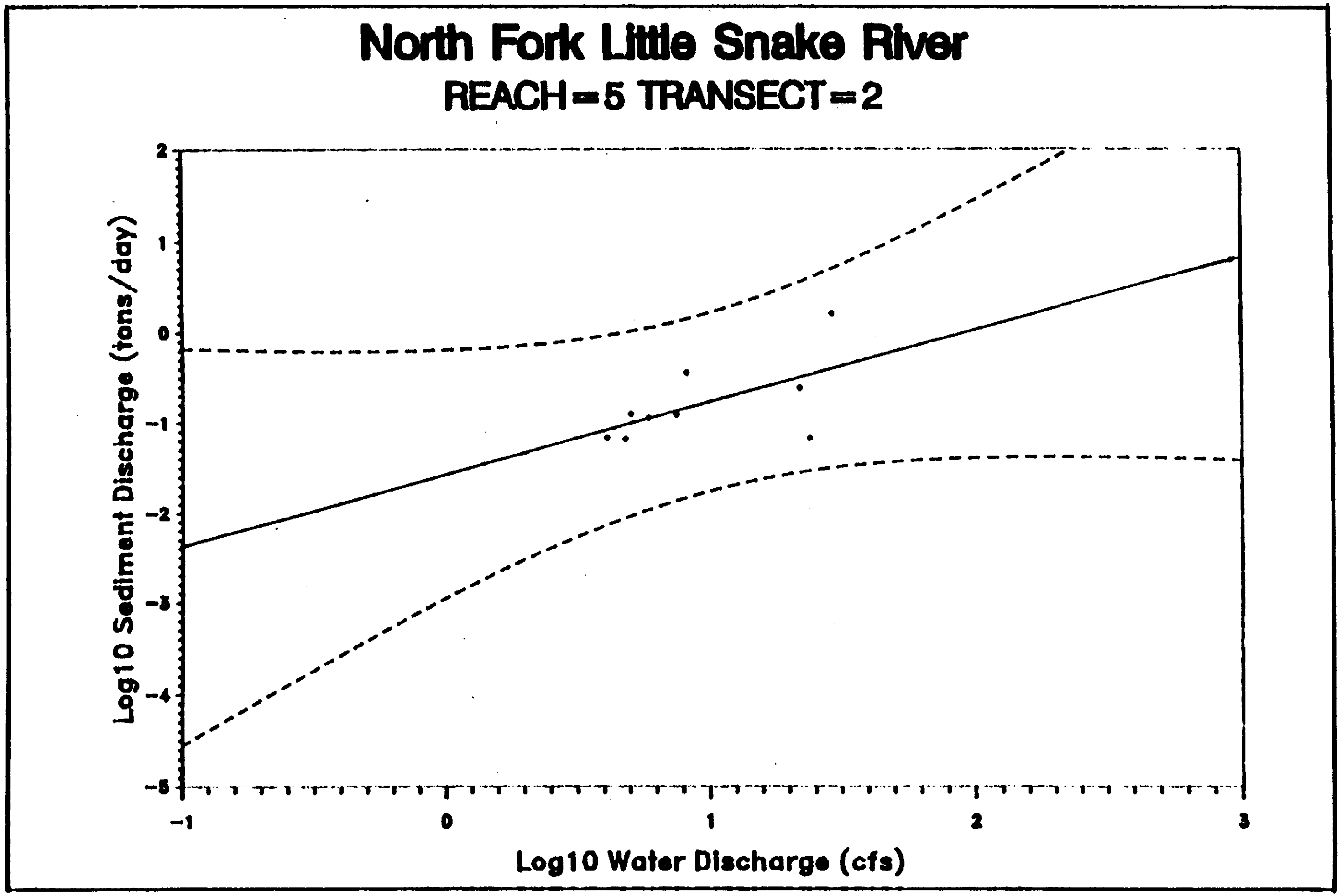


Figure A - 63. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 2, Reach 5, North Fork Little Snake River.

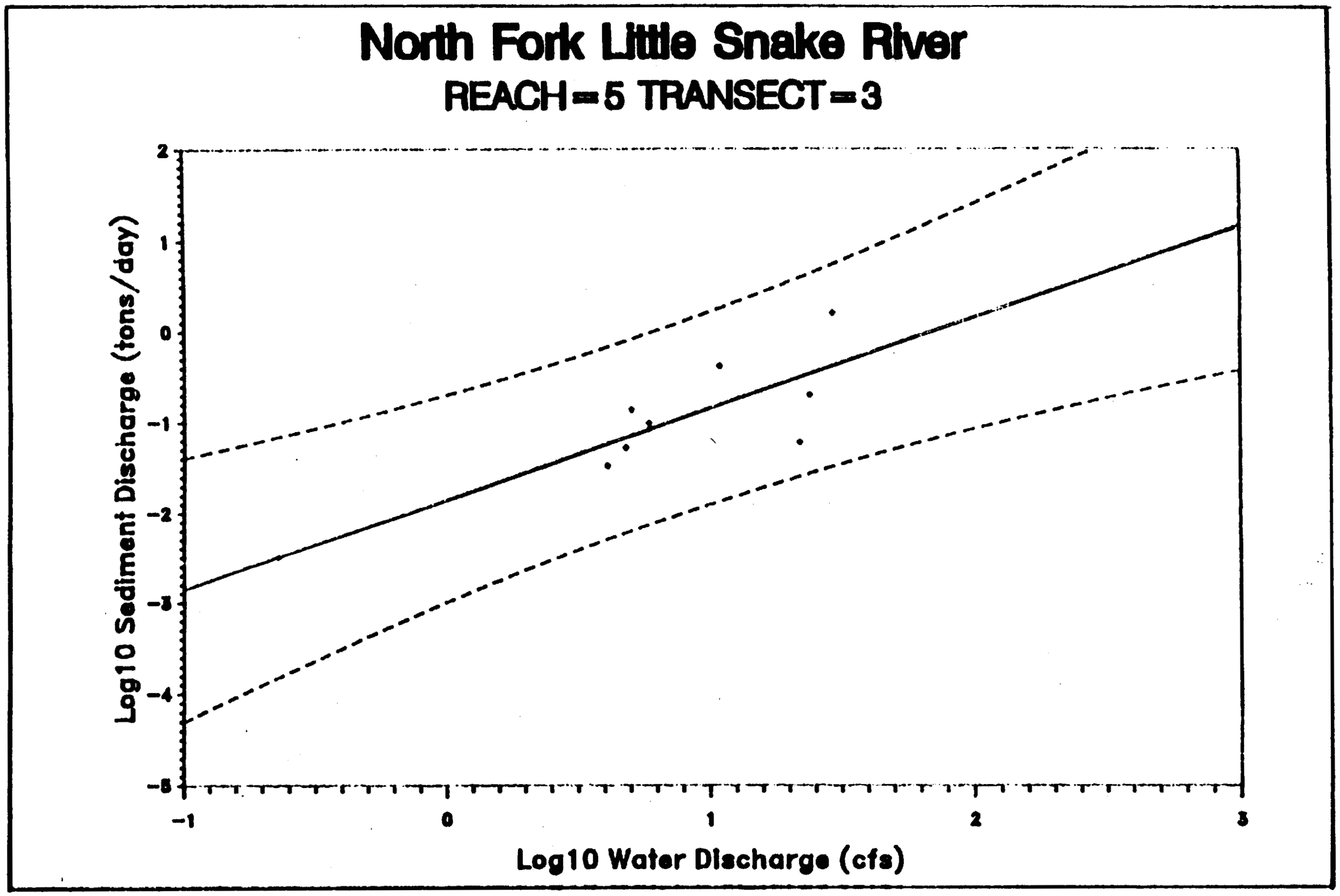


Figure A - 64. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 3, Reach 5, North Fork Little Snake River.

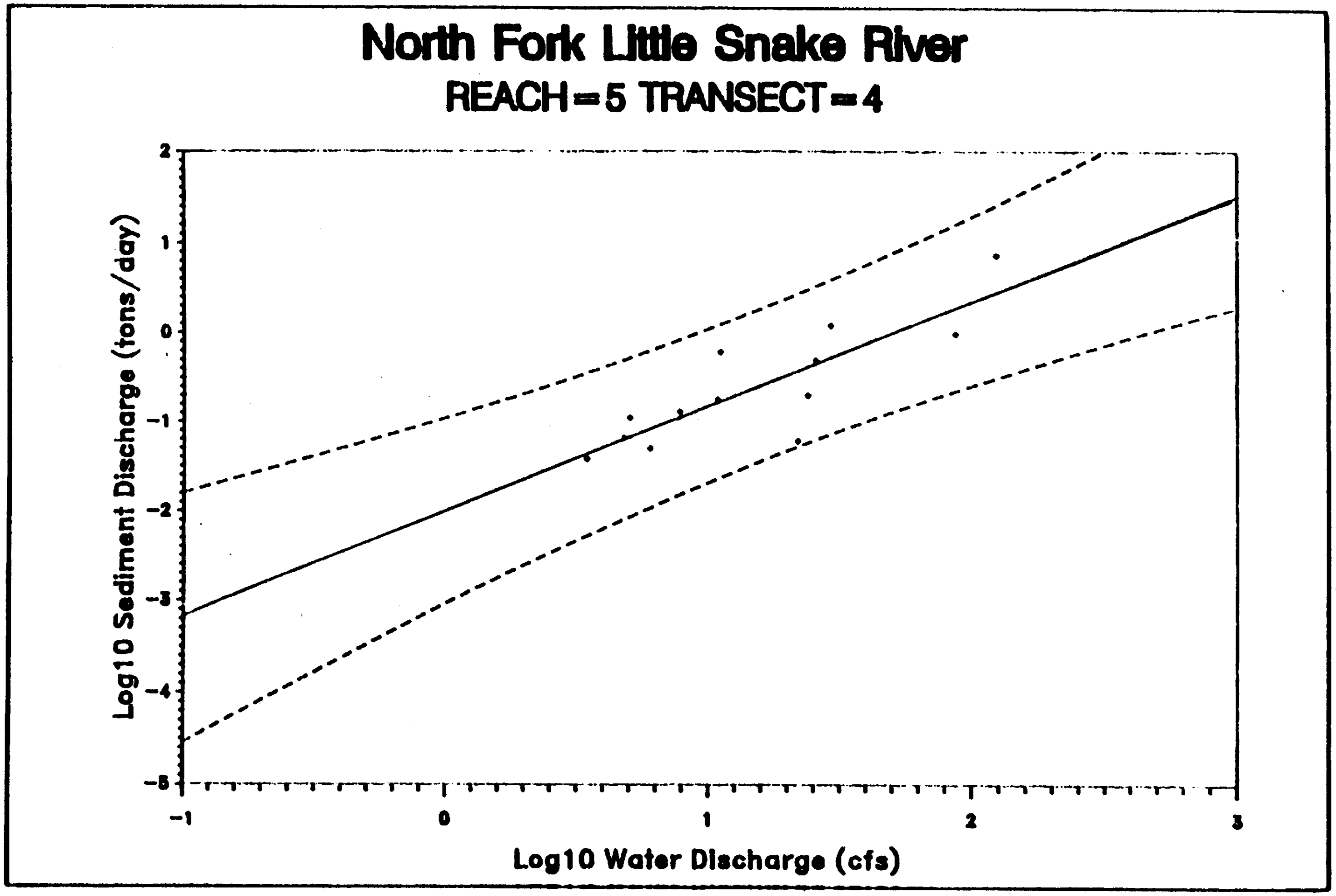


Figure A - 65. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 4, Reach 5, North Fork Little Snake River.

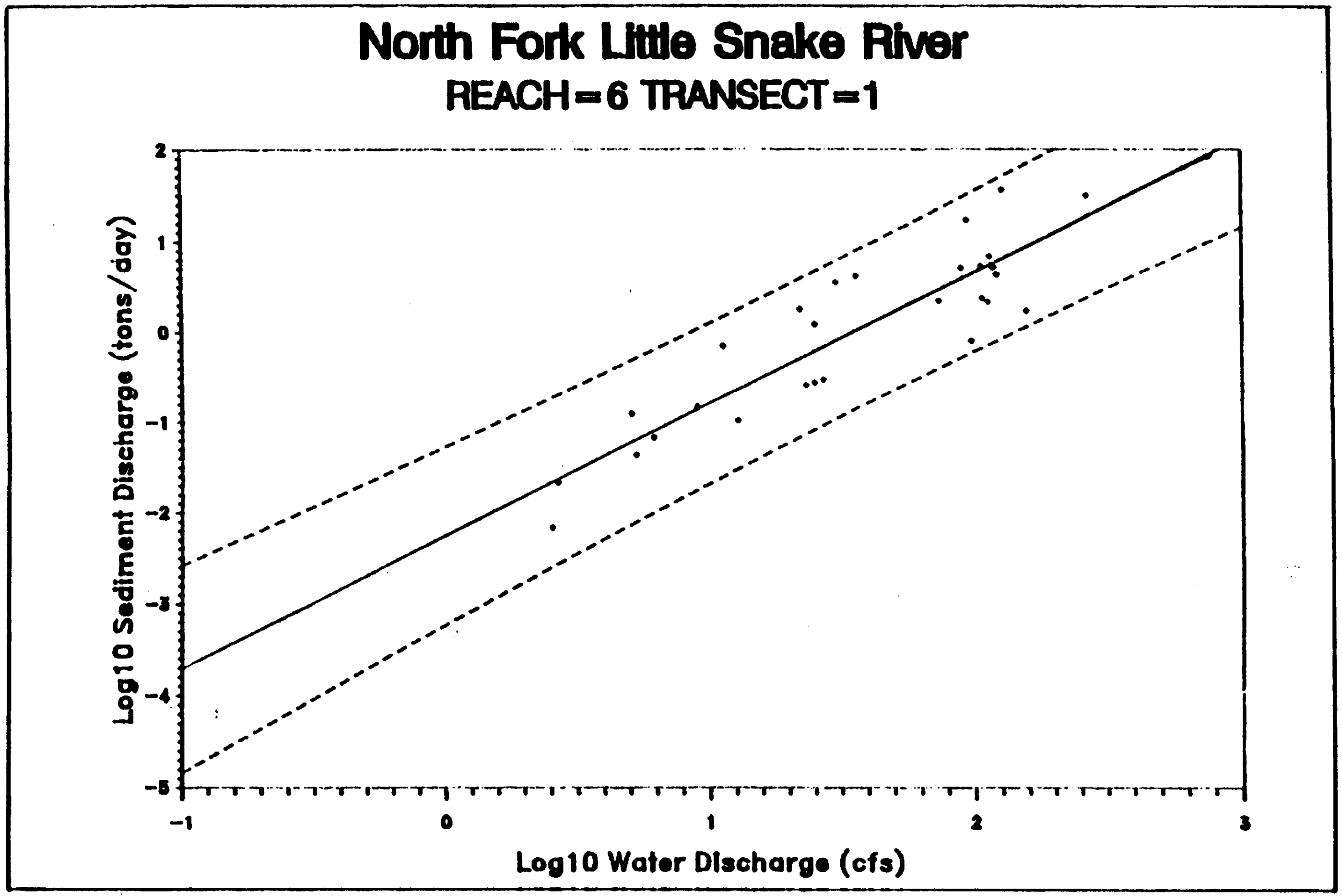


Figure A - 66. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 1, Reach 6, North Fork Little Snake River.

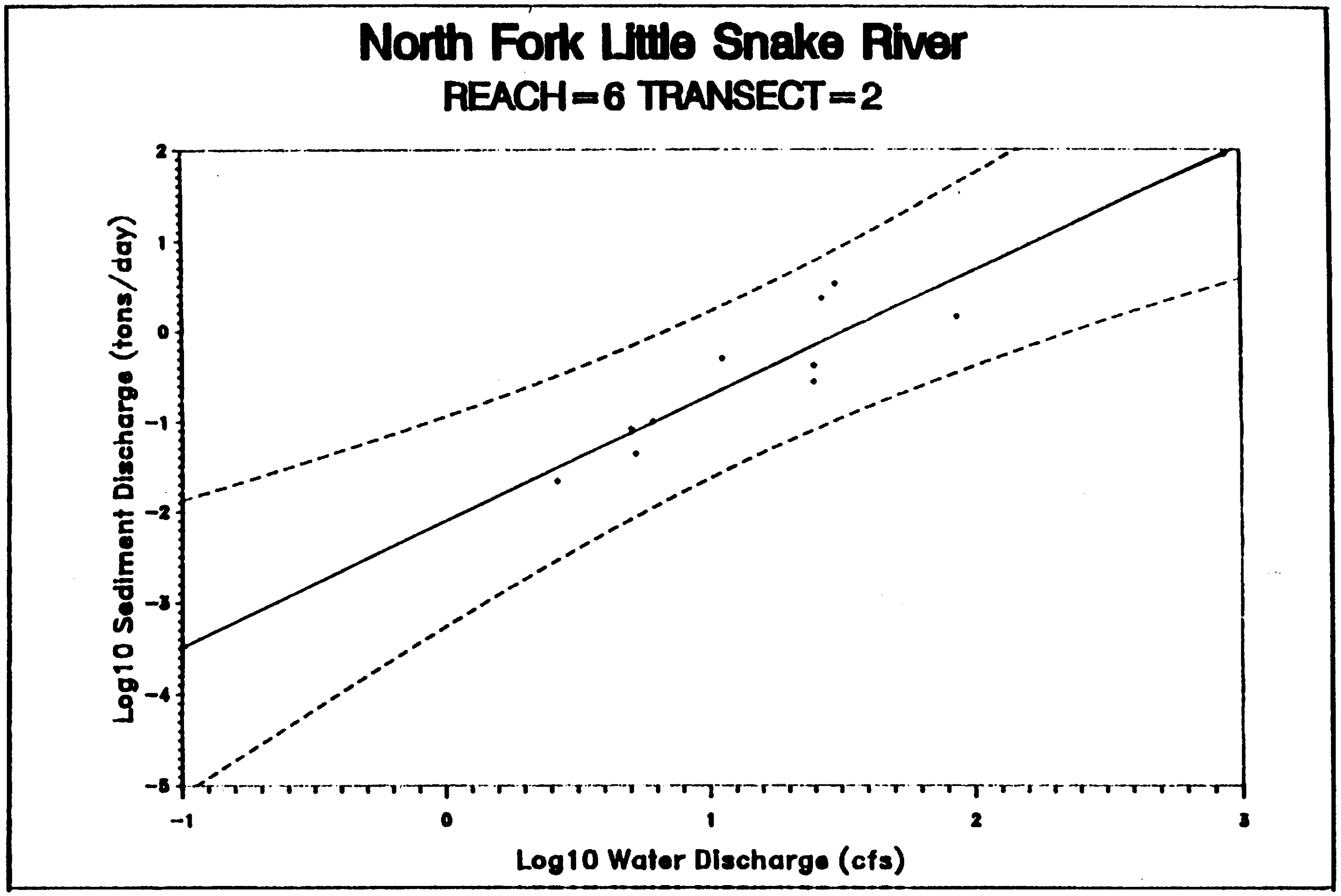


Figure A - 67. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 2, Reach 6, North Fork Little Snake River.

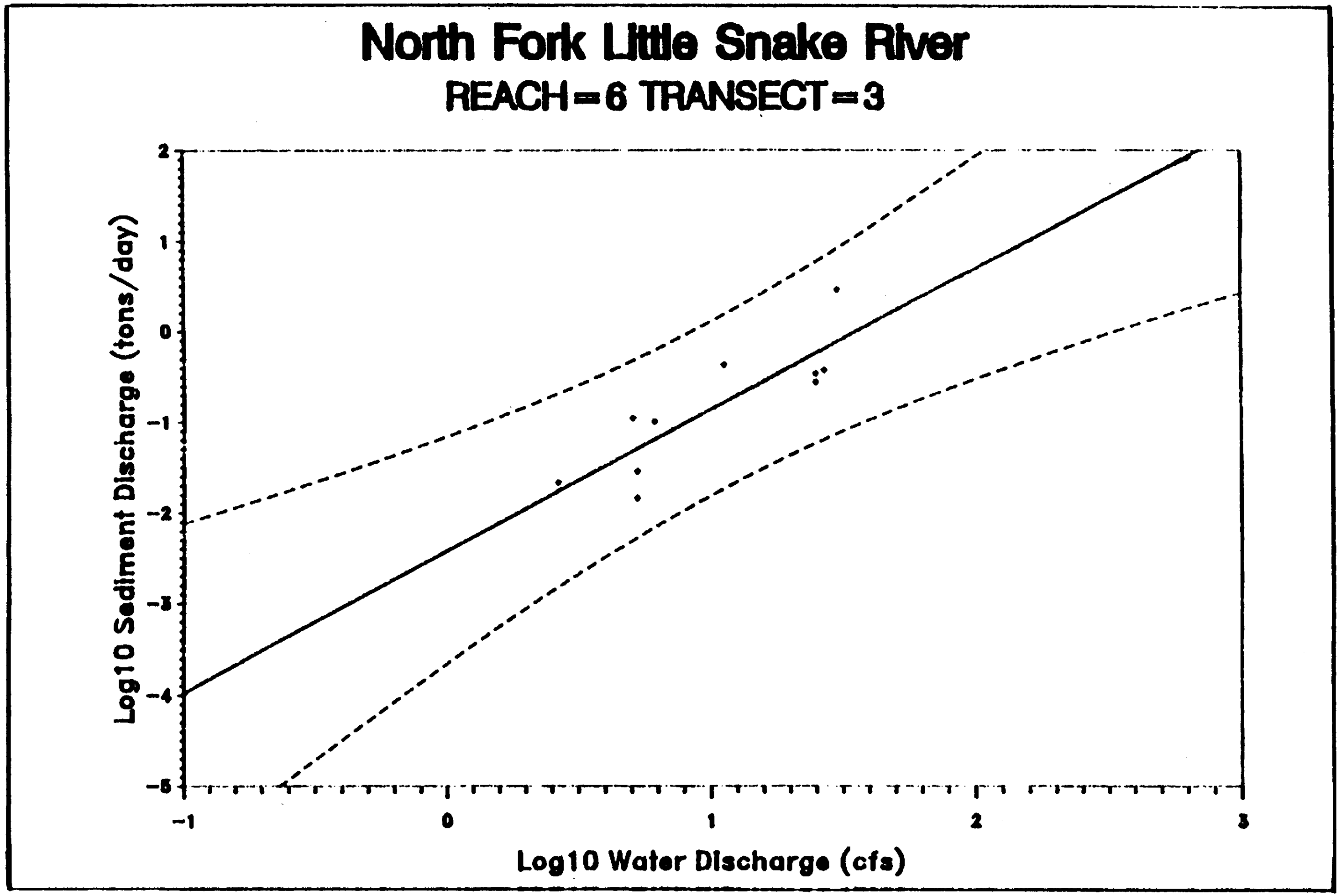


Figure A - 68. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 3, Reach 6, North Fork Little Snake River.

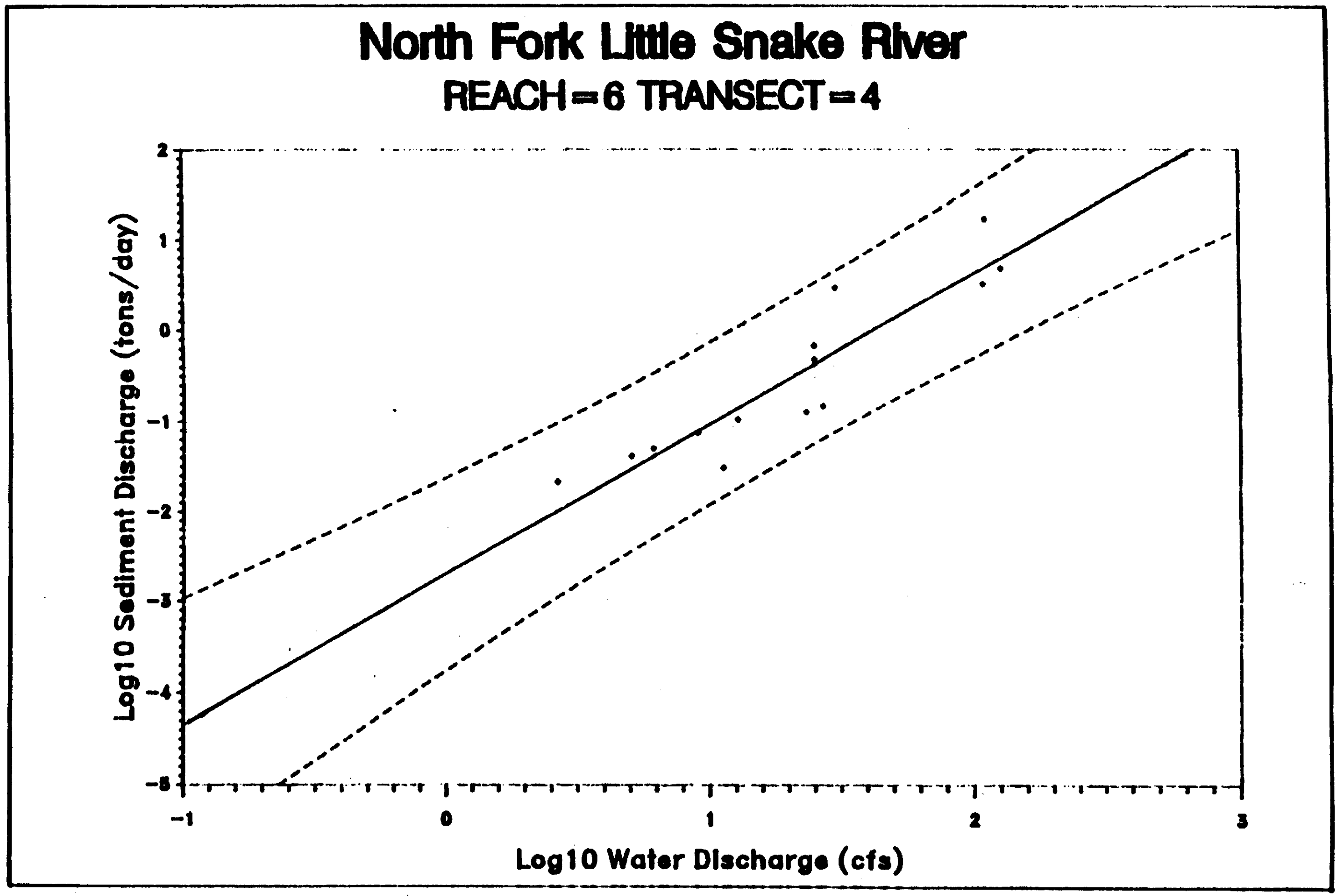


Figure A - 69. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 4, Reach 6, North Fork Little Snake River.

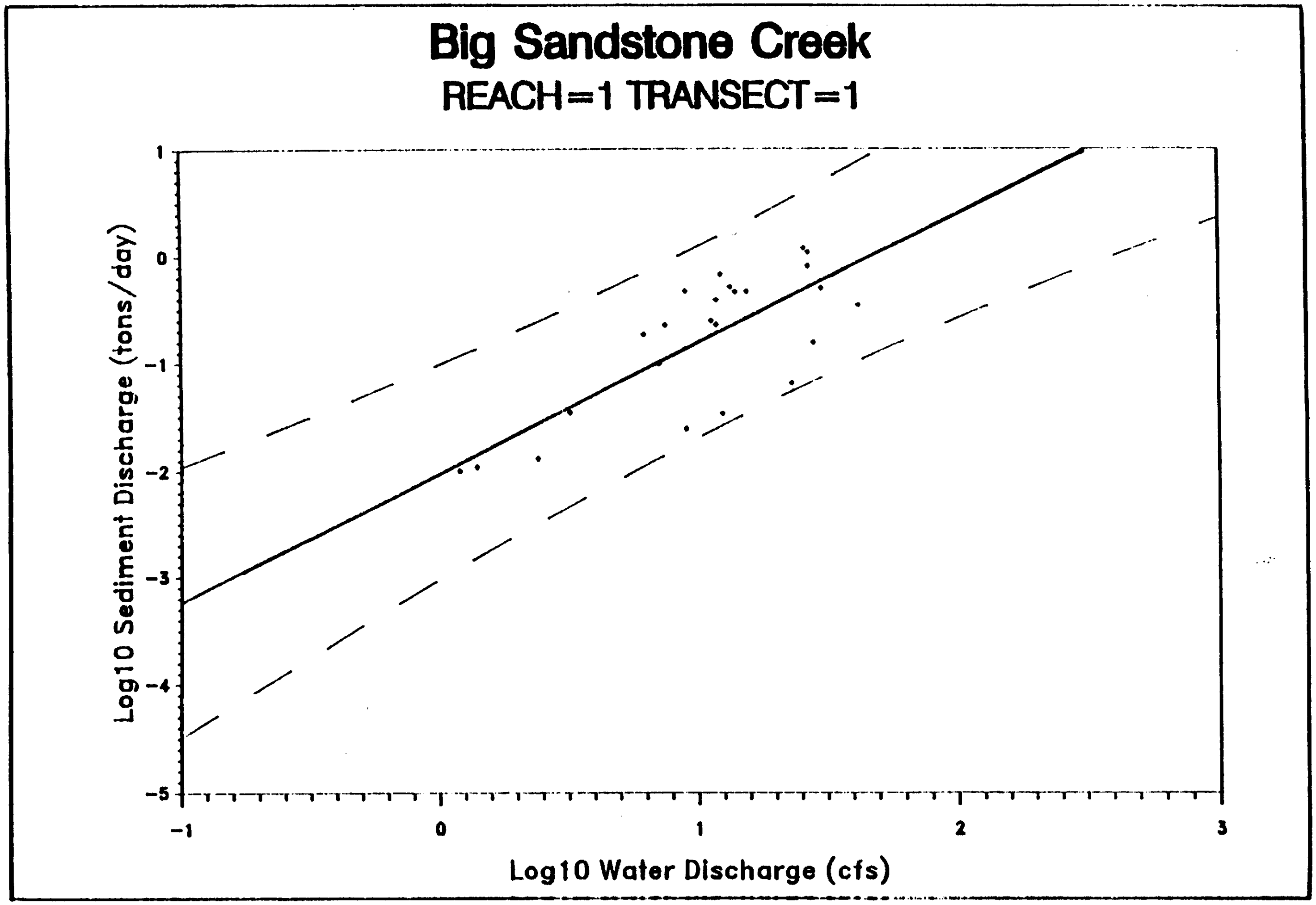


Figure A - 70. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 1, North Fork of Big Sandstone Creek.

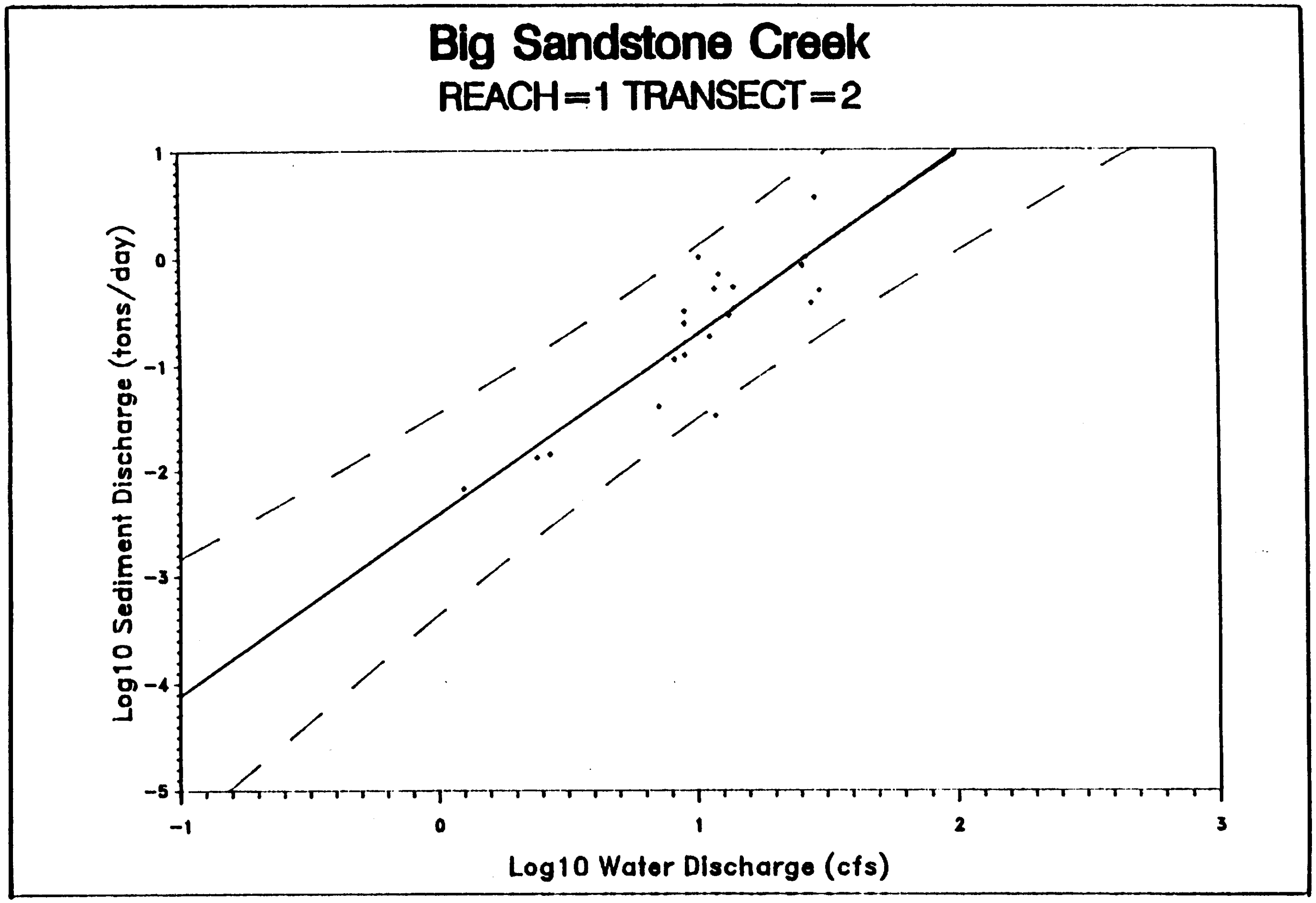


Figure A - 71. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 2, North Fork of Big Sandstone Creek.

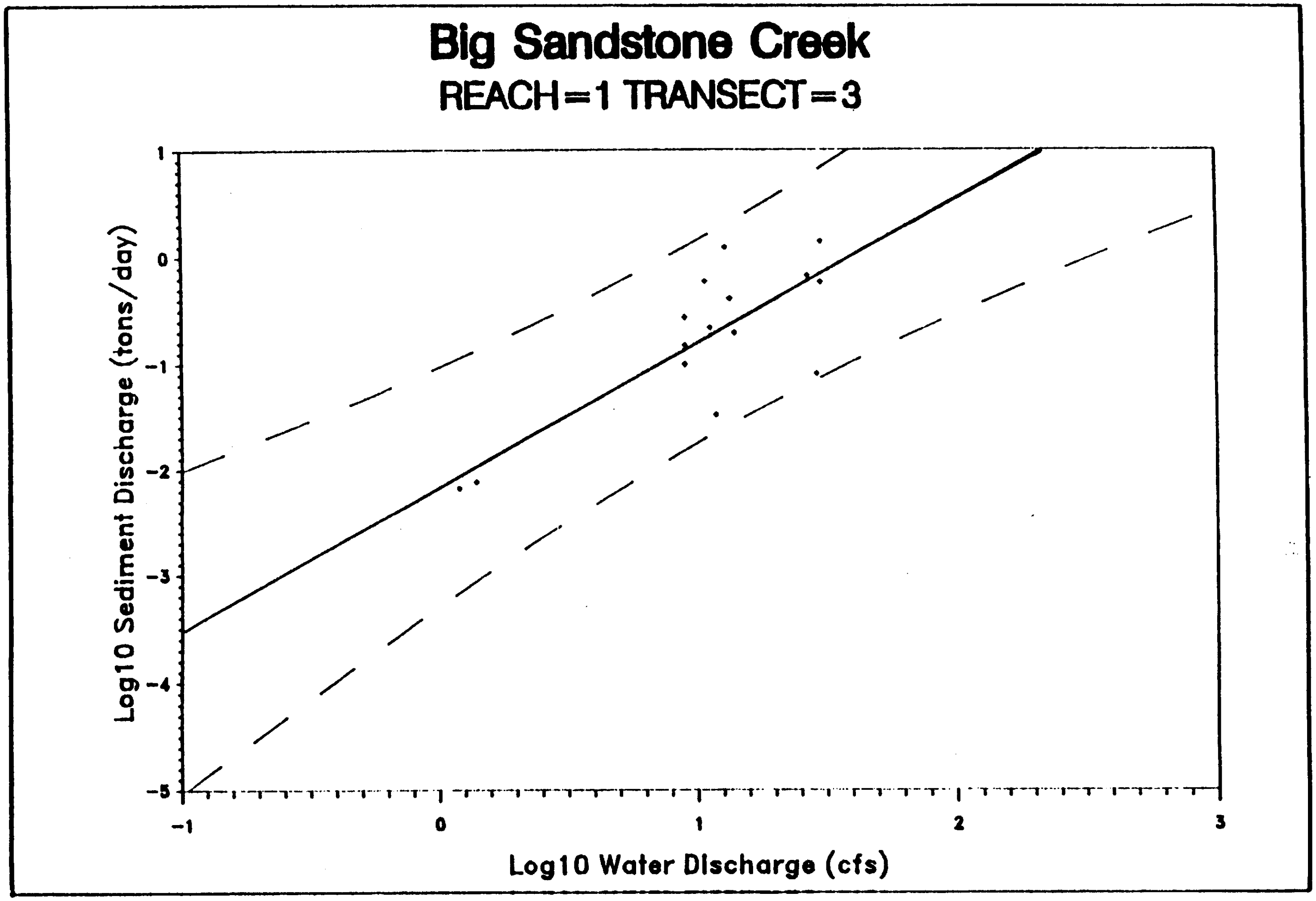


Figure A - 72. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 3, North Fork of Big Sandstone Creek.

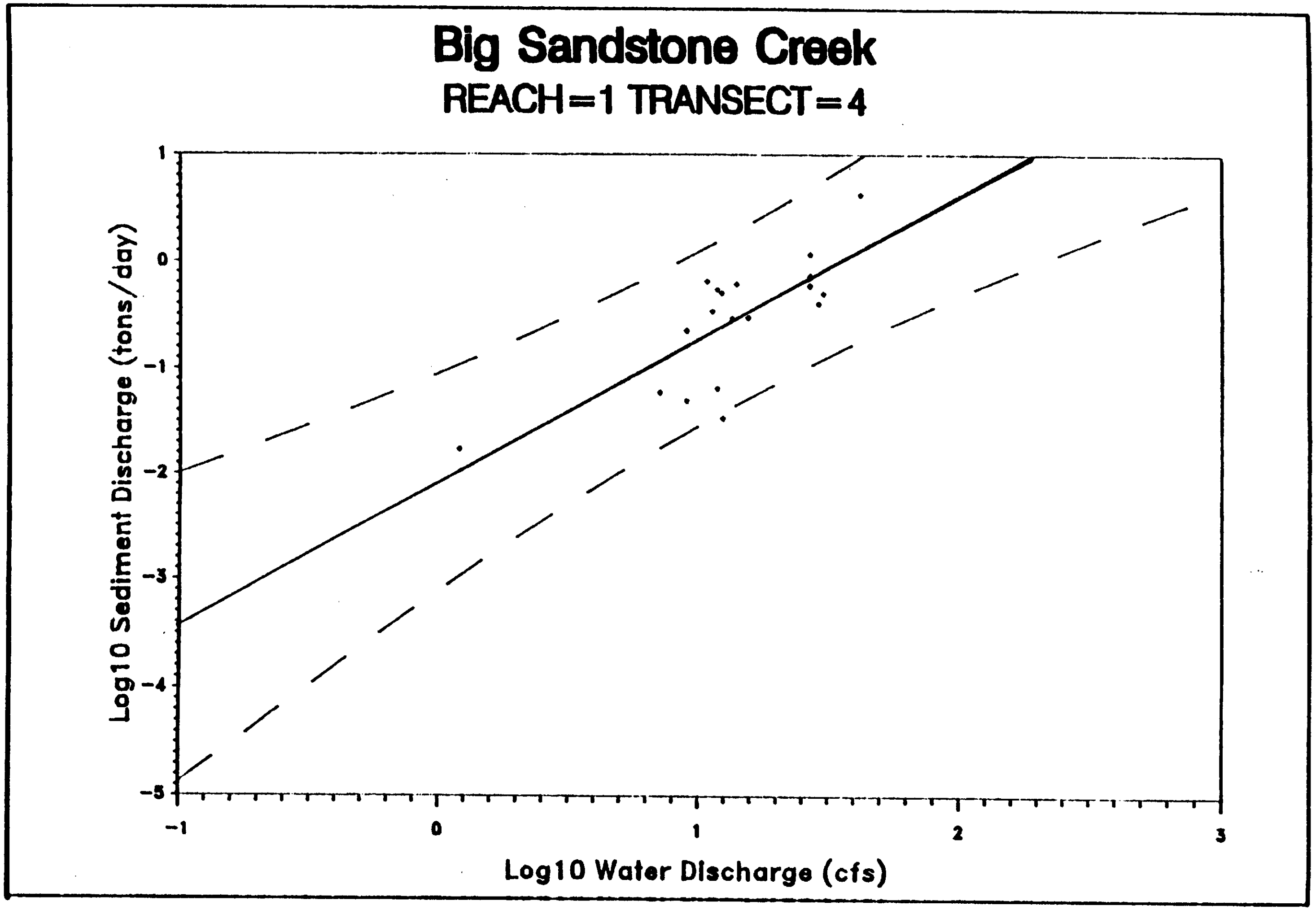


Figure A - 73. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 4, North Fork of Big Sandstone Creek.

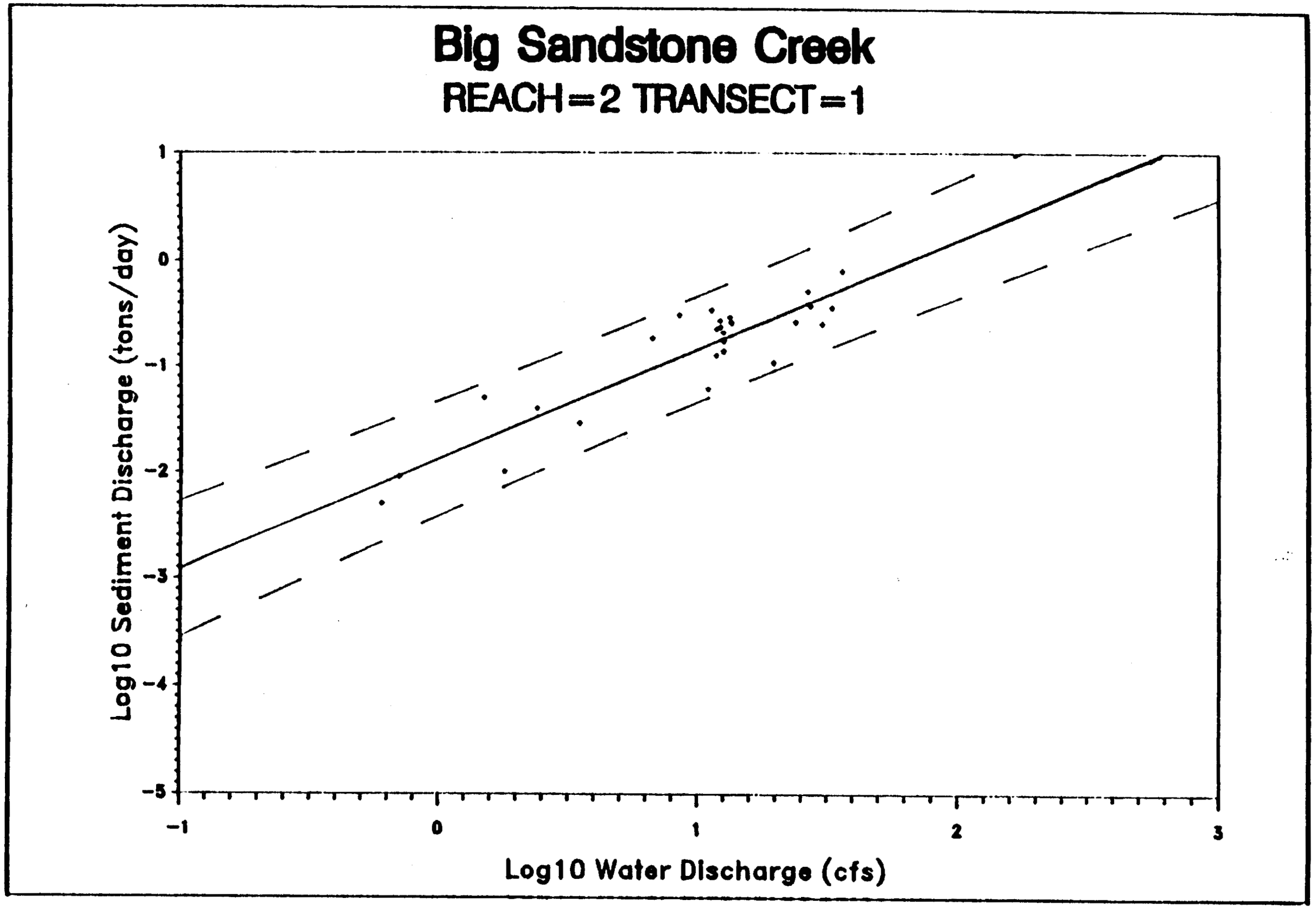


Figure A - 74. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 1, South Fork of Big Sandstone Creek.

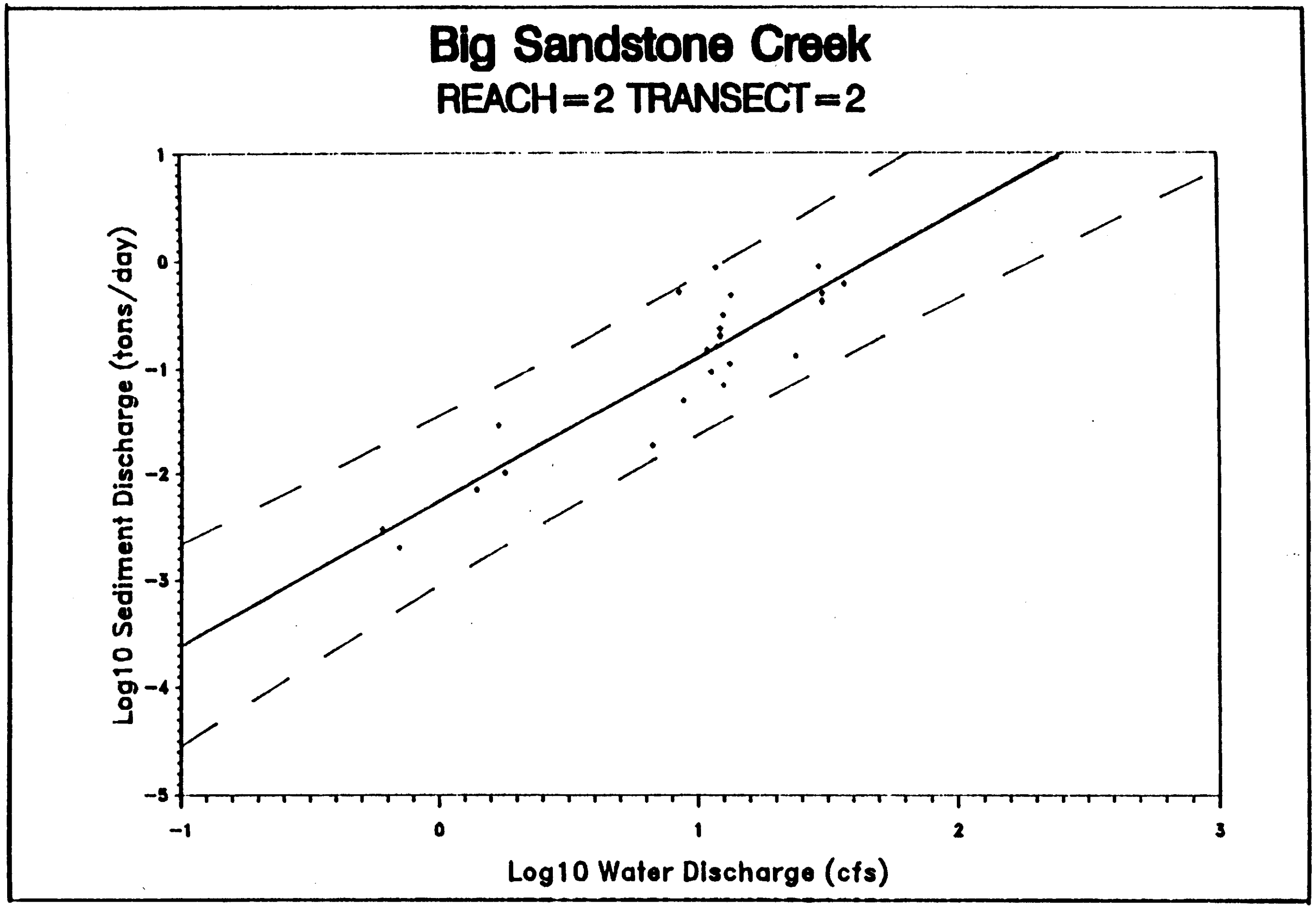


Figure A - 75. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 2, South Fork of Big Sandstone Creek.

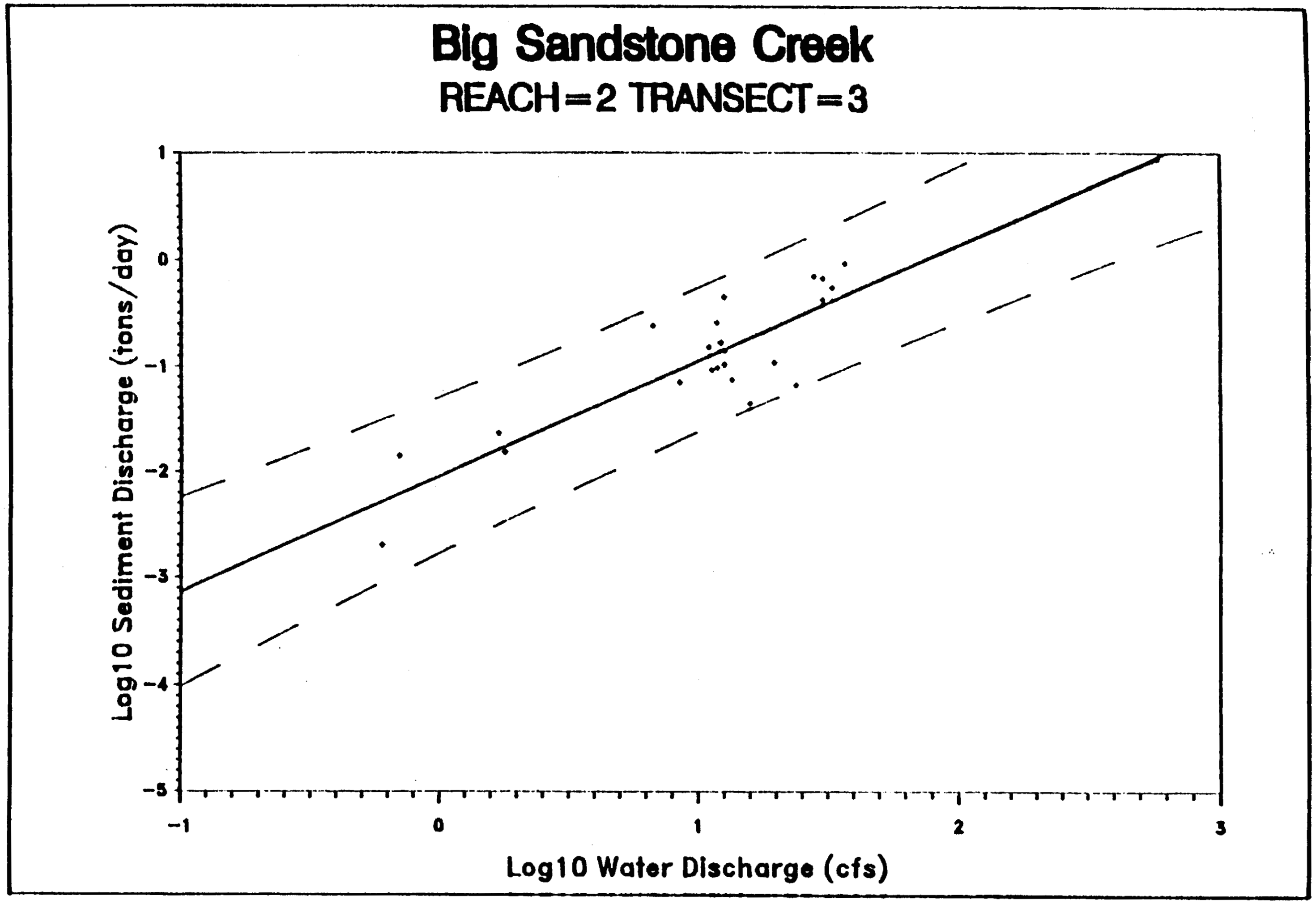


Figure A - 76. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 3, South Fork of Big Sandstone Creek.

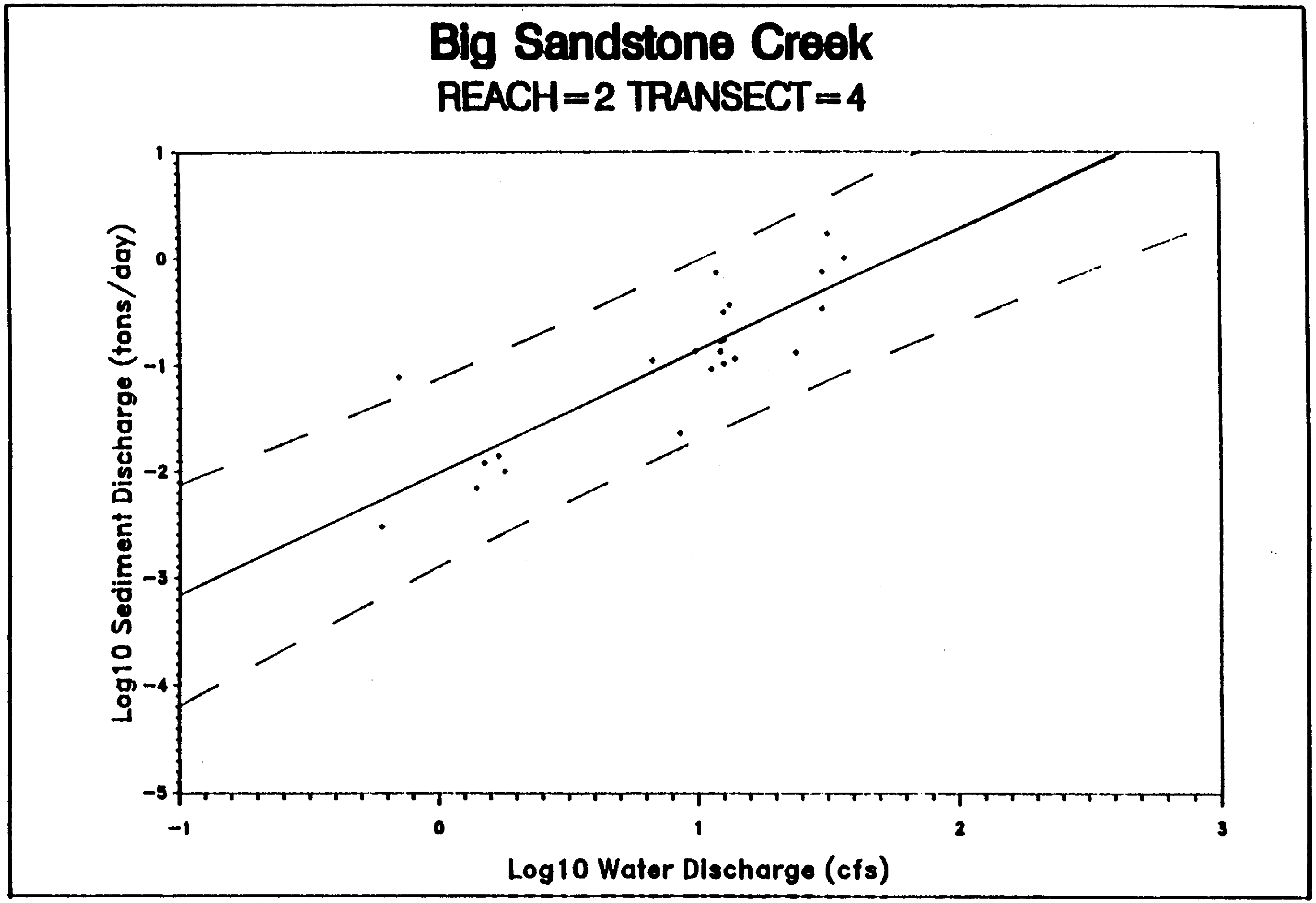


Figure A - 77. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 4, South Fork of Big Sandstone Creek.

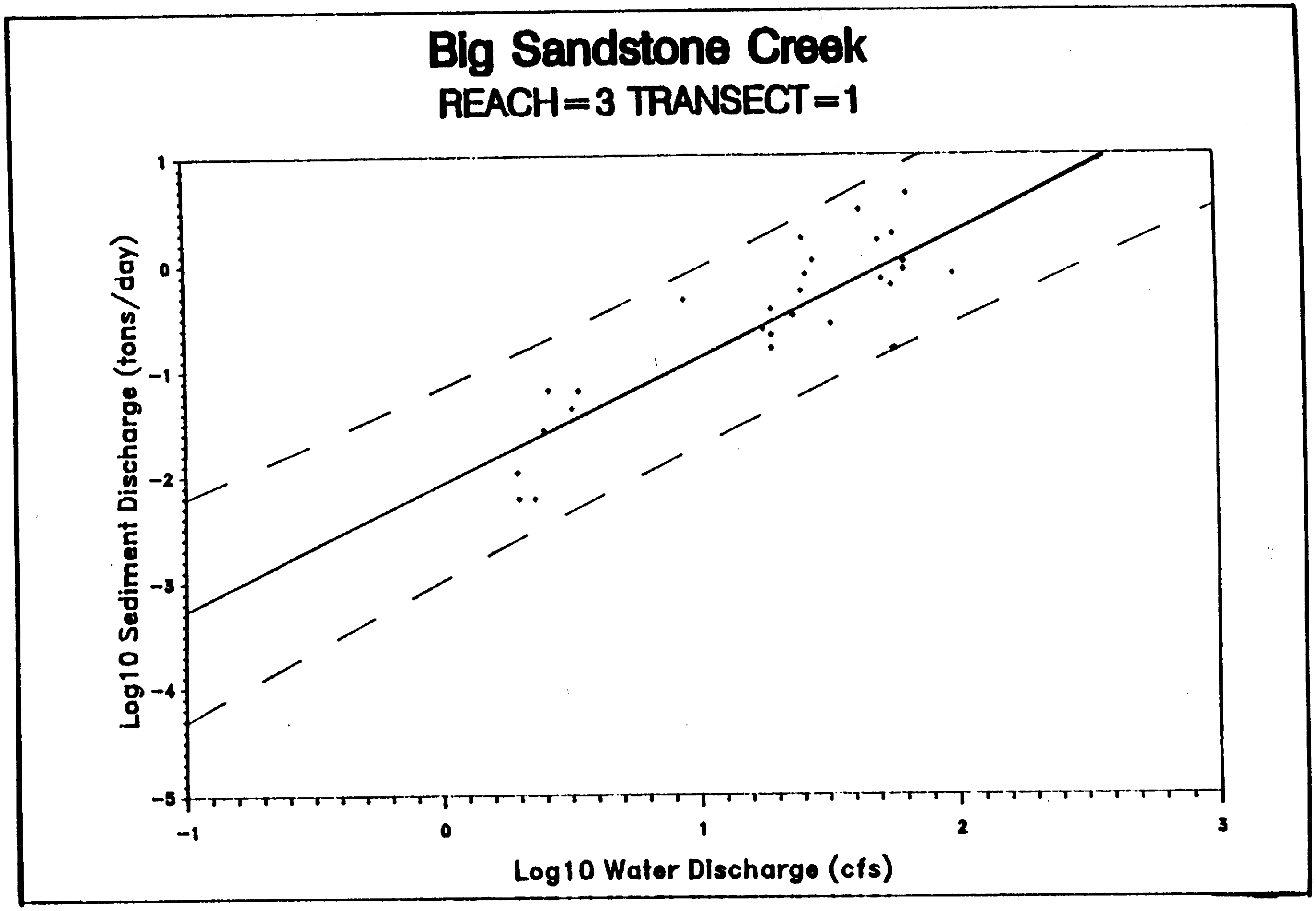


Figure A - 78. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 1, Big Sandstone Creek.

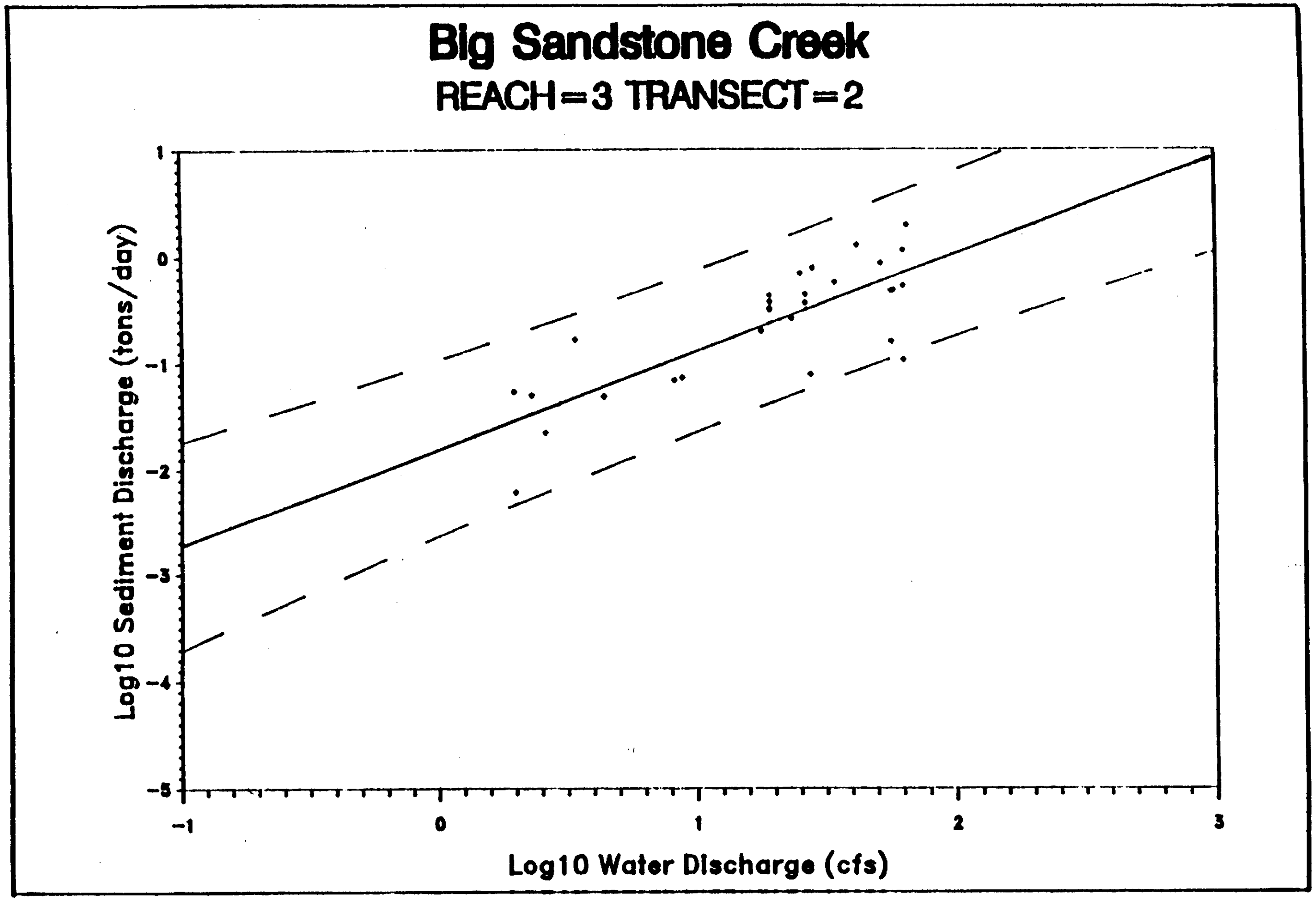


Figure A - 79. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 2, Big Sandstone Creek.

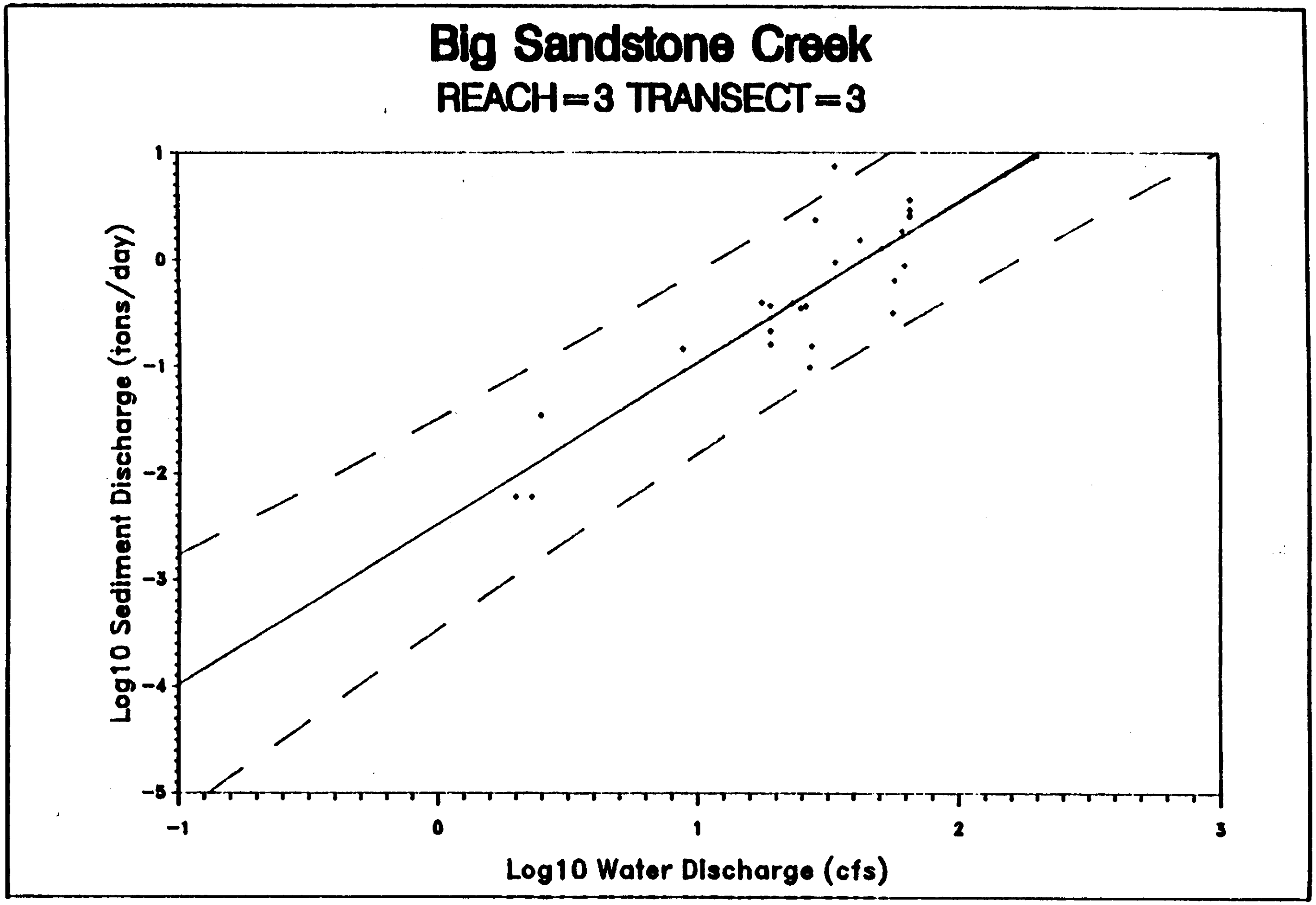


Figure A - 80. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 3, Big Sandstone Creek.

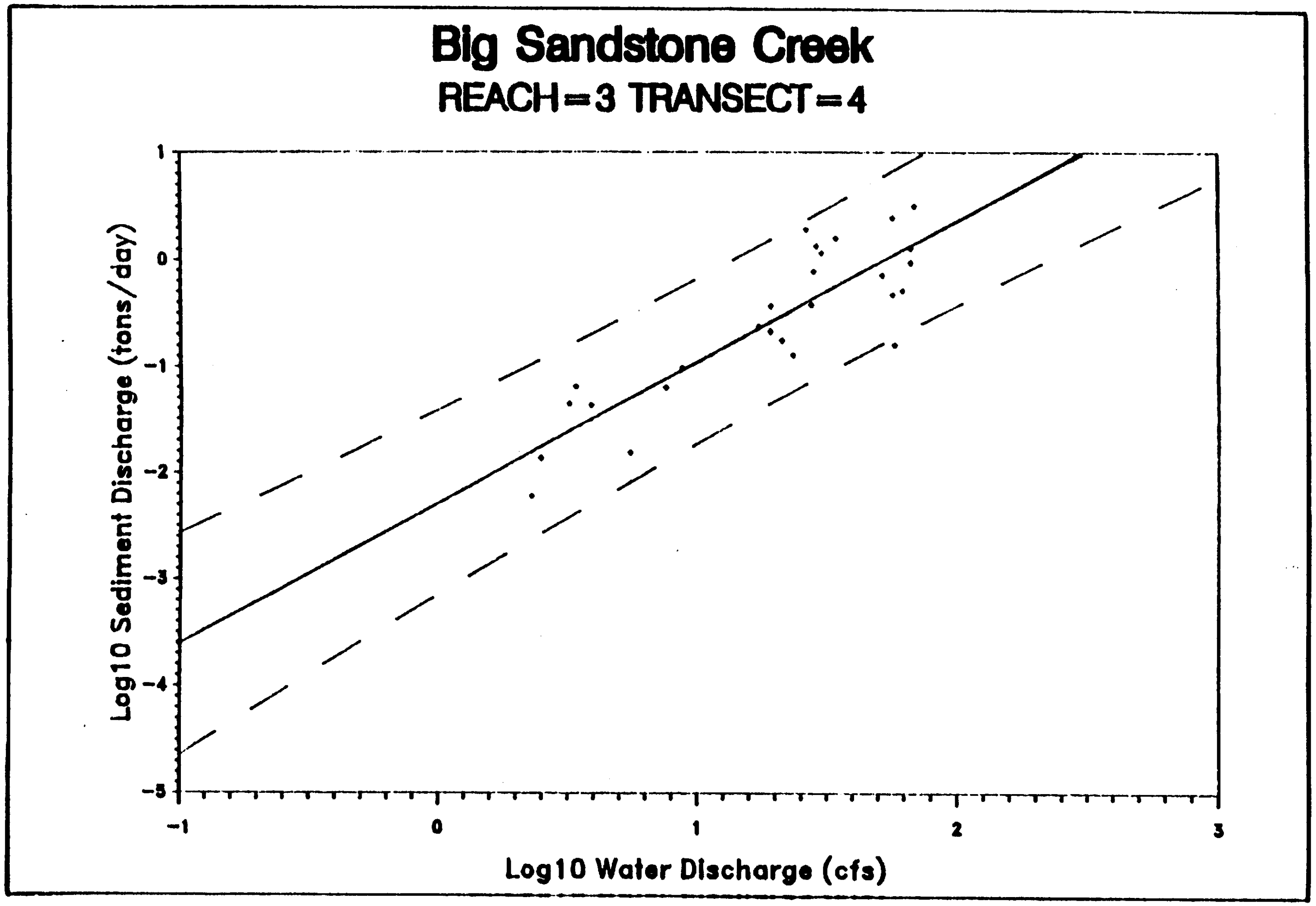


Figure A - 81. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 4, Big Sandstone Creek.

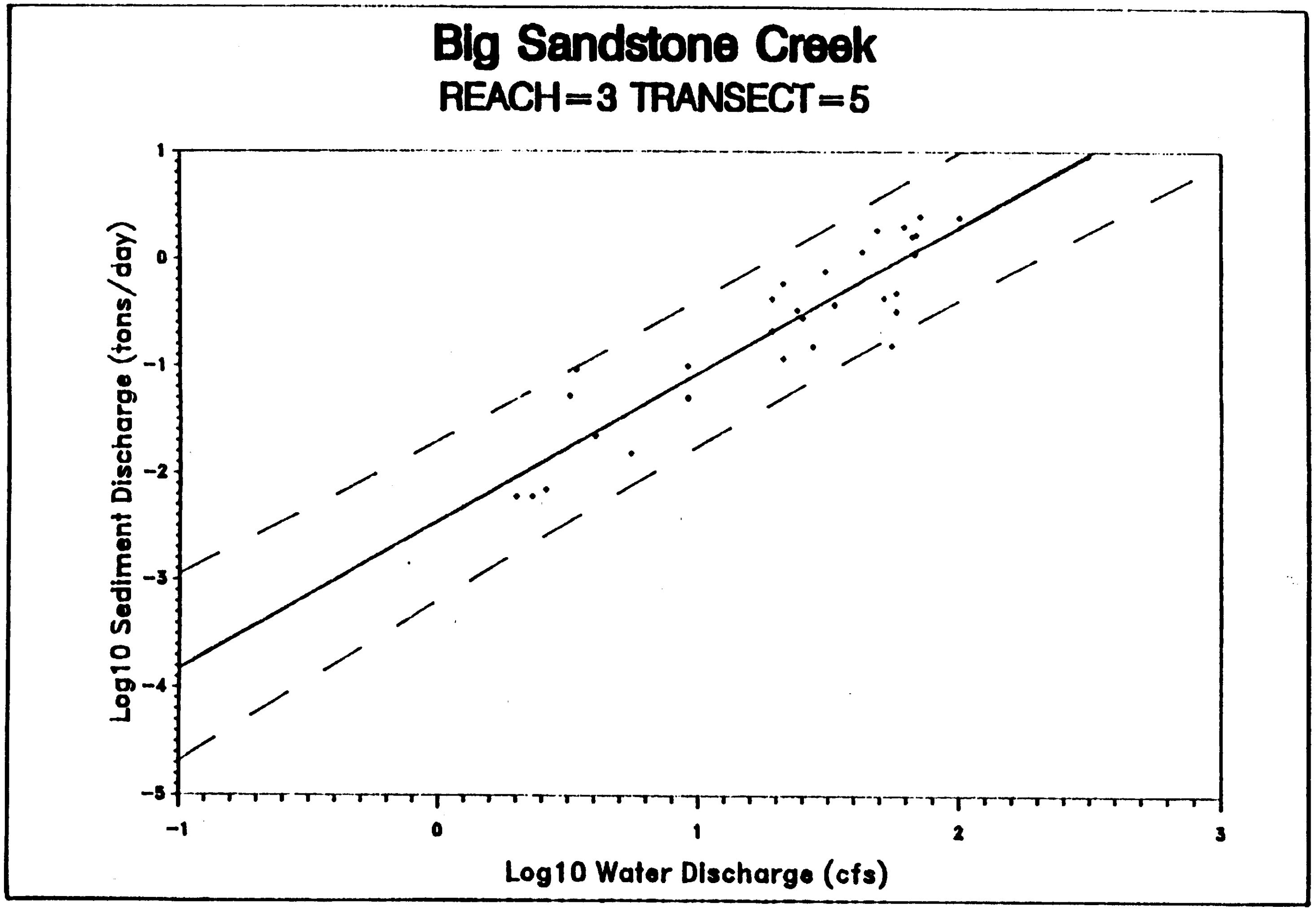


Figure A - 82. Relation of suspended sediment load discharge to water discharge, with 95 percent confidence belts, at Transect 5, Big Sandstone Creek.