Evaluation of Sediment Transport Data for Clean Sediment TMDLs

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EXECUTIVE SUMMARY

Excessive erosion, transport, and deposition of sediment in surface waters is a major problem in the United States. A national strategy is needed to develop scientifically defensible procedures to facilitate the development of TMDL's for clean sediment in streams and rivers of the United States. In the first part of this study data sets which contain sediment transport and flow data were identified from non-USGS sites. In the second part of this study, an existing method for evaluating impairment of streams by sediment (Rosgen-Troendle technique) was evaluated, problems were identified and a revised technique was developed. This revised technique will be useful in the identification of problems, water quality indicators, and target values for clean sediment TMDLs in streams and rivers (USEPA, 1999).

A search of existing data sets yielded 108 sites in the United States with detailed sediment and flow data suitable for testing of procedures for the development of clean sediment TMDLs. The data from these streams was from 11 different states and nine different physiographic provinces of the country and would serve as a valuable resource for further development of procedures to detect impairment due to clean sediment.

The Rosgen-Troendle technique (Troendle, 2000, written communication) assumes clean sediment can be identified as a problem for a given stream based on a relation between sediment transport and flow discharge for one of the 48 stream types of the Rosgen classification (Rosgen, 1996). The technique assumes that each of the stream types will have a unique dimensionless sediment transport rating that can be used to establish baseline or reference conditions for other streams of the same Rosgen stream type. As a method of conveying information on channel form, the Rosgen classification works well, however, problems were found with using the Rosgen classification to define baseline or reference types for sediment because some of the types are inherently unstable (types D, F and G, Table 4-1, Rosgen, 1996). Another problem encountered with the Rosgen classification is that the most important level-one criteria do not correlate well with sediment transport. The scaling method used in the Rosgen-Troendle technique does not allow valid comparisons of different sized streams, but in some cases obscures differences in sediment transport rates.

In this study a revised methodology was developed. The methodology is as follows: 1) Classify the stream according to Rosgen (1996); 2) Determine the stage of channel evolution (Simon and Hupp, 1986; Simon, 1989b) and rank the relative degree of channel instability using a channel-stability index (Simon and Downs, 1995); 3) Determine index of biologic integrity or other means of evaluating ecological health; 4) Develop sediment-transport versus discharge (ratings) and magnitude-duration relations for sediment transport and excess shear stress; and 5) Compare slope of sediment-transport rating, total sediment load at the effective (1.5 year) discharge, with physical and biologic indices to determine possible "departure" from the reference condition and impairment to the designated use of the waterbody.

The determination that a given stream has a significantly different rate of sediment transport than a corresponding reference stream is one facet of the TMDL problem. Another problem is determining the link between excess sediment and a measurable impairment to the designated use of the waterbody. When aquatic life is the designated or existing use of the stream, the link between excess sediment and a measurable impairment needs to be established. A preliminary study is underway at the National Sedimentation Laboratory to determine the effects of suspended sediment and the degree of bed material (substrate) movement on the biota

of streams. Thresholds of toxicity based on the frequency and duration of given rates of suspended sediment and substrate movement will be studied in field and laboratory settings.

The methodology outlined above is still in a state of development. Stages of channel evolution need to be compared to sediment transport relations on streams from other physiographic provinces of the country. The link between the degree of sediment change and the designated use of a stream or river also needs to be established.

INTRODUCTION AND PURPOSE

Excessive erosion, transport, and deposition of sediment in surface waters is a major problem in the United States. The 1996 National Water Quality Inventory (Section 305(b) Report to Congress) indicates that sediments are ranked as a leading cause of water-quality impairment of assessed rivers and lakes. Impairment by sediment can be separated into problems resulting from chemical constituents adsorbed onto the surface of fine-grained sediments (sediment quality), problems resulting from sediment quantities (clean sediment) irrespective of adsorbed constituents, and alteration of substrate (bed material) by erosion or deposition. The maximum allowable loadings to, or in a stream or waterbody that does not impair designated uses has been termed the “TMDL” (total maximum daily load). A national strategy is needed to develop scientifically defensible procedures to facilitate the development of TMDL’s for clean sediment in streams and rivers of the United States.

Sediment loads (transport rates) in steams vary by orders of magnitude over time and by location. Controls such as geology and channel-boundary materials, land use, channel stability, and the type and timing of precipitation events make prediction of sediment loads difficult and complex. Still, in order to determine the amount of sediment that impairs a given waterbody (TMDL), one must first be able to determine the total sediment load that would be expected in an unimpaired stream of a given type and location. However, baseline conditions of flow, sediment concentrations, and transport rates for streams in the wide variety of physiographic provinces and under a wide variety of land uses of the United States are poorly understood.

Initiating a data collection program to obtain a comprehensive data set from a sufficient number of streams from each of the major physiographic provinces of the nation for use in the development of clean sediment TMDL’s is impractical from both time and monetary standpoints. A logical alternative is to make use of high-quality, historical data sets containing corresponding flow and sediment-transport information that have been collected by government and private agencies at various locations around the nation. The clean sediment TMDL development process consists of seven steps (Figure 1-2, USEPA, 1999). This study will be only concerned with the first two steps of this process: Problem Identification, and Development of Numeric Targets.

There are a number of ways this problem may be approached. The EPA is presently working under the hypothesis that the first two steps in the development of a clean-sediment TMDL for a given stream can be fundamentally based on a sediment-transport rating (relation between sediment concentration and flow discharge) for a specific stream type as classified by the Rosgen system (Rosgen 1996). This hypothesis assumes, therefore, that each of the Rosgen stream types (48 in all) will have a unique sediment-transport rating that can be used to establish baseline, or reference conditions for other streams of the same Rosgen stream type. The operating hypothesis also infers that divergence of some type and/or amount from this baseline or “reference” sediment-transport rating could then be considered as indicating a certain level of impairment, which, in turn, could be used in the development of a clean-sediment TMDL for the stream type. This is the general approach that has been outlined by Rosgen and Troendle in their work for EPA in Rocky Mountain streams (Troendle, 2000, written communication). This approach will hereafter be referred to as the Rosgen-Troendle technique. Simon (1989a) was able to show that the slopes of the relations representing suspended-sediment transport ratings varied systematically with their stage of channel evolution, indicating that sediment transport ratings can indicate degrees of impairment and instability.

To be consistent with this previous research on clean sediment TMDL's, the methods outlined by the Rosgen-Troendle technique needed to be evaluated in regions of the U.S. other than the Rocky Mountains. To this end, this study addresses aspects of sediment-transport ratings, their potential use as a means of establishing baseline or reference conditions for Rosgen stream types, and their applicability for differentiating between impaired and unimpaired streams. The viability of the Rosgen stream classification system for use in differentiating baseline- or reference-stream conditions is also presented. Following this evaluation, directions for improvements in the technique are presented.

The principal objectives of this study are to:

1. Compile a list of historical sediment-transport data sets from as many non-U.S. Geological Survey sites as possible.
2. Evaluate the Rosgen-Troendle technique (Troendle, 2000, written communication) at two sites from each of two locations in physiographic provinces different than where the technique was first developed, and
3. Explore and evaluate alternative strategies independent of and building on the Rosgen-Troendle technique.

Two sites on Goodwin Creek, Mississippi and the Toutle River System, Washington were selected because of their excellent historical databases and known disturbances. The historical data base includes suspended- and bedload-transport data, particle-size distributions and cross-section surveys.

BACKGROUND of the ROSGEN and TROENDLE TECHNIQUE for CLEAN-SEDIMENT TMDL'S

The basic procedure of the Rosgen-Troendle technique for establishing whether a stream departs from a reference condition in the TMDL process can be summarized as follows:

1) The reference condition (natural range of variability) sediment-transport relationship for stable systems (systems capable of carrying the sediment being delivered without change in dimension, pattern, or profile) can be defined as a function of: (a) stream type (Rosgen classification), (b) stability rating by stream type (Pfankuch rating), and (c). watershed size.

2) In disturbed streams, departure of the sediment transport relationship from the reference condition can be quantified and documented by stream type (Troendle, 2000, written communication).

In other words, each major stream type would have a dimensionless sediment rating curve for the reference condition that could be compared to streams of the same type to determine if there was departure from the stable reference condition. This situation would exist for each of the 48 stream types in the Rosgen (1994,1996) classification. Thus, to evaluate the Rosgen-Troendle technique, one must first look in detail at the Rosgen classification's use of "stream types" and the definition of reference conditions for a given stream type.

Rosgen and Alternative Classification

The Rosgen (1996) classification uses channel sinuosity, entrenchment ratio, channel slope, and sediment particle size of the boundary to arrive at the "type" of stream. While these characteristics are suitable to describe the general morphology of the stream, it may be problematic to use these parameters to describe a stable reference type.

Of fundamental significance in evaluating the proposed methodology to develop reference sediment-transport relations for each stream type is the premise that a "reference" condition for each of the Rosgen stream types can be obtained. It is crucial, therefore, to define "reference"as it relates to a:

1. reach or condition for each stream type in the Rosgen classification scheme and,
2. sediment-transport relation for each stream type in the Rosgen classification scheme.

For the sole purpose of stream classification, a "reference" condition is the "representative" morphology defined for a specific stream type because variance in reach morphology is absorbed into the Rosgen Classification as a change to a different stream type. Thus, a "reference" condition can be obtained for each of the stream types by utilizing the level-one criteria outlined by Rosgen (1996); that is using channel sinuosity, entrenchment ratio, channel slope, and particle size. Rosgen (1996), however, extends the definition of "reference" condition to include the implicit assumption that it also represents a stable condition.

It is quite another matter, however, to define a "reference" condition for a sediment-transport relation (by stream type) and "departure" from that relation which implies disturbance and potentially, impairment to a designated use. The principle flaw in this approach is that some of the Rosgen stream types (D, F and G) are inherently unstable. Thus, the "reference" morphology for some of these stream types already represents a "departed" condition from a stable channel in dynamic equilibrium. The corresponding sediment-transport relation for that reference condition would indicate accelerated sediment transport and therefore, an overestimate of the transport rate for a stable channel in that particular environment. For these reasons, the Rosgen classification of a stream is unsuitable for use in defining categories of stable reference stream types. The classification is useful, however, as a shorthand method of communicating the physical characteristics of a stream.

The reason for these difficulties is founded in the conceptual basis of the Rosgen classification itself. Rosgen's classification is based primarily on channel form (entrenchment ratio, width/depth ratio, and channel sinuosity) and to a lesser degree, on the slope of the channel and the particle-size distribution of the channel boundary. The processes associated with sediment transport and channel formation are not the main criteria in the Rosgen classification. Yet it is the channel and watershed processes interacting with the sediments comprising the watershed and channel that ultimately determine sediment-transport rates.

For these reasons, and for the purpose of evaluating alternative strategies of obtaining regionally-based clean-sediment TMDL's, a process-based classification scheme relying on stages of channel evolution rather than stream types (Simon and Hupp, 1986; Simon 1989b) is used (Table 1, Fig. 1). The working hypothesis for the use of this classification scheme is that sediment-transport rates will vary systematically by stage of channel evolution because stage of evolution is used as a surrogate for dominant channel processes and the relative stability of the channel boundary. Disturbances in parts of the watershed resulting in dramatic shifts in the amount of sediment delivered to the channel system will manifest themselves in diagnostic characteristics of channel form such as bank failures, tree stems buried by deposited sediment, and actively growing bars and berms.

In alluvial channels, disruption of the dynamic equilibrium results in a systematic set of changes to channel geometry that are clearly expressed in specific channel forms, deposits, and the quantity and condition of riparian vegetation (Table 1). Once destabilized, streams generally exhibit some amount of upstream channel degradation and downstream aggradation. In the channel evolution model (Simon and Hupp, 1986; Simon, 1989b) we can consider the dynamic equilibrium channel as the initial, predisturbed stage (I) of channel evolution, and the disrupted channel as an instantaneous condition (stage II). Rapid channel degradation of the channel bed ensues as the channel begins to adjust (stage III, Fig. 1a). Degradation flattens channel gradients and consequently reduces the available stream power for given discharges with time. Concurrently, bank heights are increased and bank angles are often steepened by fluvial undercutting and by pore-pressure induced bank failures near the base of the bank. Thus, the degradation stage (III) is directly related to destabilization of the channel banks and leads to channel widening by mass-wasting processes (stage IV) once bank heights and angles exceed the critical shear-strength conditions of the bank material. The aggradation stage (V) becomes the dominant trend in previously degraded downstream sites as degradation migrates further upstream because the flatter gradient at the degraded site cannot transport the increased sediment loads emanating from degrading reaches upstream. This secondary aggradation occurs at rates roughly 60% less than the associated degradation rate (Simon, 1992). These milder aggradation rates indicate that bed-level recovery will not be complete and that attainment of a new dynamic equilibrium (stage VI) will take place through further (1) bank widening and the consequent flattening of bank slopes, (2) the establishment and proliferation of riparian vegetation that adds roughness elements, enhances bank accretion, and reduces the stream power for given discharges, and (3) further gradient reduction by meander extension and elongation.

The Pfankuch Rating

The Rosgen-Troendle technique evaluates the condition of the channel bed and banks using the method of Pfankuch (1978). These procedures were developed to systemize measurements and evaluations of the resistive capacity of bed and bank materials to erosion and transport by flows. The Pfankuch rating is applied to a channel reach or to a longer length of channel and uses the sum of numerical scores for the condition of the upper bank, lower bank and channel bottom to assign a rating of excellent, good, fair, or poor (Table 2). As can be seen from the values assigned to various attributes, the stability rating is subjective with some conditions far out-weighing others. In addition, the rating seems particularly skewed to western, high-gradient coarse-grained systems. The Pfankuch stability rating was undoubtedly the part of the Rosgen-Troendle technique to be used as an index of watershed condition and degree of departure or disturbance. A logical next step would be to relate the Pfankuch rating to sediment transport records at several sites and use it at sites where sediment transport data is lacking, as a rapid method to determine whether excess sediment is a problem on a given channel. The Pfankuch rating was determined for the four sites of this study. Several problems were encountered in its application in this study because it was developed for mountain stream channels.

A semi-quantitative, empirically-based ranking of the state of channel stability can serve as an alternative to the Pfankuch scheme (Simon and Downs, 1995). This scheme is objective in that it does not weight individual variables, was originally designed to evaluate channel stability in the vicinity of bridges over a broad range of physiographic settings, and has been used by the U. S. Geological Survey at thousands of sites across the United States. The ranking shown here has been modified somewhat from that reported in Simons and Downs (1995) to reflect channel-stability conditions away from bridge crossings (Table 3). An additional scheme that accounts for those physical characteristics that can directly effect biologic integrity was also devised (Table 4) based largely on the physical characterization/water quality field data sheet contained in Barbour et al., (1999). Although the development of these ranking schemes was not an original objective of this study, they are included here for two reasons: 1) they are being used as part of a major effort in Mississippi to develop clean-sediment TMDL's, and 2) they represent a part of a suggested procedure for determining degree of disturbance and impairment, described in a later section of this report.

Watershed Size

An unbiased method to scale the flow and sediment-transport rate of different size streams is important to allow valid comparisons. This procedure must be carefully conceived or misleading results will likely occur (Barenblatt, 1987). In the Rosgen-Troendle technique comparisons in sediment rating curves are made by scaling the discharge (Q) by the bankfull discharge (Q_{bf}) and scaling the sediment concentration (C) by the sediment concentration at bankfull flow (C_{bf}). This scaling technique has the effect of forcing the dimensionless sediment transport relations (C/C_{bf} versus Q/Q_{bf}) through the point (1,1). While the dimensionless sediment transport relations allow the comparison of streams with a variety of sizes, these dimensionless relations obscure all differences at the bankfull flow by forcing all sediment relations through the same point (1,1). The bankfull discharge has been shown by several researchers to correspond closely with the discharge that moves the most sediment over a period of years (effective discharge; e.g. Andrews and Nankervis, 1995; Kuhnle et al., 1999). It is important to have a valid comparison of the relative rates of sediment movement by streams at this flow. We propose to compare the potential for bed material transport, the concentration of suspended sediment, and the slope of the sediment transport relation at the bankfull or effective discharge (see below).

METHODS

I. Identification of Sediment-Transport Data Sets

Using literature sources and computer-based searches, sediment-transport data sets from streams across the United States were identified. This search was concentrated on locating data sources other than the U. S. Geological Survey. Data that are needed to evaluate the Rosgen-Troendle technique include not only information on sediment transport including the particle-size distribution of the channel boundary but also various characteristics of channel form. However, the minimum criteria for an acceptable data set were ones that included instantaneous flow and suspended-sediment data. These data include instantaneous concentrations and discharges determined from stage information collected at intervals of 15-min or less. For a complete data set the following information is desirable. All of the data sets identified had all or most of the following information:

1. Flow and sediment-transport data
    a. Instantaneous flow discharge (*Q*) and other relevant flow parameters

    b. Instantaneous suspended fine (< 0.062 mm) sediment concentration
    c. Instantaneous suspended sand (0.062 - 2 mm) concentration
    d. Bed load (mass/time/unit width)
2. Bed-material data
    a. Particle-size distribution of the bed and bank material
3. Data for classification by stream type (Rosgen, 1996)
    a. Width /depth ratios
    b. Sinuosity
    c. Gradient (bed surface slope)
    d. Valley width
    e. Channel boundary grain-size distribution
    f. Bankfull discharge determination
    g. Channel-stability index (Pfankuch, 1978)
4. Classification by stage of channel evolution (Simon and Hupp, 1986; Simon, 1989)
    a. See Table 1

Detailed Analysis of Four Sites from Two Watersheds

Four sites, two from the Toutle River watershed in Washington State, and two from the Goodwin Creek watershed in Mississippi were chosen for detailed analysis. These sites were located in the Sierra Cascade Mountain and Coastal Plain physiographic provinces, respectively, whereas most of the data used by Rosgen and Troendle was from the Rocky Mountain division provinces (Fig. 2). This allowed the Rosgen-Troendle technique to be tested for streams in physiographic provinces other than those used in its development. A good summary of the Toutle River sediment data is contained in Dinehart (1998). Additional data for the Toutle River is contained in Simon (1999). The sediment transport data for Goodwin Creek was summarized by Willis et al. (1986) and Kuhnle et al. (1989a). The data from Goodwin Creek is also available on the internet at *http://www.sedlab.olemiss.edu*.

Description of the Field Areas

The two sites from Goodwin Creek are located in the Coastal Plain province (Raisz, 1957) in the bluff hills of the Yazoo River Basin, in northern Mississippi. The bluff hills are directly east of the flood plain of the Mississippi River. Elevation on the watershed ranges from 71 to 128 m above sea level, with a mean channel slope of 0.004. Runoff generally is flashy and is caused by intense rain storms that occur most commonly during the winter and spring . Mean annual rainfall is 1,400 mm/yr. The upland area of the watershed has a thin cap of loess, incised by gullies and channels exposing underlying coastal plain material. Land use has changed from completely wooded when European settlers arrived in the 1830's to almost completely cleared and in cotton production from the middle of the nineteenth century to the middle of the twentyth. Current land use in the watershed is about 48% pasture, 26% forest, 15% cultivated and 11% idle (Bingner, 1998). During the years of intense cultivation a large amount of sediment eroded from the fields was deposited in the channels. A major channel dredging and straightening project was undertaken in the 1930's. The combination of the major changes in land use and the channel dredging and straightening resulted in unstable channels.

The channels are deeply incised and were actively eroding their beds until a series of grade-control structures were constructed in the watershed in the late 1970's and early 1980's. While the structures have greatly reduced bed erosion, bank erosion is still active at several places in the watershed. The two sites chosen for this study: station 2 and station 5 on Goodwin Creek have drainage areas of 17.9 and 4.3 km^2, respectively. More details on the watershed are contained in Binger (1998).

The two sites chosen on the Toutle River are located in the Sierra Cascade Mountains physiographic province (Raisz, 1957) in southwestern Washington. Precipitation in the area of Mount St. Helens ranges from 1,140 mm/yr near the Columbia River to 3,200 mm/yr on the upper slopes of Mount St. Helens. About 75% of the annual precipitation occurs between October and March, with most flood peaks between November and February. Snowfall accumulation ranges from 0.5 m in the lowlands to 15 m at elevations above 1,500 m (Simon, 1999). Before the 1980 eruption of Mount St. Helens, the Toutle River was characterized by dense coniferous forests dominated by Douglas fir and Western hemlock that was intensively logged prior to the eruption. About 50% of the drainage basin was harvested between 1930 and 1980. Because of logging activities, there was an extensive network of unimproved roads throughout the basin. Abundant fish populations and pristine lakes made the basin a popular recreation area. Pre-eruption stream gradients of the main stem of the Toutle were about 0.009 with well developed pool-riffle sequences. Width to depth ratios of the channels were from 60 to 100 and bed material was mostly gravel and cobbles.

The physical setting of the Toutle River Basin was drastically altered by the May 18, 1980 eruption of Mount St. Helens. Debris avalanches, lahars, and blast ashfalls rendered much of the basin topography unrecognizable after the eruption. Stream gradients along the upper North Fork Toutle River were steepened by the emplacement of a massive debris avalanche and decreased along the Toutle River main stem through large amounts of deposition from mudflows. The bed material changed from predominantly coarse gravel to fine sand at the two sites. A permanent sediment retention structure was constructed upstream of the study sites and began trapping sediment in November 1987 (Simon, 1999). The drainage areas of the two sites chosen for this study are 735 km^2 for the North Fork Toutle River at Kid Valley, and 1,326 km^2 for Toutle River at Tower Road, near Silver Lake.

Channel Classification

To define the “reference” condition and to classify each of the four sites by stream type the field procedures outlined by Rosgen (1996) were conducted. The first part of the procedure was to select representative reaches at each of the study sites by measuring the reach length and approximating the percentage of the reach represented by pools or riffles. Ten locations along the reaches were selected for the collection of morphologic and particle-count data. Surveyed cross-sections at each site yielded information on width/depth ratios, valley width, and bankfull depth. At the two sites from Goodwin Creek (stations 2 and 5) three cross-sections were measured, while high water conditions at the Toutle River sites permitted only one cross section to be surveyed at each site. A representative cross-section for each site is shown in Figures 3 - 6. Bankfull levels were required to evaluate the Rosgen-Troendle technique because the bankfull discharge is used as a scaling factor for flow and sediment-transport rates. However, the bankfull discharge, originally defined as that elevation at which the flow begins to spread out across the active floodplain surface, can often be approximated by the flow that occurs, on average, about every 1 to 2 years. Various authors have also shown that the "effective discharge" (that flow or range of flows that transports the most sediment over the long term) can be approximated by the bankfull discharge or the 1 to 2-year recurrence interval flow (Andrews and Nankervis 1995). Bankfull depths in the field were identified as the lowermost limit of permanent woody vegetation. Bankfull depths were converted to flow discharge using data from adjacent gauging stations and were found to be within the one- to two-year return interval event at all four sites. These bankfull discharges were used for the 4 sites. Sinuosity and channel gradient were determined by surveying the thalweg at each site. A channel stability evaluation was conducted at each of the sites (Table 5) using the method of Pfankuch (1978).

Particle-count data at 100 positions at each of the sites yielded information on the size of the bed and bank material sediment. These data were collected using two different methods. The Rosgen (1996) method of particle counting for the purpose of classification instructs the collector to start at the bankfull elevation along one bank and to measure particles at fixed intervals down the bank, across the channel bottom and up the opposite bank. This method has the conceptual flaw of defining average or median particle-size (d_{50}) statistics based on potentially two distinct sample populations: the bed and the banks. For example, a channel with silt/clay banks and a gravel bed may have an identical d_{50} to a channel composed completely of sand. For this reason particle-count data was also collected and analyzed separately for the bed and the banks as individual populations. The median grain sizes for the four sites of this study are shown in Table 6. The size class of the boundary material changed for three of the four sites of this study (Table 6). It is clear that the mean size of the boundary material and thus the class in the Rosgen classification varies according to how the boundary sediment material is sampled.

Sediment-Rating Curves

The existence of comprehensive sediment-sampling programs at the sites permitted reliable total sediment-load relations to be derived. This type of data treatment of the total sediment load is important as designated uses of streams may be impacted by a disruption in the transport of fine or coarser sediment sizes. Instantaneous flow and sediment-transport data were used to develop sediment-transport ratings (Glysson, 1987). The erosion and transport of fine (<0.062 mm) sediment results from a series of processes best represented by using a watershed model (e.g. AGNPS 98; Bingner and Theurer, 2001). Due to the time constraints, limited budget and scope of this project, watershed models were not used for this purpose.

The sediment data from Goodwin Creek station 2 is composed of a series of fine, sand and gravel sediment samples. Three techniques were used to sample the total load because of the different processes involved in transport and different problems of sampling the three sizes. An example set of transport data is shown in Figure 7 for sand transport at station 2. Most of the variability shown in Figure 7 is not measurement error, but results from the variable nature of sediment transport with a given flow (Kuhnle and Southard, 1988; Kuhnle et al., 1989a, Kuhnle, 1996). Another source of variation in the data is the presence of hysteresis loops associated with the passage of the hydrograph (Glysson, 1987; Kuhnle, 1992). All of the data from the three sample types were used to derive a least squares relation between sediment concentration and flow discharge, however, at station 5, only two types of samples were collected because of the small amounts of gravel in the bed upstream of station 5.

Instantaneous flow and sediment-transport data from the Toutle River at Kid Valley and Tower Road were also obtained. The Toutle River watershed was chosen for this study because it is a unique system that was rendered very unstable after the eruption of Mount Saint Helens in 1980. A wealth of sediment-transport data was collected in the Toutle River watershed to document the effect of the disturbance on sediment transport and the return to stable conditions. Total sediment loads for the Toutle River sites were calculated using relations between suspended fines and sand to flow rate, coupled with a relation derived from a number of bed load samples that predicted the percentage of bed load to the total sediment load.

Dimensionless Rating Curves

To compare sediment data from streams and rivers of different sizes, the Rosgen-Troendle technique recommended making both axes of the sediment-rating curves dimensionless. The sediment-transport rating curves were made dimensionless by dividing the flow discharge by the bankfull discharge and the sediment-concentration values by the concentration predicted at bankfull discharge (see Fig. 13). The use of dimensionless groups was designed to scale the rating curves to allow comparisons of systems with different sizes.

RESULTS

Available Data Sets

To the extent possible with available time and funding, the location, land use, physiographic province (Raisz, 1957), available data types, and time period over which the data was collected was compiled (Table 7). A total of 108 sites in 11 states from 9 physiograhic provinces were located that could be used to test techniques for establishing clean-sediment TMDL's (Fig. 8).

Test of Rosgen-Troendle Technique and Alternatives for Determining Departure

The first step in evaluating the Rosgen-Troendle technique is to classify each of the stream reaches according to the Rosgen (1996) scheme. This was accomplished using the field methods outlined previously. The data listed in Table 8 shows how field data was used to systematically classify the reaches by working through the classification system and eliminating possible choices to arrive at a single stream type for each reach. Three of the channels classified as "F" with the other (Goodwin Creek station 5) classifying as an E (Table 8). With regard to the Pfankuch (1978) stability rating, three sites were rated as "good" with the fourth rated as "poor".

Sediment-Transport Relations

Total load at Goodwin Creek station 2 was calculated for the range of measured flows by summing the calculated values for fines, sand, and gravel for each of a series of flows (Kuhnle et al., 1989b). A similar procedure was followed for station 5. Total sediment concentration versus discharge is shown for stations 2 and 5 in Figures 9 and 10, respectively. The sediment rating curves for total sediment concentration for the Toutle River System sites at Kid Valley and Tower Road are shown in Figure 11. For comparison purposes sediment rating curves for all four sites are shown in Figure 12.

The total sediment-transport rating curves (Figs. 9-12) do not show any data points because they were calculated from sediment transport relations derived from independent sets of transport samples for the different size fractions. Although all four total sediment-transport relations were derived from sediment transport samples, no comprehensive set of total sediment load samples exists for the sites on Goodwin Creek and the Toutle River. Scatter around the curves in Figures 9-12 would be expected to be of the same order as shown in Figure 7.

Relations between dimensionless groups for total sediment load at the four sites are shown in Figure 13. Note that the method used to make the data dimensionless requires that all best-fit lines pass through the point 1:1. The slope of the sediment rating curves in the dimensionless plots is unchanged from the dimensional plots, however, all of the relations must pass through the point 1:1. A slightly different form of scaling was also suggested by Troendle (2000, written communication) which only divides the discharge by the bankfull value. This semi-dimensionless technique was applied to the rating curves for the four study sites and is shown in Figure 14.

It was found in this study that the dimensionless transformation of both flow and sediment variables has the effect to mask differences in rating curves which have slopes of similar value, but different elevations. This aspect was explored using sediment rating curve data from Goodwin Creek station 2 and the Toutle River at Kid Valley. Rating curves for fines for Goodwin Creek station 2 and Toutle River at Kid Valley show significant departures (Zar, 1984) due to the elevation difference of the relations between 1981 and 1982, and between 1987 and 1988 (Fig. 15). The two rating curves when made dimensionless, however, nearly overlie one another and do not show significant differences (Fig. 16a,b). The presence of departure for sediment rating curves that have significant differences in their slopes (Fig. 17a-d) was found to not be obscured in the dimensionless plots.

Summary of Evaluation of Rosgen-Troendle Technique

The number of sites in this study was too small to serve as a definitive test of the Rosgen-Troendle hypothesis that each Rosgen stream type represents a unique reference condition. There are compelling reasons, however, to reject this hypothesis because the Rosgen classification depends primarily on variables that are related to form rather than the processes involved in sediment transport, and the classification contains several unstable stream types (see above).

Sediment transport data from the four sites indicates that the scaling technique used by the Rosgen-Troendle technique is flawed and we do not advocate its use. Differences in transport rates at the bankfull discharge are obscured by this technique. Figures 15, 16, and 17 indicate that when both axes are made dimensionless, differences in elevation between significantly different rating curves with similar slopes are hidden. This was shown with examples from the Toutle River and Goodwin Creek. A similar observation about the obscuring effect of a relation between dimensionless flow and sediment transport rate was made by Troendle (2000, written communication). The technique of making only the discharge dimensionless appears to be a better alternative for the comparison of rating curves from streams of different size.

ALTERNATIVE METHODS FOR DETECTING REFERENCE CONDITIONS, DEPARTURE AND IMPAIRMENT

The foundation for the alternative scheme for detecting reference conditions, departure, and ultimately, impairment due to sediment is based on comparing physical, biological, and sediment-transport relations for stage I and VI "reference" channels with stage III, IV, and V "disturbed" channels. The procedure operates under the assumption that clean sediment can impact designated uses, particularly ecological health via two principle mechanisms. Firstly, very high concentrations of suspended sediment can be toxic to fish. Secondly, frequent high rates of bed-material transport or conversely bed-material deposition can adversely effect benthic macro-inverterbrates by destroying their habitat.

Components of an alternative to the Rosgen-Troendle technique can be accomplished as follows: 1) Classify the stream according to Rosgen (1996); 2) Determine the stage of channel evolution (Simon and Hupp, 1986; Simon, 1989b) and rank the relative degree of channel instability using a channel-stability index (Table 3; Simon and Downs, 1995); 3) Determine index of biologic integrity or other means of evaluating ecologic health; 4) Develop sediment-transport versus discharge (ratings) and magnitude-duration relations for sediment transport and excess shear stress; and 5) Compare slope of sediment-transport rating, total sediment load at the effective (1.5 year) discharge and sediment magnitude-duration relations, with physical and biologic indices to determine possible "departure" from the reference condition and impairment to the designated use of the waterbody.

Although the individual tasks that are recommended above have been used in a variety of settings across the United States, the entire process has been tested at a limited number of sites and under a limited range of environmental and physiographic settings. The Rosgen scheme has been used nationwide with varying degrees of success to classify streams. The original channel-stability index (Simon and Downs, 1995) and variants (Table 3), including identification of stage of channel evolution has been used at tens of thousands of sites nationwide, particularly by the U.S. Geological Survey in evaluating channel-stability conditions in the vicinity of bridges (e.g. Bryan et al., 1995; Fischer, 1995). A sample data-collection form to be used to rapidly (1 to 2 hours) evaluate stream conditions and provide the input data for the channel-stability index (Table 3) is shown in Table 9. Similar forms were used and were applicable across the United States in bridge-scour studies (Simon and Downs, 1995). Indices of biologic integrity are beyond the scope of this report but are commonly used to evaluate ecological health (Barbour et al., 1999). With regard to relating biologic communities to channel conditions and stage of channel evolution, Knight et al. (1997; and written communication) have shown that populations of fish species vary with stage of channel evolution in the loess hills of Mississippi. Sediment-transport ratings are a standard technique to evaluate sediment loadings in waterbodies with varying discharge (Glysson 1987).

Sediment-transport relations represent the "average" amount of sediment transported for given flow discharges, with greater amounts of sediment transport generally corresponding to higher discharges. For a given flow discharge, however, one can envision that a disturbed, unstable stream will transport more sediment than a stable stream at that same discharge due to a greater supply of fine sediment. Another possibility is that the impacted channel will have a greater flow strength than a non-impacted one for comparable flows because of a greater slope from channel straightening, or because of higher flow rates for a given rainfall due to land use changes. Thus, sediment-transport relations from stages representing disturbance and adjustment processes (particularly stages III, IV and V) would show greater sediment-transport rates than the more stable conditions represented by stages I and VI. Previous work has found that (1) sediment-transport relations for West Tennessee streams in stages III and IV had much higher slopes when compared with undisturbed or re-stabilized streams, and (2) that the slopes of these transport relations could be categorized by stage of channel evolution (Simon, 1989a). This pattern was also supported by the data collected at the four sites in this study (Table 10). The differences in transport ratings by stage of channel evolution are shown graphically in Figure 18 and points to stage IV conditions where both the bed and banks are eroding and producing the most sediment. It is more likely that suspended-sediment concentrations may impact fish and other organisms sensitive to wash load during this stage. Similarly, rates of bed-material transport are maximized during stage III where the dominant fluvial process is downcutting (Simon, 1989a; Figure 19) and the streambed is frequently in motion. Consequently, stage III may represent a critical condition for benthic macroinverterbrate populations because of poor substrate conditions.

Conversely, sediment-transport relations for stage I and VI stream reaches represent two different types of "reference" stable conditions and can be used as such. Stage I conditions represent a "pre-disturbed" or completely "natural" reference stream such as in the mid-western United States prior to land clearing and agricultural development in the middle of the 19th century. As one might expect, transport relations from stage I streams have the lowest slopes, indicating that they produce and transport less sediment for a given amount of water than a disturbed stream or watershed (Simon, 1989a). Stage VI conditions, however, represent re-stabilized "reference" stream reaches under the present set of land use and rainfall-runoff conditions. Streams and reaches in stage VI probably represent a more realistic "reference" condition for which to target rehabilitation of a disturbed stream.

With the bankfull flow often representing the "effective discharge" (one that transports the most sediment over the long term), the sediment rating curves should also be compared to each other at the sediment concentration predicted for the bankfull flow. The slopes of the sediment relations and the sediment concentration at bankfull flow for the four sites of this study are consistent with their stage of channel evolution. That is, Tower Road and Kid Valley (both stage IV) have higher slopes and greater sediment concentrations at the bankfull discharge than the two sites from Goodwin Creek, which were both stage V's (Fig. 14).

The hypothesis that stages III and IV will show significantly higher sediment concentrations for a given flow than the stable stage I or VI "reference" streams offers an alternative means of detecting departure. Of course this needs to be verified for streams in other physiographic provinces and climatic regions of the country.

Verification of Suggested Procedure

Our recommended procedure for the verification of the five-part procedure outlined above would be as follows. First streams with sediment and flow data from the main physiographic divisions of the country would be identified. Next a field visit to each site would be made to classify the stream reach according to Rosgen (1996) for use as a communications tool regarding stream form, and to determine the index of channel instability, including stage of channel evolution (Simon and Hupp, 1986; Simon, 1989b). Within this group of streams from a specific physiographic province, it is important that there be a range of stages of channel evolution so that the "reference" (either stage I or stage VI) and disturbed conditions can be identified and evaluated. The frequency and duration of sediment transport will be calculated from available flow and sediment transport data. Ultimately, the physical characteristics of the stream represented by the channel-stability index and the stage of channel evolution would be related to the sediment concentration at the bankfull depth (1 to 2 year flow) and to the slope of the sediment transport (mg/l) versus flow discharge (Q) relation and compared to biological indices. With the inclusion of data from the main physiographic provinces of the country, the robustness of this hypothesis could be established in a definitive manner.

The Missing Link: Departure versus Designated Use

The determination that a given stream has a significantly different rate of sediment transport than a corresponding stable reference stream is one facet of the clean-sediment TMDL problem. Another distinct problem is determining the link between sediment change and a measurable impairment to the designated use of the waterbody. When aquatic life is the designated or existing use of a stream, the link between changes in sediment and a measurable impairment to the biota needs to be established. Most often impacts are assumed to be from excess sediment, however, in some instances too little suspended sediment may adversely affect the biota. With only a few exceptions, such as salmonid fish, very little information is available as to the levels of sediment that are harmful (toxic) to stream biota. We envision toxicity to sediment as some combination(s) of concentration levels and the frequency and duration of those levels.

To make the comparison between sediment and biological impairment, information on the concentration of suspended sediment as well as on the duration and frequency of a given sediment concentration would, therefore, be required. Similar types of information are also required for the movement of bed material (substrate). Methods to calculate suspended-sediment concentration, duration, and frequency of sediment movement using flow and sediment sampling data have been developed. The sediment and flow data from Goodwin Creek station 2 are used as a test case for these sediment parameters. The fraction of time that the suspended-sediment concentration in the water column is equal to or above a given value has been calculated for Goodwin Creek station 2 (Fig. 20). Organisms may be able to survive a given concentration of sediment for a limited time without negative effects, however, at greater durations, toxic conditions may occur. One way to address this question is by expressing sediment concentration in terms of its expected duration for a given recurrence interval flow. In this case the concentration (4118 mg/l) at a return interval of 1.1 years (bankfull flow) was used (Fig. 21). When this concentration represents some kind of toxicity threshold if maintained for a specified duration, this type of graph could be used to determine the maximum allowable concentration for a clean-sediment TMDL.

Potentially detrimental changes to the substrate (bed) of a stream include excessive erosion, deposition, and changes in grain sizes. Mobilization of the substrate can be considered from information on the frequency and duration of bed sediment movement. This was accomplished by calculating a relative boundary shear stress (ratio of average boundary shear stress to critical shear stress for motion of the bed material) where a value > 1.0 indicates mobilization of the streambed (Fig. 22). A similar relation for the expected duration of a shear stress greater than the specified value (in this case 27 Pa) is shown in Figure 23. The value of 27 Pa corresponds to the shear stress at which all sizes of the bed material are in motion (Kuhnle and Willis, 1992). The establishment of the ranges and durations of bed movement the biota can tolerate without impairment would make plots like Figures 22 and 23 useful to determine whether movement of the substrate were within allowable limits for a given stream.

In a related project at the NSL, an initial inquiry into the effect of sediment on the biota in streams and rivers has been initiated. The study will combine sediment data and biological indicators and seek to find correlations between the two. The link between stage of channel evolution (Simon and Hupp, 1986; Simon, 1989b) and sediment transport will also be further refined. This study will initially concentrate on twelve sites in the Demonstration Erosion Control Watersheds (DEC) in northern Mississippi that have good historical data bases of flow, sediment transport, and biological indicators. Geomorphic assessments of these twelve sites will be added to the data base along with the index of channel stability, which is based on diagnostic physical characteristics of the channel (Table 3). The links among the geomorphic, sediment and biological data will be derived for these 12 DEC sites. The information on the fraction of time, duration, and recurrence interval, of sediment concentration and bed shear stress will be combined with biological data collected by cooperating biological scientists at the National Sedimentation Laboratory. The link between the degree of impairment of the biota and the frequency and duration of the sediment concentration or mobilization will be made for streams in the northern part of Mississippi. The type of information in Figures 20 - 23 will be used at Goodwin Creek and the other DEC sites along with laboratory flume experiments of sediment toxicity to determine the ranges of shear stress and/or suspended sediment concentration that will adversely affect the biota. This will be the first study to our knowledge where these links have been explored in warm-water coastal plain streams. Similar studies are needed for other physiographic provinces of the nation.

Conclusions

A search for data sets was conducted from non-U.S. Geological Survey sources. This search yielded 108 sites on streams in the United States with detailed sediment and flow data. The data from these streams was from eleven different states and nine different physiographic provinces of the country and would serve as a valuable resource for further development of the procedure to detect impairment due to clean sediment.

The proposed Rosgen-Troendle technique for evaluating excess sediment in streams was tested and found to have problems. Based on the knowledge learned in this evaluation, a revised methodology was proposed which can be summarized as follows: 1) Classify the stream according to Rosgen (1996); 2) Determine the stage of channel evolution (Simon and Hupp, 1986; Simon, 1989b) and rank the relative degree of channel instability using a channel-stability index (Simon and Downs, 1995); 3) Determine index of biologic integrity or other means of evaluating ecologic health; 4) Develop sediment-transport versus discharge (ratings) and magnitude-duration relations for sediment transport and excess shear stress; and 5) Compare slope of sediment-transport rating, total sediment load at the effective discharge, with physical and biologic indices to determine possible “departure” from the reference condition and impairment to the designated use of the waterbody.

The methodology developed by this study needs to be tested and verified in a wider range of physiographic provinces on streams with a comprehensive record of flow and sediment transport. The proposed methodology should be applicable over a broad range of environmental settings and spatial scales because the diagnostic criteria obtained through channel evaluations are used as measures of dominant channel processes and how these processes relate to the production and transport of sediment. Stage of channel evolution has similarly been used successfully to identify the systematic adjustment of stream channels in areas ranging from the southeastern Coastal Plain to the Cascade Mountains. Differences in transport ratings as well as magnitude and duration relations for sediment transport reflect differences in the balance between driving and resisting forces which are evaluated in a general way by the procedure outlined above. The stage of channel evolution needs to be related to the sediment transport at bankfull flow and the slope of the sediment transport relation. The ultimate goal of this testing is to allow the stage of channel evolution to predict reliably the likelihood that a stream is impaired for clean sediment. Another area of research that needs to be studied further is the link between the amount of excess sediment and its effect on the designated use of the waterbody. A preliminary study is underway at the NSL to investigate the effect of the magnitude, frequency, and duration of sediment transport on the biota of streams and rivers.

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Fig. 23. - Duration of bed shear stress at or above 27 Pa for a given recurrence interval at Goodwin Creek station 2. The shear stress of 27 Pa is the flow strength at which all sizes of the bed material are completely in motion. Flows above this strength would be disruptive of the substrate environment of the stream.

Table 1. Stages of Channel Evolution (Simon, 1989a)

Stage		Dominant processes			
Number	Name	Fluvial	Hillslope	Characteristic forms	Geobotanical evidence
I	Premodified	Sediment transport; mild aggradation; basal erosion on outside bends; deposition on inside bends.	--	Stable, alternate channel bars; convex top-bank shape; flow line high relative to top bank; channel straight or meandering.	Vegetated banks to low-flow line.
II	Constructed	--	--	Trapezoidal cross section; linear bank surfaces; flow line lower relative to top bank.	Removal of vegetation (?).
III	Degradation	Degradation; basal erosion on banks.	Pop-out failures.	Heightening and steepening of banks; alternate bars eroded; flow line lower relative to top bank.	Riparian vegetation high relative to flow line and may lean towards channel.
IV	Threshold	Degradation; basal erosion on banks.	Slab, rotational and pop-out failures.	Large scallops and bank retreat; vertical-face and upper bank surfaces; failure blocks on upper bank; some reduction in bank angles; flow line very low relative to top bank.	Tilted and fallen riparian vegetation.
V	Aggradation	Aggradation; development of meandering thalweg; initial deposition of alternate bars; reworking of failed material on lower banks.	Slab, rotational and pop-out failures; low-angle slides of previously failed material.	Large scallops, bank retreat; vertical face, upper bank and slough line; flattening of bank angles; flow line low relative to top bank; development of new flood plain (?).	Tilted and fallen riparian vegetation; re-establishing vegetation on slough line; deposition of material above root collars of slough-line vegetation.
VI	Restabilization	Aggradation; further development of meandering thalweg; further deposition of alternate bars; reworking of failed material; some basal erosion on outside bends; deposition of flood plain and bank surfaces.	Low-angle slides; some pop-out failures near flow line.	Stable, alternate bars; convex short vertical face on top bank; flatten- of bank angles; development of new flood plain (?); flow line higher relative to top bank.	Re-establishing vegetation extends up slough line and upper bank; deposition of material above root collars of slough-line and upper-bank vegetation; vegetation establishing on bars.

Table 2. Criteria used by Pfankuch(1978): Channel Stability Evaluation (from Rosgen, 1996; Table 6-7).

CHANNEL STABILITY (PFANKUCH) EVALUATION AND STREAM CLASSIFICATION SUMMARY (LEVEL III)

Reach Location____________________ Date__________ Observers________________

Stream Type ____

		Category	EXCELLENT	
UPPER BANKS	1	Landform Slope	Bank Slope Gradient <30%	2
	2	Mass Wasting	No evidence of past or future mass wasting.	3
	3	Debris Jam Potential	Essentially absent from immediate channel area.	2
	4	Vegetative Bank Protection	90%+ plant density. Vigor and variety suggest a deep dense soil binding root mass.	3
LOWER BANKS	5	Channel Capacity	Ample for present plus some increases. Peak flows contained. W/D ratio <7.	1
	6	Bank Rock Content	65%+ with large angular boulders. 12"+ common.	2
	7	Obstructions to Flow	Rocks and logs firmly imbedded. Flow pattern without cutting or deposition. Stable bed.	2
	8	Cutting	Little or none. Infreq. raw banks less than 6".	4
	9	Deposition	Little or no enlargement of channel or pt. bars.	4
BOTTOM	10	Rock Angularity	Sharp edges and corners. Plane surfaces rough.	1
	11	Brightness	Surfaces dull, dark or stained. Gen. not bright.	1
	12	Consolidation of Particles	Assorted sizes tightly packed or overlapping.	2
	13	Bottom Size Distribution	No size change evident. Stable mater. 80-100%	4
	14	Scouring and Deposition	<5% of bottom affected by scour or deposition.	6
	15	Aquatic Vegetation	Abundant Growth moss-like, dark green perennial. In swift water too.	1
			TOTAL	☐

		Category	GOOD	
UPPER BANKS	1	Landform Slope	Bank Slope Gradient 30-40%	4
	2	Mass Wasting	Infrequent. Mostly healed over. Low future potential.	6
	3	Debris Jam Potential	Present, but mostly small twigs and limbs.	4
	4	Vegetative Bank Protection	70-90% density. Fewer species or less vigor suggest less dense or deep root mass.	6
LOWER BANKS	5	Channel Capacity	Adequate. Bank overflows rare. W/D ratio 8-15	2
	6	Bank Rock Content	40-65%. Mostly small boulders to cobbles 6-12"	4
	7	Obstructions to Flow	Some present causing erosive cross currents and minor pool. filling. Obstructions newer and less firm.	4
	8	Cutting	Some, intermittently at outcurves and constrictions. Raw banks may be up to 12"	6
	9	Deposition	Some new bar increase, mostly from coarse gravel.	8
BOTTOM	10	Rock Angularity	Rounded corners and edges, surfaces smooth, flat.	2
	11	Brightness	Mostly dull, but may have <35% bright surfaces.	2
	12	Consolidation of Particles	Moderately packed with some overlapping.	4
	13	Bottom Size Distribution	Distribution shift light. Stable material 50-80%.	8
	14	Scouring and Deposition	5-30% affected. Scour at constrictions and where grades steepen. Some deposition in pools.	12
	15	Aquatic Vegetation	Common. Algae forms in low velocity and pool areas. Moss here too.	2
			TOTAL	☐

		Category	FAIR	
UPPER BANKS	1	Landform Slope	Bank slope gradient 40-60%	6
	2	Mass Wasting	Frequent or large, causing sediment nearly year long.	9
	3	Debris Jam Potential	Moderate to heavy amounts, mostly larger sizes.	6
	4	Vegetative Bank Protection	<50-70% density. Lower vigor and fewer species from a shallow, discontinuous root mass.	9
LOWER BANKS	5	Channel Capacity	Barely contains present peaks. Occasional overbank floods. W/D ratio 15 to 25.	3
	6	Bank Rock Content	20-40% with most in the 3-6" diameter class.	6
	7	Obstructions to Flow	Moder. frequent, unstable obstructions move with high flows causing bank cutting and pool filling.	6
	8	Cutting	Significant. Cuts 12-24" high. Root mat overhangs and sloughing evident	12
	9	Deposition	Moder. deposition of new gravel and course sand on old and some new bars.	12
BOTTOM	10	Rock Angularity	Corners and edges well rounded in two dimensions.	3
	11	Brightness	Mixture dull and bright, ie 35-65% mixture range.	3
	12	Consolidation of Particles	Mostly loose assortment with no apparent overlap.	6
	13	Bottom Size Distribution	Moder. change in sizes. Stable materials 20-50%	12
	14	Scouring and Deposition	30-50% affected. Deposits & scour at obstructions, constrictions, and bends. Some filling of pools.	18
	15	Aquatic Vegetation	Present but spotty, mostly in backwater. Seasonal algae growth makes rocks slick.	3
			TOTAL	☐

		Category	POOR	
UPPER BANKS	1	Landform Slope	Bank Slope Gradient 60%+	8
	2	Mass Wasting	Frequent or large causing sediment nearly year long or imminent danger of same.	12
	3	Debris Jam Potential	Moder. to heavy amounts, predom. larger sizes.	8
	4	Vegetative Bank Protection	<50% density, fewer species and less vigor indicate poor, discontinuous and shallow root mass.	12
LOWER BANKS	5	Channel Capacity	Inadequate. Overbank flows common. W/D ratio >25	4
	6	Bank Rock Content	<20% rock fragments of gravel sizes, 1-3" or less.	8
	7	Obstructions to Flow	Sediment traps full, channel migration occurring.	
	8	Cutting	Almost continuous cuts, some over 24" high. Failure of overhangs frequent.	16
	9	Deposition	Extensive deposits of predom. fine particles. Accelerated bar development.	16
BOTTOM	10	Rock Angularity	Well rounded in all dimensions, surfaces smooth.	4
	11	Brightness	Predom. bright, 65%+ exposed or scoured surfaces.	4
	12	Consolidation of Particles	No packing evident. Loose assortment easily moved.	8
	13	Bottom Size Distribution	Marked distribution change. Stable materials 0-20%.	16
	14	Scouring and Deposition	More than 50% of the bottom in a state of flux or change nearly year long.	24
	15	Aquatic Vegetation	Perennial types scarce or absent. Yellow-green, short term bloom may be present.	4
			TOTAL	☐

Table 3. -CHANNEL-STABILITY RANKING SCHEME

1. Primary bed material

Bedrock	boulder/cobble	gravel	sand	silt/clay
0	1	2	3	4

2. Bed/bank protection

Yes	No	(with)	1 bank	2 banks
			Protected	
0	1		2	3

3. Degree of incision (Relative elev. of "normal" low water; floodplain/terrace @ 100%)

0 – 10%	11 – 25%	26 – 50%	51 – 75%	76 – 100%
4	3	2	1	0

4. Degree of constriction (Relative decrease in top-bank width from up to downstream)

0 – 10%	11 – 25%	26 – 50%	51 – 75%	76 – 100%
0	1	2	3	4

5. Stage of channel evolution

I	II	III	IV	V	VI
0	1	2	4	3	1.5

6. Streambank erosion (Each bank)

	None	fluvial	mass wasting (failures)
Left	0	1	2
Right	0	1	2

7. Streambank instability (Percent of each bank failing)

	0 – 10%	11 – 25%	26 – 50%	51 – 75%	76 – 100%
Left	0	0.5	1	1.5	2
Right	0	0.5	1	1.5	2

8. Established riparian woody-vegetative cover (Each bank)

	0 – 10%	11 – 25%	26 – 50%	51 – 75%	76 – 100%
Left	2	1.5	1	0.5	0
Right	2	1.5	1	0.5	0

9. Occurrence of bank accretion (Percent of each bank with fluvial deposition)

	0 – 10%	11 – 25%	26 – 50%	51 – 75%	76 – 100%
Left	0	0.5	1	1.5	2
Right	0	0.5	1	1.5	2

Table 4. Channel Stability/Biologic Ranking Scheme

CHANNEL STABILITY / BIOLOGIC RANKING SCHEME

1. **Pool-substrate composition**

GP & firm SP	Soft SP & ML-CL	All ML-CL or All SP	Hardpan/Bedrock
4	3	2	1

2. **Active streambed/bar deposition**

0 – 20%	21 – 50%	51 – 80%	81 – 100%
4	3	2	1

3. **Streambed exposure**

0 – 20%	21 – 50%	51 – 80%	81 – 100%
4	3	2	1

4. **Bank instability**

0 – 5%	6 – 30%	31 – 60%	61 – 100%
4	3	2	1

5. **Riparian-zone width**

	> 20 m	10 - 20 m	5 – 10 m	< 5 m
Left	2	1.5	1	0.5
Right	2	1.5	1	0.5

6. **Availability of favorable habitat (snags, submerged logs, undercut banks; average of LWD and detritus)**

> 50%	30 – 50%	10 – 30%	< 10%
4	3	2	1

7. **Sinuosity**

3 – 4	2 – 3	1 – 2	straight
4	3	2	1

8. **Pool-riffle sequence (% Pool + % riffle)**

>80%	51 – 80%	20 – 50%	< 20%
4	3	2	1

9. **Degree of “hard” alteration**

Absent	Minor or Historic	40 – 80% Disrupted	>80 Disrupted
4	3	2	1

Table 5.

Channel Stability (Pfankuch) Evaluation

Stream Type	**Goodwin Creek-2** **F5**	**Goodwin Creek-5** **E6**	**Toutle River at Kid Valley** **F4**	**Toutle River at Tower Road** **F4**
Upper Banks ** Slope Characteristics ** Erosion Potential	24.2	30.8	21.8	27.3
Lower Banks ** Channel Capacity ** Erosion Potential	30	33.7	24.3	28.5
Bottom ** Bed Material Characteristics ** Erosion Potential	42.7	41.7	47.5	37.5
Pfankuch Stability Rating	96.9	106.2	93.6	93.3

Reach Condition Conversion				
Good	90-115	40-63	85-110	85-110
Fair	116-130	64-86	111-125	111-125
Poor	131+	87+	126+	126+

Table 6. Median Grain Size (d_{50}) of Channel Boundary Material

Location	Rosgen d_{50}	n	Class	Bed d_{50}	n	Class	Bank d_{50}	n	Class
Kid Valley	15 mm	170	4	20 mm	99	4	12 mm	71	4
Tower Road	48 mm	200	4	148 mm	102	3	13.5 mm	98	4
Goodwin 2	0.35 mm	103	5	7 mm	30	4	0.031 mm	73	6
Goodwin 5	0.031 mm	106	6	0.35 mm	16	5	0.031 mm	90	6

Table 7. Identified Sites with Flow and Sediment Data.

Name	Location	No. of Sites	Land Use	Physiographic Province	Available Data Types	Years of Record
Oauchita National Forest	AR	1	Timber and Recreation	Ouachita	15-minute Instantaneous	5 yrs (1979-1984)
Ozark National Forest	AR	1	Timber and Recreation	Ozark Plateaus	15-minute Instantaneous	5 yrs (1979-1984)
Walnut Gulch	AZ	4	Rangeland	Basin and Range	15-minute Instantaneous	
Casper Creek	CA	2	Timber and Recreation	Pacific Border	15-minute Instantaneous	33 yrs (1964-1997)
Casper Creek Tributaries	CA	13	Timber and Recreation	Pacific Border	15-minute Instantaneous	33 yrs (1964-1997)
Redwood Creek	CA	1	Timber and Recreation	Pacific Border	15-minute Instantaneous	33 yrs (1964-1997)
Broad River	GA	1	Timber and Recreation	Piedmont	15-minute Instantaneous	
Reynolds Creek	ID	9	Rangeland	Columbia Plateaus	15-minute Instantaneous	35 yrs (1965 - present)
Goodwin Creek #2	MS	1	Forest and Agriculture	Coastal Plain	brk-point Instantaneous	19 yrs (1981-present)
Goodwin Creek #5	MS	1	Forest and Agriculture	Coastal Plain	brk-point Instantaneous	19 yrs (1981-present)
Pigeon Roost Creek	MS	10	Forest and Agriculture	Coastal Plain	brk-point Instantaneous	20 yrs (1957-1976)
Yalobusha River	MS	1	Forest and Agriculture	Coastal Plain	15-minute Instantaneous	2 yrs (1997-1999)
Topashaw Creek	MS	1	Forest and Agriculture	Coastal Plain	15-minute Instantaneous	2 yrs (1997-1999)
Abiaca21-Cr	MS	1	Forest and Agriculture	Coastal Plain	15-minute Instantaneous	5 yrs (1991-1996)
Abiaca6-SP	MS	1	Forest and Agriculture	Coastal Plain	15-minute Instantaneous	4 yrs (1991-1995)
Batupan	MS	1	Forest and Agriculture	Coastal Plain	15-minute Instantaneous	6 yrs (1989-1995)
Hickahala	MS	1	Forest and Agriculture	Coastal Plain	15-minute Instantaneous	8 yrs (1988-1995)
Hotopha	MS	1	Forest and Agriculture	Coastal Plain	15-minute Instantaneous	7 yrs (1989-1996)
Harland	MS	1	Forest and Agriculture	Coastal Plain	15-minute Instantaneous	6 yrs (1989-1995)
Long	MS	1	Forest and Agriculture	Coastal Plain	15-minute Instantaneous	7 yrs (1988-1995)
Otoucalofa	MS	1	Forest and Agriculture	Coastal Plain	15-minute Instantaneous	
Senatobia	MS	1	Forest and Agriculture	Coastal Plain	15-minute Instantaneous	
Fannegusha	MS	1	Forest and Agriculture	Coastal Plain	15-minute Instantaneous	
Niobrara River	NE	1	Rangeland and Agriculture	Great Plains	Instantaneous	6 yrs (1948-1953)
Middle Loup River	NE	1	Rangeland and Agriculture	Great Plains	Instantaneous	5 yrs (1948-1952)
Rio Puerco	NM	1	Rangeland	Basin and Range	15-minute Instantaneous	
Little Washita River	OK	2	Rangeland	Great Plains	15-minute Instantaneous	5 yrs (1979-1984)
Little Washita Tributaries	OK	11	Rangeland	Great Plains	15-minute Instantaneous	5 yrs (1979-1984)
Obion River	TN	11	Agriculture	Coastal Plain	15-minute Instantaneous	
Hatchie River	TN	2	Forest and Agriculture	Coastal Plain	15-minute Instantaneous	
Beaver Creek	TN	1	Forest and Agriculture	Coastal Plain	15-minute Instantaneous	
Wolf River	TN	4	Forest and Agriculture	Coastal Plain	15-minute Instantaneous	
Forked Deer	TN	7	Agriculture	Coastal Plain	15-minute Instantaneous	
Green River	WA	1	Timber and Recreation	Sierra Cascade Mountains	15-minute Instantaneous	10 yrs (1980-1990)
South Fork Toutle	WA	1	Timber and Recreation	Sierra Cascade Mountains	15-minute Instantaneous	10 yrs (1980-1990)
North Fork Toutle	WA	1	Timber and Recreation	Sierra Cascade Mountains	15-minute Instantaneous	10 yrs (1980-1990)
Toutle River at Kid Valley	WA	1	Timber and Recreation	Sierra Cascade Mountains	15-minute Instantaneous	10 yrs (1980-1990)
Toutle River at Tower Road	WA	1	Timber and Recreation	Sierra Cascade Mountains	15-minute Instantaneous	18 yrs (1980-1990)
Puerto Rico		6	Forest and Agriculture		15-minute Instantaneous	
Total Number of Sites		108				

Table 8. Classification of the Four Sites According to Rosgen (1996).

Stream Channel ID	**Entrenchment Ratio**	**Width/Depth Ratio**	**Channel Sinuosity**	**Water Surface Slope**	**Channel Materials**
Kid Valley	1.2	28	1.2	0.002	15 mm
Tower Road	1.3	32	1.2	0.002	48 mm
Goodwin 2	1.3	24	1.3	0.002	0.35 mm
Goodwin 5	4.23	11	1.5	0.005	0.031 mm
Stream Type Selection					
Kid Valley	A,G,F,D,Da	F,B,C,Da	A,G,F,B,C,D		Gravel
Tower Road	A,G,F,D,Da	F,B,C,Da	A,G,F,B,C,D		Gravel
Goodwin 2	A,G,F	F,B,C	G,F,B,C		Sand
Goodwin 5	E,C	A,G,E	G,F,B,C,E		Silt/Sand
Resulting Classification					
Kid Valley	**F4**				
Tower Road	**F4**				
Goodwin 2	**F5**				
Goodwin 5	**E6**				

Entrenchment is the vertical containment of a river and the degree to which it is incised in the valley floor. The entrenchment ratio is the ratio of the width of the flood-prone area to the surface width of the bankfull channel.

The width/depth ratio is the ratio of the bankfull surface width to the mean depth of the bankfull channel.

Channel sinuosity is the ratio of stream length to valley length or as the ratio of valley slope to channel slope.

Table 9a.

RAPID GEOMORPHIC ASSESSMENT STREAM-EVALUATION DATA SHEET

Index Variables:

Date:__________ Agency: __________ Personnel:_____________

Stream:_________________ Station ID #:_____________ River Basin:_______________

General Description:

Flow:__________ Flow Depth:___________ Flow type:___________
(high, medium, low) (@ center, in m) (none, smooth, pool & riffle, run, rapid-tumbling)

Percent Pool: _______; Percent Riffle:_______; Percent Run:_______
(Pool + Riffle + Run = 100%)

Structure:____ Type__________
(Yes, No) (bridge, grade control, bank)

Top-Bank Width: U/S end: _______m mid reach: _______m D/S end: _______m

Floodplain Land Use: Left______/______/______ Right______/______/______
(urban, forest, pasture, row crop/ riparian buffer / width)

High Flow Planform: ____________ Sinuosity:_________
(straight, mildly sinuous, meandering, tortuous, braided)

Low Flow Planform: ____________ Sinuosity:_________
(straight, mildly sinuous, meandering, tortuous, braided)

Bankfull Indicators:__________; __________; __________
(none-incised, active floodplain, berm, woody vegetation, bar tops)

Relative Elevation at Bankfull: __________ Relative Elevation of low water:_____________
(Assume top height = 100%) (Assume top height = 100%, N/A if appropriate)

Bed width: _____m- method: ___ Berm width: _____m- method: ___
(Method: tape=T; rangefinder=R; acoustic device=A; pace=P)

% Detritus:___________ % LWD:____________

Table 9b.

Channel-Bed Description:

Primary bed-material type:_______________Secondary Bed-material type: ___________
(gravel=GP; sand=SP; silt=ML; clay=CL; bedrock=BR)

Bed controls: __________; __________ Active Bed Deposition:____________
(none; bedrock; cohesive materials; armored; structure; rip-rap) (GP-SP, SP, ML, CL)

Pool Substrate:____
(GP with firm SP; Soft SP with ML-CL; All ML-CL or All SP; Hard Pan CL or Rock)

Bed Exposed:__________
(% Area out of water)

Knickpoint present? _____; Height: _______ Material: _____________
(Yes; No) (in m) (GP, SP, ML, CL, BR)

Planform Sketch:

Table 9c.

Bank Description:

Side (L, R); _____; Reach Type (I=inside; O=outside; S= straight) _____; Stage of Evolution _____;
(I, II, III, IV, V, VI)

Percent Failing _____; Percent Bank Accretion (excluding bars) _____

Width of Riparian Zone; _______m Percent Woody Cover; _______ Percent Herbaceous; _______

Surfaces (y, n): VF____; UB____; SL____; DS____; CB____; CS/Bar____;

Height of VF____; Height of CB____;

Surficial Material: VF ___/___; UB___/___; SL___/___; DS___/___; CB___/___; CS/Bar___/___
(Origin / Type) (I=*insitu*; D=deposited; F=failed; CL=clay, ML=silt, SP=sand, GP=gravel)

Type of Accreted Sediment: _____ (N=none, SP=sand, ML=silt, CL=clay);

Dominant Type of Process: VF_____; UB_____; SL_____; DS_____; CB_____; CS/Bar_____;
(N=none-stable, MW=mass wasting, F=fluvial erosion, , S=Sapping, D=deposition, N/A)

Bank Sketch:

Table 9d.

Bank Description:

Side (L, R); _____; Reach Type (I=inside; O=outside; S= straight) _____; Stage of Evolution _____;
Percent Failing _____; Percent Bank Accretion (excluding bars) _____

Width of Riparian Zone; _______ Percent Woody Cover; _______ Percent Herbaceous; _______

Surfaces (y, n): VF____; UB____; SL____; DS____; CB____; CS/Bar____;

Height of VF____; Height of CB____;

Surficial Material: VF ____/____; UB____/____; SL____/____; DS____/____; CB____/____;
(Origin / Type) CS/Bar____/____
(I=*in situ*; D=deposited; F=failed; CL=clay, ML=silt, SP=sand, GP=gravel)

Type of Accreted Sediment: _____ (N=none, SP=sand, ML=silt, CL=clay);

Dominant Type of Process: VF_____; UB_____; SL_____; DS_____; CB_____; CS/Bar_____;
(N=none-stable, MW=mass wasting, F=fluvial erosion, , S=Sapping, D=deposition)

Bank Sketch:

Table 9e.

Photographs: Camera; ___________; Photographer; ___________

No. ______; Subject____

No. ______; Subject____

No. ______; Subject____

No. ______; Subject____

No. ______; Subject____

No. ______; Subject____

No. ______; Subject____

No. ______; Subject____

No. ______; Subject____

No. ______; Subject____

Table 10. Relative Efficiency of Suspended-Sediment Transport as Determined from the Slopes of the Power Functions fit to Sediment Ratings in tons/day and ft^3/s.

Stream	Slope	Stage	Category	Sediment concentration at bankfull flow
Hatchie River (1)	1.00	1	Low	
Hatchie River (2)	1.20	1	Low	
Hatchie River (3)	0.76	1	Low	
Beaver Creek	1.63	6	Moderate	
South Fork Obion	1.75	3	Moderate	
Obion River	1.71	5	Moderate	
N.F. Forked Deer	1.68	5	Moderate	
Mosses Creek	1.58	5	Moderate	
Big Muddy Creek	1.76	5	Moderate	
Wolf River	1.77	5	Moderate	
Goodwin Creek #2	1.76	5	Moderate	4118 mg/l
Goodwin Creek #5	1.47	5	Moderate	2824 mg/l

Table 10 (continued)

North Fork Obion	2.12	4	High	
S.F. Forked Deer (1)	2.36	4	High	
S.F. Forked Deer (2)	2.50	4	High	
Loosahatchie River	2.45	4	High	
Toutle River at Tower Rd.(1987-1990)	2.40	4	High	8242 mg/l
Toutle River at Kid Valley (1987-1990)	2.23	4	High	7190 mg/l

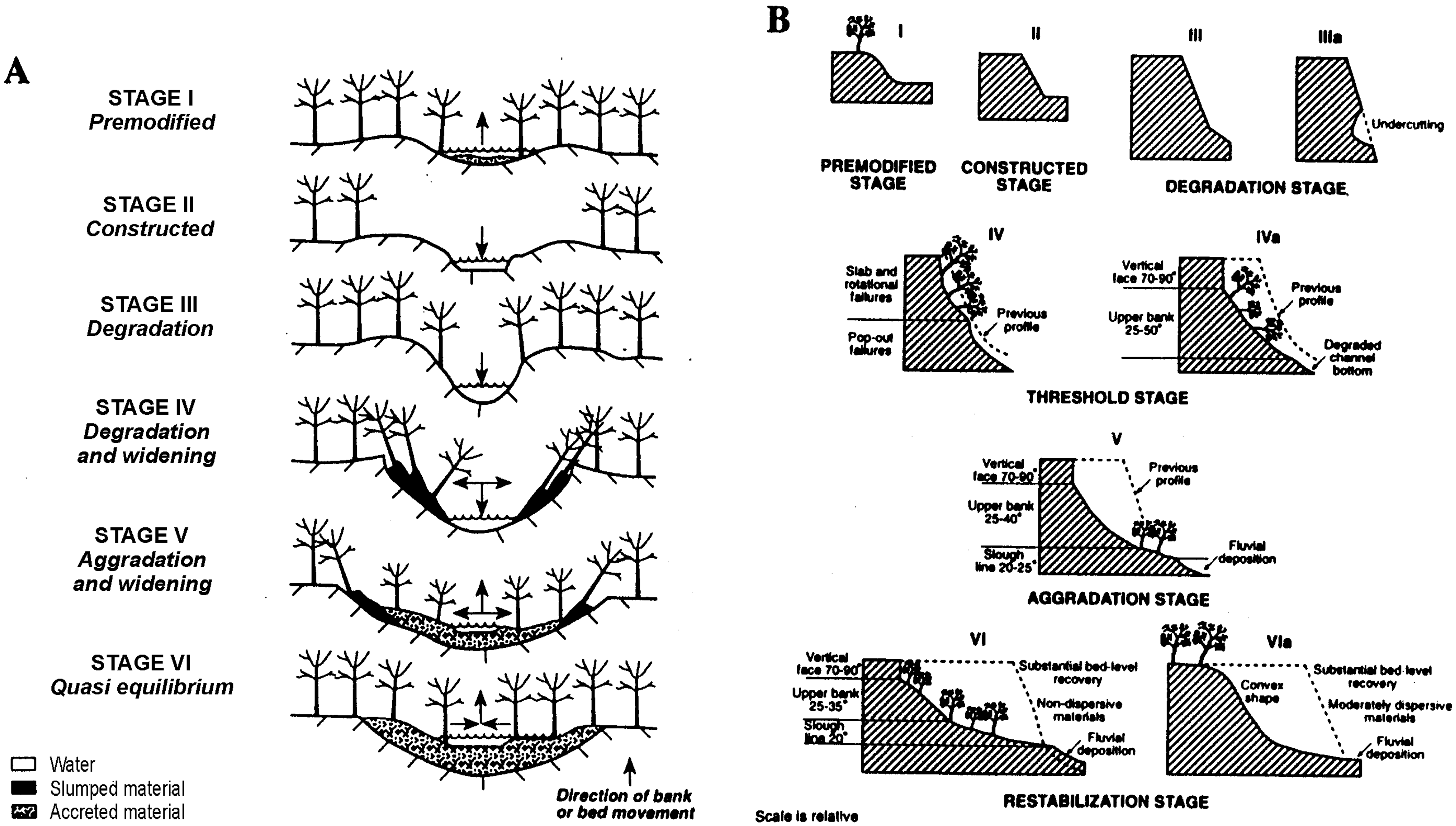


Fig. 1.- Models of (A)channel evolution and (B) bank-slope development for disturbed alluvial channels (Simon and Hupp, 1986).

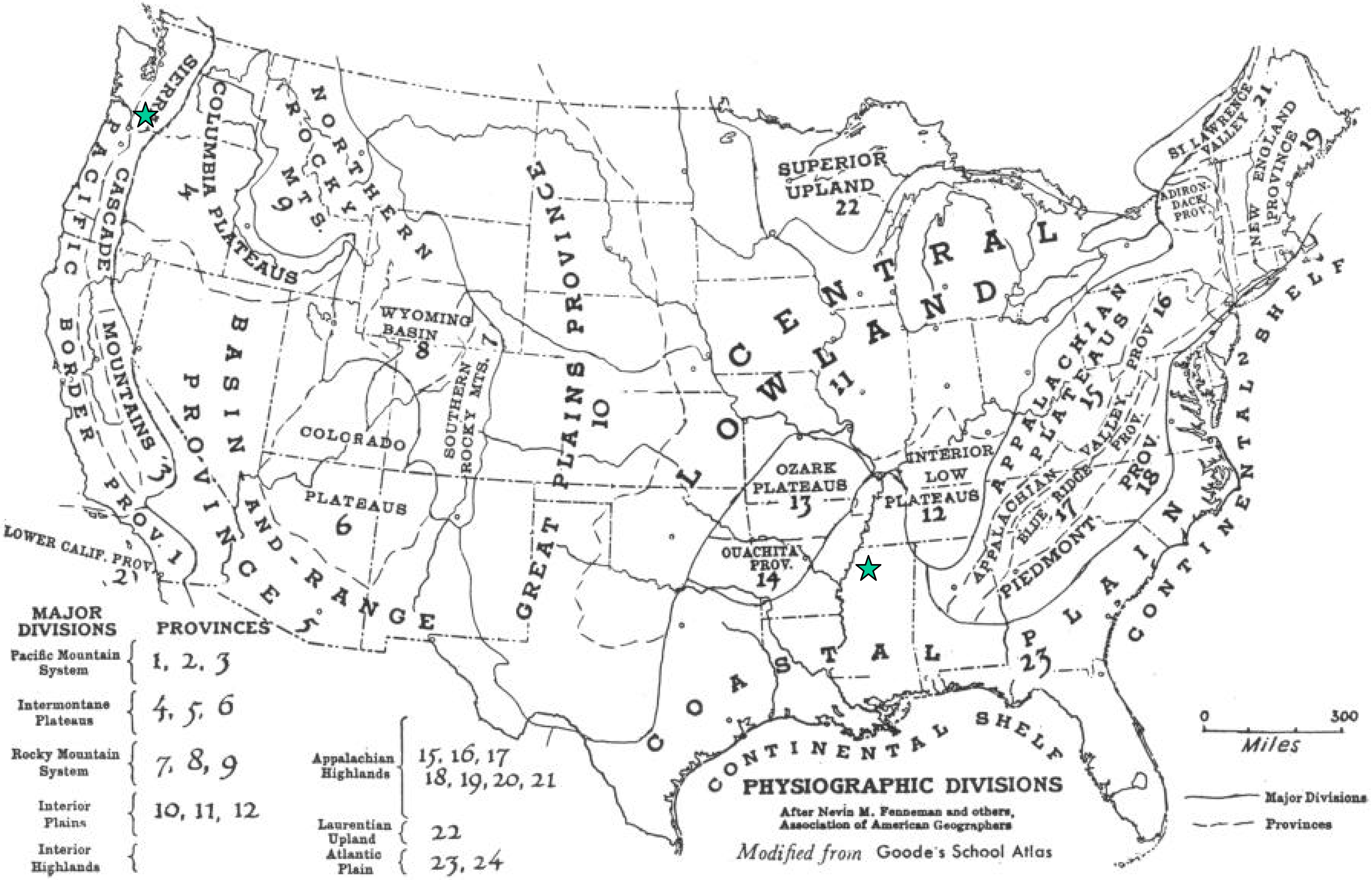


Fig. 2.- Physiographic provinces of the United States (Raize, 1957). Location of study sites shown by colored stars.

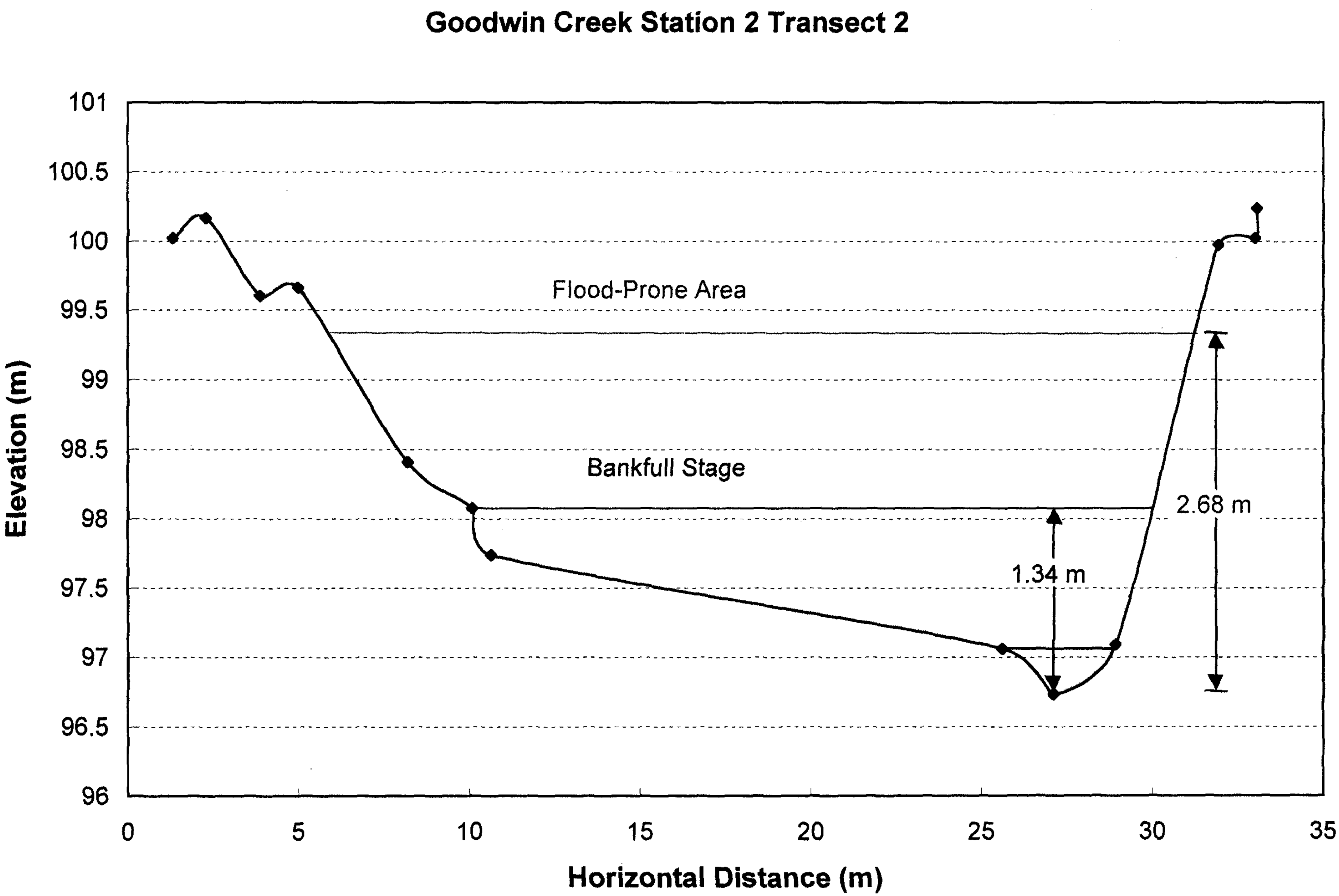


Fig. 3.- Representative cross-section, Goodwin Creek station 2.

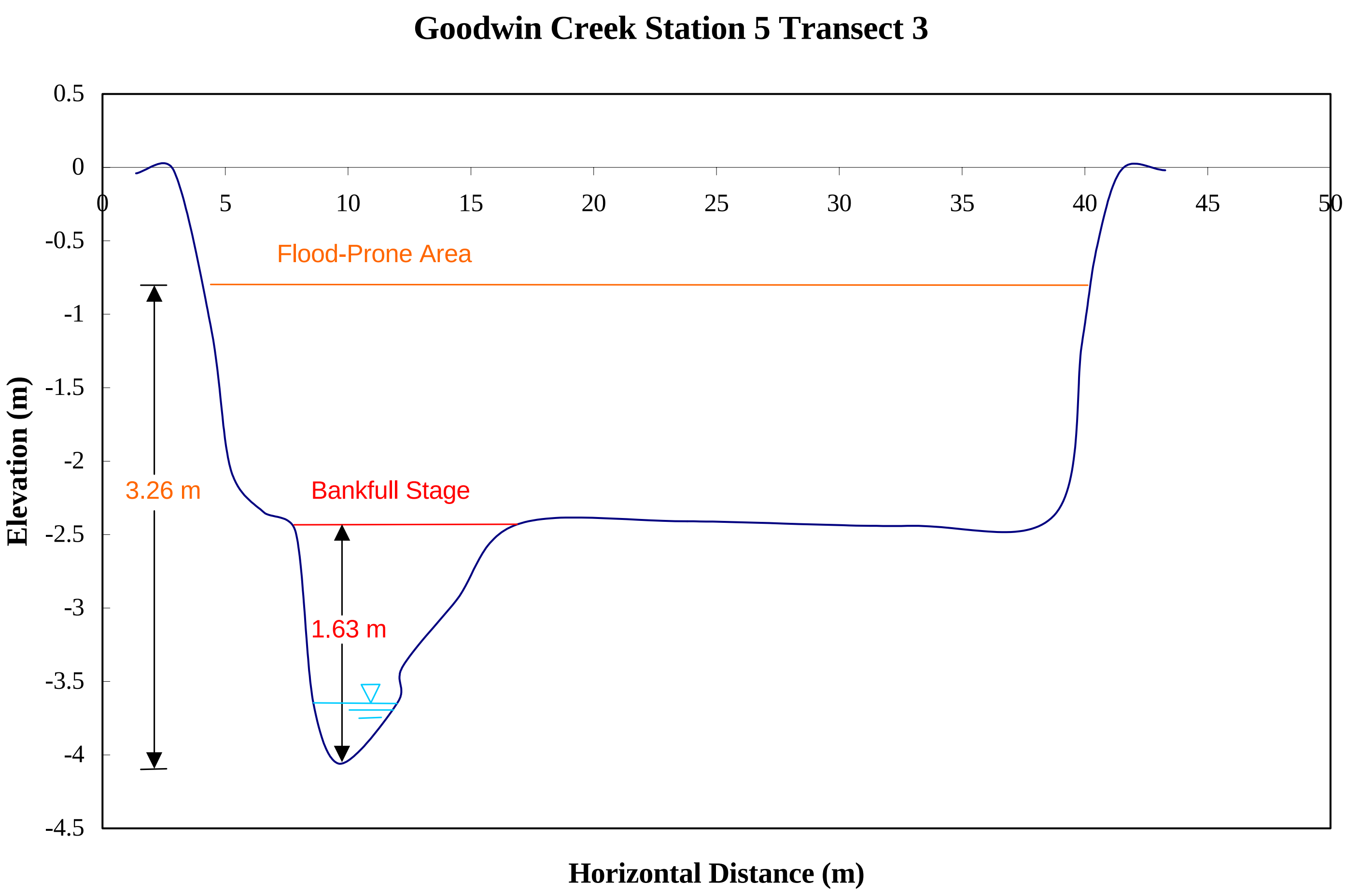


Fig 4.- Representative cross-section for Goodwin Creek station 5.

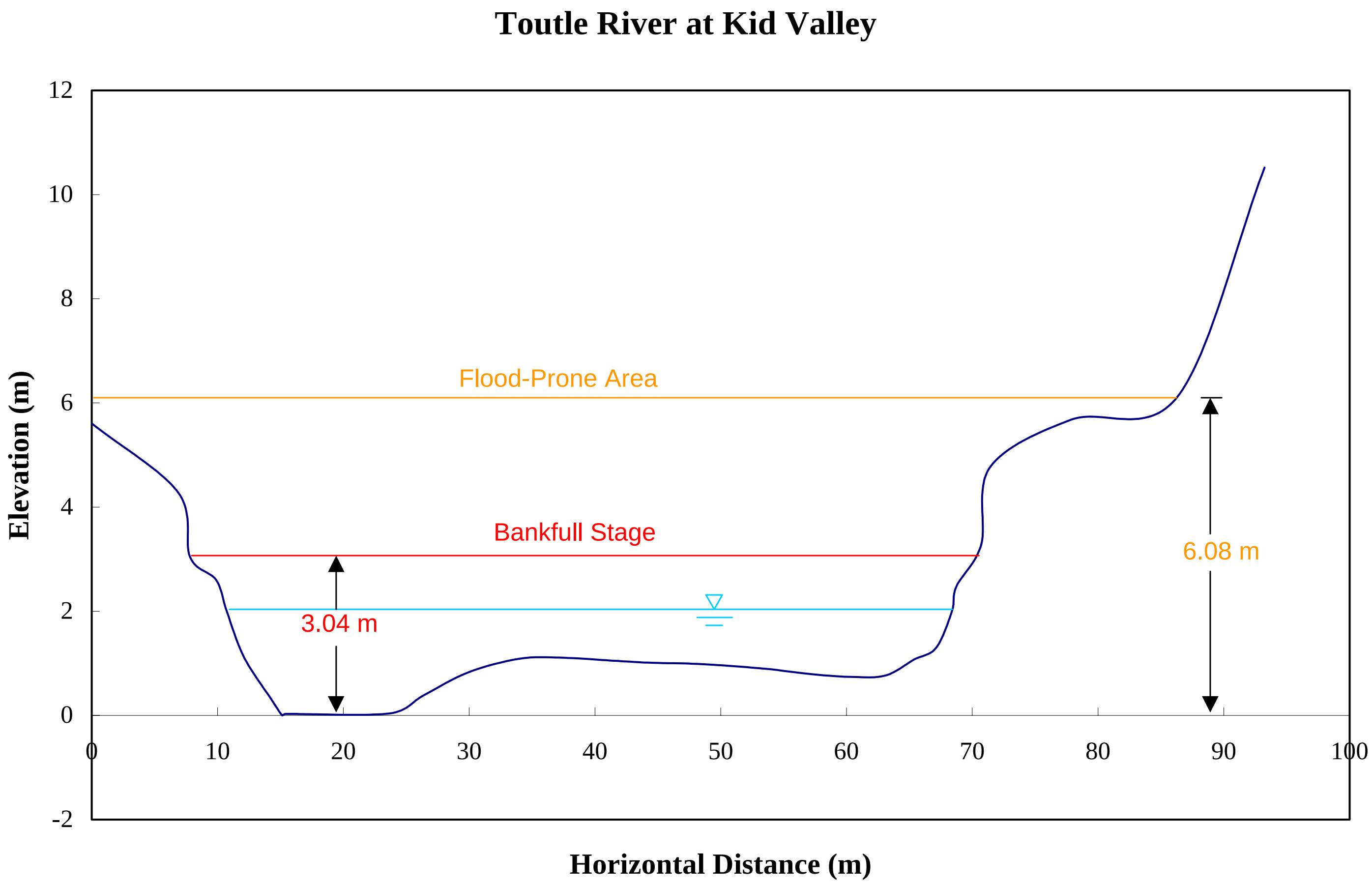


Fig 5.- Representative cross-section for Toutle River at Kid Valley.

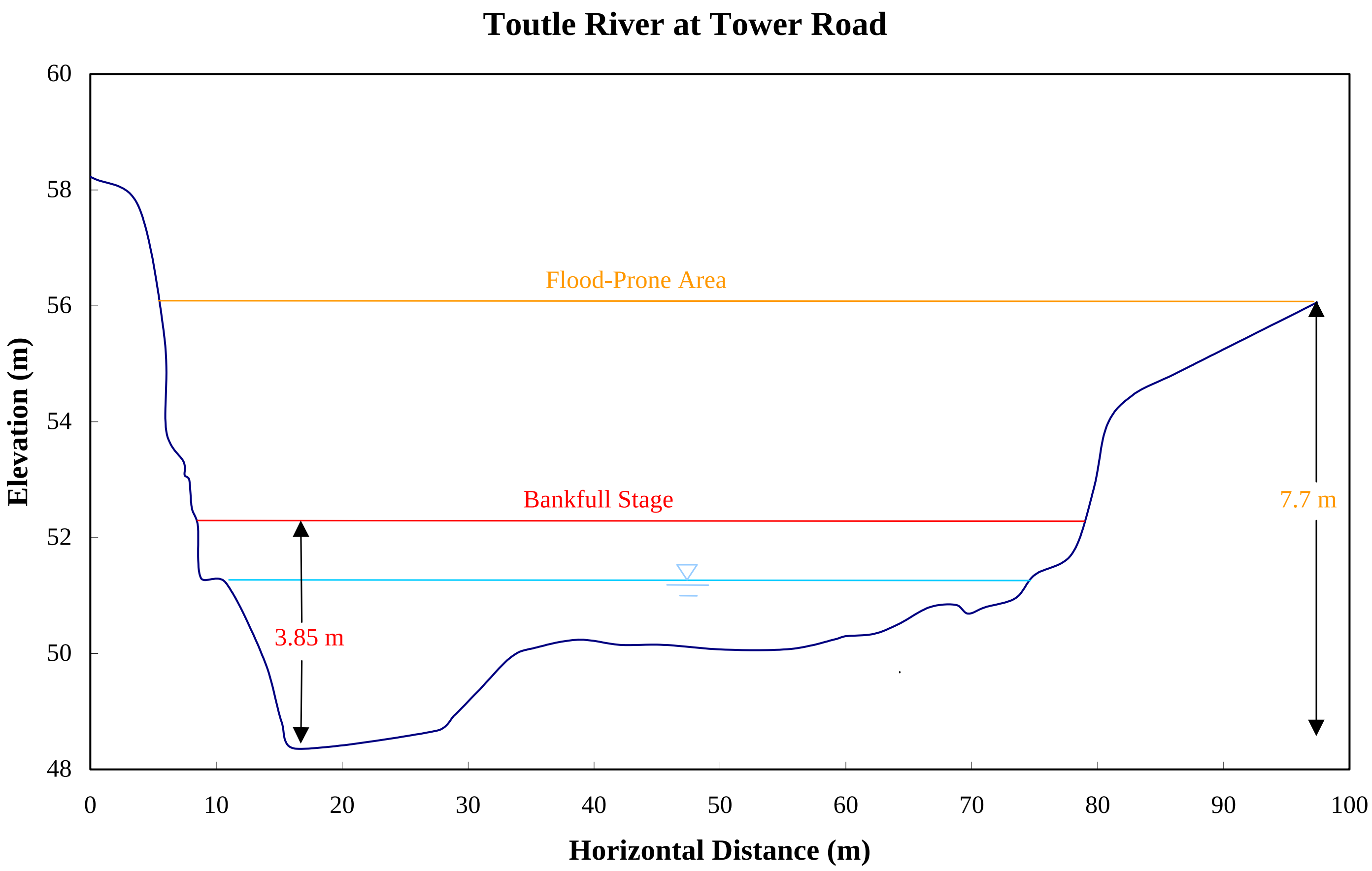


Fig 6.- Representative cross-section for Toutle River at Tower Road.

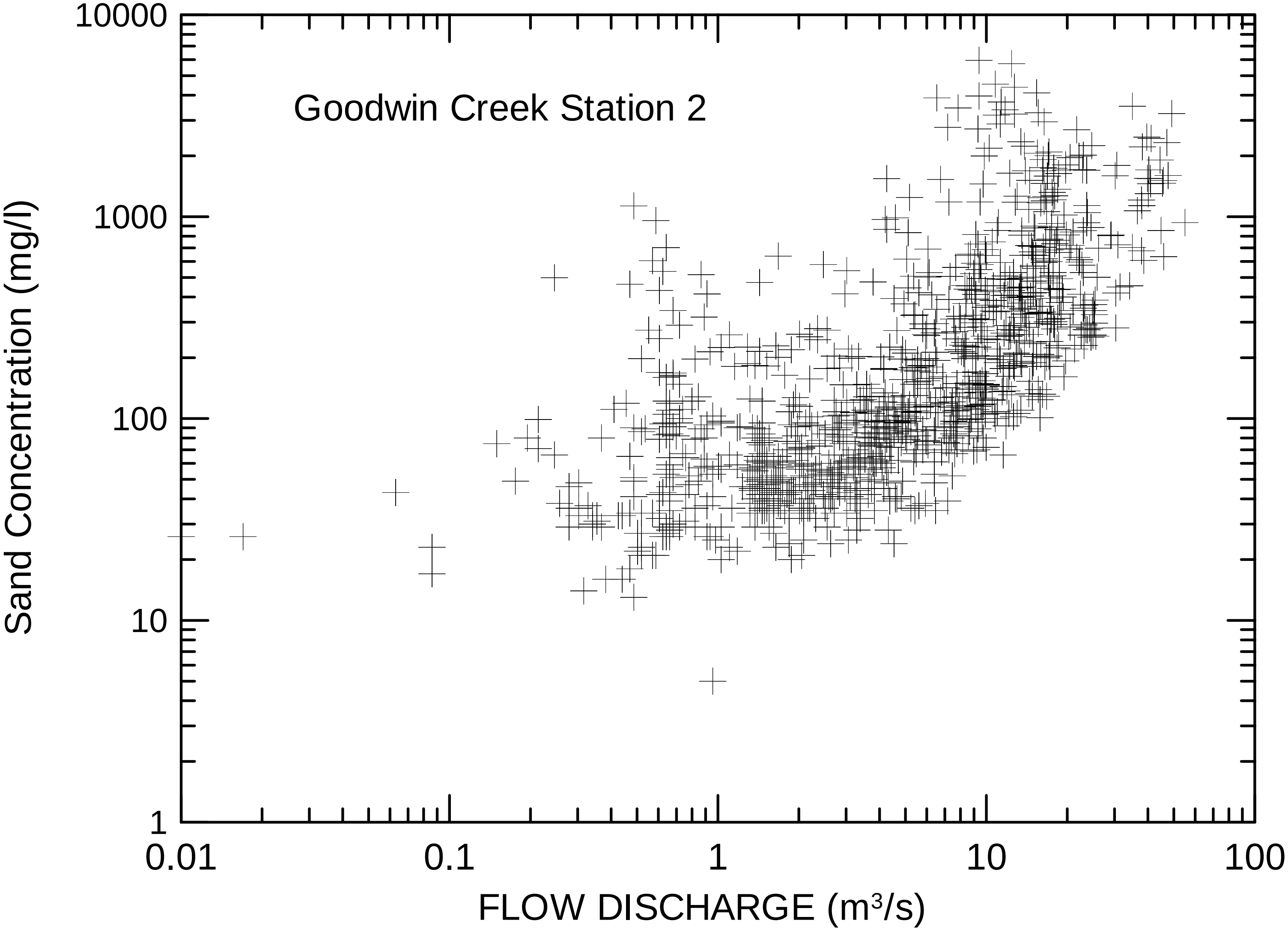


Fig. 7.- Transport samples for sand from Goodwin Creek station 2

Fig. 8.- Locations of identified data sets shown as stars. Numbers refer to multiple sites at some locations.

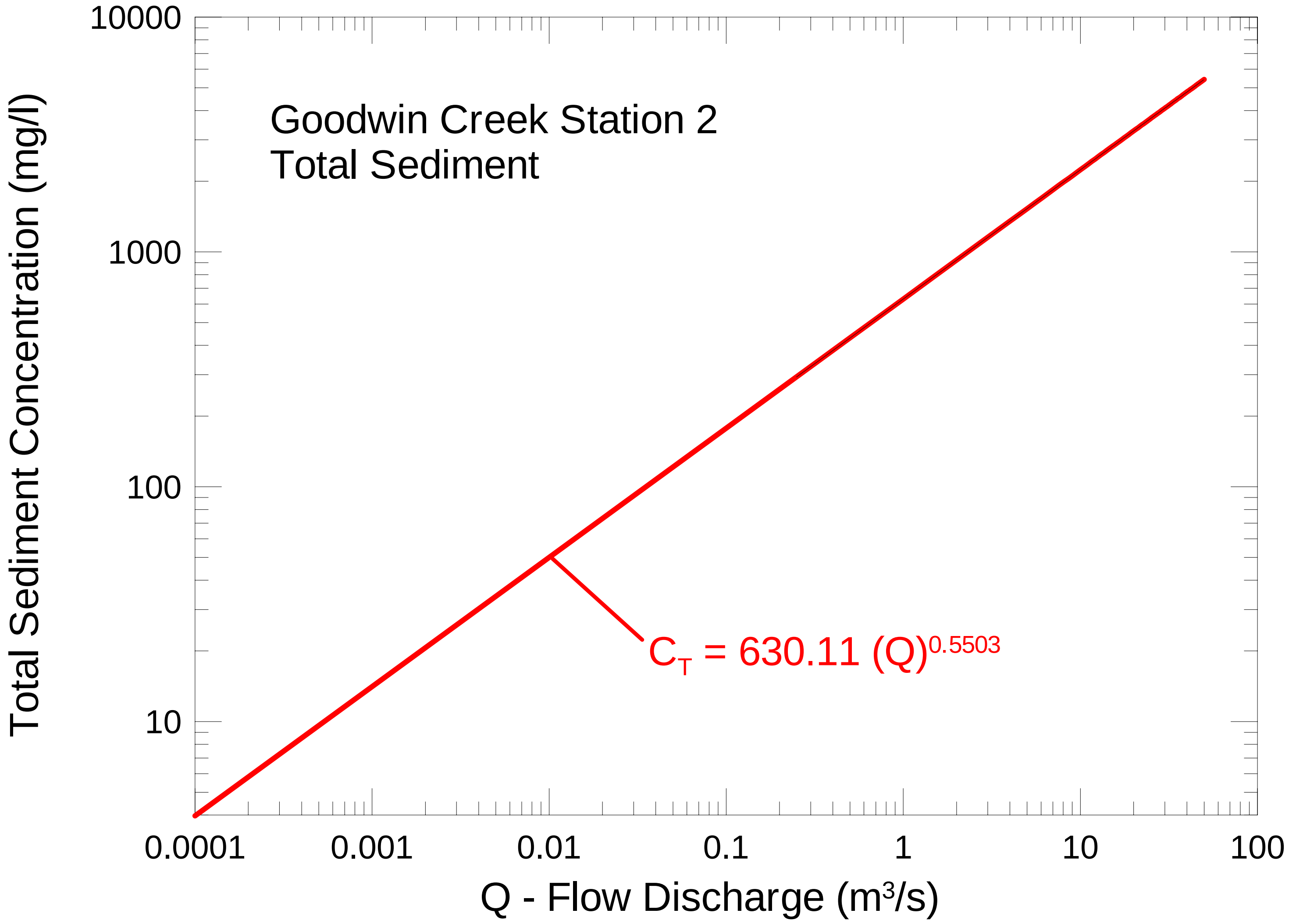


Fig. 9.- Total sediment rating curve for Goodwin Creek station 2.

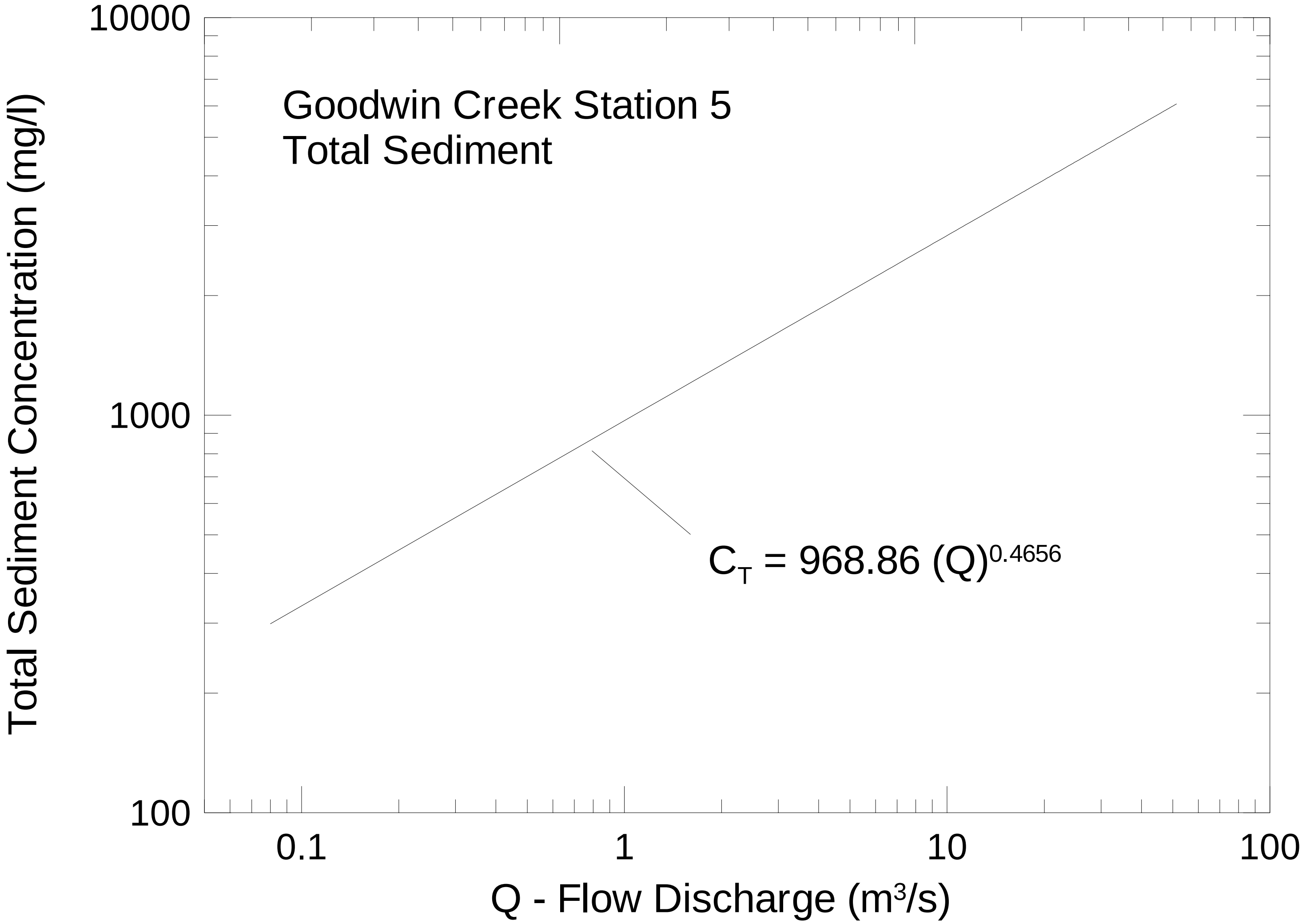


Fig. 10.- Total sediment rating curve for Goodwin Creek station 5.

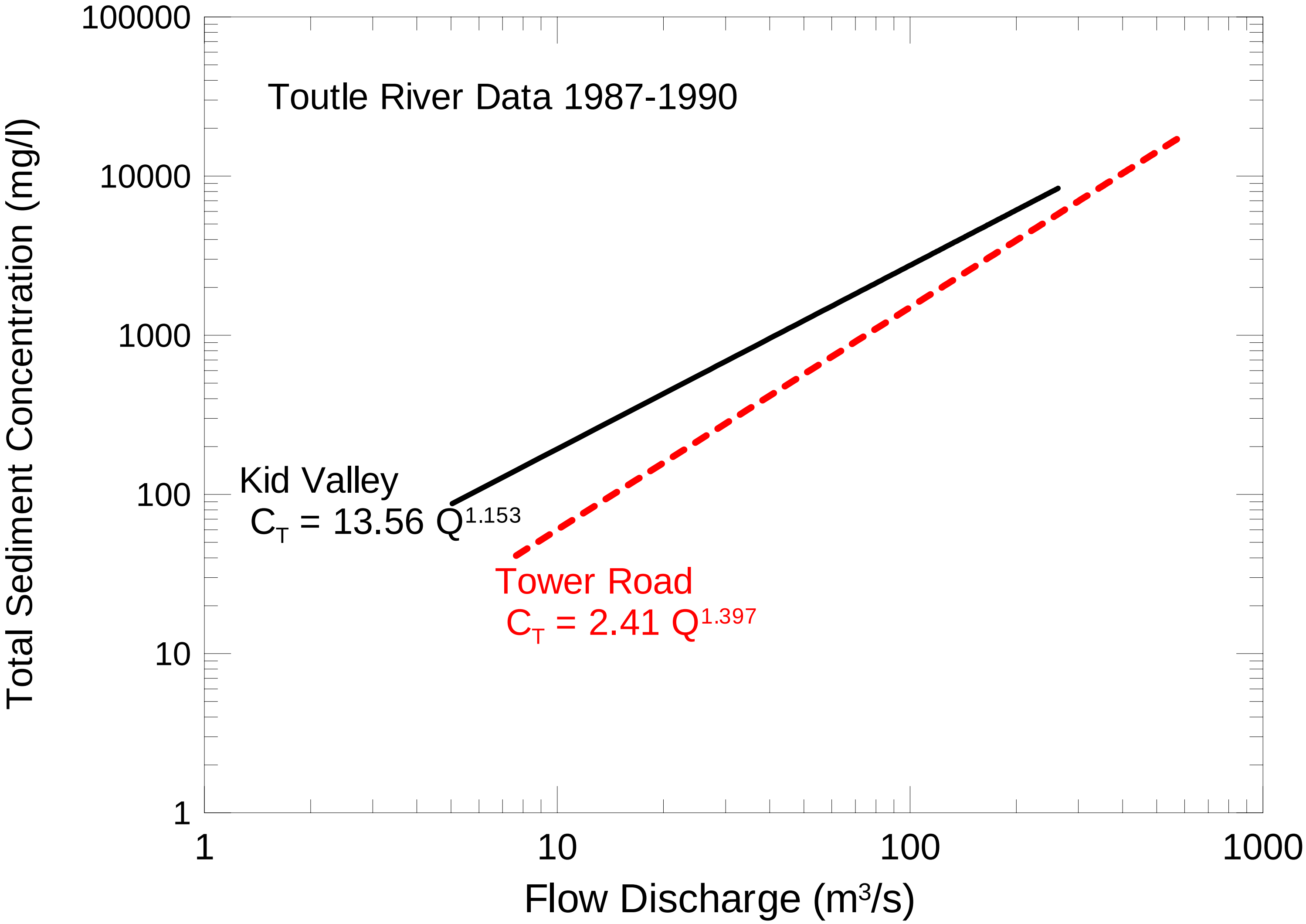


Fig. 11.- Total sediment rating curve for Toutle River at Kid Valley and Tower Road.

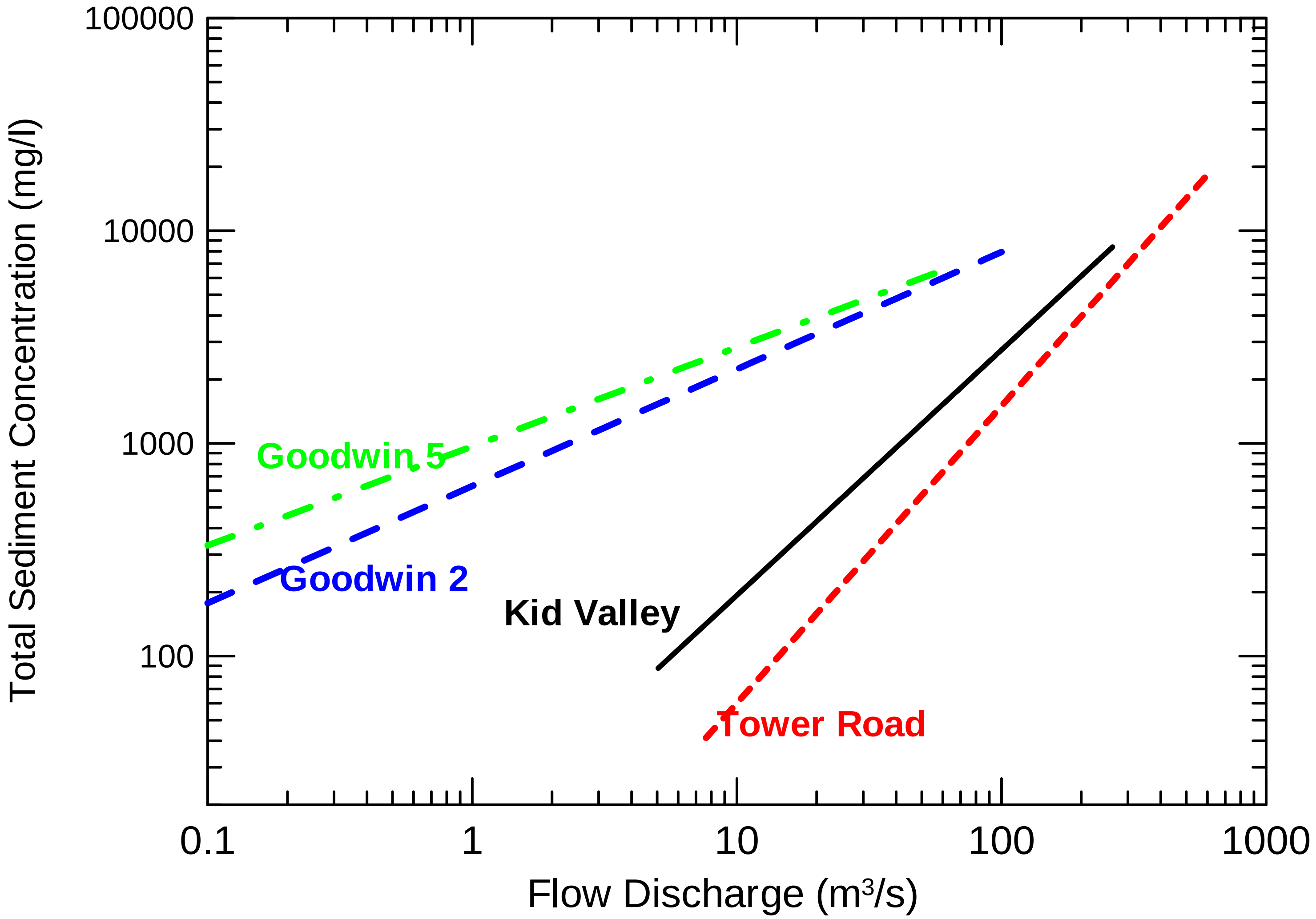


Fig. 12.- Total sediment rating curves for the four sites.

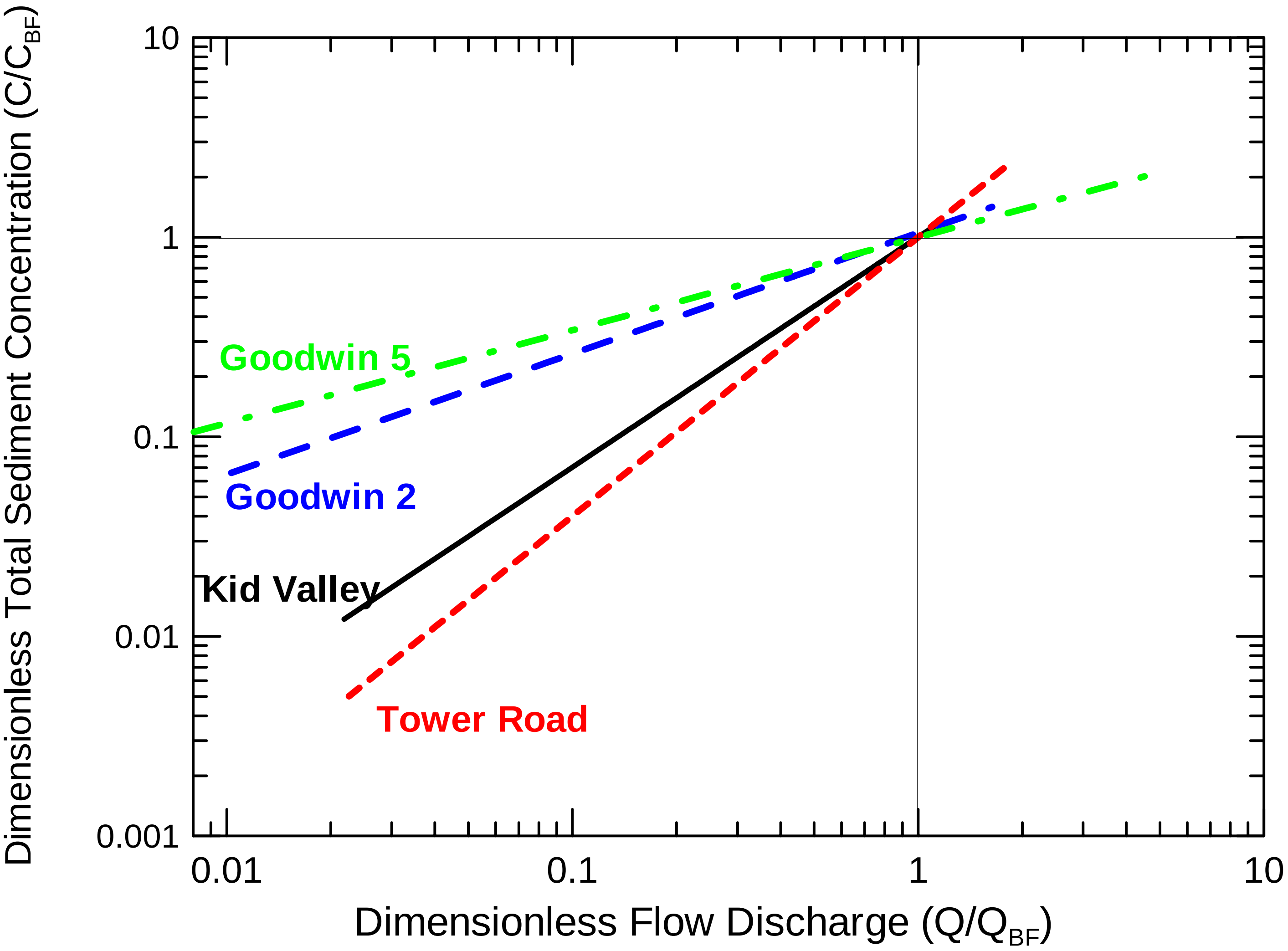


Fig. 13.- Dimensionless rating curves for the four sites.

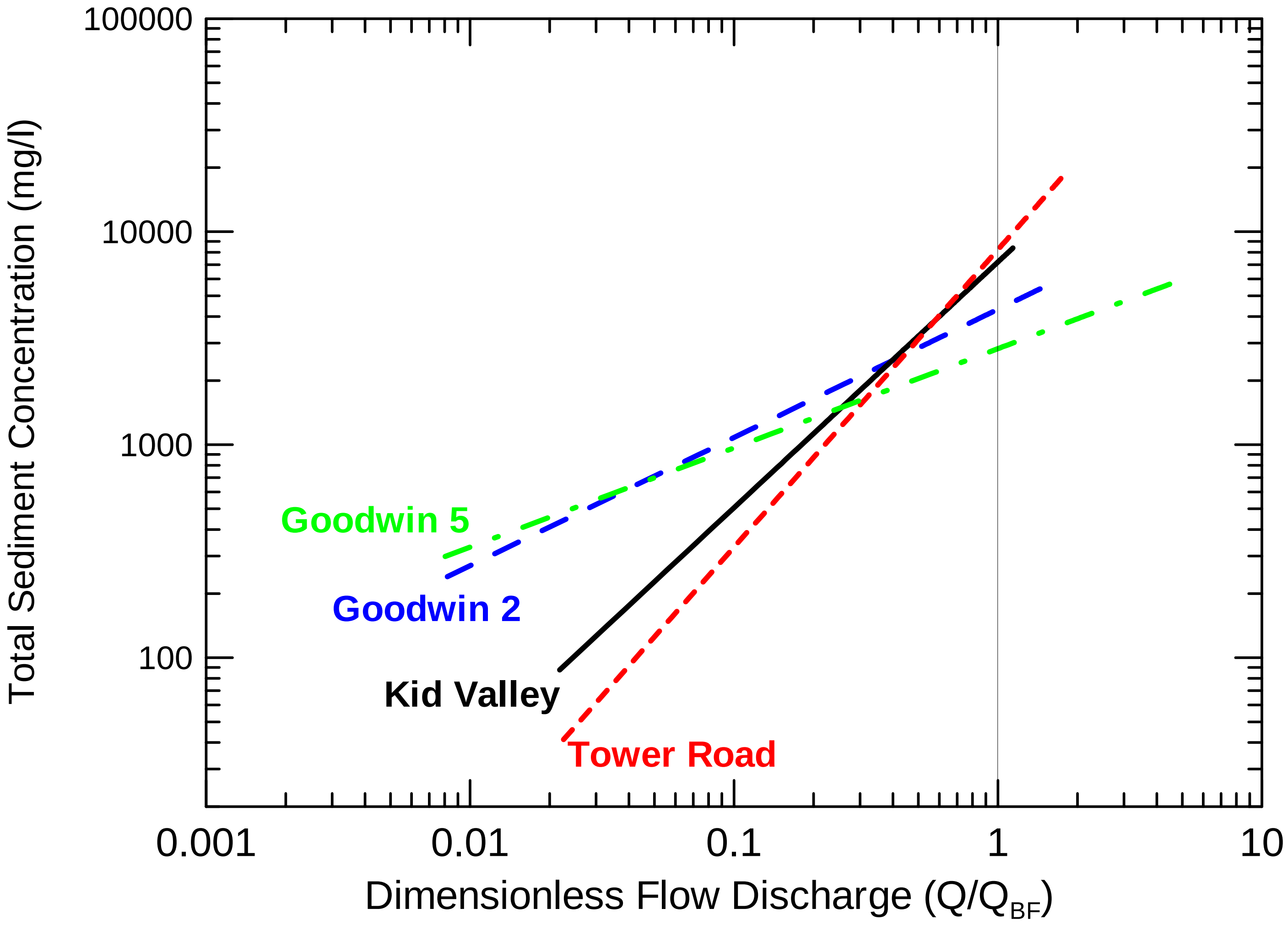


Fig. 14.- Sediment concentration versus dimensionless discharge for the four sites.

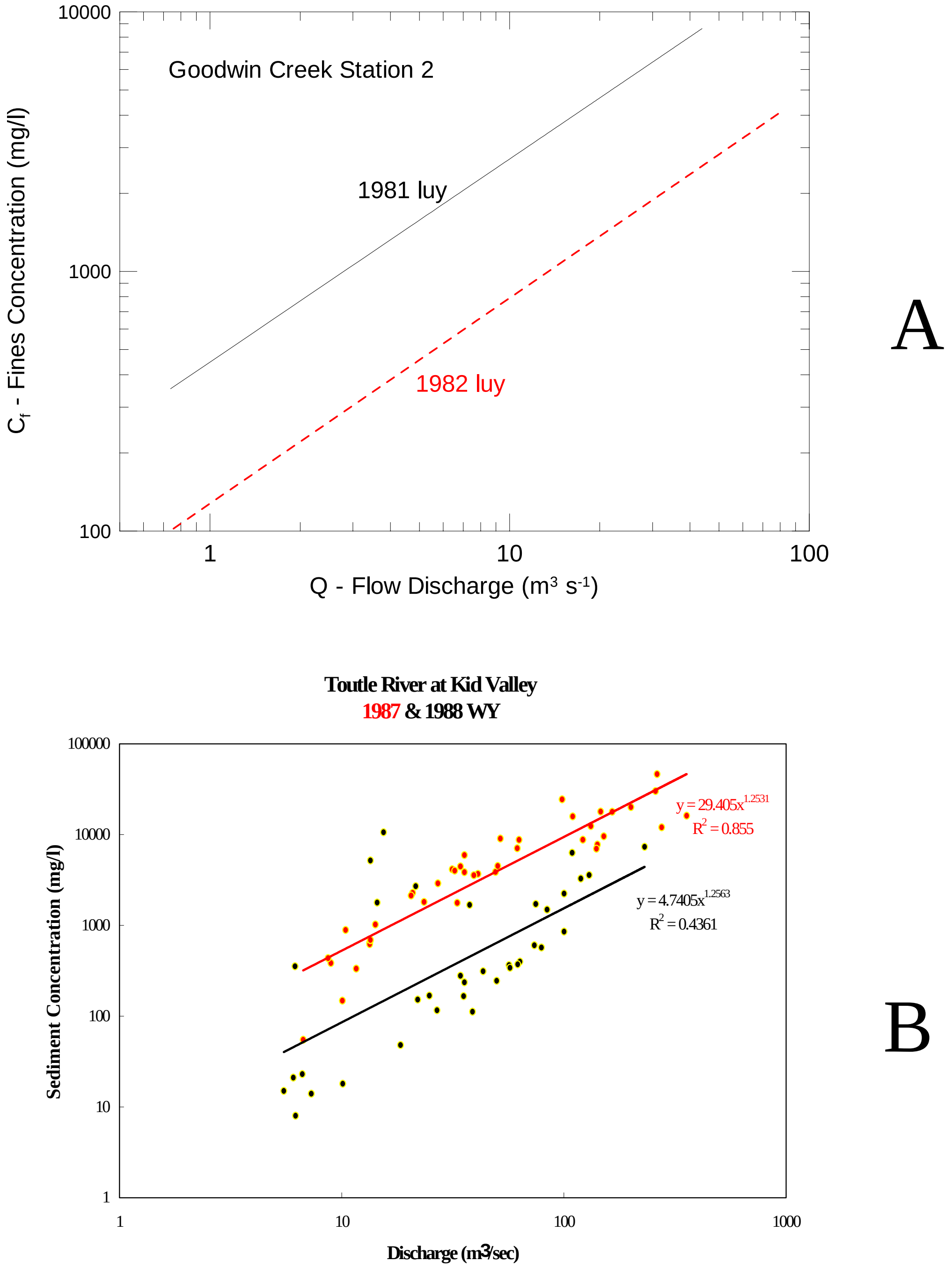


Fig. 15.- A) Goodwin Creek station 2 fine sediment rating curves for 1981,1982;
B) Toutle River at Kid Valley suspended sediment rating curves for 1987, 1988.

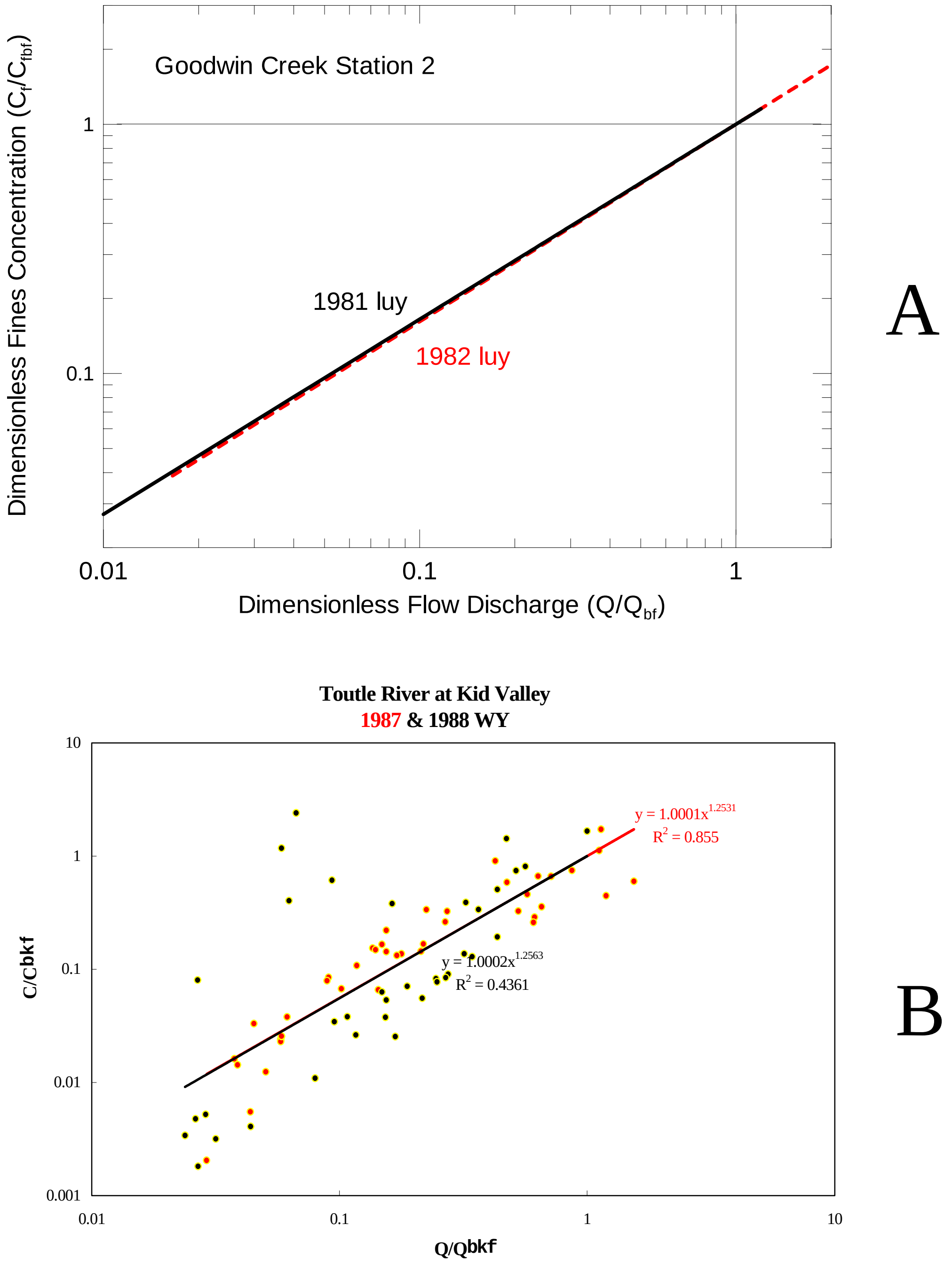


Fig. 16.- A) Goodwin Creek station 2 dimensionless fine sediment rating curves for 1981, 1982; B) Toutle River at Kid Valley dimensionless suspended sediment rating curves for 1987, 1988.

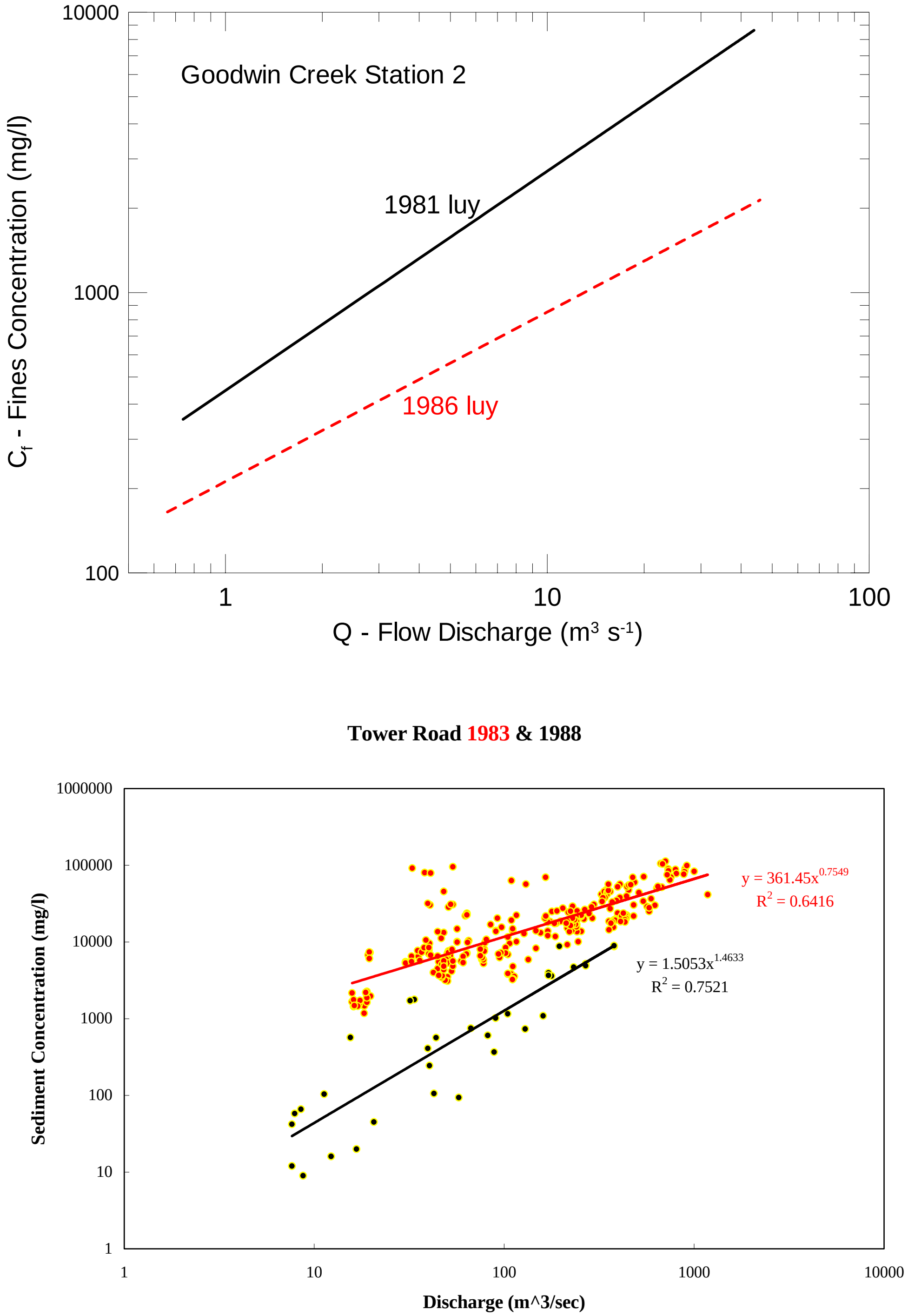
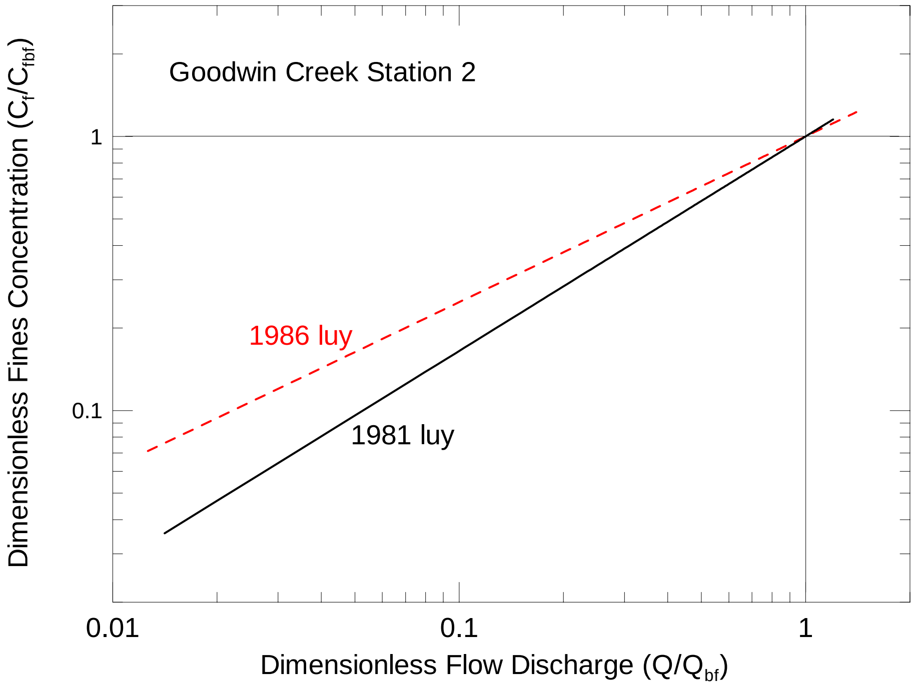


Fig. 17a.- Dimensional rating curves for 1981 and 1986 Goodwin Creek station 2 (top), and for Toutle River at Tower Road for 1983 and 1988 (bottom).



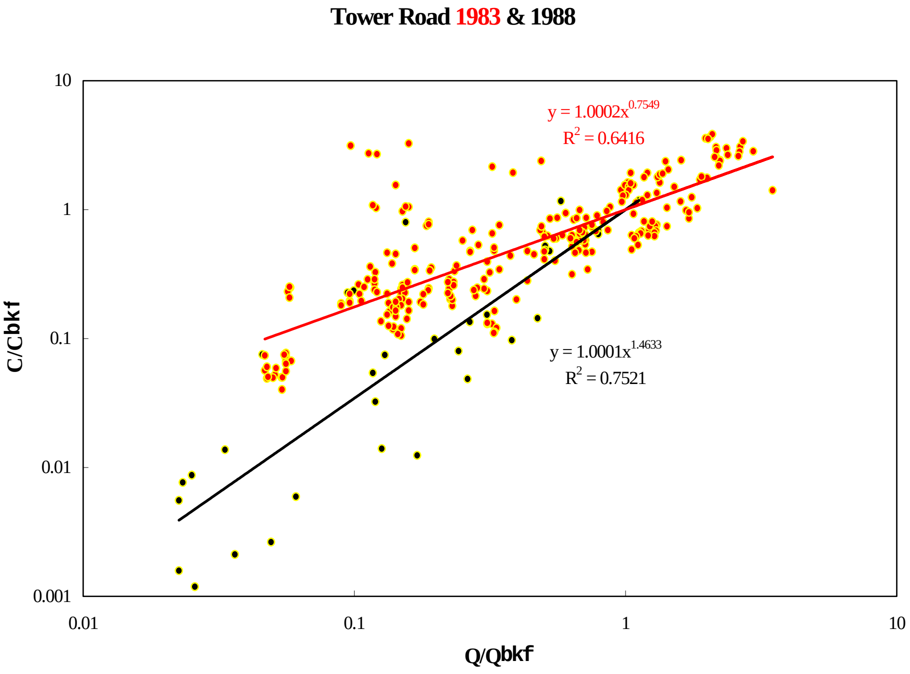

Tower Road 1983 & 1988

Fig. 17b.- Dimensionless sediment rating curves for Goodwin Creek station 2 for 1981 and 1986 (top), and for Toutle River at Tower Road for 1983 and 1988 (bottom).

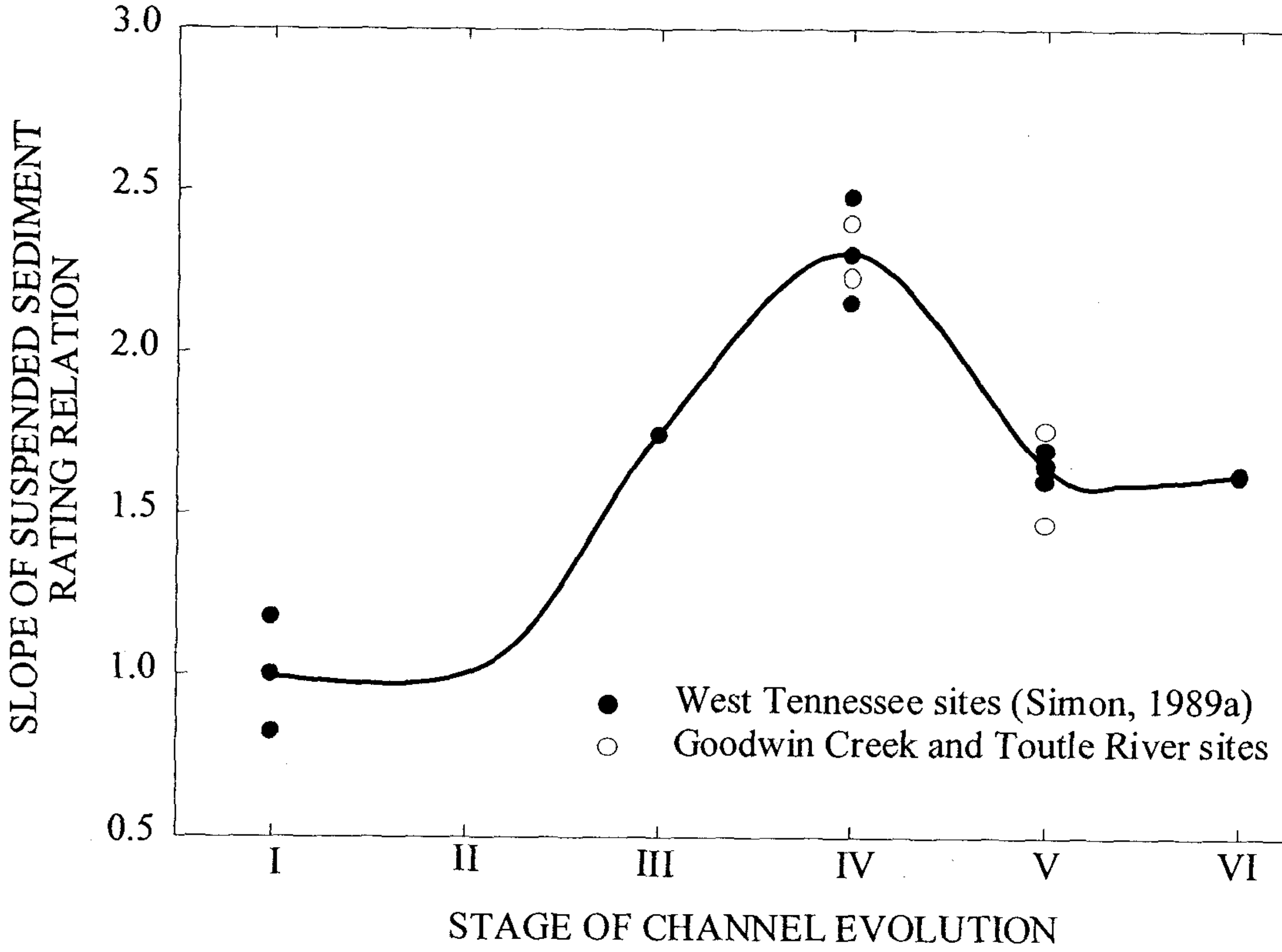


Fig. 18.- The slope of the suspended sediment rating curves versus stage of channel evolution.

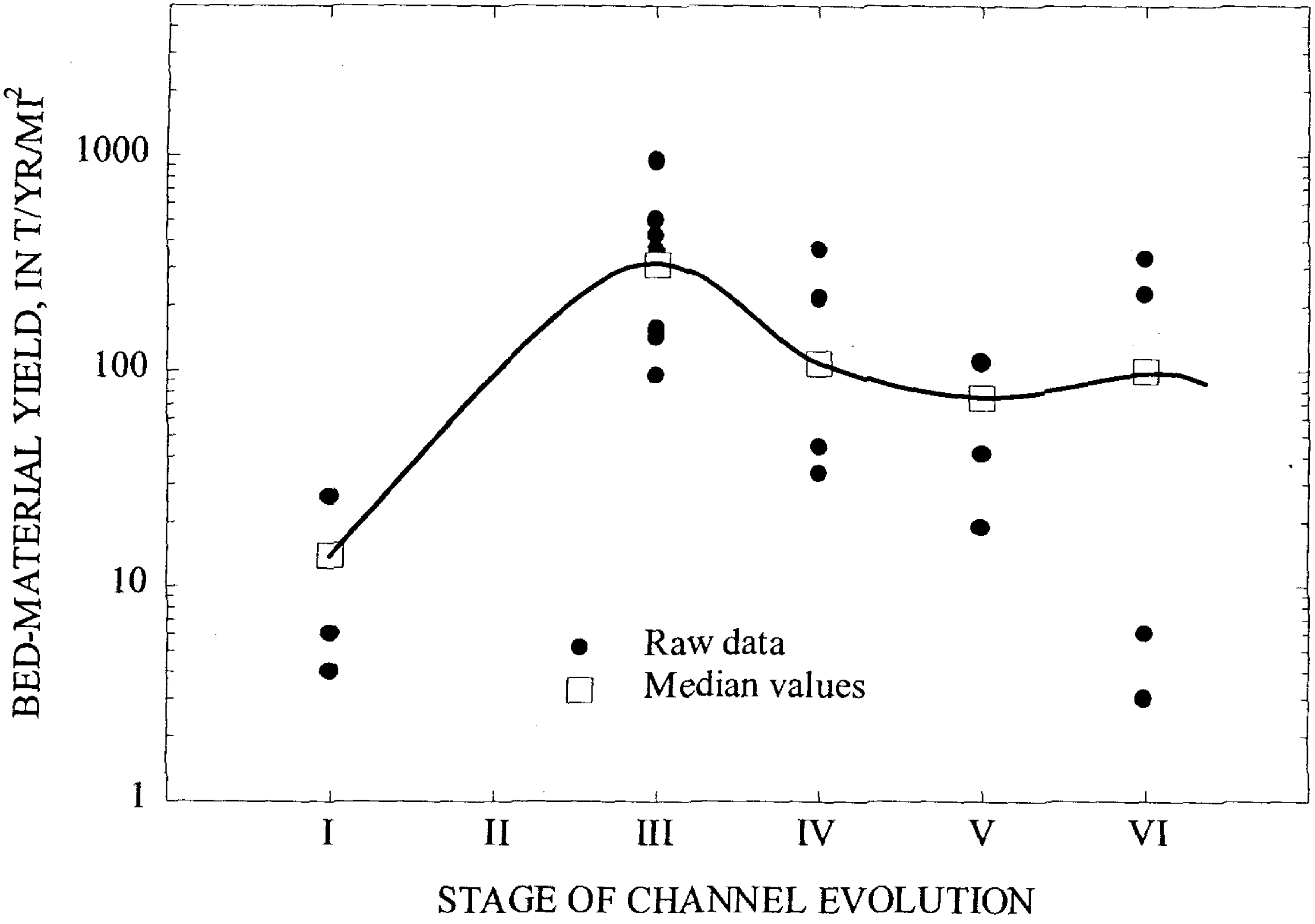


Fig. 19.- Rates of bed load transport versus stage of channel evolution.

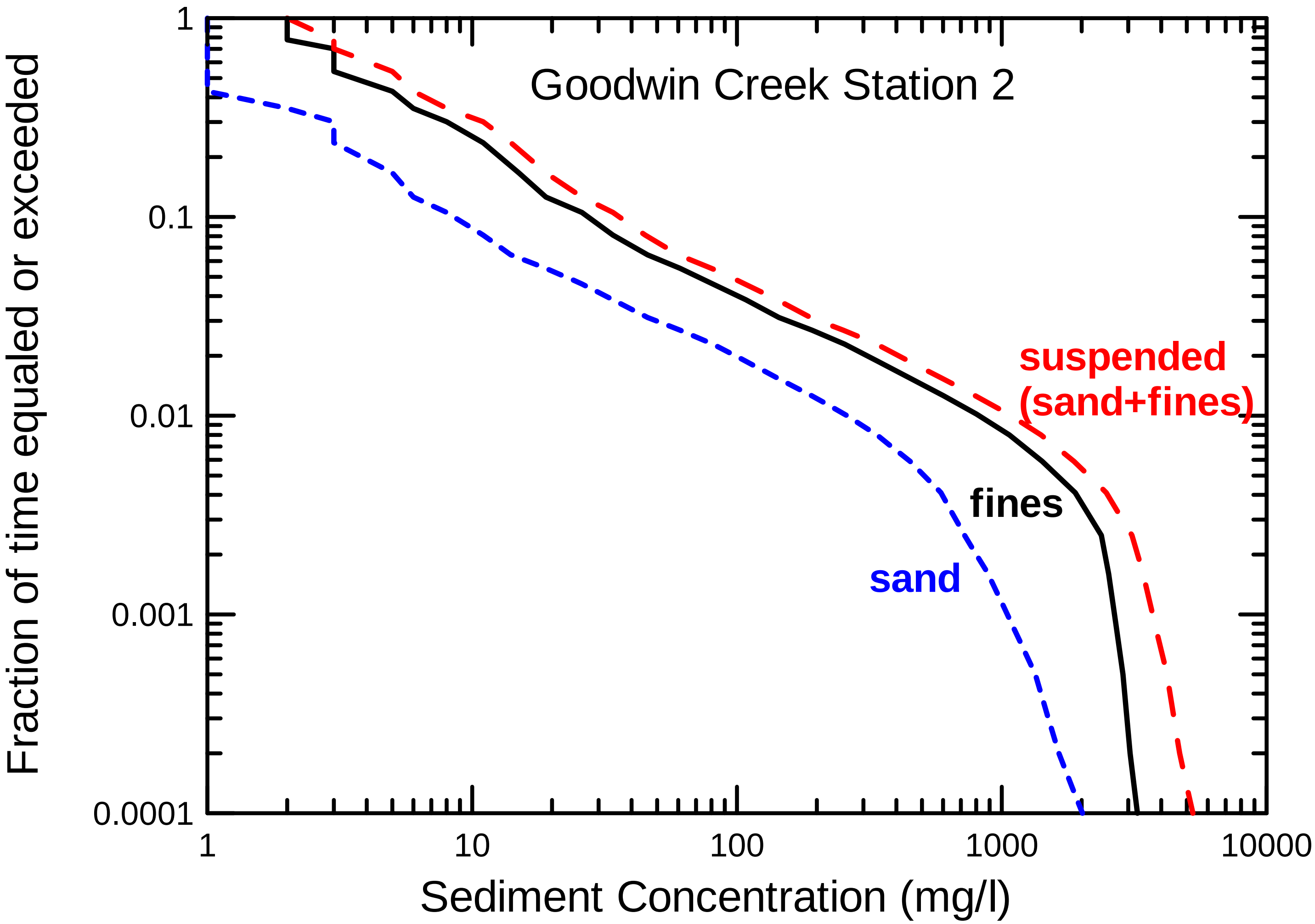


Fig. 20.- Fraction of time a given concentration of suspended sediment is equaled or exceeded at Goodwin station 2.

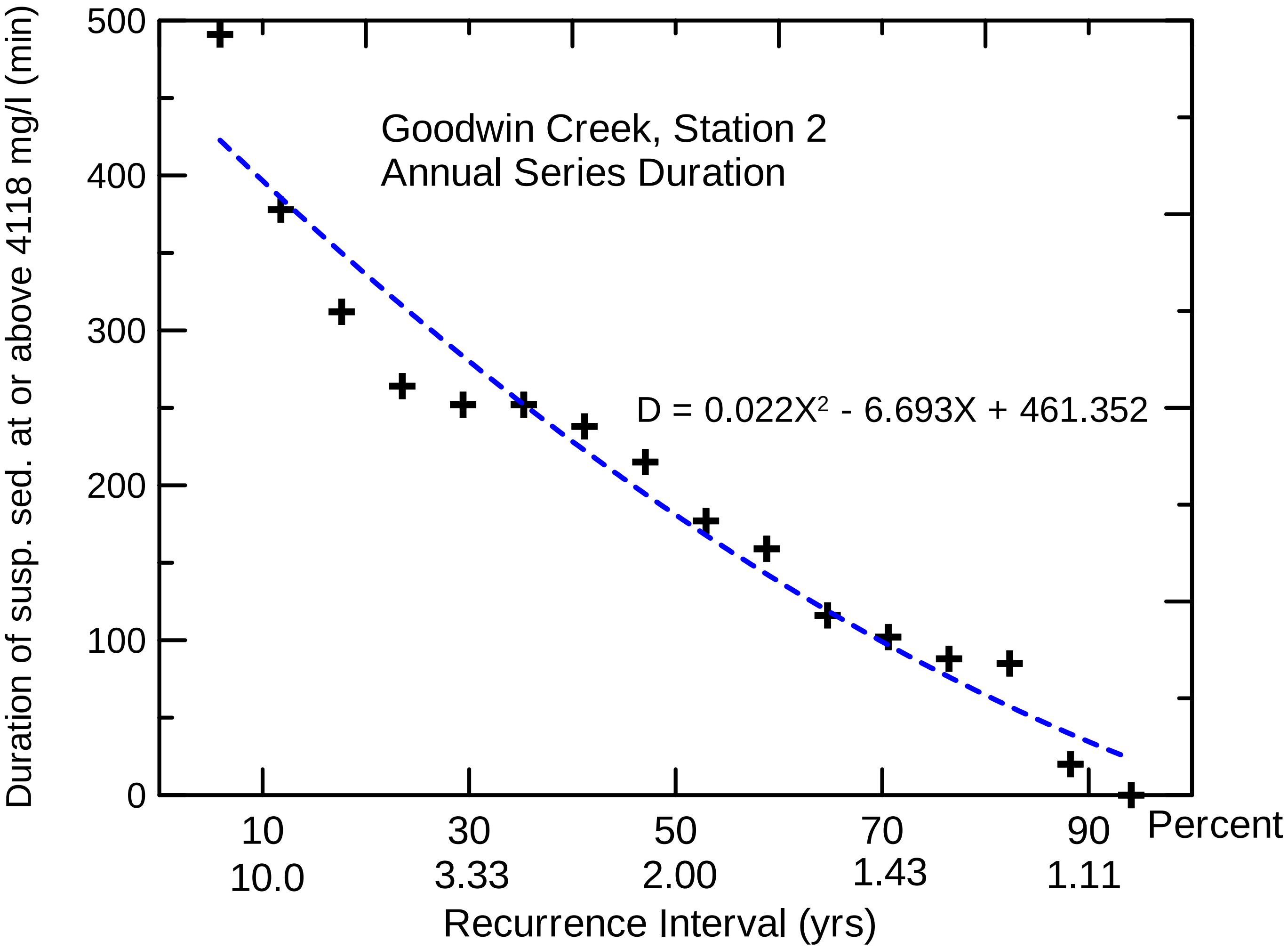


Fig. 21.- Duration of suspended sediment at or above 4118 mg/l for a given recurrence interval at Goodwin Creek station 2. From this relation the expected duration in minutes may be determined for this sediment concentration for a given recurrence interval.

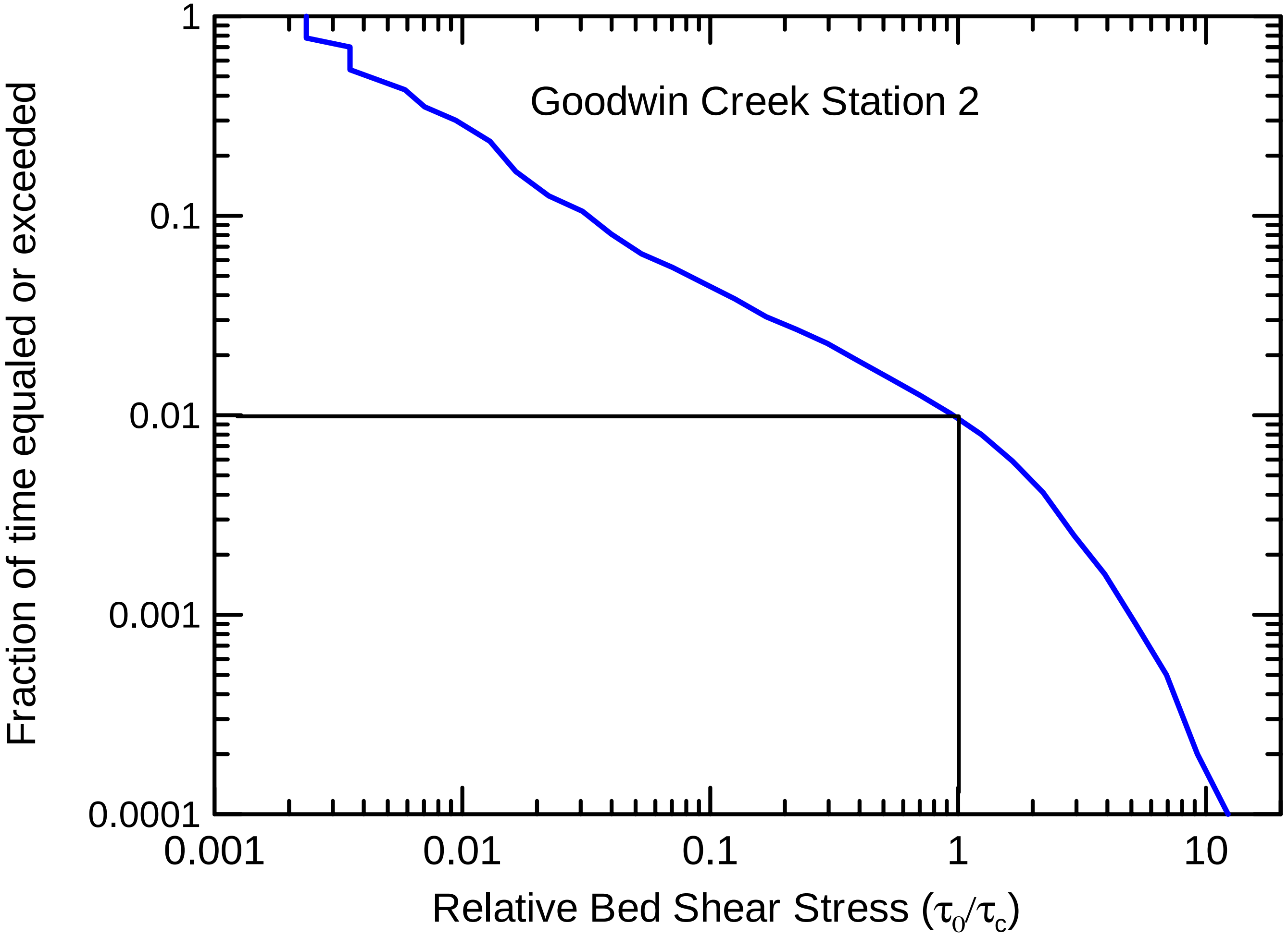


Fig. 22.- Fraction of time a given relative bed shear stress is equaled or exceeded at Goodwin Creek station 2. When the shear stress is equal to one, the bed sediment of a stream begins to move. Streams which have a high degree of motion of the bed material have been related to negative impacts on the biota.

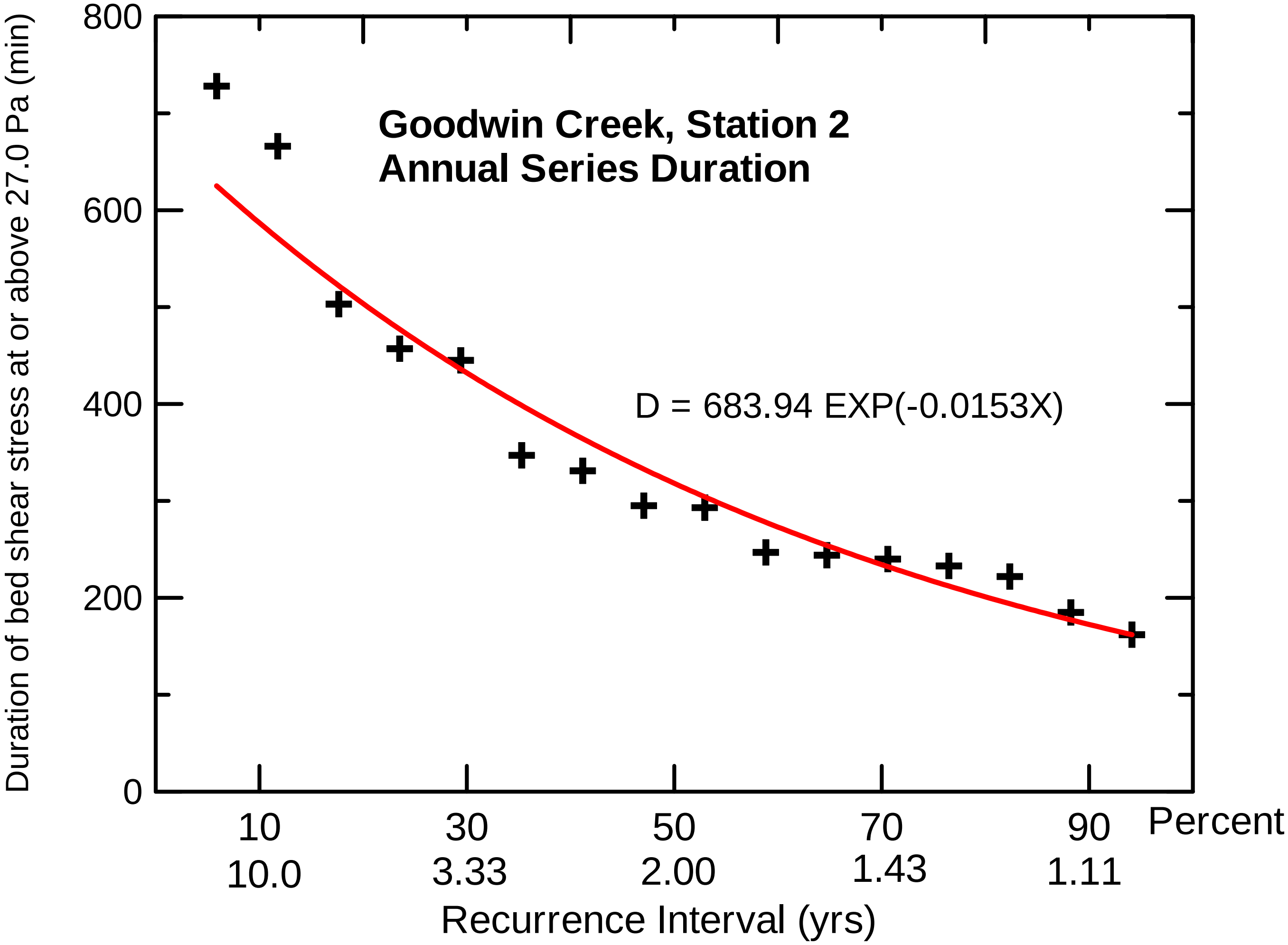


Fig. 23.- Duration of bed shear stress at or above 27 Pa for a given recurrence interval at Goodwin Creek station 2. The shear stress of 27 Pa is the flow strength at which all sizes of the bed material are completely in motion. Flows above this strength would be disruptive of the substrate environment of the stream.