Physical Stream Habitat Dynamics in Lower Bear Creek, Northern Arkansas

Biological Science Report
USGS/BRD/BSR–2003-0002

U.S. Department of the Interior
U.S. Geological Survey

Prepared in cooperation with the National Park Service, Water Resources Division and the Buffalo National River

Technical Report Series

The Biological Resources Division publishes scientific and technical articles and reports resulting from the research performed by our scientists and partners. These articles appear in professional journals around the world. Reports are published in two report series: Biological Science Reports and Information and Technology Reports.

Series Descriptions

Biological Science Reports ISSN 1081-292X

This series records the significant findings resulting from sponsored and co-sponsored research programs. They may include extensive data or theoretical analyses. Papers in this series are held to the same peer-review and high-quality standards as their journal counterparts.

Information and Technology Reports ISSN 1081-2911

These reports are intended for publication of book-length monographs; synthesis documents; compilations of conference and workshop papers; important planning and reference materials such as strategic plans, standard operating procedures, protocols, handbooks, and manuals; and data compilations such as tables and bibliographies. Papers in this series are held to the same peer-review and high-quality standards as their journal counterparts.

Copies of this publication are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161 (1-800-553-6847 or 703-487-4650). Copies also are available to registered users from the Defense Technical Information Center, Attn.: Help Desk, 8725 Kingman Road, Suite 0944, Fort Belvoir, Virginia 22060-6218 (1-800-225-3842 or 703-767-9050).

An electronic version of this report is available on-line at: *<http://www.cerc.usgs.gov/pubs/center/pdfDocs/BSR_2003_0002.pdf>*

Cover photo: Riffle in the Crane Bottom study area, Lower Bear Creek.

Physical Stream Habitat Dynamics in Lower Bear Creek, Northern Arkansas

Biological Science Report
USGS/BRD/BSR-2003—0002
July 2003

By Joanna M. Reuter[1], Robert B. Jacobson[1], Caroline M. Elliott[2]

Prepared in coperation with the National Park Service, Water Resources Division and the Buffalo National River.

[1] U.S. Geological Survey, Biological Resources Division, Columbia Environmental Research Center, 4200 New Haven Road, Columbia, MO 65201
[2] AScI Corporation, Columbia Environmental Research Center, 4200 New Haven Road, Columbia, MO 65201

Contents

Page

Tables

Figures

Abstract

We evaluated the roles of geomorphic and hydrologic dynamics in determining physical stream habitat in Bear Creek, a stream with a 239 km^2 drainage basin in the Ozark Plateaus (Ozarks) in northern Arkansas. During a relatively wet 12-month monitoring period, the geomorphology of Bear Creek was altered by a series of floods, including at least four floods with peak discharges exceeding a 1-year recurrence interval and another flood with an estimated 2- to 4-year recurrence interval. These floods resulted in a net erosion of sediment from the study reach at Crane Bottom at rates far in excess of other sites previously studied in the Ozarks. The riffle-pool framework of the study reach at Crane Bottom was not substantially altered by these floods, but volumes of habitat in riffles and pools changed. The 2- to 4-year flood scoured gravel from pools and deposited it in riffles, increasing the diversity of available stream habitat. In contrast, the smaller floods eroded gravel from the riffles and deposited it in pools, possibly flushing fine sediment from the substrate but also decreasing habitat diversity.

Channel geometry measured at the beginning of the study was used to develop a two-dimensional, finite-element hydraulic model to assess how habitat varies with hydrologic dynamics. Distributions of depth and velocity simulated over the range of discharges observed during the study (0.1 to 556 cubic meters per second, cms) were classified into habitat units based on limiting depths and Froude number criteria. The results indicate that the areas of habitats are especially sensitive to discharge at low to medium flows. Races (areas of swift, relatively deep water downstream from riffles) disappear completely at the lowest flows, and riffles (areas of swift, relatively shallow water) contract substantially in area. Pools also contract in area during low flow, but deep scours associated with bedrock outcrops sustain some pool area even at the lowest modeled flows. Modeled boundary shear stresses were used to evaluate which flows are responsible for the most mobilization of the bed, and therefore, habitat maintenance. Evaluation of the magnitude and frequency of bed-sediment entrainment shows that most of habitat maintenance results from flows that occur on average about 4 to 7 days a year.

Our analysis documents the geomorphic and hydrologic dynamics that form and maintain habitats in a warmwater stream in the Ozarks. The range of flows that occurs on this stream can be partitioned into those that sustain habitat by providing the combinations of depth and velocity that stream organisms live with most of the time, and those flows that surpass sediment entrainment thresholds, alter stream geomorphology, and therefore maintain habitat. The quantitative relations show sensitivity of habitats to flow variation, but do not address how flow may vary in the future, or the extent to which stream geomorphology may be affected by variations in sediment supply.

Keywords: aquatic habitat, geomorphology, hydrology, Ozarks, Arkansas

Suggested Citation:
Reuter, J.M.; Jacobson, R.B., and Elliott, C.M., 2003, Physical Stream Habitat Dynamics in Lower Bear Creek, Northern Arkansas, USGS/BRD/BSR–2003-0002, 49 p.

Introduction

Like many streams, Bear Creek in northern Arkansas (fig. 1) is subject to competing demands for its available discharge. Changes in water use, land use, or climate would have the potential to alter the quantity and timing of discharge in Bear Creek. A general question in many streams is how changes in hydrology can affect the processes that create, maintain, and sustain physical stream habitat, the template upon which biologic communities are built (Plafkin and others, 1989).

Streams of the Ozark Plateaus (Ozarks; fig. 1) drain rural landscapes dominated by forest and agricultural lands, with scattered, small, urbanized areas. Because of generally low land-use stress and substantial contributions of spring flow from karst aquifers, Ozarks streams have generally good water quality. Nutrients and bacteria are elevated in agricultural drainage basins but they rarely exceed drinking water standards (Petersen and others, 1998). Probably because of the generally high water quality and low levels of habitat disturbance, Ozarks streams maintain high biological diversity, hosting approximately 175 fish species (Petersen, 1998). Thirty species of fish have been identified in Bear Creek (Petersen, 2002, pers. comm.; Magoulick, 2002, pers. com).

Bear Creek is a tributary to the Buffalo River, a National River managed by the National Park Service. Preservation of the aquatic ecosystem of the Buffalo River is a substantial challenge for the National Park Service because it owns only a corridor along the river, amounting to 11 percent of the Buffalo River drainage area. Hence, the National Park Service has an interest in understanding how changes in water and watershed management affect physical stream habitats, and in understanding biological responses to habitat change.

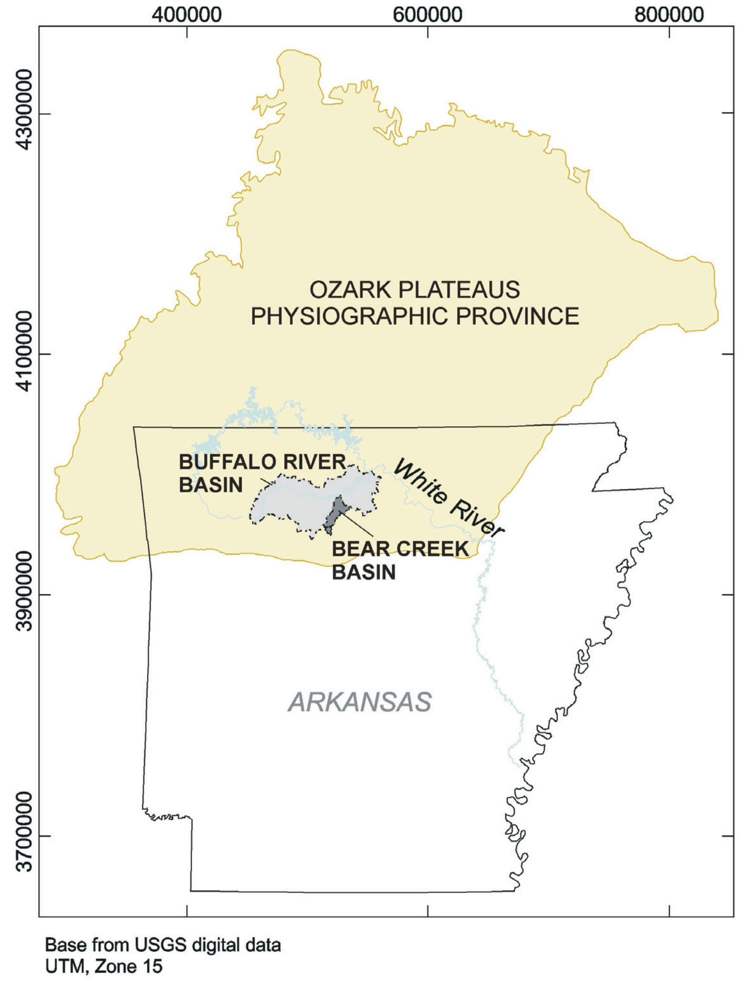


Figure 1. Location of Bear Creek and Buffalo River basins.

In 1997, a site in the upper Bear Creek drainage basin (fig. 2) was proposed for construction of a water-supply reservoir. A dam at the proposed location would impound approximately 11 per cent of the drainage area of Bear Creek. Assessment of the potential effects of such an impoundment requires a quantitative understanding of how flow changes would affect the physical habitat template, and the stream ecosystem.

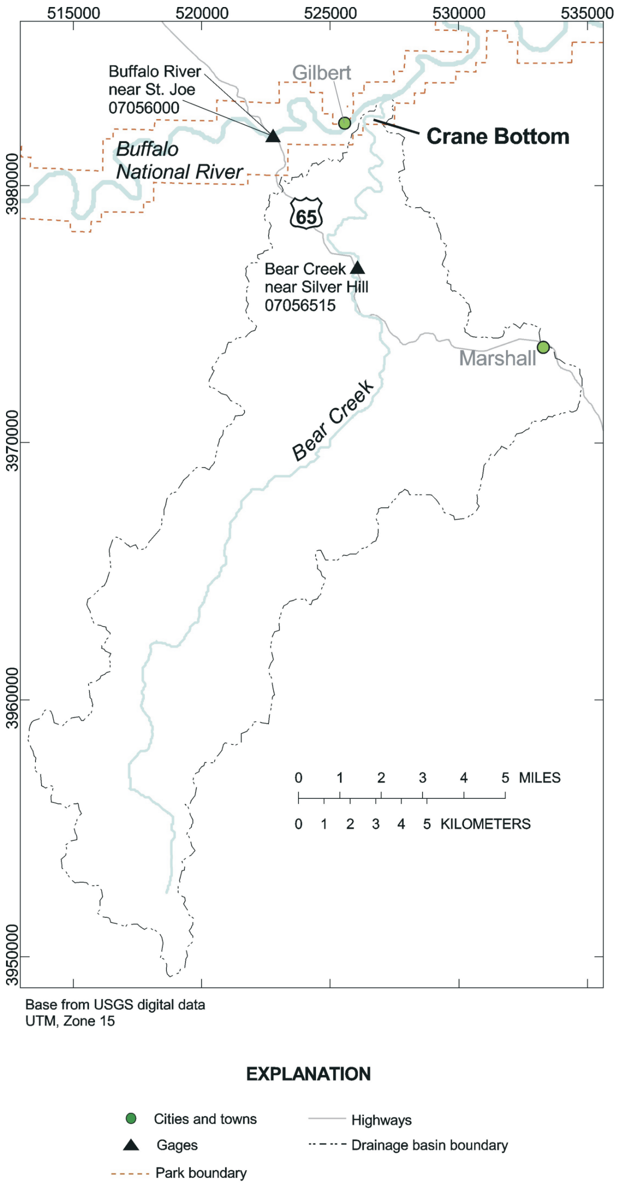
Purpose and Scope

The purpose of this report is to document and analyze sensitivity of physical stream habitat on Bear Creek to geomorphic and hydrologic dynamics. The scope includes two components: evaluation of habitat sensitivity to erosion and deposition events and assessment of habitat sensitivity to hydrologic variation.

The first component was addressed through monitoring of geomorphic change over a 12-month period, evaluation of channel scour, a painted rock experiment, and modeling of bed-material entrainment. Although measurement of geomorphic change over a short time period cannot address the possible long-term effects of erosion and deposition, it can provide useful estimates of rates and observations of processes. In addition, measurements and modeling are used to estimate threshold conditions for bed-material entrainment to indicate which flows are necessary to maintain physical habitat.

The second component was addressed through hydraulic modeling of habitats resulting from a range of discharges while keeping channel morphology constant. The approach is typical of instream flow studies wherein a two-dimensional (depth-averaged) hydraulic model is used to simulate depth and velocity distributions with discharge. The modeled results are then summarized in terms of hydraulic habitats as defined by Panfil and Jacobson (1999). A three-year record of flows on Bear Creek is used to evaluate flow exceedances and flood frequencies associated with modeled discharges.

Habitat availability and geomorphic dynamics in Bear Creek ultimately need to be addressed over time frames longer than the available three-year hydrologic record. Evaluation of how habitats in Bear Creek might respond to hydrologic alterations within the Bear Creek drainage basin will require either long-term hydrologic records or results of basin-scale hydrologic simulation models. In addition, changes in sediment supply as a result of contemporary land-use practices, or ongoing adjustment of the drainage basin to historical land uses, could substantially alter geomorphology of reaches of Bear Creek in the future.



Base from USGS digital data
UTM, Zone 15

Figure 2. Location of the Crane Bottom study reach in the Bear Creek drainage basin, and locations of U.S. Geological Survey streamflow gaging stations on the Buffalo River and Bear Creek.

Acknowledgments

We acknowledge the Buffalo National River and the Water Resources Division of the National Park Service for monetary and logistical support. We are especially grateful to Park Service employees David Mott, Jessica Caplinger, Faron Usrey, John Petty, and Greg Comer for help in field work. Harold Johnson and Gary D'Urso (U.S. Geological Survey) contributed to field surveys. Terry Waddle (U.S. Geological Survey) and Peter Steffler (University of Alberta) provided guidance in hydraulic modeling.

Background

Streams respond to changes in their drainage basins in inherently complex ways (Jacobson and others, 2001). The interactions of hydrology, sediment supply, sediment routing, water quality, and thresholds of stream instability typically result in only broadly predictable trends in physical habitats. In addition to the uncertainties of stream-habitat responses, biological responses are subject to interactions among food webs, population dynamics, predator/prey relations, and competition. Assessment and prediction of stream ecological responses depend fundamentally on an understanding of the physical and biological context of the stream system.

Stream geomorphology and physical habitat

Habitat is defined, in general, as the three-dimensional structure in which organisms live (Gordon and others, 1992). Stream habitat typically is defined to include physical and chemical attributes of the volume occupied by specific stream or riparian organisms. Physical stream habitat is used here to describe depth, velocity, and substrate available to all stream organisms. Physical stream habitat results from interaction of water with the morphology of the stream channel and adjacent flood plains. Stream hydrology determines how much water is in the channel and when. Stream morphology determines how the water is distributed across the channel, and therefore the spatial distribution of depth, velocity, and substrate.

Physical stream habitat characteristics vary through time because of changes in river discharge and because erosion and deposition alter the morphology of the river. Stream habitat dynamics can be divided into two general time domains: those associated solely with hydrologic variation (hydrologic dynamics and habitat-sustaining flows) and those associated with erosional and depositional changes to topography (geomorphic dynamics and habitat formation and maintenance flows). These two domains overlap at discharges where significant sediment transport takes place.

Although physical stream habitats are highly dynamic, low-flow classification systems typically are used to organize data and facilitate communication. The hydraulic habitat (meso-scale habitat) classification system used in this report (figs. 3, 4) is modified from McKenney (1997). This hierarchical classification system was developed particularly to optimize description of low-gradient, cobble-gravel streams typical of the Ozarks. The highest level of the classification separates units based on whether they are in the main flow (longitudinal units) or at the margins.

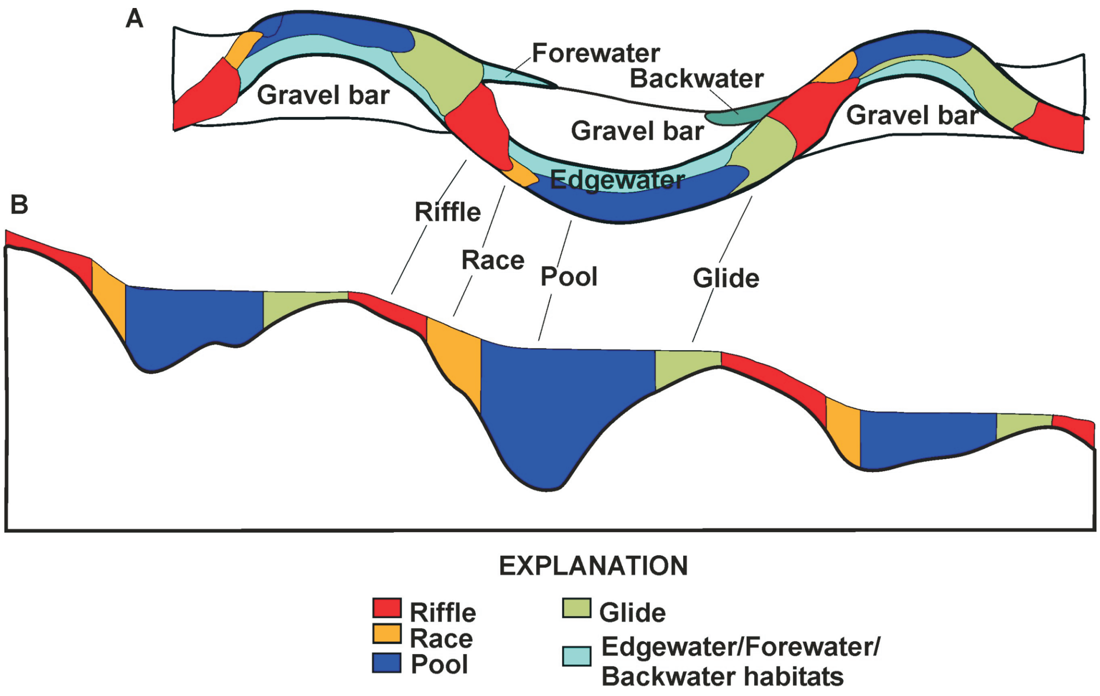


Figure 3. Typical arrangement of physical stream habitat units in Ozarks streams, after McKenney (1997), Panfil and Jacobson (2001). A. Planview showing longitudinal and marginal habitats. B. Longitudinal view along thalweg. See figure 4 for additional descriptions.

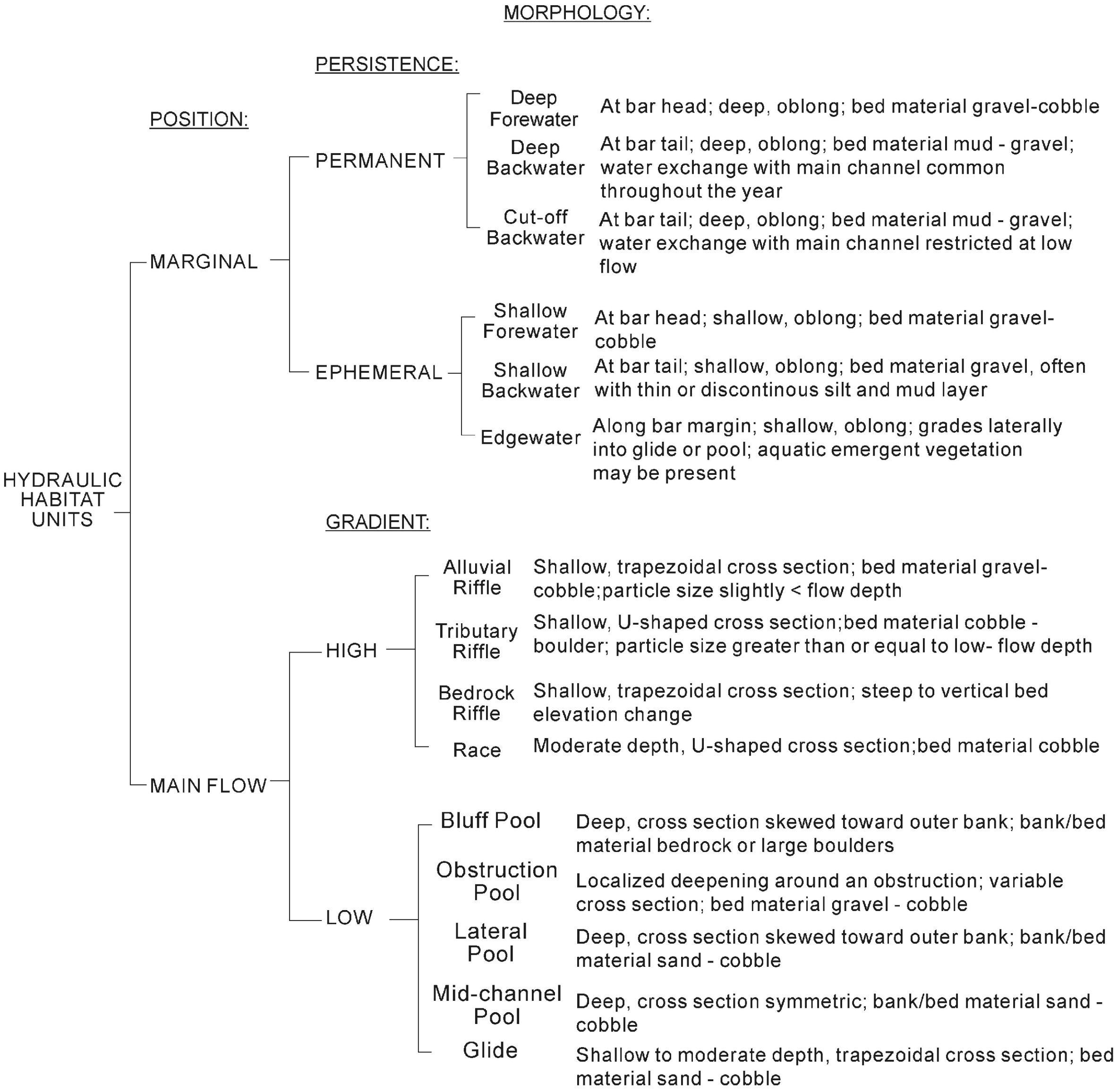


Figure 4. General physical stream habitat unit (meso-scale) classification system for Ozarks streams (from McKenney 1997). Not all units are present at Crane Bottom.

The system further subsets according to gradient, persistence (sensitivity to discharge), and morphology (fig. 4).

Ultimately, most management, social, and ecological interests focus on the biological endpoints of altered ecosystems, rather than the physical habitat template. Although this report focuses on physical stream habitat, the fundamental role of physical processes in structuring stream ecosystems allows some ecological inference.

At a very basic level, ecologists generally accept that habitat diversity is associated with biological diversity because a greater range of physical environments potentially allows more species to thrive in the stream channel (Gorman and Karr, 1978; Schlosser, 1987; Jeffries and Mills, 1990). Physically, greater diversity of elevations within a stream reach assures that during low-flow periods, more wetted area will be available. At high flows, greater physical diversity will create refuge areas for fish to escape high velocities and shear stresses. Therefore, physical processes that homogenize habitat by filling pools or eroding riffles, for example, would be considered to diminish habitat diversity.

More specifically, physical habitats of Ozarks streams have been shown to be highly associated with specific ecological processes, individual species, or assemblages of species. For example, net community productivity has been found to be significantly higher in riffles and glides than in pools (Whitledge and Rabeni, 2000). Peterson and Rabeni (2001) found that long-ear sunfish (*Lepomis megalotis*), smallmouth bass (*Micropterus dolomieu*), and shadow bass (*Ambloplites ariommus*) were associated with pools in Ozarks streams, whereas species such as rainbow darter (*Etheostoma caeruleum*) and Ozark minnow (*Notropis nubilus*) were associated with higher velocities in riffles and races. These authors also found that habitat affinities varied by season and size of streams. Similarly, Doisy and Rabeni (2001) documented that benthic invertebrate community composition, diversity, and functional groups in an Ozarks stream correlated with basic hydraulic descriptors, including Froude number (a dimensionless hydraulic variable), indicating a strong physical habitat control on benthic communities.

While fish species can swim to take advantage of habitats that move from place to place because of erosion and deposition, benthic invertebrates in general are more dependent on stability of the substrate that comprises their habitat. Some organisms, like mussels, require relatively stable substrate over periods of seasons to decades, whereas many benthic insects depend on stability for a year or less (Barbour and others, 1999). For maintenance of habitats for the less mobile benthic invertebrates, the stream should contain patches of substrate that are subject to neither deposition nor erosion. Absolute stability, however, usually is not considered desirable since accumulation of fine sediment may diminish the volume and quality of benthic habitat. Periodically, flows capable of entraining the bed are needed to flush fine sediments and rejuvenate the substrate (Milhous, 1982).

Physical habitat also varies over time as hydrologic variations influence environmental variables such as temperature, dissolved oxygen, and turbidity. Life stages of aquatic species may be synchronized to periods of high or low flow because of the associated environmental variables (Poff and others, 1997). For example, smallmouth bass are known to spawn only when temperatures reach 16-19 ^{o}C (Scott and Crossman, 1973); therefore, they need flow over gravel substrate at that temperature for successful reproduction. Because life histories are related to flow, temperature, and habitat in complex ways, a simplified approach to assessing the effects of flow alteration is to compare the altered hydrograph to a nonregulated hydrograph (Richter and others, 1997) rather than to consider individual species requirements. In limiting cases the effects of flow variation can be quite clear. For example, flow alteration that would dry up perennial riffles and pools would have significant effects on the stream ecosystem.

Geomorphic context of Ozarks streams

Previous studies on streams of the Ozark Plateaus have documented that Ozarks streams have always carried a large volume of gravel-cobble size bed load (Jacobson and Pugh, 1992; Jacobson, in press). Stratigraphic and historical studies have also documented that Ozarks streams have responded to historical land-use disturbances by releasing large quantities of excess bed load that are now in transit through stream systems (Jacobson, 1995; Jacobson and Primm, 1997; Jacobson and Gran, 1999). Waves of bed-material sediment with wavelengths measured in tens of meters to kilometers are a persistent, slowly traveling source of geomorphic disturbance. Rates and processes of geomorphic dynamics, and implications for stream habitats, have been addressed in a related series of studies (McKenney and others, 1995; McKenney and Jacobson, 1996; McKenney, 1997; Jacobson and Pugh, 1997; and McKenney, 2001). These studies refined a classification of Ozarks stream habitats and documented spatial variability in geomorphic processes of habitat alteration. In particular, these authors determined: 1) lateral erosion processes on Ozarks streams are concentrated in discrete disturbance reaches separated by stable reaches; 2) long, straight stable reaches are efficient transporters of bed load, whereas bed load is deposited and episodically removed from disturbance reaches; 3) vertical, transient aggradation in pools proceeds from downstream to upstream, resulting in alteration of pools into glides; 4) deposition of excess bed load in wave-like forms can create transient riffles, resulting in high variability in riffle spacing.

The sensitivity of habitats to hydrologic variation was assessed by Panfil and Jacobson (1999) on Jacks Fork, Missouri. This study implemented a two-dimensional hydraulic model for a 500 m reach of Jacks Fork where the drainage area upstream of the reach was 422 km^2. The authors assessed potential biologic importance of modeled flows by defining habitat fields (combinations of depth and velocity) based on depth criteria and Froude number.

$$F = v \Big/ \sqrt{g * d}$$

where, F = Froude number, v = depth averaged water velocity, g = gravitational acceleration constant, and d = water depth.

By modeling a range of discharges that did not involve significant sediment transport, Panfil and Jacobson (1999) determined that areas of races (concentrated flow downstream of riffles) and riffles were most sensitive to changing discharge; both habitats increased substantially in area with increasing discharge. Pool area at their study site was relatively insensitive to hydrologic variation because bedrock bluffs created favorable hydraulic conditions for deep scour, resulting in areas of deep, slow flow that persisted over a wide range of discharges.

A series of additional studies have addressed Ozarks physical stream habitats at the scale of drainage basins. These are associative studies that explore the synoptic spatial relations between stream habitats and characteristics of their drainage basins. In an associative study of stream habitats of 41 sites in the Ozarks, Femmer (1997) found that stream morphology variation was associated mostly with physiography and drainage-basin size; land-use factors were more important at the scale of individual reaches where riparian land use in the stream corridor controlled shading and seemed to be related to bank erosion. Petersen (1998) worked with a subset of the same habitat data plus fish community samples from the reaches, and concluded that fish communities were influenced primarily by elevated nutrients and greater canopy openness (resulting in more sunlight and periphyton growth) in agricultural drainage basins compared to forested drainage basins. Petersen (1998) also noted some relations between fish communities and geomorphic factors including channel sinuosity, channel width, channel depth, width:depth ratio and drainage area. Panfil and Jacobson (2001) used a refined habitat-assessment protocol to explore relations between drainage-basin conditions and stream morphology in 19 tributary streams to the Buffalo River in Arkansas and 24 tributaries to the Current River, Missouri. They concluded that physiography and drainage-basin size were dominant influences on physical stream habitat; however, when subset by river and physiographic unit, subtle land-use associations could be detected. Two confounding factors in associative studies are: a) that transport of sediment through drainage basins requires years to hundreds of years and so physical stream habitats have lagged responses to land-use effects (Jacobson and others, 2001); and b) many landscape-scale variables are co-variant, resulting in obscured cause and effect links.

The general geomorphic context of the Ozarks indicates that physical stream habitats in Bear Creek can be expected to vary with time according to hydrology and geomorphology. The history of geomorphic adjustments of Ozarks streams (Jacobson, 1995; Jacobson and Primm, 1997; Jacobson and Gran, 1999) indicates that habitats in Bear Creek have been and probably will be affected by waves of land-use-derived bed load moving through the stream network. These waves would be expected to affect reaches of Bear Creek by filling in the downstream ends of pools – and in severe cases – resulting in transient riffles due to episodic bed load accumulation. Effects of future hydrologic alterations in the drainage basin would occur within the context of ongoing geomorphic adjustments.

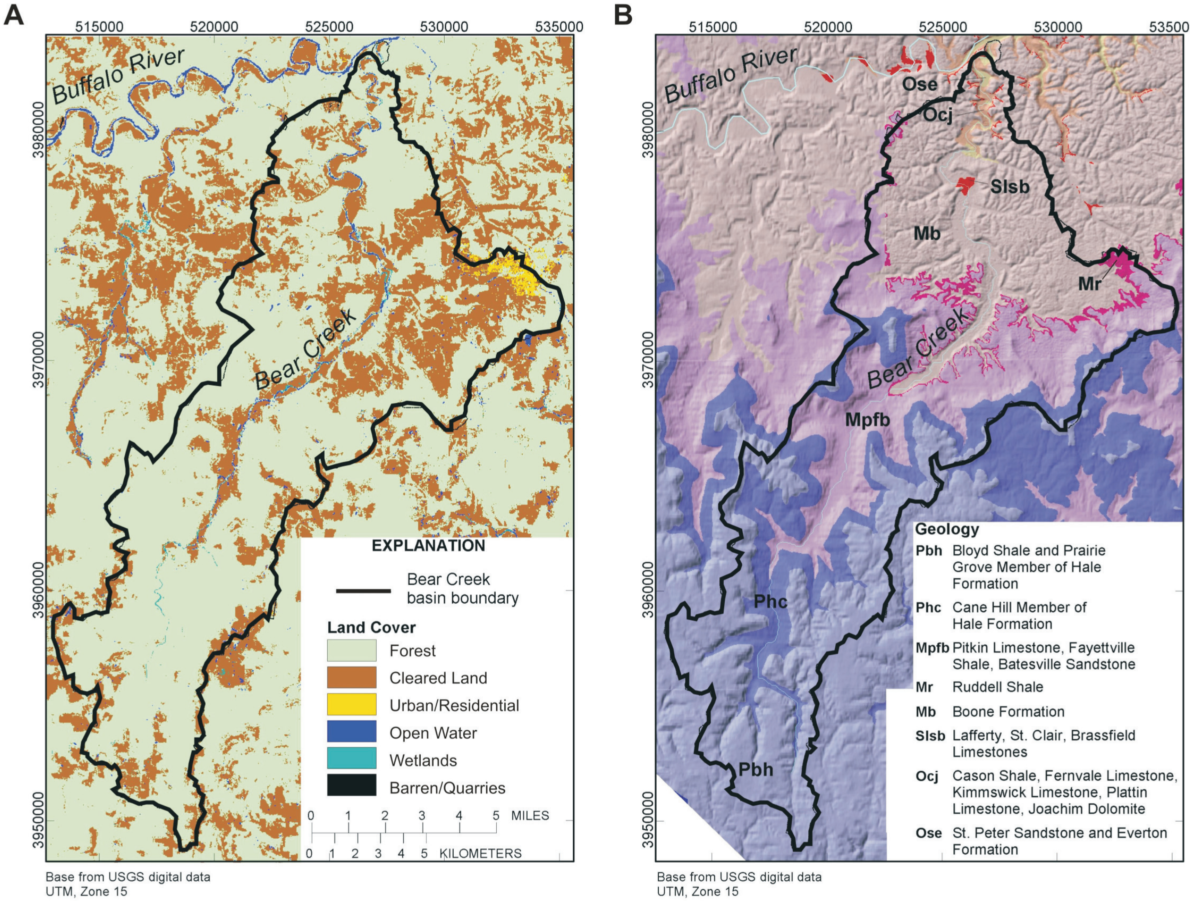
Physical setting of Bear Creek and Crane Bottom

The Buffalo River drainage basin lies within the Ozark Plateaus physiographic province (fig. 1), a region dominated by relatively flat-lying Paleozoic sedimentary rocks. Physiographically, the Buffalo River drains portions of the Boston Mountains, Springfield Plateau, and Salem Plateau. The Buffalo River's largest tributaries flow into the Buffalo from the south, where the high relief Boston Mountains are most prominent.

Bear Creek flows northward for a distance of approximately 45 kilometers from its headwaters to its junction with the Buffalo National River near the town of Gilbert. At the junction, Bear Creek has a drainage area of 239 km^2, making it the fifth largest of the Buffalo River's tributaries. The headwaters are in the rugged Boston Mountains, which are dominated by sandstone and shale bedrock formations of Pennsylvanian age. For much of its length, Bear Creek flows through a wide, flat valley that is heavily used as pasture land (fig. 5). The wide valleys are preferentially formed on the Mississippian Boone Formation, a highly permeable formation composed of soluble limestone and non-soluble chert. This chert tends to break into gravel-size pieces and is a major bed sediment source. For the 10 km just upstream of the junction with Buffalo River, Bear Creek flows in a valley floored by less permeable carbonate and sandstone of Ordovician age.

Approximately two kilometers before flowing into the Buffalo River, Bear Creek crosses the park boundary of the Buffalo National River (figs. 1, 2). The reach selected for this study (known as Crane Bottom) is the uppermost one kilometer of Bear Creek within the Buffalo National River boundary (fig. 6). The reach is entrenched and bordered on the river left (left bank when facing downstream) over most of its length by a steep bedrock bluff and on the river right by fluvial terraces. The presently forming flood plain of Bear Creek is composed of gravel bars and partially vegetated surfaces inset at elevations 3-4 m below the general elevation of the fluvial terraces.

The Crane Bottom reach has a representative selection of hydraulic habitat units. The upstream end is a long glide with scattered boulders in the middle and left of the channel. At cross section 26 (fig. 7), Bear Creek bends to the right, forming a pool against the bedrock bluff. Downstream of cross section 26, Bear Creek has three riffle-race-pool sequences. At cross section 2, Bear Creek has another bluff pool as the channel bends to the left.



Base from USGS digital data
UTM, Zone 15

Base from USGS digital data
UTM, Zone 15

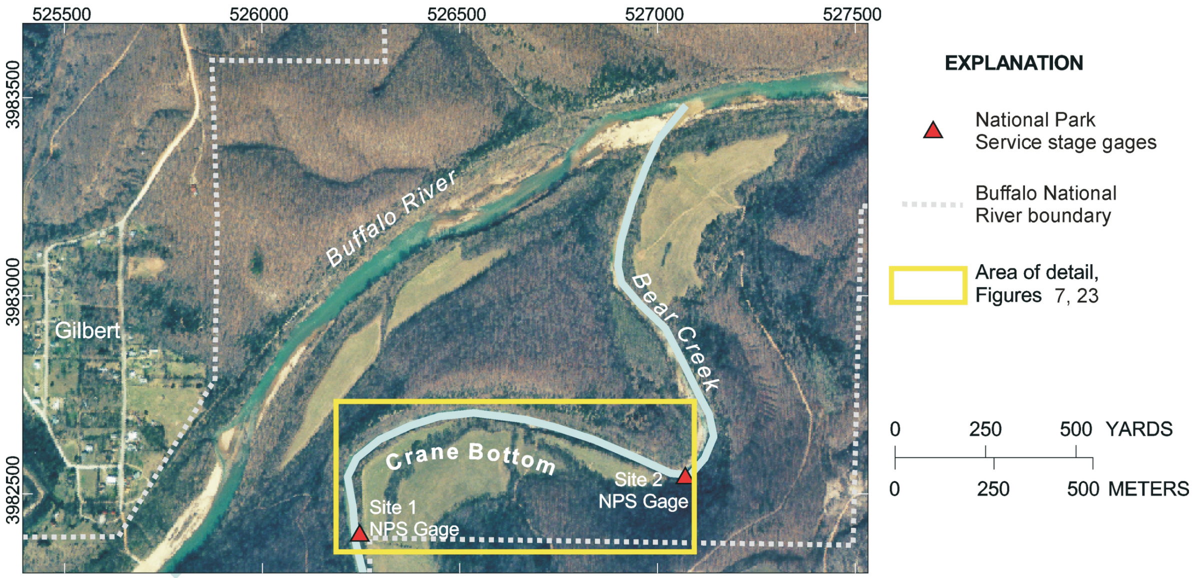
Figure 5. Maps of the Bear Creek drainage basin. A. Land use map showing major land-use categories. B. Geologic map on shaded relief, showing the steep slopes of the upper basin and the wide valley of Bear Creek cut into the Boone Formation. Digital elevation model from U.S. Geological Survey (2000a). Land-cover data from U.S. Geological Survey (2000b); geology data from Hofer and others (1995).

The high banks of the fluvial terraces are dominantly composed of particles sand size and smaller, with minor lenses of gravel-cobble sized material. The active channel is dominated by gravel and cobble, with patches of boulders and bedrock.

Local vegetation communities on the gravel-cobble bars include monocultures of perennial water willow (*Justicia americana*), patches of more diverse herbaceous vegetation including grasses, and, on higher bars, young trees, dominantly American sycamore (*Platanus occidentalis*) (fig. 8). The steep banks, as well as a buffer zone extending from the top of the steep banks to cleared fields, are vegetated with a combination of deciduous trees, herbaceous vegetation, and local stands of cane (*Arundinaria gigantea*). The cleared areas on the terraces are maintained as hay fields, and are therefore free of woody vegetation.

The climate of Bear Creek is humid, temperate with a mean annual temperature of 14.7 °C (58.5 °F) and mean annual precipitation of 1110 mm (43.7 in) (Marshall, Arkansas weather station, National Oceanic and Atmospheric Administration, 2002). Peaks in the seasonal distribution of precipitation occur in March-May and in November (fig. 9). Although measurable snowfall occurs in almost every year, snowfall is a minor component of total precipitation and rarely remains more than a few days.

Bear Creek is gaged at U.S. Highway 65 where the drainage area is 212.7 km^2 (83.1 mi^2), or approximately 91% of the total drainage of Bear Creek upstream of the junction with Buffalo River (Petersen and others, 2002; fig. 2). This streamgage was installed by the U.S. Geological Survey in January 1999 and has been operated to the present (2003). Streamflow is highly variable, reflecting the combined effects of high runoff and highly variable meteorological inputs (fig. 10). Mean daily stream discharge for the period of record (January 22, 1999 – July 15, 2002) is 2.94 cubic meters per second (cms). This value is considerably higher than 1.58 – 1.78 cms values cited in Petersen and others (2002) because it is averaged over a longer time period and includes large



Base from USGS digital data
UTM, Zone 15

Figure 6. Detailed map of the Crane Bottom study reach, boundaries of the Buffalo National River, and locations of the stage gages operated at Crane Bottom.

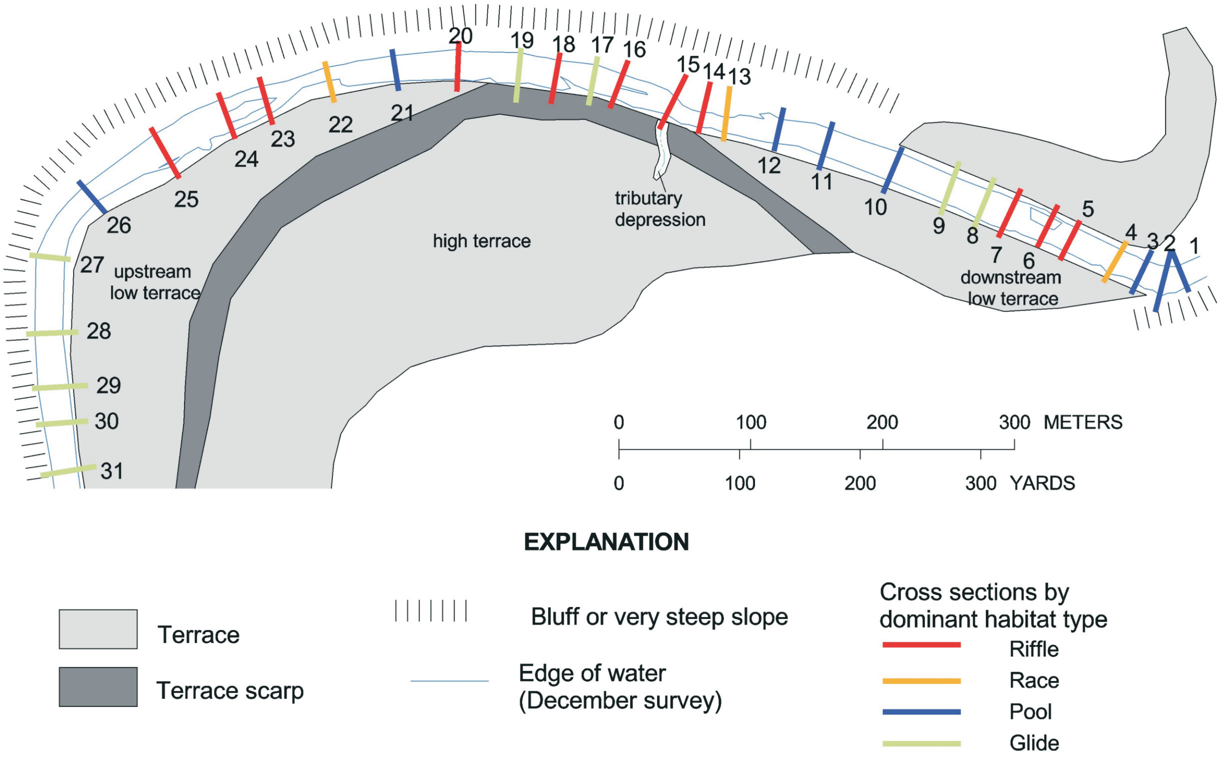


Figure 7. Detailed map of Crane Bottom study reach showing cross section locations and physiographic details.

discharges in calendar years 2001 – 2002.

Bear Creek has high concentrations of nutrients, dissolved organic carbon, fecal-indicator bacteria, and suspended sediment relative to the Buffalo River mainstem and other lowland-use-impact reference basins in the Ozarks; however, nutrient concentrations in Bear Creek were considerably lower than those found in the Illinois River (Arkansas), a river affected by waste-water treatment outfalls, extensive pastureland, and poultry waste (Petersen and others, 2002).

Approach

This study used a combination of field- and modeling-based analytical tools. Field-based data collection was used to document and quantify geomorphic changes and to collect data for construction, calibration, and validation of hydraulic models. Two-dimensional modeling was used to assess habitat variation with discharge as well as bed-material entrainment flows.

We addressed geomorphic dynamics–the rates and processes of erosion and deposition that change channel and flood-plain topography–by measuring geomorphic change in three ways. The most fundamental measure of geomorphic change was obtained by resurveys of thirty-one channel cross sections and by direct calculation of erosion and deposition between surveys. A pair of cross-section surveys can reveal *net* surface topographic change, but in cases of erosion followed by deposition, the total amount of change cannot be detected by cross-section surveys alone. To address this, we used scour chains to assess whether scour and fill took place in the channel. Finally, we attempted to use painted rocks to identify flow conditions that are sufficient to initiate sediment movement.

We constructed, calibrated, and validated a two-dimensional, finite-element hydraulic model based on field measurements of topography, vegetation, particle-size distributions, and water-surface elevations. Results of the model were analyzed in a geographic information system (GIS) to quantify habitat classes that exist during a range of discharges. The timing and duration of habitat availability were

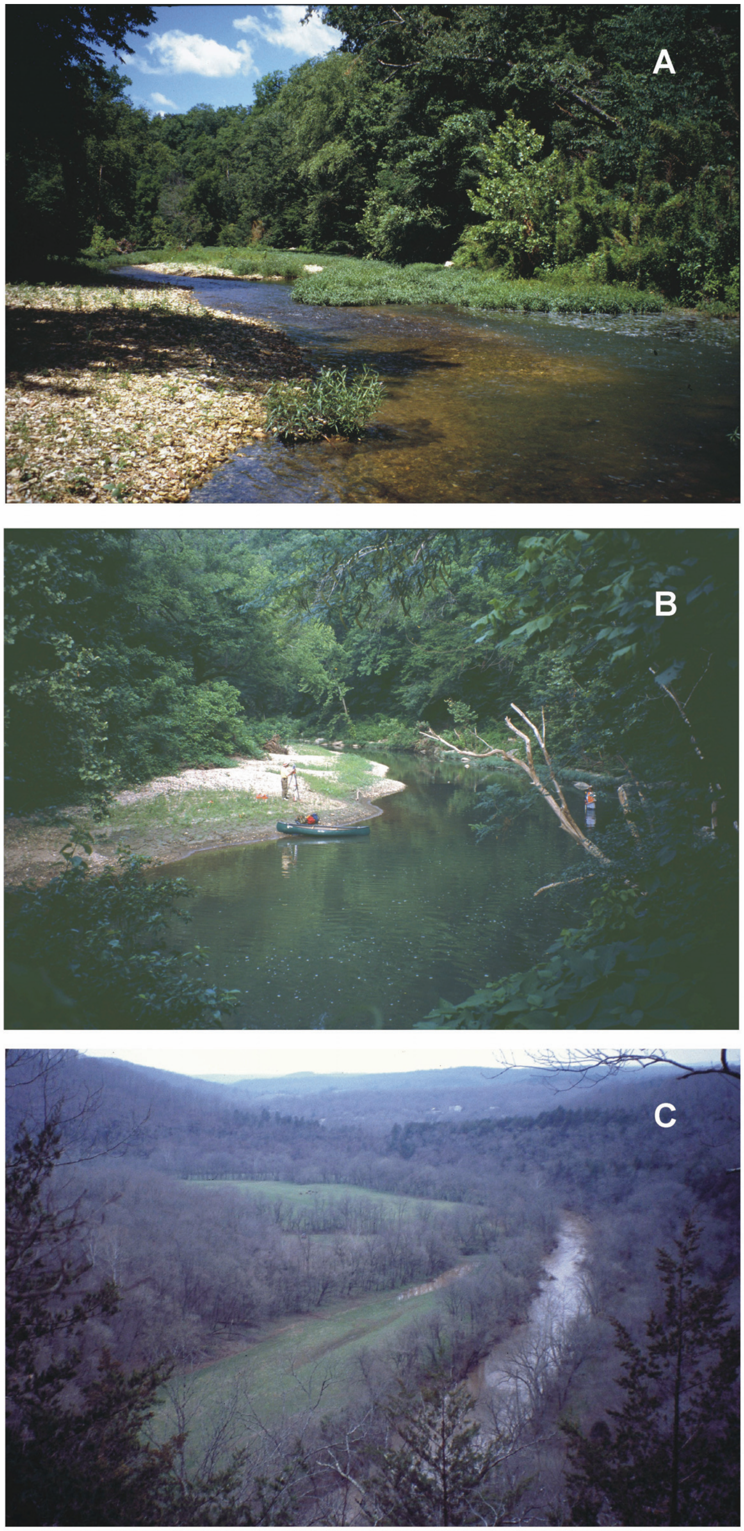


Figure 8. Photographs of vegetation at Crane Bottom. A. View of Bear Creek at stream level showing gravel bars with water willow and deciduous woody vegetation on banks. View is looking upstream near cross section 23. B. View of downstream pool at cross section 1 showing sparse vegetation on gravel bar. C. Overview of Crane Bottom looking to the west and upstream, just after an overbank flood, March 19, 2002. Foreground is downstream low terrace, cross sections 5-12. Banks have deciduous woody vegetation and terrace surfaces are in grass.

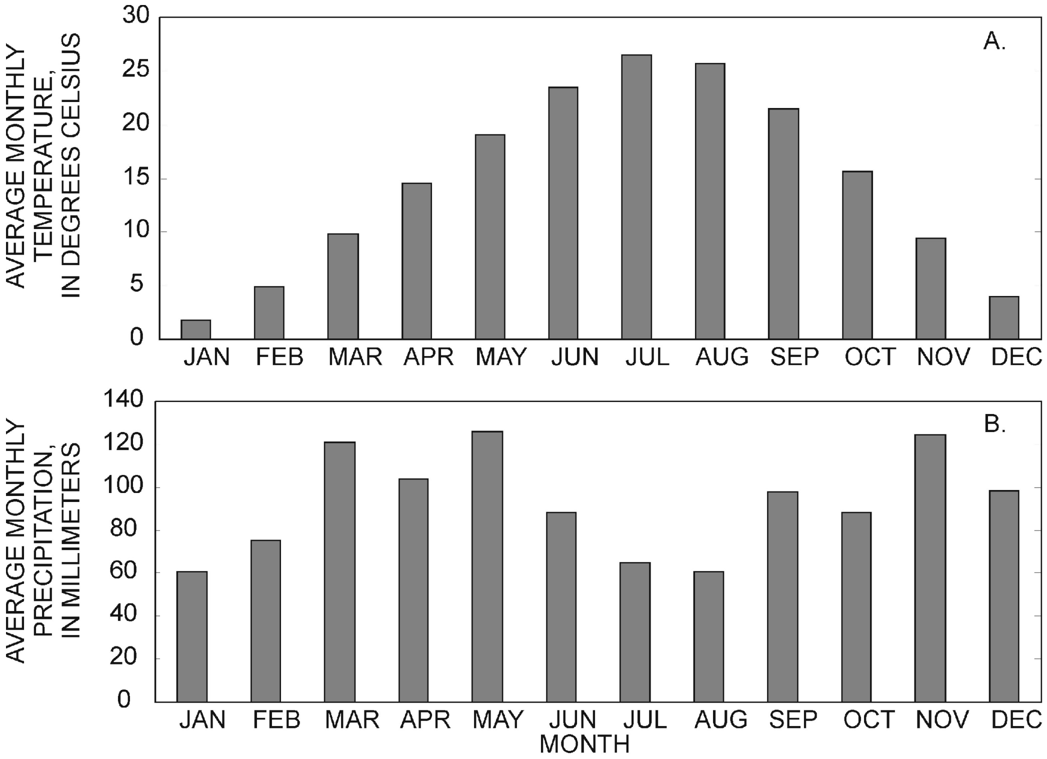


Figure 9. Climatological data from Marshall, Arkansas. A. Monthly average temperature. B. Monthly average precipitation. Data from National Oceanic and Atmospheric Administration (2002).

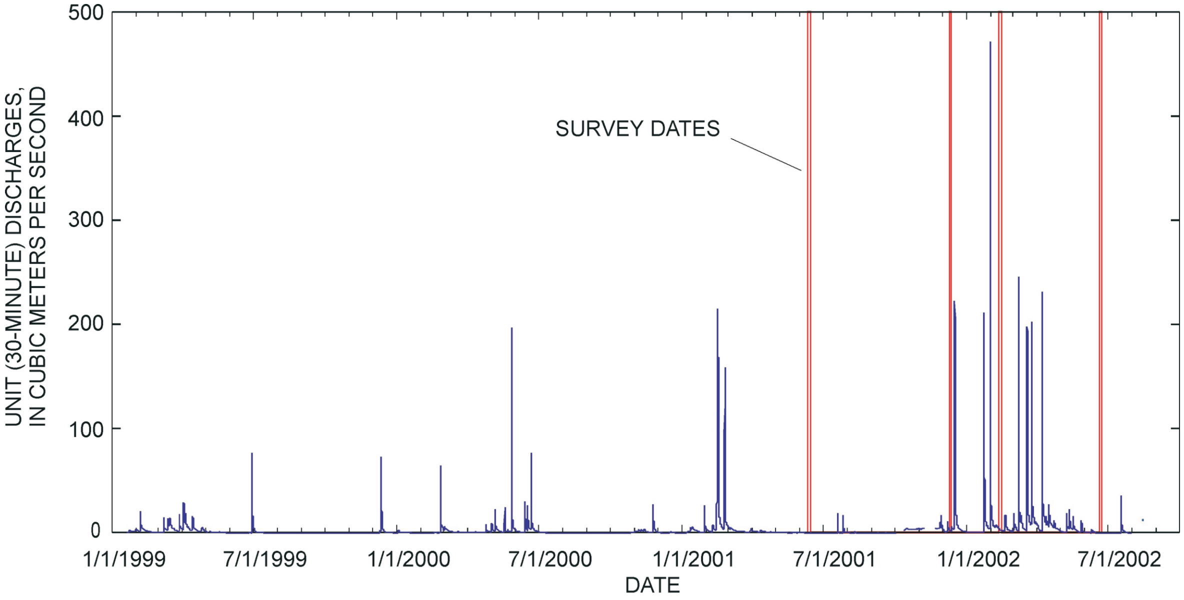


Figure 10. Hydrologic record of 30-minute discharge values. U.S. Geological Survey streamflow gaging station Bear Creek near Silver Hill, Arkansas, and dates of cross section surveys at Crane Bottom.

quantified using discharge data from the U.S. Geological Survey streamgage on Bear Creek. The frequency of bed-material entrainment events were assessed from the monitoring data and from simple boundary shear-stress calculations from the two-dimensional hydraulic model. The model shear stress calculations are compared with particle-size distributions on the bed of Bear Creek to determine the frequencies of flows that are capable of initiating movement of bed material and maintaining habitats under present-day conditions.

These analyses quantify physical habitat dynamics under the prevailing, baseline hydrologic conditions. This understanding is important background for assessing potential effects of future hydrologic alterations on habitat sustaining and maintaining flows. Prediction of actual differences attributable to flow alterations on Bear Creek, however, would require synthesis of a hydrologic time series for the altered future conditions; this level of analysis is beyond the scope of this report.

Analysis of the quantity of habitat available at various discharges depends on the assumption that channel morphology does not change with discharge. This is a common assumption for instream flow studies and many hydraulic modeling efforts, but the assumption limits ability to address the role of high flows in creating and maintaining habitat through erosion and deposition. Conventionally, instream flows are separated into those that provide habitat for stream organisms most of the time (and with emphasis on minimum low flows) and those that maintain habitat, or so-called flushing flows (Gordon and others, 1992). In reality, there is a continuum among flows because morphology is subject to alteration as soon as sediment transport begins. In rivers where substrate is dominated by coarse bed material, sediment transport may initiate over a narrower range of flows (compared to rivers with mixed-size bed material) and the assumption of distinctly different flows regimes would be better justified. In this report, habitat availability is calculated for the entire range of modeled discharges, but reliability of habitat estimates is considered less for sediment-transporting discharges near or above bankfull.

The following sections of this report present information on:

- Hydrology of Bear Creek at the Crane Bottom study reach.
- The effects of geomorphic dynamics on habitats measured from cross section monitoring, scour chains, and painted rocks experiments.
- The effects of hydrologic dynamics on habitats assessed through hydraulic modeling.
- Analysis of sediment transport potential from hydraulic modeling.

The specific methods used in each study component are presented with the results.

Hydrology of Bear Creek at Crane Bottom

Understanding of stream habitat dynamics of Bear Creek at Crane Bottom requires an understanding of the magnitude, frequency, duration, and sequence of flows that sustain and maintain habitats. This section presents information on the hydrology of Bear Creek as measured at Silver Hill, Arkansas, and extended to the Crane Bottom study site (fig. 2).

Methods

Crane Bottom does not have a discharge-rated streamgage with a record of sufficient length for understanding variability of flow over time; therefore we developed our understanding of hydrology at Crane Bottom by reference to the U.S. Geological Survey streamflow gaging station record for Bear Creek near Silver Hill, Arkansas. We used data from this streamgage for the period from January 1999 (when the streamgage was installed) to July 2002 (the end of active data collection for this study). Because the Silver Hill streamflow record is only about 3.5 years long, however, we also used additional streamgage records for reference (fig. 11). Ideally, these records would be from drainage basins that are located near Bear Creek, drain similar physiographic terrain, are of comparable drainage area, and cover the same period of record as the Silver Hill streamgage but extend further back in time. These conditions cannot all be met; reference gages are listed in table 1 and shown in figure 11.

Two pressure transducers and data loggers were installed to document water-surface elevations at the upstream and downstream ends of the Crane Bottom reach (fig. 7). The pressure transducers were surveyed into the coordinate system used for cross section surveys. The loggers were set to record water depths at 15-minute intervals. Discharge measurements were made by National Park Service personnel at Crane Bottom in conjunction with routine water-quality sampling, using standard streamgaging techniques for wading measurements. These discharge measurements are used to construct stage-discharge relations for low flows at the site and to evaluate relations between discharge at Crane Bottom and discharges measured upstream at the U.S. Geological Survey streamgaging station at Silver Hill.

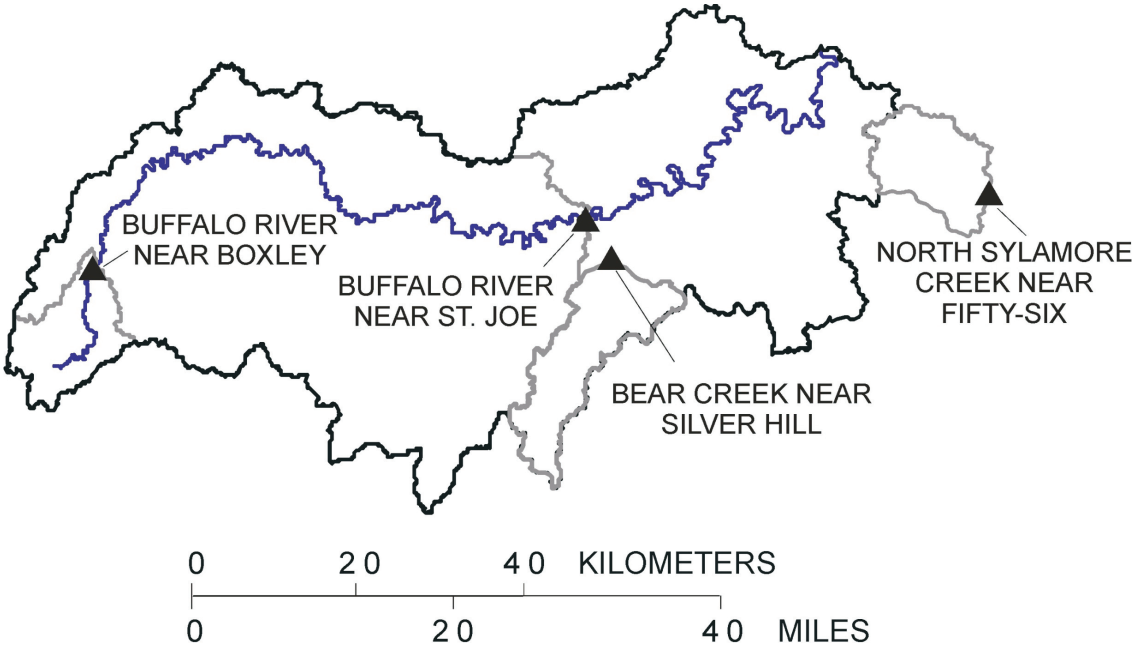


Figure 11. Locations of streamflow gaging stations used in hydrologic analysis.

Flow duration

The time period during which channel morphology was monitored at Crane Bottom (June 2001 – June 2002) was wet relative to the average. Five rain gages maintained by the National Park Service in the Bear Creek drainage basin vicinity received totals of 1473, 1610, 1422, 1671, and 1547 mm (millimeters) of rainfall June 1, 2001 – May 30, 2002 (National Park Service, Harrison, Arkansas, unpublished data), compared to the annual average rainfall of 1110 mm, 1971 – 2000 (National Oceanic and Atmospheric Administration, 2002). Daily mean discharge for Buffalo River near St. Joe during 6/1/2001 – 6/30/2002 was 44.6 cms compared to a long-term daily mean discharge (1940 – 2002) of 30.0 cms (U.S. Geological Survey, 2003). Furthermore, the periods of higher-than-normal rain were concentrated in the winter and early spring months. Hence, during the study period Bear Creek probably had higher flows and more geomorphic activity than average.

The percent of time that given flows are equaled or exceeded is a basic reference for the temporal distribution of flow. In this report, flow exceedance values are referenced to the percent of the total period of record of each gage; for short records that do not sample average hydroclimatic conditions, these exceedance values could be biased. Flow exceedances – using daily mean flows, undifferentiated by season or year – for Bear Creek at Crane Bottom (as stages), Bear Creek near Silver Hill, Buffalo River near Boxley, and North Sylamore River near Fifty Six show that most of the time flow in these small drainage basins is constant and low (fig. 12). The interquartile range of stages (stages equaled or exceeded between 25 and 75 percent of the time) was only 23 cm at the upstream streamgage and 32 cm at the downstream streamgage at Crane Bottom (fig. 12A); flows with stages in excess of 2 m above the lowest stages occur only 1-2 percent of the time, or 3-7 days per year.

Discharge-rated streamgaging stations on similar streams show similar variation. Despite substantial differences in drainage area, North Sylamore Creek, Buffalo River at Boxley, and Bear Creek near Silver Hill have similar flow-duration curves (fig. 12B, C). Compared to Buffalo River at Boxley and North Sylamore Creek, Bear Creek at Silver Hill has a more constant baseflow discharge; North Sylamore Creek is somewhat flashier than the other two streams at flows greater than the median. The interquartile ranges of discharges on Bear Creek near Silver Hill, Buffalo River near Boxley, and North Sylamore Creek are 2.1, 2.7, and 0.8 cms. These comparisons should be evaluated cautiously because of the relatively short record lengths for Bear Creek near Silver Hill and Buffalo River near Boxley (table 1).

Seasonality of flows is especially important to aquatic biota whose life cycles are synchronized to characteristics like seasonal habitat availability, water temperature, or length of day. Seasonality and flow duration were addressed using frequency hydrographs for two gages with sufficient record lengths, North

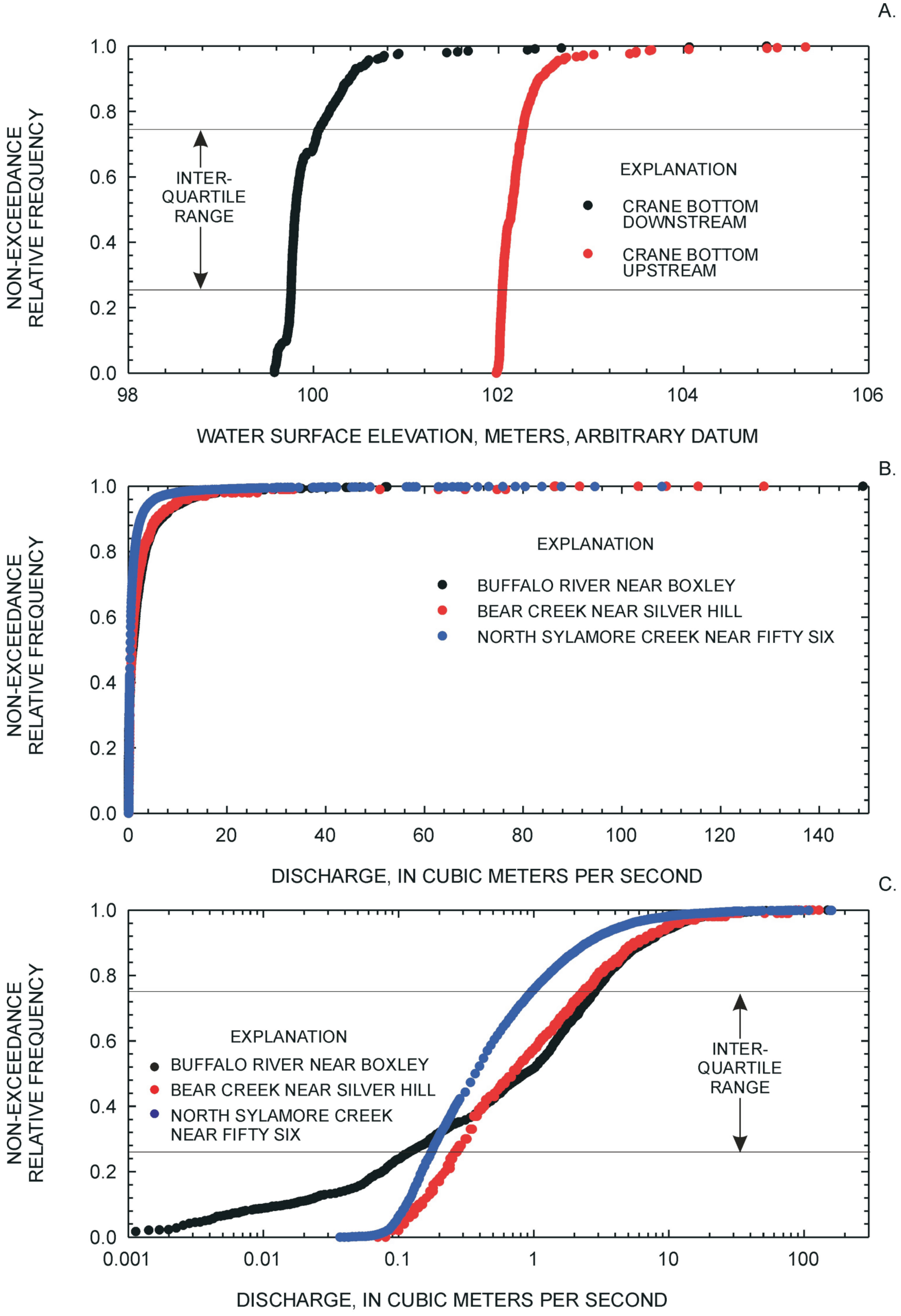


Figure 12. Flow duration data for Bear Creek at Crane Bottom and reference streamgages. A. Elevation durations at two stage gages, Crane Bottom. B. Flow durations for Buffalow River near Boxley, Bear Creek near Silver Hill, and North Sylamore Creek near Fifty Six. C. Flow duration data for three gages above, using a logarithmic plot.

Table 1. Information on streamgaging station data used in this report

Gage	USGS number	Drainage area, square kilometers	Length of record, notes
Bear Creek near Silver Hill, Arkansas	07056515	212.7	Daily streamflow, 1/22/1999 to present[1] Annual peak flow, 3 events
Buffalo River near St. Joe, Arkansas	07056000	2122.2	Daily streamflow, 10/1/1939 to present Annual peak flow, 64 events
Buffalo River near Boxley, Arkansas	07055646	146.9	Daily streamflow, 4/17/1993 to present Annual peak flow, 8 events
North Sylamore Creek near Fifty-Six, Arkansas	07060710	148.7	Daily streamflow, 12/9/1965 to present Annual peak flow, 36 events

[1] present = July 2002; streamgaging continues at these gages.

Sylamore near Fifty Six and Buffalo River near St. Joe (fig. 13). These diagrams include a cumulative frequency analysis of flow for every day of the year during the period of record. When the frequencies are plotted by day of year, the seasonal variability is apparent in variation along the x-axis and inter-annual variation is apparent in variation along the y-axis.

As representatives of drainage basins in northern Arkansas, these two records show the broad seasonality of increased discharge March-May and low flow August – November. The lowest flows occur in September. The period November – December is characterized by large inter-annual variability. The highest flows during the year can occur any time during September – June.

Peak flows

Flows capable of transporting large quantities of sediment are typically considered floods. Geomorphic theory supports the idea that the floods that are most effective at maintaining the channel and transporting sediment are bankfull flows, with typical recurrence intervals of 1.5 – 2.0 years (Wolman and Miller, 1960; Andrews, 1984). The length of record for Bear Creek at Silver Hill is insufficient for flood frequency analysis, so the probabilities of floods on Bear Creek during the course of this study were assessed by reference to probabilities calculated for North Sylamore near Fifty Six, Buffalo River near Boxley, and Buffalo River near St. Joe (table 2). This analysis used the annual series of peak discharges, fit to a Log Pearson Type III curve following the guidelines of the Interagency Advisory Committee on Water Data (1982); the U.S. Geological Survey software PEAKFQ v. 4.1 (Thomas and others, 1998) was used in this analysis.

A short record of peak flows (eight years) on Buffalo River near Boxley results in wide 95% confidence intervals for flood probabilities (fig. 14A). The longer record at North Sylamore (fig. 14B) provides a more accurate estimate of flood frequency in drainage basins of this size; the record of Buffalo River near St. Joe (fig. 14C) may be somewhat unrepresentative of flood frequencies on Bear Creek because the drainage area is so much larger (table 1).

By comparing probabilities (or recurrence intervals) for the same floods – and noting similarities or differences – in peak flows per unit drainage area (unit peak discharges) the Bear Creek floods can be put into context. Unit peak discharges generally decrease with increasing drainage area because of decreasing probabilities of receiving uniformly intense rainfall over larger drainage basins. Hence, unit peak discharges would be expected to be larger for floods of comparable recurrence on North Sylamore and Buffalo River near Boxley, compared to Bear Creek. Conversely, unit peak discharges on Buffalo River near St. Joe would be expected to be smaller for floods of the same probability. Based on these references, the floods of 2/16/2001 and 3/19/2002 were estimated to have recurrence intervals close to one year, whereas the flood of 12/16/2001 was estimated at slightly higher, 1-2 years. The flood of 1/31/2002 was estimated at between 2 and 4 years recurrence based on the high unit discharge and National Park Service precipitation records that indicated the Bear Creek basin received considerably more precipitation than the upper Buffalo River near Boxley.

Backwater

Flows at Crane Bottom are affected at times by high water on the mainstem Buffalo River, nearly 1 km downstream. For example, during the flood of December 2001, the mainstem Buffalo River streamgage (approximately 9 km upstream from the Bear Creek junction) peaked at a stage of 8.5 m, 12 hours after Bear Creek. The first rise from this flood on Bear Creek at Crane Bottom occurred at about midnight, but a second peak occurred 6 hours later, simultaneous with the peak on the Buffalo River. The second peak was higher at the downstream stage gage at Crane Bottom than at the upstream stage gage at Crane bottom (fig. 15A.). Hence, this backwater substantially decreased the slope of Bear Creek in the study reach.

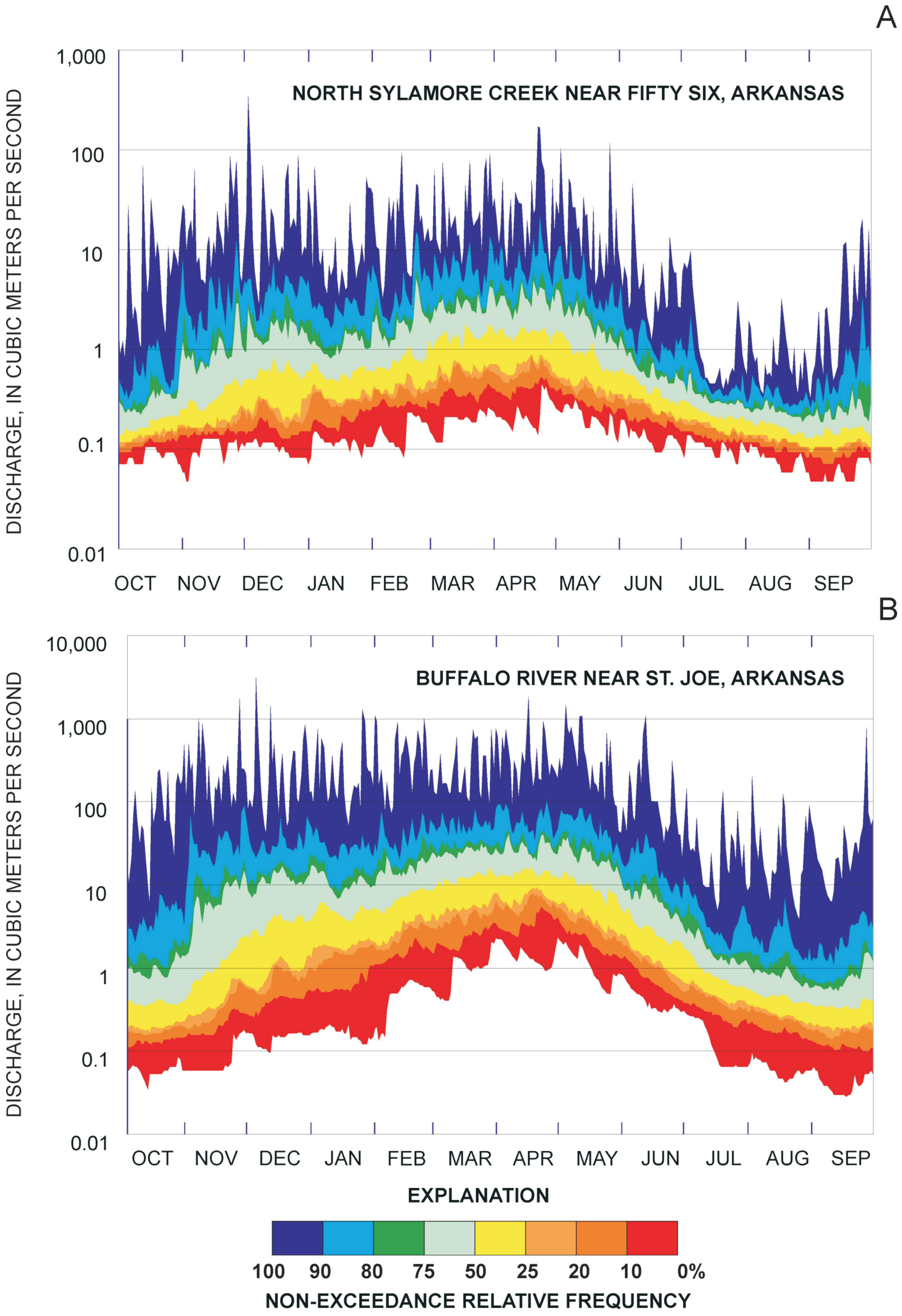


Figure 13. Frequency hydrographs for streamgaging stations at: A. North Sylamore Creek near Fifty Six, Arkansas and B. Buffalo River near St. Joe, Arkansas.

Table 2. Peak discharges, exceedance probabilities, and approximate recurrence intervals for four floods, February 2001 - March 2002. Three reference gages show comparable values for the same flood. Probabilities were calculated from U.S. Geological Survey peak-flow files, using the recommended "Bulletin 17-B" guidelines with regional skew coefficients (Interagency Advisory Committee, 1982).

[km^2, square kilometers; cms, cubic meters per second; est., estimated]

Gage	Drainage area, km^2	Peak, cms	Unit peak discharge, cms/km^2	Approximate annual exceedance probability	Recurrence interval, years	Peak, cms	Unit peak discharge, cms/km^2	Approximate annual exceedance probability	Recurrence interval, years
		2/16/2001				**12/16/2001**			
Bear Creek near Silver Hill	123	220	1.79		*est.: 1*	310	2.52		*est.: 1-2*
Buffalo River near Boxley	147	130	0.88	0.9	1.1	290	1.97	0.44	2.3
Buffalo River near St. Joe	2,122	820	0.39	0.6	1.7	1200	0.57	0.44	2.3
North Sylamore Creek near Fifty Six	149	80	0.54	0.68	1.5	150	1.01	0.42	2.4
		1/31/2002				**3/19/2002**			
Bear Creek near Silver Hill	123	460	3.74		*est.: 2-4*	200	1.63		*est.: 1*
Buffalo River near Boxley	147	150	1.02	0.88	1.1	200	1.36	0.75	1.3
Buffalo River near St. Joe	2,122	920	0.43	0.56	1.8	1530	0.72	0.32	3.1
North Sylamore Creek near Fifty Six	149	220	1.48	0.28	3.6	100	0.67	0.58	1.7

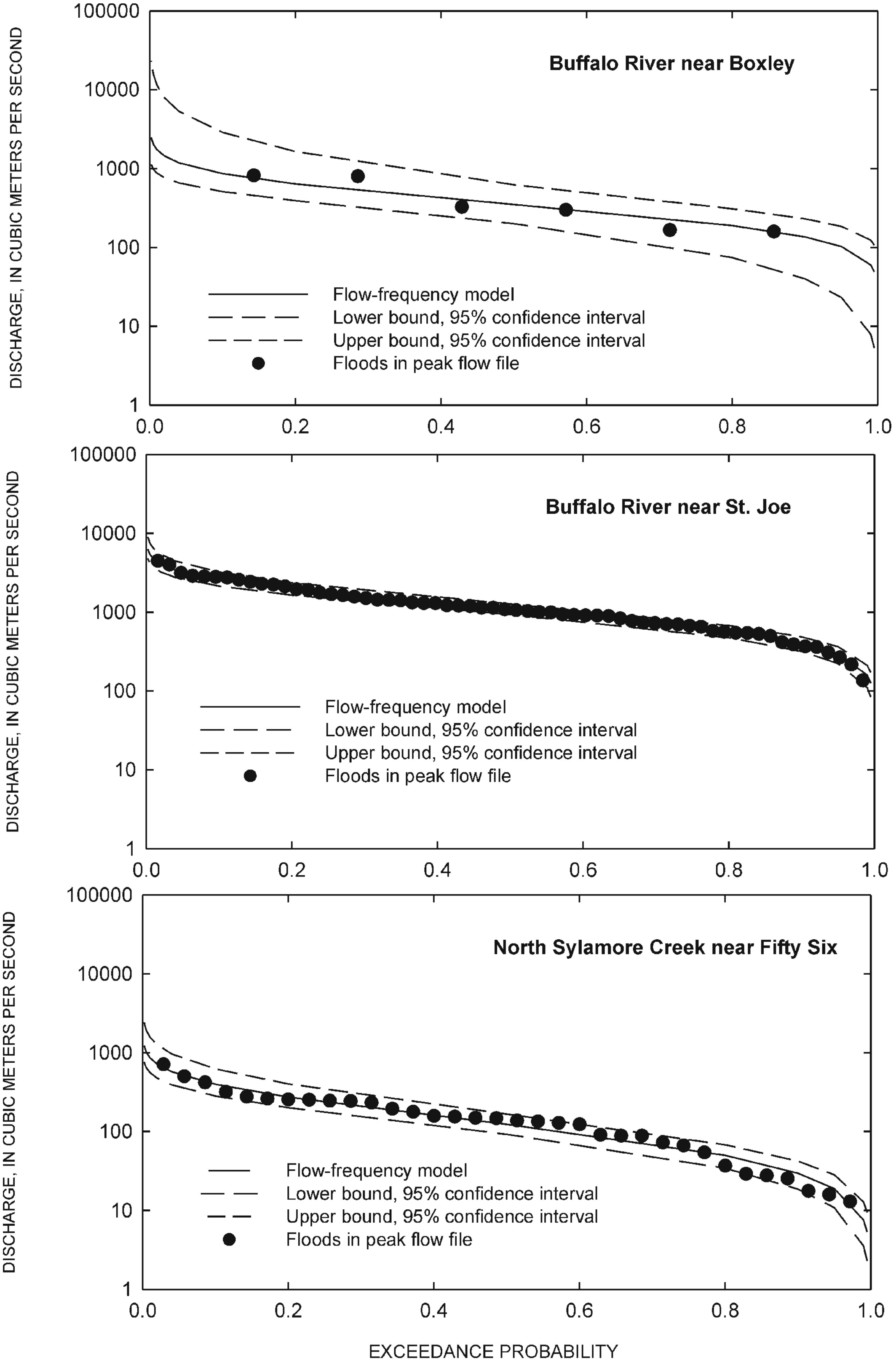


Figure 14. Flood frequency analyses showing annual exceedance probabilities for A. Buffalo River near Boxley, Arkansas, B. Buffalo River near St. Joe, Arkansas, and C. North Sylamore Creek near Fifty Six, Arkansas.

In comparison, the flood of January 24, 2002 was of smaller magnitude on Buffalo River, and the flow of Bear Creek at Crane Bottom was unaffected by backwater (fig. 15B). The flood of January 31, 2002 (fig. 15C) was intermediate on the Buffalo River (about 5 m rise), and affected water-surface elevations on Bear Creek, but to a lesser extent compared to the December flood.

These examples indicate that backwater can affect flood flows at Crane Bottom when stages of about 5 m or greater occur on the mainstem within about 24 hours of peaks on Bear Creek. Because flows on the Buffalo River and Bear Creek generally result from the same weather systems, backwater is a possibility when Buffalo River is in flood. Small, concentrated storm cells over the Bear Creek drainage basin could possibly cause floods on Bear Creek without corresponding floods on Buffalo River. It is also possible that backwater from floods on the mainstem could affect Bear Creek at Crane Bottom when flows are

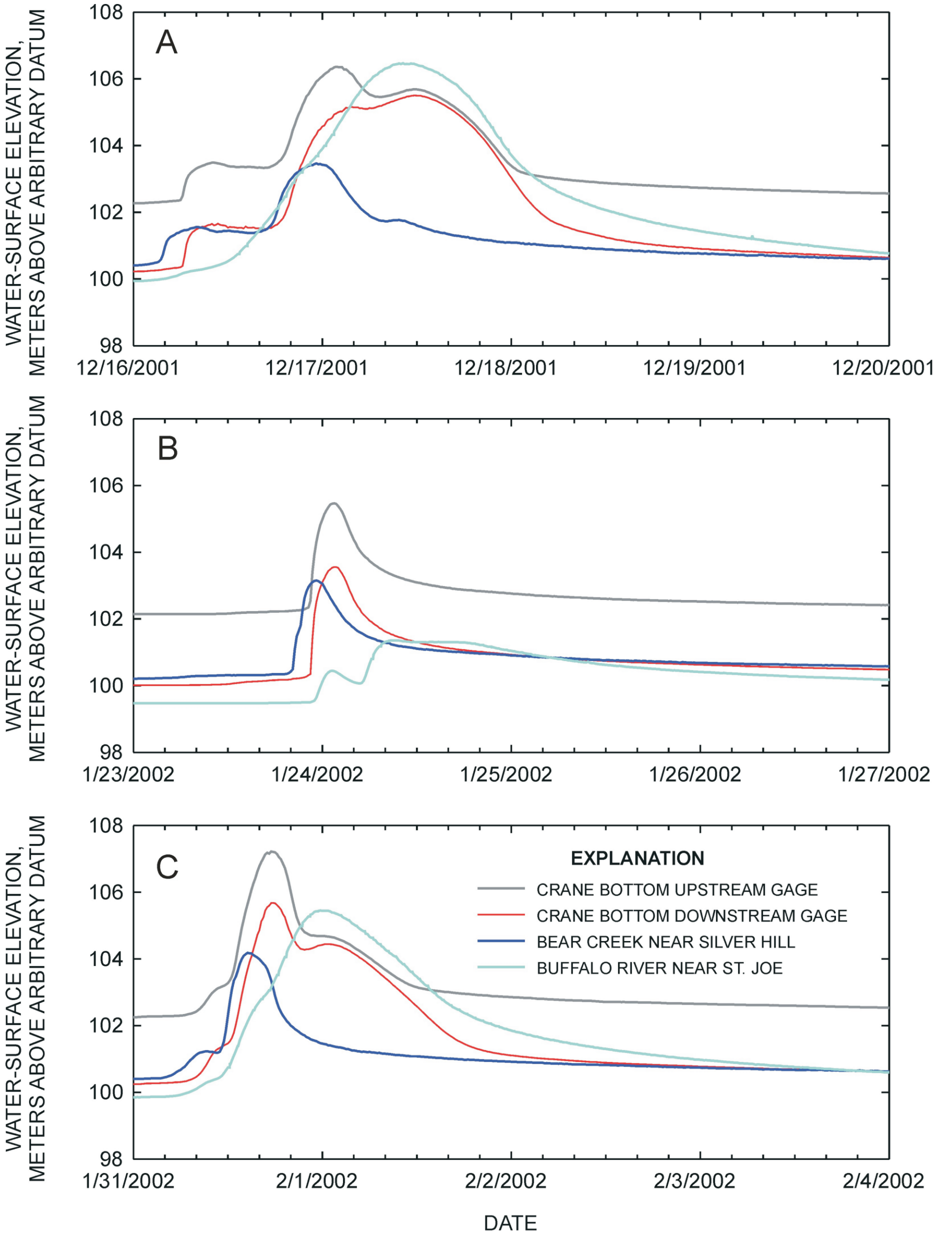


Figure 15. Hydrographs showing stages at Buffalo River near St. Joe, Arkansas and Bear Creek, near Silver Hill, Arkansas, and backwater effects at Crane Bottom. The Crane Bottom stages are graphed on the same arbitrary datum; the stages for Buffalo River and Bear Creek near Silver Hill have been shifted vertically for ease of comparison. A. Flood of December 16-20, 2001. B. Flood of January 23-27, 2002. C. Flood of January 31-February 4, 2002.

low on Bear Creek.

Water-surface slope serves as an indicator of backwater at Crane Bottom. Under normal variation of flows without backwater effects, the water-surface slope of Bear Creek tends to decrease with increasing discharge (fig. 16A). The relation between slope and discharge developed from estimated discharges at Crane Bottom and measured slopes between the two stage gages indicates that slope decreases rapidly from 0.002 to 0.0016 as discharge increases from 0 to about 15 cms. Water-surface slope then decreases less rapidly to a minimum value of 0.0013 at 556 cms (about 4-year recurrence flow).

During a flood event affected by backwater, however, water-surface slopes can be substantially decreased. For example, the flood of 12/16 – 12/18/2001 exhibited an expected decrease in slope with increasing discharge during the non-backwater part of the flood (figs.15, 16B). About mid-day on 12/17/2001, however, flow on the Buffalo River

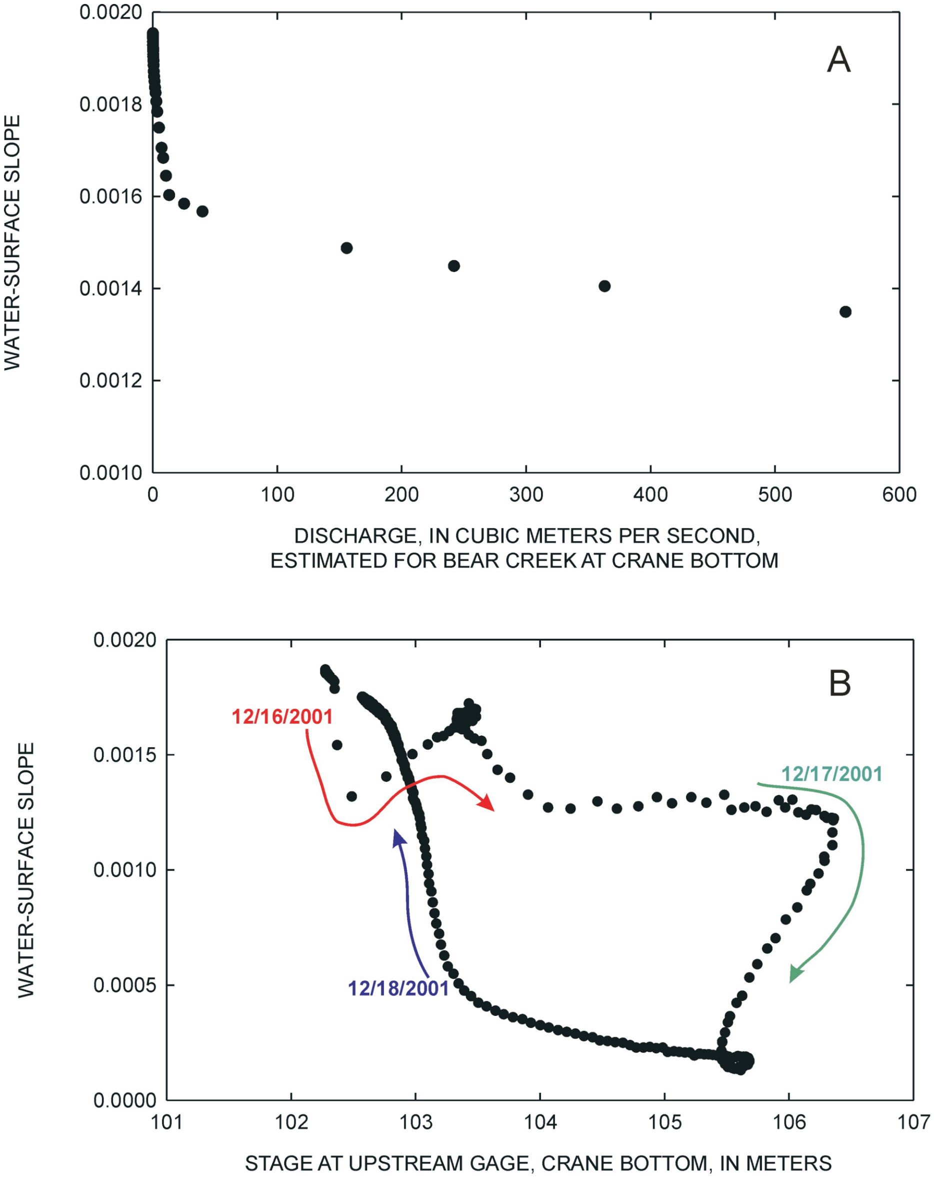


Figure 16. Discharge, stage, and water-surface slopes at Crane Bottom illustrating backwater conditions. A. Water-surface slope and estimated discharge for Bear Creek at Crane Bottom for non-backwater conditions. B. Relation between upstream stage and water-surface slope calculated between upstream and downstream gages at Crane Bottom, showing effects of backwater from the Buffalo River mainstem on water-surface slope at Crane Bottom.

mainstem began to create a backwater effect at Crane Bottom, and slopes decreased to as low as 0.00014 before recovering on 12/18/2001 as the backwater effect diminished.

The temporal distribution of backwater effects was assessed by evaluating how often water-surface slopes decreased below 0.0013 at the study site; a slope of 0.0013 would still maintain flow through the reach, so this slope is a conservative threshold that indicates a slowing of velocities rather than a zero-velocity backwater conditions. The cumulative frequency distribution of water-surface slopes at Crane Bottom for the period from May 2001 to July 2002 (approximately 340 days when both gages were operating) shows that water-surface slopes were in excess of 0.0013 92% of the time.

Although backwater conditions are infrequent, they have the potential to alter sedimentation patterns, and hence habitat characteristics. Because backwater conditions typically occur toward the end of the flood events on Bear Creek, high shear stresses and bed-material entrainment conditions are followed by low water-surface slopes, low shear stresses, and conditions favorable to deposition of sediment. Backwater events have the potential, therefore, to deposit finer sediment and perhaps more sediment than would be deposited without the backwater conditions. However, the riffle-pool framework of fluvial habitats is presumably maintained by the non-backwater peak flows that typically occur before the onset of backwater conditions. Because this study is concerned with habitats that exist most of the time for stream organisms, the hydraulic model to evaluate sensitivity of habitats to flow ignores backwater effects. Our analysis of habitat maintaining flows concentrates on the sediment-transporting capabilities of peak flows exclusive of backwater conditions because understanding of the functions of these flows is applicable to most of the length of Bear Creek that is not subject to backwater effects.

Geomorphic Dynamics and Habitat

Geomorphic dynamics refers to the changes in physical habitat template that occur because of erosion and deposition. We evaluated geomorphic dynamics using field measurements of channel changes.

Methods

A modified “Wolman” pebble count (Wolman, 1954) was performed at cross sections in June 2001 to document substrate size in the Crane Bottom reach. The technique follows that of Panfil and Jacobson (2001) in which 100 particles were randomly selected from the bed and measured with calipers (or if too large, with an engineer’s ruler). This protocol samples along a cross-section, and approximately 5 m upstream and downstream, between the estimated bankfull elevations of both banks. The particle size data were used in statistical descriptions of stream substrate and as an aid to estimating roughness height values for hydraulic modeling.

Thirty-one topographic cross sections were benchmarked during June 2001 to document geomorphic change and to aid in construction of a topographic mesh for hydraulic modeling (fig. 7; table 3). Cross-section endpoints were established with pieces of 13 mm diameter rebar that were driven into the ground and tagged. Endpoints were located at elevations above anticipated flows, typically at elevations consistent with the alluvial terraces on the right bank. When possible, the rebar was placed just downstream of a large tree to reduce the chance of disturbance, as well as to help in finding the cross sections for subsequent surveys.

The cross sections were surveyed with a total station, and data were automatically logged into commercial software. Cross sections were referenced to an arbitrary local coordinate system that was used throughout the survey and modeling process. Each surveyed cross-section point was also classified according to the dominant particle size class (that is, the particle size class that is most dominant in the 1-m radius area around the point). Points along the cross sections were positioned on significant topographic breaks and were spaced no more than 5 m; most point spacings were on the order of 2 m except in very uniform topography. Cross sections had an average of 35 points per survey. Reproducibility of topographic cross-section surveys are limited mainly by point spacing and depth to which a surveying prism pole will sink into the ground, or around soil and sediment particles (DeVries and Goold, 1999). Sediment and soil material along these cross sections ranged from mud (0 – 0.05 mm) to large boulders (greater than 512 mm). Most of the materials that were eroded or deposited during the course of this project were in the sand to small-cobble size range (2-128 mm); accordingly, rod-placement error is estimated to be no more than 128 mm.

Cross sections were surveyed four times during the course of the study (June 2001, December 2001, February 2002, and June 2002). For each survey, a tag line was strung between the rebar endpoints to ensure that the original, straight cross section was surveyed. Geomorphic changes at each cross section were calculated by importing survey data (horizontal position and elevation) into a GIS, constructing polygons in the plane of the cross section, and intersecting data from subsequent dates to produce polygons of erosion or deposition. Net change was calculated as depositional area minus erosional area. Total

Table 3. Locations and descriptions of monumented cross sections used in this study
[c.s., cross section; diam., diameters; cm, centimeter; m, meter; d.s., downstream; u.s., upstream; lb, left bank; rb, right bank; n/a, not applicable]

Cross section number	Approximate distance to next c.s., in meters	Dominant habitat	Location of rebar	
			Left bank	Right bank
1	RB--25; LB--0	Pool	In shrubs, shared with C.S. 2.	Along pressure transducer pipe near bend.
2	18	Pool	In shrubs, shared with C.S. 1.	Upper bench near valley wall, just d.s. from 1 ft diam. mulberry
3	21	Pool	Near top of high bank; at base of roots of 46 cm box elder on u.s. side of tree.	Top of high bank, not next to a tree; about 1 m back from edge of steep bank; about 3 m u.s. from 5 cm diam. box elder; near trail to gage.
4	38	Race	Top of high bank just d.s. of 10” diam. dead tree and behind very large box elder.	On high bank just u.s. of 8 cm diam. box elder; very close to corner of field.
5	20	Riffle	At top of high bank, not near tree (except poison ivy).	Top of high bank just u.s. of small hackberry (approximately 5 cm diam. trunk is broken off near ground); fairly thick low vegetation.
6	31	Riffle	Top of high bank just d.s. of paw paw (3 small trunks all less than or equal to 2.5 cm diam.).	Top of high bank, not near a big tree; behind a fallen tree and in cane.
7	21	Riffle	On high bank, just d.s. of a small spicebush with multiple stems and near a couple of small paw paws.	Between 2 grape vines, just u.s. of 25 cm diam. elm.
8	28	Glide	Top of high bank, lower terrace; just d.s. of 5 cm diam. redbud; uphill from 20 cm diam. ash (also flagged).	Top of high bank; approximately 60 cm d.s. of a box elder with several small trunks (mostly < 2 cm diam.); nearest big tree is 38 cm diam. elm--this is about 6 m d.s. and slightly down bank.
9	45	Glide	Top of high bank, lower terrace, just before rise to upper terrace; approximately 60 cm d.s. of dead 3 cm diam. tree; a leaning box elder approximately in line with stake and approximately ½ way down bank also flagged.	Top of high bank, approximately 2 m d.s. of locust with twisted vines; small hackberry towards stream and d.s. of rebar also flagged.
10	54	Pool	Approximately 3 m d.s. of an 20 cm diam. locust.	Top of high bank; in cane, not near a big tree; a 30 cm diam. elm near top of bank and approximately 1 m d.s. of c.s. also flagged.
11	38	Pool	Top of high bank, not by a tree; an 20 cm diam. elm part way down bank and slightly d.s. of c.s. was flagged.	Top of high bank; through thicket of cane, immediately d.s. of dead tree (diam. > 30 cm); several other large trees nearby.
12	41	Pool	Top of high bank; not near any large trees, but a lot of small shrubs; a box elder (approximately 30 cm diam.) at base of high bank flagged--it is slightly u.s. of c.s. line. Barbed wire near base of high bank.	Just d.s. and slightly up bank of 38 cm box elder; approximately 1.5 vertical meters below top of high bank.
13	17	Race	Top of high bank, approximately 1 m d.s. of post oak with 3 trunks (approximately 30 cm, 25 cm, and 15 cm).	Top of high bank, approximately 2 ft u.s. of 46 cm diam. post oak; almost to u.s. edge of lower field. Original stakes washed out, replaced further along section.
14	24	Riffle	Top of high bank d.s. from approximately 13 cm diam. locust; among cane and other thick vegetation.	Top of high bank, just off corner of lower field and approximately in line with location where road drops down to the lower field; hackberry with 2 trunks that is leaning out over bank is approximately 2.5 m from rebar (approximately along c.s.). Original stakes washed out, replaced further along section.
16	20	Riffle	Just d.s. of 8 cm diam. osage orange with vine growing on it; vegetation is very dense.	Just d.s. of 30 cm diam. hackberry (2 large hackberries growing close together--the rebar is by the one that is set back farther from the bank).
17	29	Glide	In a thicket at very roughly the same elevation as right bank--go up slope at slab of rock that is against base of high bank; the elm tree next to this rock is flagged.	Top of high bank just d.s. of 30 cm diam. elm; back from edge of bank a few meters; separated from upper field by cane.

Table 3. Locations and descriptions of monumented cross sections used in this study**--Continued**

[c.s., cross section; diam., diameters; cm, centimeter; m, meter; d.s., downstream; u.s., upstream; lb, left bank; rb, right bank; n/a, not applicable]

Cross section number	Approximate distance to next c.s., in meters	Dominant habitat	Location of rebar	
			Left bank	Right bank
18	29		In thicket; not near any big trees; some small boulders present at base of bank; an elm tree approximately 18 cm diam. is growing at base of bank approximately 2 or 3 m above c.s.--this elm is also flagged.	Top of high bank, back from edge of bank approximately 10 m; d.s. of 5 cm diam. hackberry; a hornbean approximately in line w/ c.s. and part way down bank is also flagged.
19	46	Glide	1 m d.s. of 10 cm diam. persimmon; another persimmon down the bank and along the c.s. is also flagged.	Top of high bank (but not the higher terrace); d.s. of 5 cm diam. box elder which is growing within 15 cm of a 25 cm diam. redbud.
20	48	Riffle	Just d.s. of 20 cm diam. cedar that is at top of lowest ledge of bluff; just d.s. of first major bluff outcrop at stream level.	Top of high bank (lower terrace); just d.s. of 25 cm diam. honey locust
21	51	Pool	In thicket, not near a big tree; on bench at top of eroding steep bank; below the bluff.	Top of high bank, separated from field by stand of cane; just u.s. of 2 honey locusts, each 3 cm diam.; a hackberry part way down bank and approximately 1.5 m d.s. of c.s. also flagged
22	50	Race	At base of ash (15 cm diam.) and elm (25 cm diam.) growing together; approximately ½ way between stream level and rock bluff above.	Top of high bank, just d.s. of group of 3 osage orange trunks (approximately diam.: 15 cm, 10 cm, 5 cm); approximately 2 m back from steep slope.
23	32	Riffle	Just d.s. of approximately 30 cm diam. hop hornbean w/ poison ivy vine; approximately ¾ of way between stream level and bluff line.	Top of high bank, a few m back from drop off; in cane thicket, no big trees nearby.
24	56	Riffle	Below and d.s. of cave entrance (cave has large metal fence); at top of eroding bank; just u.s. of runoff channel from cave; a small (4 cm diam.) hickory approximately 2 m down slope along c.s. flagged.	Top of high bank; approximately 45 cm d.s. of 2 cm diam. elm; a small box elder in line with c.s. and part way down bank also flagged.
25	64	Riffle	Biggest tree downslope of the u.s. cave fence is a red oak (close to 60 cm diam.); rebar is just u.s. of red oak.	Top of high bank, just d.s. of 15 cm diam. locust (visible from field); back from edge of steep bank approximately 2 m.
26	RB--44; LB--67	Pool	D.s. and approximately 2 m uphill of 45 cm diam. dead tree; c.s. crosses large slab of rock.	Top of high bank, not immediately next to big tree; u.s. 6 m from dead tree covered in vines; thick low vegetation.
27	58	Glide	3 m uphill of 5 cm diam. paw paw; a large ash is leaning out over the water approximately 5 m d.s. of c.s. line.	Below top of high bank; 5 m uphill of 20 cm diam. ash; approximately 30 cm d.s. of 2 cm diam. hackberry.
28	42	Glide	Top of high bank, just d.s. of 45 cm diam. dead (?) tree with lots of vines; view to field obscured by cane and other vegetation.	Near base of 10 cm diam. paw paw
29	27	Glide	30 cm d.s. from 30 cm diam. maple.	Top of high bank, middle of slump; just d.s. of 38 cm diam. honey locust.
30	36	Glide	45 cm d.s. from 15 cm diam. elm.	Top of high bank, approximately 1.5 m back from edge of bank; a 10 cm diam. hackberry u.s. of stake and at edge of steep bank also flagged.
31	n/a	Glide	Between 2 paw paws, each approximately 5 cm diam.	Top of high bank, d.s. 45 cm from 15 cm diam. mulberry; dead log that is hiding pressure transducer pipe; leads to mulberry tree.

depositional, erosional, and net-change volumes for the three time periods were calculated by multiplying cross section area changes by channel lengths (one-half of the distance to the upstream and downstream cross sections).

In addition to the erosion and deposition calculation for the entire cross section, we calculated the erosion and deposition that occurred in the portion of the channel below the water surface elevation as surveyed on December 13, 2001, when the discharge was approximately 6.2 cms, the flow equaled or exceeded only 10% of the time. This reference water-surface elevation serves several purposes:

1) Cross-section re-survey errors tend to be greatest on steep banks where the cross sections intersect large boulders or slump blocks, or pass through dense vegetation; consideration of data below the reference elevation minimizes these errors.
2) Use of the reference water-surface elevation provides a subset of geomorphic change measurements for the portion of the frequently wetted channel that is more directly relevant to stream organisms.
3) Calculations relative to this fixed water-surface elevation are consistent for all cross sections and dates.
4) Calculations relative to this fixed water-surface elevation are not biased by large erosional and depositional volumes associated with slumps of the high bank that occurred during the monitoring period.

As with the calculation for the whole cross section, the reference channel calculation was accomplished by intersecting polygons of subsequent survey dates.

Scour chains were installed at 18 sites (fig. 17) in September 2001 to evaluate how much of the bed was disturbed during sediment-transporting events. Each scour chain consisted of a length of “dog chain” that was attached to an anchoring device and driven vertically into the streambed (fig. 18). The chain was trimmed at the bed surface and the location was surveyed with a total station to help with recovery. Total length of chain depended on bed conditions; most were 45 – 60 cm long. We attempted to locate scour chains in February and June 2002 by resurveying locations and using a metal detector. When located, the chain was excavated to note the depth at which the chain had been reoriented to a near-horizontal position, thereby indicating the maximum depth of scour.

An additional sediment transport experiment was carried out using painted rocks as tracers. This experiment was intended to document a threshold of bed-material entrainment and, possibly, average transport distance of particles. During a period of low flow, on December 14, 2001, we placed painted rocks of two size classes in the bed of the stream just downstream of cross section 18 (fig. 17). Approximately 2000 particles sieved to the 16-32 mm size range (coarse gravel) and painted neon green were placed in a line about 20 meters in length, extending across a gravel bar from near the base of the high right bank to approximately one-half of the channel width.

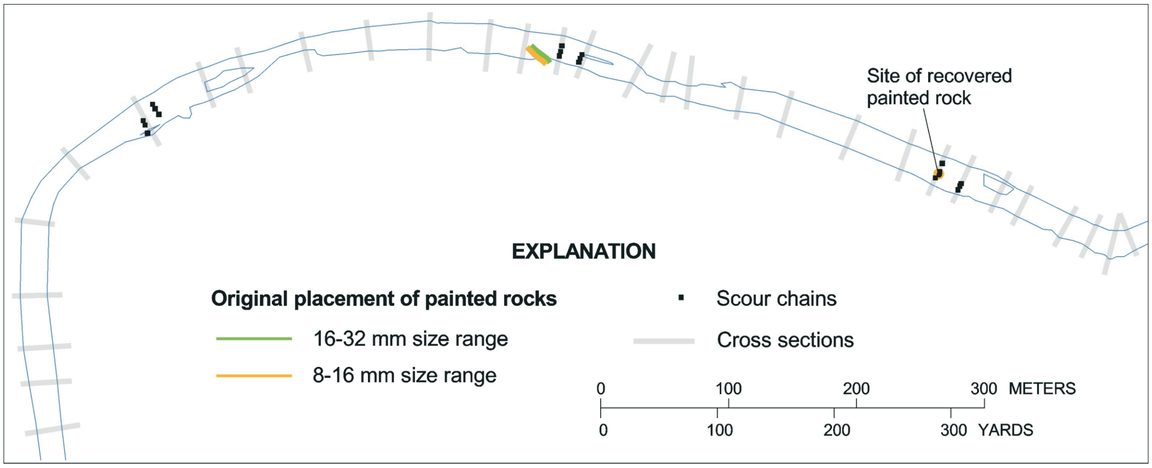


Figure 17. Map of study reach at Crane Bottom showing locations of cross sections, scour chains, and painted rock experiment.

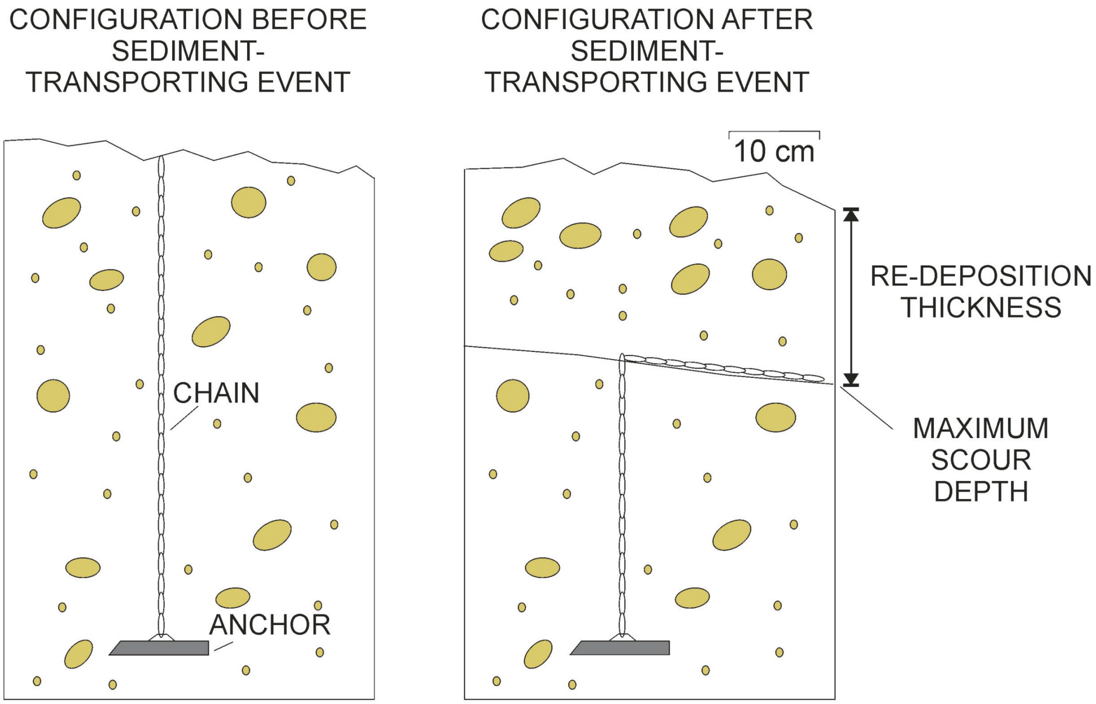


Figure 18. Schematic diagram showing how scour chains are used to document erosion and redeposition.

Approximately 5000 particles sieved to the 8-16 mm size range (medium gravel) and painted neon orange were placed in a line parallel to and just upstream of the first group. All particles were above the summer low flow water level, although some were placed as much as 10 cm under the water surface.

Results

Bed Particle Size Distributions

Particle-size distributions by cross section are shown in figure 19. Generally, particle size varies with habitat units, with pools being noticeably finer than riffles and races (fig. 19A). Because pebble counts sample only the top layer of sediment, they reflect only the most recent deposition. Fine sediment in pools may therefore record deposition from slack current on the receding limb of flood hydrographs, rather than relating to maximum velocities in pools during peak flows.

Cross section 24 (figs. 19B, C) stands out as being substantially coarser than other cross sections. This riffle is just downstream of a deep pool on a bedrock-defended bend; the coarse sediment size may be relict from a large flood that scoured the pool and left a lag of very large substrate on the next riffle downstream.

Geomorphic Change at Cross Sections

Cross sections were installed in June 2001 and resurveyed three times, thereby allowing calculation of change in three transitions (fig. 20): June – December 2001; December 2001 – February 2002; February 2002 – June 2002. Cross section locations are on figure 7 and the surveys are shown in Appendix 1. Some cross sections were affected by large bank slumps of alluvial terrace sediments along the right bank. The volume of these slump features dominated some aspects of geomorphic change calculations; although they represent important parts of the sediment budget, the slump volumes obscure the geomorphic changes to in-channel habitats. Hence, two sets of calculations are provided; one set is based upon the full, surveyed cross sections, while the other set of calculations is limited to geomorphic changes below a reference elevation at each cross section (table 4).

Calculated geomorphic change was highly variable over the three transition periods. When change was substantial, it varied systematically along the study reach (fig. 20). From June 2001 to December 12, 2001 (when the December survey was completed), the largest daily mean flow of Bear Creek at Silver Hill was only 10.6 cms. The resulting geomorphic change was very small with no clear spatial pattern

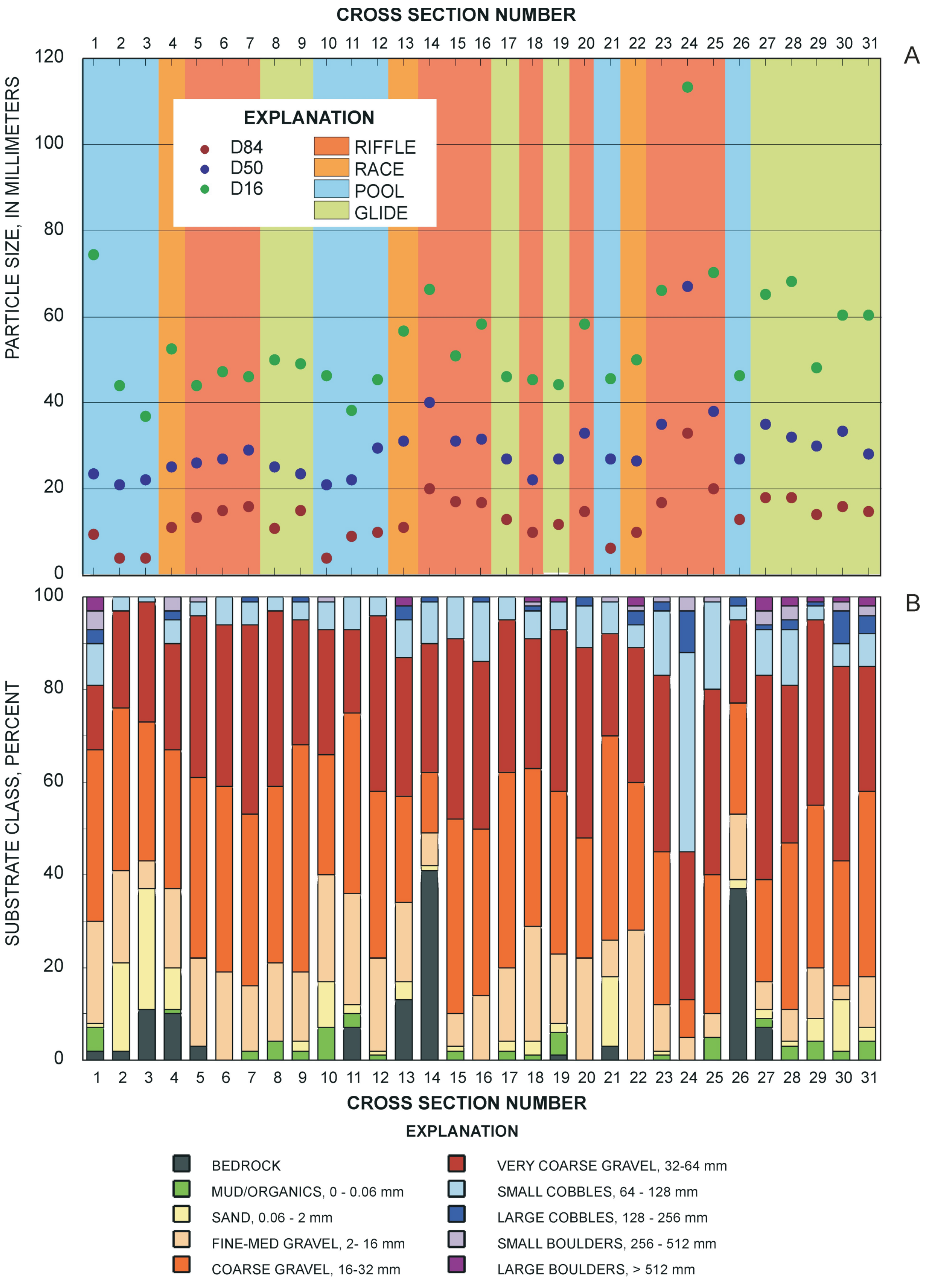


Figure 19. Particle-size data from pebble counts, Bear Creek at Crane Bottom. A. D84 (84th percentile), D50 (50th percentile), and D16 (16th percentile) plotted by cross section. B. Particle-size classes for each cross section.

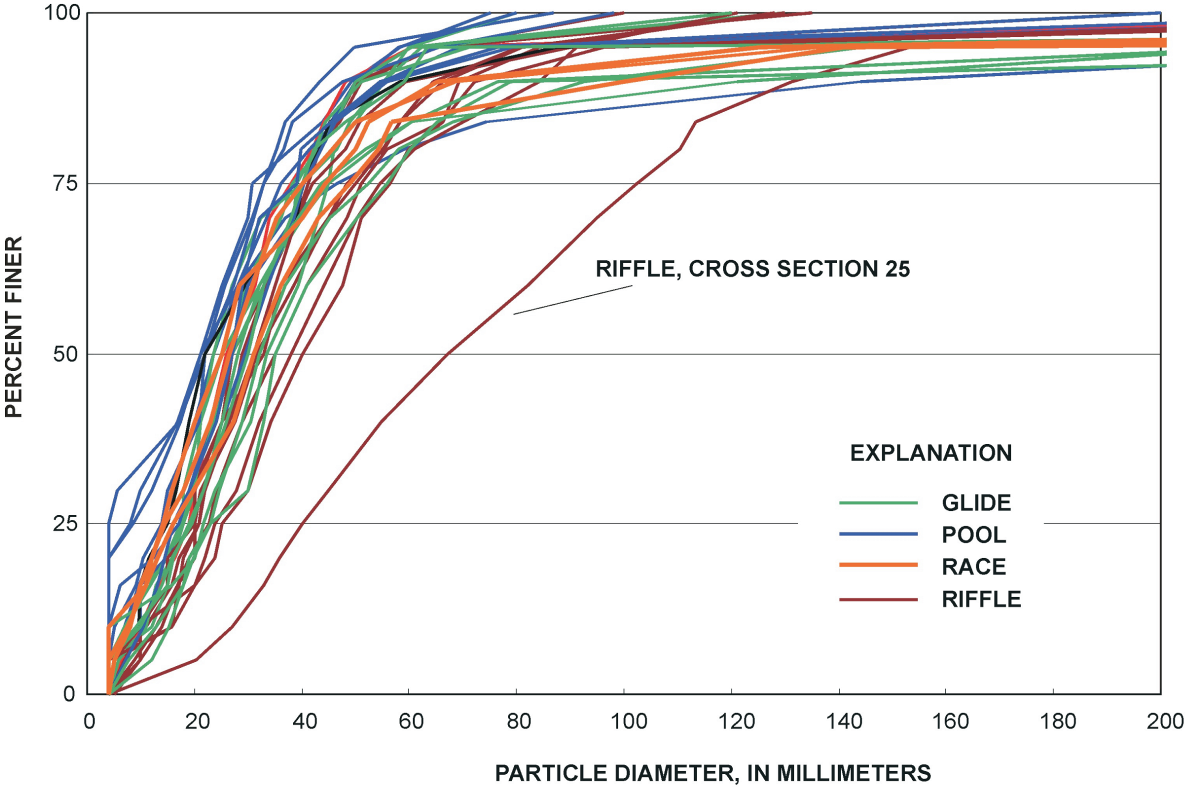


Figure 19 (cont.) Particle-size data from pebble counts, Bear Creek at Crane Bottom. C. Cumulative particle-size distributions for pebble counts at cross sections.

(figure 20A). The net geomorphic change was –216 m^3 in the entire channel area, and +34 m^3 in the reference channel (table 4).

Between December 12, 2001 and February 11, 2002 Bear Creek experienced a flood of about 310 cms followed by the largest flood of the study period with about 460 cms (discharges measured at the Silver Hill streamgage) with an estimated 2- to 4-year recurrence interval (table 2). These floods were responsible for a net geomorphic change of –2,652 m^3 based on the full cross-section calculations and -2,770 m^3 within the reference channel. In the reference channel, erosion dominated over deposition by a factor of about 3. The total change in the reference channel was 6.4 times greater than the total reference-channel change in the previous survey period. Erosion was clearly focused in glides and pools and deposition occurred in riffles and races (fig. 20B). By eroding from pools and depositing in riffles, this flood was responsible for enhancing habitat variability and hydraulic diversity.

Between February 2002 and June 2002, Bear Creek experienced four floods in excess of 60 cms (fig. 10). The flood of March 19, 2002 was estimated to have a recurrence interval of about 1 year (table 2). In contrast to the previous period, erosion and deposition in the reference channel were nearly equal, with a net deposition of 107 m^3. Total change to the reference channel in this period was only 3,927 m^3 compared to 5,570 m^3 in the previous period. When considering the total cross-sectional area, erosion outbalanced deposition by 3,506 m^3 to 2,979 m^3. Total-area calculations included some large slump blocks on the right bank that eroded during this period. Also in contrast to the previous survey period, the locations of erosion and deposition were reversed, with the bulk of erosion occurring in riffles and races and the bulk of deposition occurring in pools and glides (fig. 20C).

For the entire monitoring period June 2001 – June 2002, the net change based on the full cross sections was –3,397 m^3, indicating a net erosive period. For the reference channel, the period was also dominated by erosion, with net change of –2,630 m^3 (table 4). By habitat unit, the net change during this time period was dominated by erosion in pools and glides (fig. 20D).

The amount of geomorphic change experienced in the Crane Bottom reach during this study was large, probably due in part to the unusually high number of large floods. Annual total and net volumetric changes per unit drainage area at Crane Bottom were 8-40 times greater than similar erosion calculations

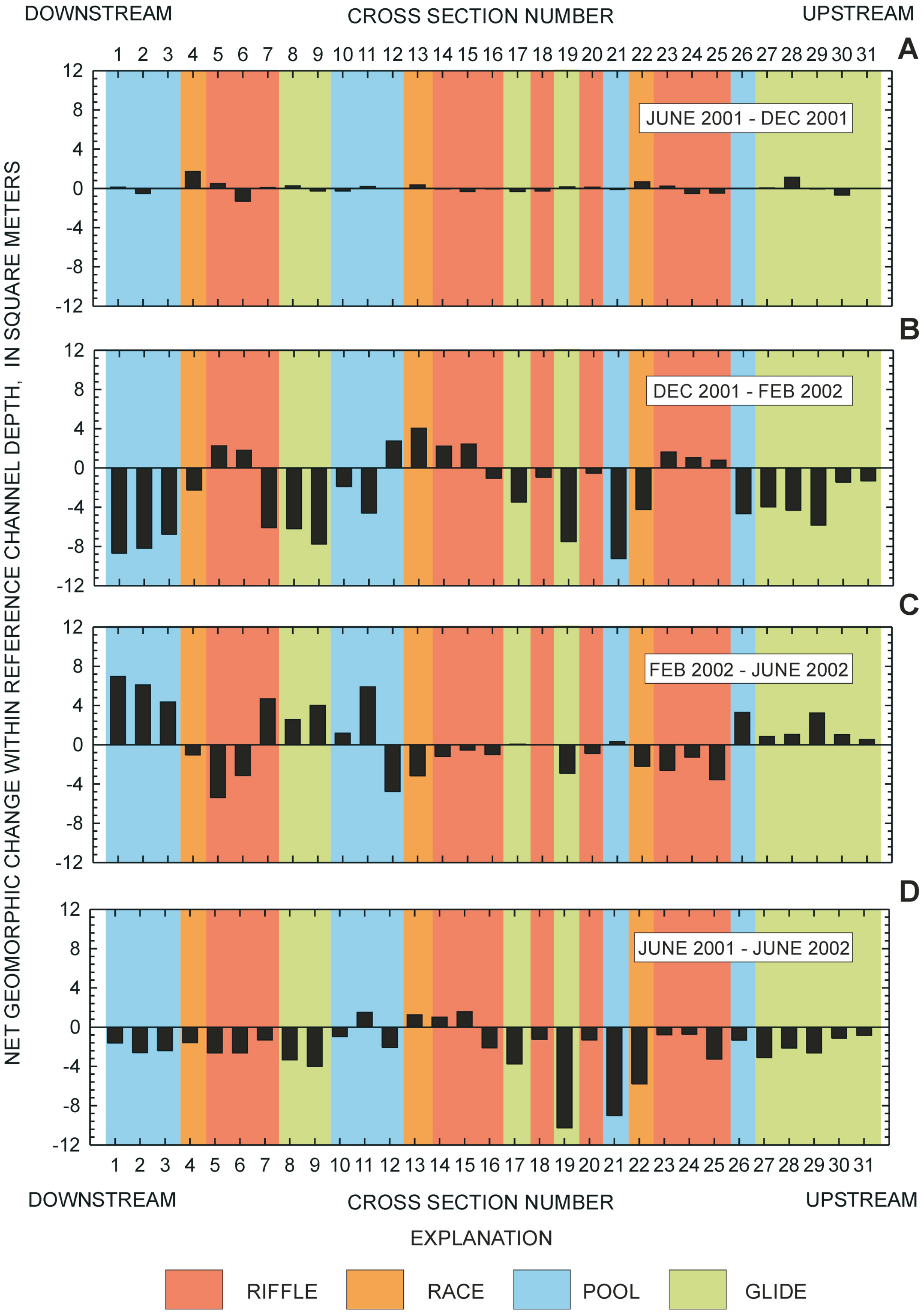


Figure 20. Net erosion and deposition by cross section for three survey intervals and for entire monitoring period, Bear Creek at Crane Bottom.

Table 4. Volumetric change at Crane Bottom site measured from cross section resurveys. Areal change at cross sections was multiplied by one half of distance to next cross section upstream and downstream to obtain volume.

		Volumetric change			
		June 2001 - Dec 2001	Dec 2001 - Feb 2002	Feb 2002 - June 2002	June 2001 - June 2002
Total area	Erosion, cubic meters	1,297.4	5,278.0	3,506.4	5,377.4
	Deposition, cubic meters	1,081.0	2,625.5	2,978.7	1,980.8
	Total change, cubic meters	2,378.5	7,903.5	6,485.1	7,358.1
	Net change, cubic meters	-216.4	-2,652.5	-527.7	-3,396.6
	Total change per unit channel length, cubic meters/meter	2.2	7.2	5.9	6.7
	Net change per unit channel length, cubic meters/meter	-0.2	-2.4	-0.5	-3.1
	Total change per unit drainage basin area, cubic meters/square kilometer	10.0	33.2	27.2	30.9
	Net change per unit drainage basin area, cubic meters/square kilometer	-0.9	-11.1	-2.2	-14.3
Reference channel area	Erosion, cubic meters	414.8	4,170.8	1,910.0	3,584.5
	Deposition, cubic meters	448.5	1,400.0	2,017.1	954.4
	Total change, cubic meters	863.3	5,570.8	3,927.1	4,538.8
	Net change, cubic meters	33.6	-2,770.8	107.1	-2,630.1
	Total change per unit channel length, cubic meters/meter	0.8	5.1	3.6	4.1
	Net change per unit channel length, cubic meters/meter	0.0	-2.5	0.1	-2.4
	Total change per unit drainage basin area, cubic meters/square kilometer	3.6	23.4	16.5	19.1
	Net change per unit drainage basin area, cubic meters/square kilometer	0.1	-11.6	0.4	-11.1

Table 5. Total annual and net annual geomorphic change at Bear Creek at Crane Bottom compared with seven other sites in the Ozarks (McKenney and Jacobson, 1996). [km, kilometer; m, meter]

Study Reach	Basin area, km^2	Reach length, m	Total volumetric change: Annual geomorphic change, m^3	Total volumetric change: Annual change per unit drainage area, m^3/km^2	Total volumetric change: Annual change per unit channel length, m^3/m	Total volumetric change: Annual change per channel length, per unit drainage area, $m^3/m/km^2$	Net volumtetric change, deposition minus erosion: Annual change, m^3	Net volumtetric change, deposition minus erosion: Annual change per unit drainage area, m^3/km^2	Net volumtetric change, deposition minus erosion: Annual change per unit channel length, m^3/m	Net volumtetric change, deposition minus erosion: Annual change per channel length, per unit drainage area, $m^3/m/km^2$
Bear Creek at Crane Bottom, total area	238	1096	7,358	30.9	6.7	0.0282	-3,397	-14.3	-3.1	-0.0130
Bear Creek at Crane Bottom, bankfull channel	238	1096	4,539	19.1	4.1	0.0174	-2,630	-11.1	-2.4	-0.0101
Little Piney Creek at Hickory Point, Missouri	380	760	818	2.2	1.1	0.0028	-347	-0.9	-0.5	-0.0012
Jacks Fork at Fox Farm, Missouri	87	350	286	3.3	0.8	0.0094	-34	-0.4	-0.1	-0.0011
Jacks Fork at Ratcliff Ford, Missouri	422	560	1,457	3.5	2.6	0.0062	154	0.4	0.3	0.0007
Jacks Fork at Burnt Cabin, Missouri	789	940	3,520	4.5	3.7	0.0047	-1,359	-1.7	-1.4	-0.0018
Buffalo River at Wilderness Boundary, Arkansas	150	470	241	1.6	0.5	0.0034	-173	-1.2	-0.4	-0.0025
Buffalo River at Blue Hole, Arkansas	1020	840	1,042	1.0	1.2	0.0012	-421	-0.4	-0.5	-0.0005
Buffalo River at Shine-eye, Arkansas	2150	800	3,349	1.6	4.2	0.0019	-2,434	-1.1	-3.0	-0.0014

Source for other streams: McKenney, R. and Jacobson, R.B., 1996, Erosion and deposition at the riffle-pool scale in gravel-bed streams, Ozark Plateaus, Missouri and Arkansas, 1990-95: U.S. Geological Survey Open-File Report 655-A.

elsewhere in the Ozarks over different time periods (McKenney and Jacobson, 1996; table 5). Three of the sites listed in table 5 are from the Buffalo River and three of the sites are from Jacks Fork, Missouri. The Jacks Fork sites experienced an estimated 50-year recurrence interval flood during the monitoring period. In addition to temporal and physiographic differences among sites, the comparison data in table 5 differ from the Crane Bottom study in that they were calculated from annual surveys over 3 to 7 years. Even with variations that might result from differences among sites and monitoring times, the large rates of volumetric change on Bear Creek are notable.

Different habitat units responded differently to sediment transporting events during the monitoring period. Of particular interest was the tendency of riffles and races to experience deposition during the December 2001 – February 2002 period and then to experience erosion during the succeeding February 2002 – June 2002 period, with pools and glides experiencing the opposite effects (fig. 21). Cross sections that had small reference-channel area in June 2001 (that is, mostly riffles and races) decreased in area from December 2001 – February 2002 because of deposition whereas cross sections that had large reference-channel area increased in area in the same time period because of erosion. The trend is opposite for the time period February 2002 – June 2002 when riffle-race cross sections increased in areas because of erosion and glides and pools decreased in area because of deposition.

The implication of these changes is that floods of varying magnitude can have very different effects on the quantity and quality of stream habitat. The largest

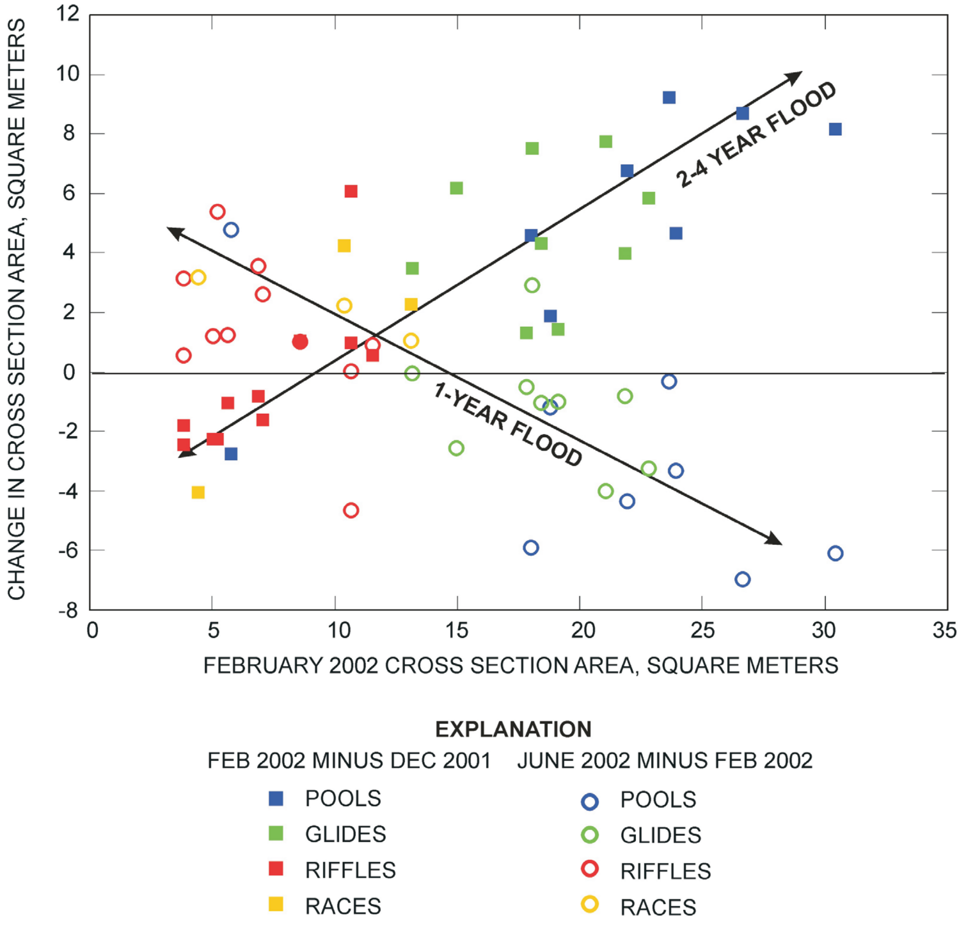


Figure 21. Change in cross section area for two survey intervals compared to February 2002 cross section area. Small cross section areas in February 2002 are riffles and large areas are pools. The 2-4 year flood between February 2002 and December 2001 increased areas of pools and decreased areas of riffles. The 1-year flood between February 2002 and June 2002 decreased the area of pools and increased the area riffles.

flood in the December 2001 – February 2002 period was estimated to have a 2- to 4-year recurrence interval whereas the largest flood in the February 2002 – June 2002 period was at most a 1-year event. Although the estimated frequencies of these two floods are not very different, they had opposite effects on stream habitat maintenance, suggesting that some threshold exists in the maintenance processes. This idea is consistent with the theory of velocity reversal (Keller, 1971), which holds that as discharge increases and water-surface slope equalizes between pools and riffles, a threshold is reached at which average velocities in pools become greater than the average velocities in riffles. The monitoring results from Bear Creek may support this idea: that at some range of discharge the shear stresses and sediment transport capacity in pools exceeds that of riffles, causing erosion in the pools and deposition in riffles. Possibly, however, the additional smaller floods during the survey periods, the sequence of floods, backwater effects, or varying sediment supply could also influence the observed geomorphic change. Calculation of boundary shear stresses from hydraulic model results, as discussed in a later section, provide further insight into the idea of a velocity reversal.

Scour and Fill Measured with Scour Chains

Excavation of scour chains confirmed that substantial scour does occur on Bear Creek; that is, changes in the surface topography measured in cross sections is a minimum measure of the volume of sediment moving through the system. Moreover, because water depths limited scour-chain installation to glides and riffles, these scour chain measurements do not necessarily measure the maximum amount of scour possible in this stream. In some cases, scour chains were not recoverable after the flood events, with the implication that they were completely removed by scour equal to at least the length of the chain (table 6). In other cases, the chains were recovered and the length of the chain that was bent over was used as an indicator of maximum scour.

Measured scour in the 15 locations varied from 0 to greater than 64 cm. The only chains that did not experience scour were in dense thickets of water willow on gravel-cobble bars (fig. 22). The water willow's dense network of rhizomes and roots provides resistance to erosion. Some areas of water willow did experience erosion, but primarily through undercutting of the plants. For example, the scour chain in the middle of the cross section downstream of CS25 (fig. 17) was installed in a stand of water willow. By June 2002, 24 cm of the chain was free in the water. A scarp capped in water willow remained adjacent to the chain indicating the former surface elevation; such scarps were apparent in several locations in the vicinity.

Scour chain results indicate that substantial erosion and redeposition are possible on Bear Creek. Geomorphic change measured in cross sections, therefore, is a minimum evaluation of total geomorphic change between surveys.

Sediment Transport Measured with Painted Rocks

In the best-case scenario, the painted rock experiment would have been able to evaluate the minimum discharge required to transport the rocks. Instead of a flood that was just capable of transporting the experimental rocks, however, Bear Creek experienced a peak discharge estimated to have a 1-2 year recurrence interval (310 cms at Silver Hill streamgage, December 16, 2001), immediately after the rocks were emplaced. No painted rocks were found at their original locations during a visit to the site on December 19. Moreover, all herbaceous vegetation had been removed from the gravel-bar location where the rocks had been placed. The high flows in December 2001 were followed by additional high flows in January and February 2002. Because flood discharges during the experiment were far in excess of the minimum needed to transport gravel, the painted rock experiment was not effective in identifying an entrainment threshold. However, the experiment was successful in confirming that a 1-2 year recurrence flood on Bear Creek is capable of substantial entrainment of 8-32 mm gravel.

The frequent, high magnitude floods during the winter and spring of 2001-2002 contributed to an extremely low recovery rate for assessing transport distance. Only one painted rock was recovered during a survey on February 15, 2002. This was an orange rock (b axis of 15 mm), recovered approximately 320 m downstream of its original location.

Hydrologic Dynamics and Habitat

We assessed habitat dynamics resulting from hydrologic variation using a two-dimensional hydraulic model of Bear Creek. The model is useful for inventorying habitat quantities over a wide range of discharges. The relation between habitat availability and discharge can then be combined with the time series of discharges to assess the temporal distribution of habitat.

Methods

The two-dimensional hydraulic model we used solves the shallow-water, depth-averaged equations to balance mass and momentum on a finite element mesh. Results from a two-dimensional model provide a map view of depth and depth-averaged velocity for a given, steady discharge. The maps of continually varying depth and velocity can be used to inventory

Table 6. Information on scour chains installed in September 2001.

[ds, downstream; us, upstream; cm, centimeter]

Cross section	Habitat	Location oncross section	Scour chain length, cm	Date of search	Approximate surface elevation change, in cm (+ for deposition, - for erosion)		Estimate of depth of scour relative to September 2001 surface	Scour chain found?	Comments
					Sept. 2001 to Feb. 2002	Sept. 2001 to June 2002			
7	Riffle	Left	43	Feb. 15, 2002	-45		45 cm	No	Bedrock exposed at former location of scour chain.
7	Riffle	Middle	60	Feb. 15, 2002	-28		at least 60 cm	No	Dug to bedrock without finding chain.
7	Riffle	Right	52	Feb. 15, 2002	-1		> 52 cm ?	No	Vegetation was present when chain was installed; no remaining roots in February. Maximum depth of search was about 30 cm. No metal detector signal.
8	Glide	Left	64	Feb. 15, 2002	-6		> 64 cm ?	No	Maximum depth of search was 20 cm below September surface level. No metal detector signal.
8	Glide	Middle	60	Feb. 15, 2002	-4		> 60 cm ?	No	Maximum depth of search was 35 cm below September surface level. No metal detector signal.
8	Glide	Right	50	Feb. 15, 2002	-32		> 50 cm ?	No	No metal detector signal.
16	Riffle	Left	63	June 20, 2002		10		No	Maximum depth of search was 22 cm below September surface level.
16	Riffle	Middle	69	June 20, 2002		14	30 cm	Yes	Angled downstream and slightly to right bank.
16	Riffle	Right	42	June 20, 2002		-6		No	Maximum depth of search was 47 cm below September surface level.
17	Glide	Left	65	June 20, 2002		-19	> 19 cm	Yes	Chain found in ambiguous position.
17	Glide	Middle	62	June 20, 2002		6	33 cm	Yes	Angled downstream and slightly to left bank.
17	Glide	Right	72	June 20, 2002		26		No	Maximum depth of search was 47 cm below September surface level.
ds of 25	Riffle	Left	63	June 23, 2002		2	0	Yes	Dense water willow roots still intact.
ds of 25	Riffle	Middle	45	June 23, 2002		-24	24 cm	Yes	Originally in water willow. 24 cm of chain loose in water and adjacent to scarp of intact water willow plants.
ds of 25	Riffle	Right	49	Feb. 14, 2002	2		0	Yes	Dense water willow roots still intact.
				June 23, 2002		3	0	Yes	Dense water willow roots still intact.
us of 25	Glide	Left	61	Feb. 14, 2002	19		40-50 cm ?	Yes	
us of 25	Glide	Middle	63	Feb. 14, 2002	19		< 8 cm	Yes	Unchanged to within 2 links (8 cm) of top of chain. Reburied chain vertically.
				June 23, 2002		6	12 cm	Yes	
us of 25	Glide	Right	46	Feb. 14, 2002	22		< 16 cm	Yes	Unchanged to within 4 links (16 cm) of top of chain. Reburied chain vertically.
				June 23, 2002		4	22 cm	Yes	

Figure 22. Photographs of rhizomes of water willow at surface of stable gravel bar.

areas and spatial characteristics of habitats over the range of modeled discharges. To model flow conditions, we used River2D (version 0.90, July 23, 2002) and its supporting programs, R2D_Bed and R2D_Mesh[1]. This two-dimensional hydrodynamic model code has several features that make it well suited for simulating flow of rivers and streams such as Bear Creek. River2D handles wetting and drying by converting to ground-water flow equations for subsurface flow, and it explicitly handles transitions between sub- and supercritical flow (Steffler and Blackburn, 2001).

We modeled steady discharges from 0.13 to 556 cms. This range corresponds to the observed range of flows during the study period, 99% exceedance to approximately a 1 in 4 year probability flood (table 7).

Input data and parameters

The topographic map of Crane Bottom (fig. 23A) is based on cross-section survey data from June 2001, augmented with additional data points as needed to define the major topographic features for the entire study reach. We used a contouring program (Surfer®, Golden Software, Golden, Colorado) and GIS software (ArcView®, ESRI, Redlands, California) to aid in contouring the data points and developing the one-meter grid that was used as model input. For the purpose of modeling, the topography was extended upstream and downstream of the surveyed reach by adding fictitious inflow and outflow chutes; this minimized problems with flow recirculation across the boundary and moved the boundary conditions away from the area used to inventory habitats.

The substrate map of the reach is based on dominant particle size data collected at survey points during the June 2001 survey. This substrate map was used to generalize and assign roughness height, the resistance parameter used by River2D (fig. 23B). D_{84} values (the 84th percentile of the cumulative particle-size distribution) calculated from the cross-section pebble-count data provided a preliminary guide for appropriate roughness height values, but final roughness height values are a product of calibration.

The mesh in figure 24 was used for the full range of flows with only minor alterations to either improve model stability (generally by increasing local mesh density) or to reduce computational effort (by trimming part of the mesh at high elevations for low flow). The boundary line, breaklines, and preliminary nodes were generated in ArcView®, and the mesh was refined in R2D_Mesh and River2D. The mesh density provides a suitable number of elements across the channel at the lowest flows.

Boundary conditions necessary to run this model are discharge at the upstream end of the reach and a fixed stage at the downstream end. Thirty-two discharges were selected to represent the range of flows observed during the study period (table 7). Because discharge data are available at Silver Hill, flow exceedance and flood-frequency analyses was

---

[1] The River 2D programs are freely available from University of Alberta: <*http://www.river2d.ualberta.ca.*> June, 2003.

Table 7. Modeled discharges, habitat areas, flow-duration, and flood-frequency data for Crane Bottom. Exceedance data are based on daily mean discharges for the period of record; flood frequency data are based on annual peak flows.

	Habitat Area, in Square Meters								
Discharge at Crane Bottom, in cms	**Edge-water**	**Glide**	**Pool**	**Race**	**Riffle**	**Total wetted habitat**	**Discharge non-exceedance relative frequency**	**Discharge exceedance Relative frequency**	**Exceedance days per year**
0.10	4,941	8,082	550	0	368	13,941	1%	99%	360.3
0.13	4,859	8,271	593	0	481	14,204	4%	96%	351.1
0.14	4,785	8,390	634	0	568	14,376	6%	94%	344.6
0.18	4,710	8,508	675	0	655	14,548	11%	90%	326.7
0.22	4,550	8,642	752	0	851	14,795	16%	84%	307.7
0.27	4,521	8,816	818	1	948	15,104	20%	80%	290.9
0.31	4,456	8,925	894	3	1,068	15,346	25%	75%	273.0
0.38	4,402	9,015	973	14	1,253	15,657	33%	67%	243.8
0.41	4,379	9,016	990	24	1,344	15,753	37%	63%	230.7
0.51	4,426	9,146	1,110	55	1,530	16,267	40%	60%	219.4
0.62	4,506	9,212	1,260	112	1,694	16,784	45%	55%	200.0
0.82	4,741	9,486	1,710	257	1,369	17,563	50%	50%	181.8
1.0	4,759	9,434	1,987	447	1,561	18,188	55%	45%	165.0
1.3	4,626	9,306	2,284	717	1,793	18,726	60%	40%	145.3
1.8	4,441	9,132	2,649	1,070	2,118	19,410	65%	35%	127.8
2.2	4,138	9,073	2,763	1,563	2,485	20,022	70%	30%	109.9
2.8	3,806	9,236	2,333	2,237	2,936	20,548	75%	25%	91.3
3.6	3,521	9,564	1,820	2,915	3,358	21,178	80%	20%	73.4
5.0	2,848	9,396	1,596	3,960	4,031	21,831	85%	15%	54.0
7.1	2,304	8,273	1,529	5,635	4,906	22,647	90%	10%	36.5
8.3	2,187	7,546	1,594	6,680	5,152	23,159	92%	8%	29.2
10.6	2,026	6,502	1,444	8,103	5,809	23,884	94%	6%	21.9
13.1	1,862	6,104	1,341	8,926	6,319	24,552	96%	4%	14.6
25.2	1,236	5,330	1,872	9,327	8,662	26,427	98%	2%	7.3
39.9	958	5,012	2,252	8,904	10,698	27,824	99%	1%	3.7
69.0	848	4,543	3,272	7,750	13,465	29,878	99%	1%	3.3
98.0	802	4,476	3,723	7,118	15,364	31,483	99%	1%	2.2
156	823	4,630	2,736	7,738	18,131	34,058	100%	0%	0.0
								Estimated Recurrence Interval[1]	
242	1,182	4,282	1,577	6,046	24,138	37,225		1	
290	4,833	7,579	2,991	10,703	21,387	47,493		1-2	
340	9,232	19,477	14,591	24,729	15,116	83,145		1-2	
450	7,082	24,437	11,487	21,589	26,174	90,769		2-4	
556	4,671	27,590	10,271	23,836	44,192	110,560		2-4	

[1] Recurrence intervals are estimated from comparisons with recurrence intervals calculated for the same floods at other streamgages with longer records. See table 2. Discharges at Crane Bottom are estimated by regression model between measured discharges at Silver Hill and Crane Bottom for flows less than 160 cms. For flows greater than 160 cms, unit area discharges at Silver Hill were multiplied by drainage area at Crane Bottom to estimate discharge at Crane Bottom.

completed on this dataset to select discharges. A regression between the Silver Hill discharge and the available Crane Bottom discharge measurements (fig. 25) was used to determine the Crane Bottom discharge for the desired exceedance and probability values. To determine the downstream fixed stage values at the Crane Bottom modeling reach associated with the desired discharges, we used a regression between the stage at Silver Hill and the downstream Crane Bottom stage, taking into account the time lag between the peak flows at Silver Hill and Crane Bottom. We selected only stages that were not influenced by rapidly changing discharges or by backwater to construct the regression.

Other parameters required by River2D include ϵ_1 and ϵ_2 (coefficients used to calculate eddy viscosity), an upwinding coefficient to parameterize the finite element solving scheme, and ground-water transmissivity and minimum depth coefficients for aiding in wetting and drying calculations at the wetted

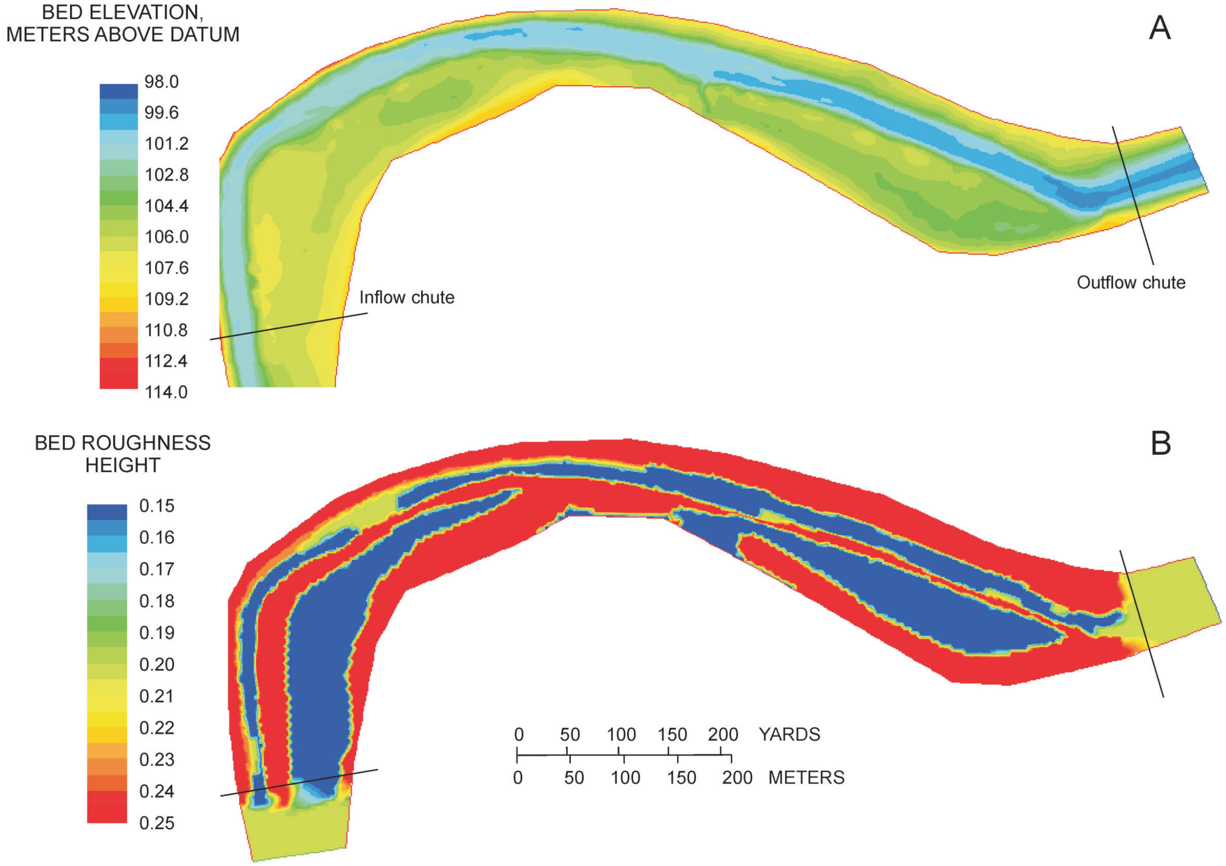


Figure 23. Model input data grids for Crane Bottom. The input map grids were used to parameterize the finite element mesh bed file. A. Elevation grid. B. Bed roughness height (k_s) grid.

boundary. Eddy viscosity and upwinding parameters were kept as default values (0, 0.5, and 0.5). Ground-water transmissivity was set at 0.01 to minimize ground-water discharge for flows of 0.1 – 0.6 cms, but was increased to the recommended default value of 0.1 for flows 0.6 – 556 cms. The minimum depth for ground-water flow determines the water depth at which the model treats discharge as ground-water flow rather than surface water. Stable models were achieved when this value was set to 0.05 for discharges 0.1 – 0.6 cms, and 0.1 for discharges 0.6 – 556 cms.

Calibration and validation

Because water-surface-elevation profiles were available over a range of discharge from a relatively low summer flow to a 2- to 4-year flood, these profiles were used as the primary means of calibration. Water surface elevations for bankfull flows and below were measured directly, while the overbank water-surface elevations were based on high-water marks after the floods. The water surface elevations from the model were extracted from the center of each cross section to compare to the water-surface elevations measured in the field.

Figure 26 shows measured and modeled water surface elevations. Water-surface elevations from June 2001 (0.45 cms), and December 2001 (3.5 cms and 340 cms) were used to calibrate the model and water-surface elevations from 0.18 to 570 cms (fig. 26A, B) were used to validate model performance. Water-surface elevations were chosen to minimize backwater effects. Measured water-surface elevations from late December 2001 (23.5 cms) and February 2002 show substantial deviations from the model because these flows occurred after the streambed was altered by high flows in December 2001 and January 2002.

In addition to close agreement between measured and modeled water-surface elevations, models were considered successful if they achieved a low net outflow (less than 5% of the flow was unaccounted by the model) over run times sufficient to achieve a steady state (usually greater than 10,000 time steps).

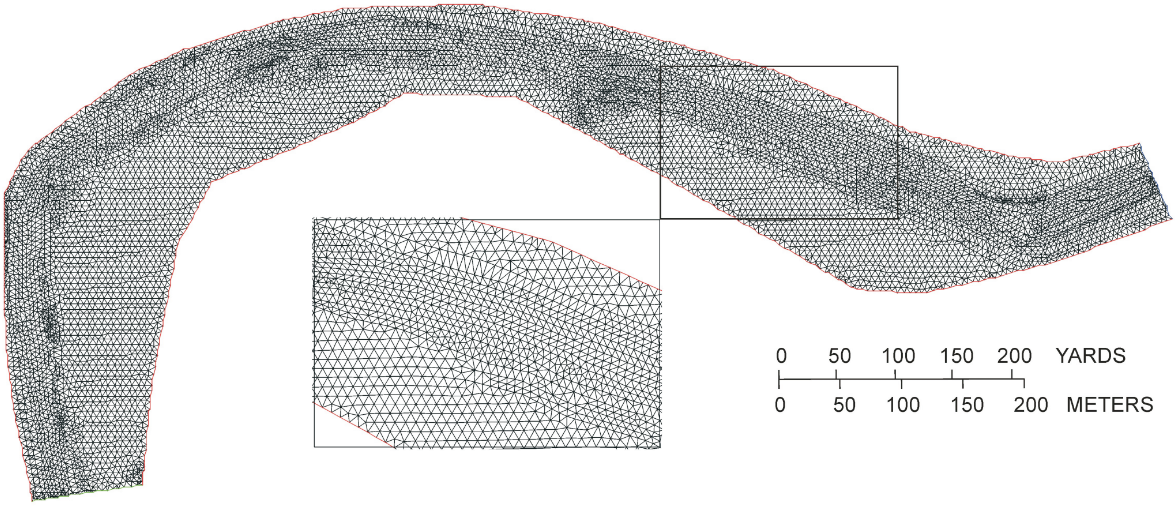


Figure 24. Finite element mesh used for 2-dimensional hydraulic modeling at Crane Bottom reach of Bear Creek.

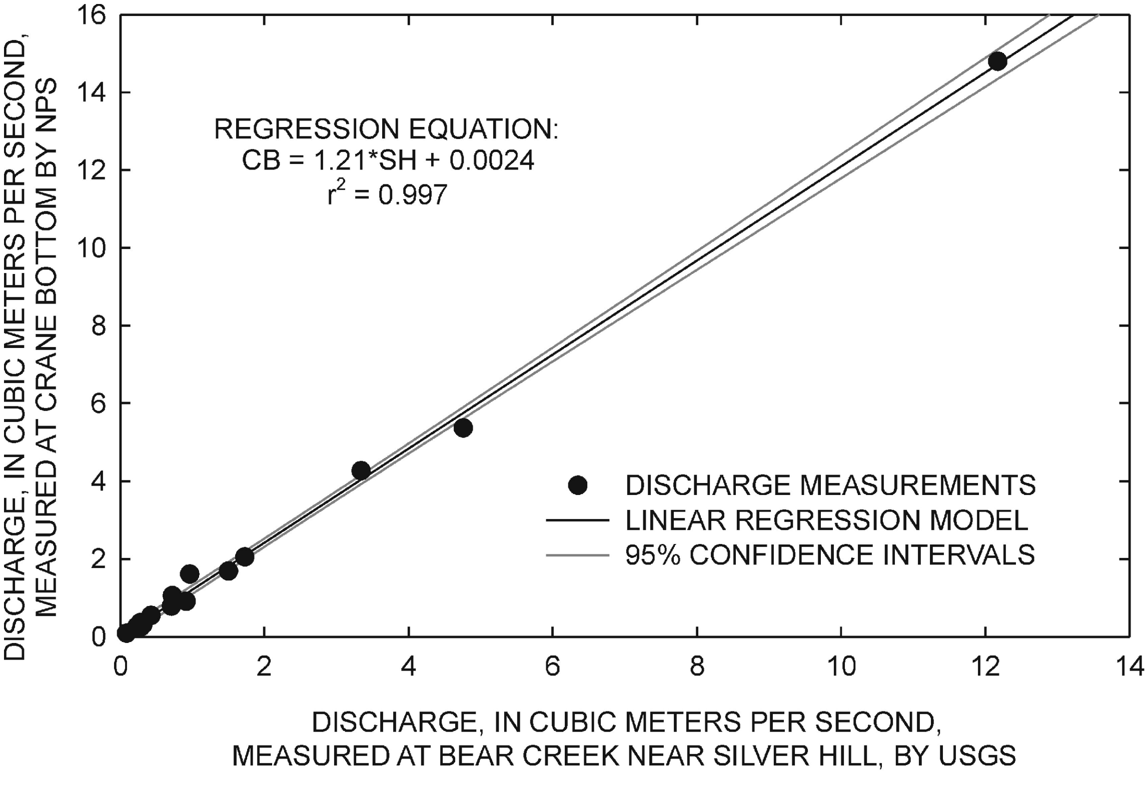


Figure 25. Regression relation between Bear Creek discharge measured by U.S. Geological Survey near Silver Hill, Arkansas and discharge measured by National Park Service at Crane Bottom study reach. CB is Crane Bottom discharge; SH is Silver Hill discharge.

Model results were also evaluated for whether they realistically reproduced known flow patterns – such as a large eddy near an embayment in the bank at cross section 29 (as inferred from field observations). In some cases, modeled local instabilities in the flow field were accepted if they affected only small areas and did not substantially affect habitat area calculations.

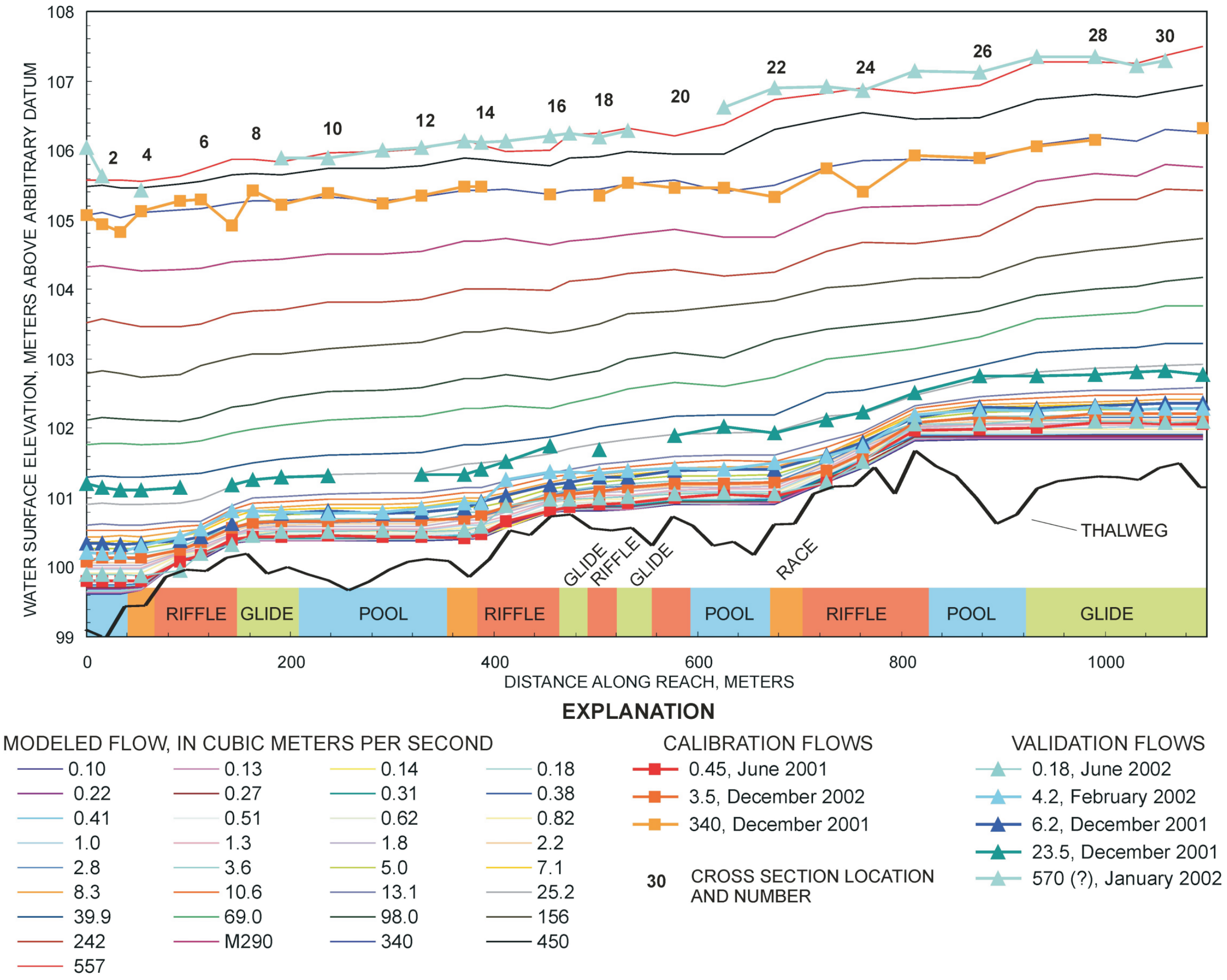


Figure 26A. Water-surface elevation data plotted along study reach showing modeled, calibration, and validation water-surface elevation datasets. Entire range of flows.

Habitat classification:

We used the habitat classification system developed by Panfil and Jacobson (1999), which is based on depth and Froude number (fig. 27). To apply the habitat classification, data were extracted from River2D on a one-meter grid. A script was used to read the depth and Froude number data files, apply the classification scheme, and produce output files with the coordinate and habitat data. These output files were converted to grids in ArcView® for further analysis.

Hydrodynamic Habitat Modeling Results

Maps of depth, velocity, Froude number, and habitat classification are included in Appendix 2; figures 28A-C show variation in habitat areas with discharge. Habitats classified at high flows need to be evaluated with caution. For example, at high flows, areas that classify as riffles have fast, relatively shallow water and high Froude numbers where the water is running over grassy substrate on the terraces. Because of the lack of gravel/cobble substrate, these areas would not have the same habitat value as riffles within the channel. Similarly, areas that classify as edgewater habitats (with shallow depths and low velocities) will have very different substrates during high discharges than those that classify as edgewater during low discharges. Because the high-flow habitats exist for short periods of time relative to low-flow habitats, they probably have substantially different influences on stream ecosystem functions. At high flows, the importance of riffles and races may be that they are high-energy areas whereas edgewaters and pools are relative energy refugia. At flows above 10% exceedance, the areas of edgewaters and pools are relatively stable, indicating little change in availability of energy refugia (fig. 28B).

From the minimum to median flows (approximately 0 to 0.9 cms), habitat areas are quite variable. At the lowest flows modeled in this study, riffles are mostly dry, leaving disconnected pool and glide areas. At these low flows, there is abundant edgewater

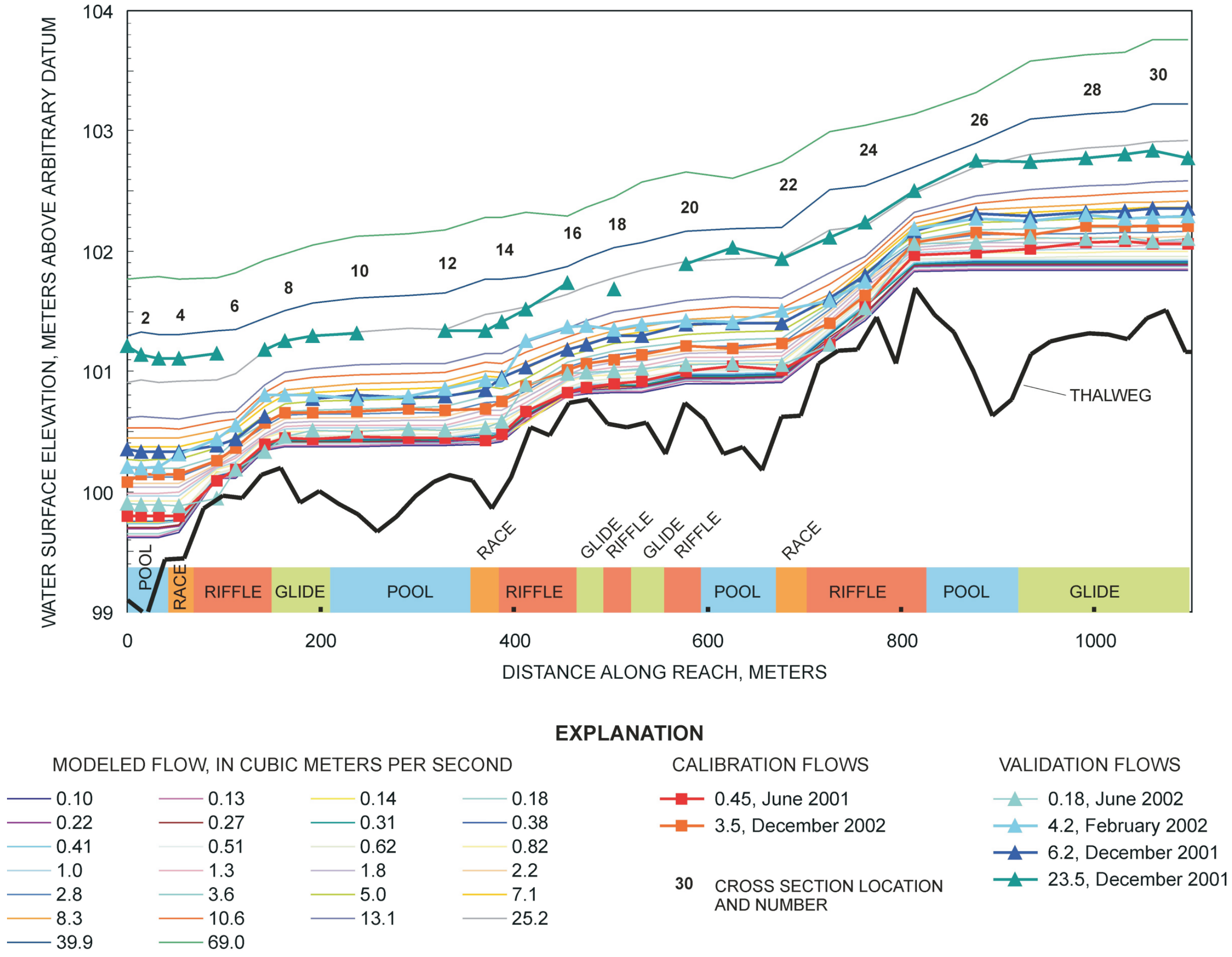


Figure 26B. Water-surface elevation data plotted along study reach, showing modeled, calibration, and validation water-surface elevation datasets. Discharges limited to 69 cubic meters per second and less.

habitat on the margins of the channel and pools area is at a minimum. Race habitats are missing completely until a discharge of about 0.3 cms (70% flow exceedance). As discharge increases, riffle, pool, race, and glide areas increase, whereas edgewaters decrease. Race area stays extremely small until nearly the median flow (0.8 cms).

An integrated measure of habitat diversity was calculated using the Shannon-Wiener diversity index (Shannon and Weaver, 1949):

$$SDI = -\sum_{i=1}^{m} (P_i * \ln P_i)$$

where SDI = Shannon-Weiner Diversity Index, P = proportion of area in habitat class i, and m = number of habitat classes. The SDI increases with number of habitat classes and with the evenness of the distribution of area among the habitat classes. For this stream reach, SDI of habitat classes increases rapidly from minimum flow to the median flow (50% flow exceedance), then increases more slowly to an asymptotic value at about 25% exceedance. As an integrated measure of habitat diversity, the SDI shows that Bear Creek habitat diversity is particularly sensitive to low flows (fig. 28A-C).

Habitat areas and diversity index values can be calculated for any discharge value by interpolating values between modeled discharges. Habitat unit time series can then be calculated for any time series of flows on Bear Creek (fig 29).

Because the habitat diversity index increases rapidly from the minimum to the median flow, periods of moderate discharge in winter to early summer are characterized by relatively high habitat diversity values, whereas late-summer and fall values are very low (fig. 29). Since January 1999, the most substantial habitat variation at Crane Bottom has been in area of riffles and races. In particular, the area of race habitat

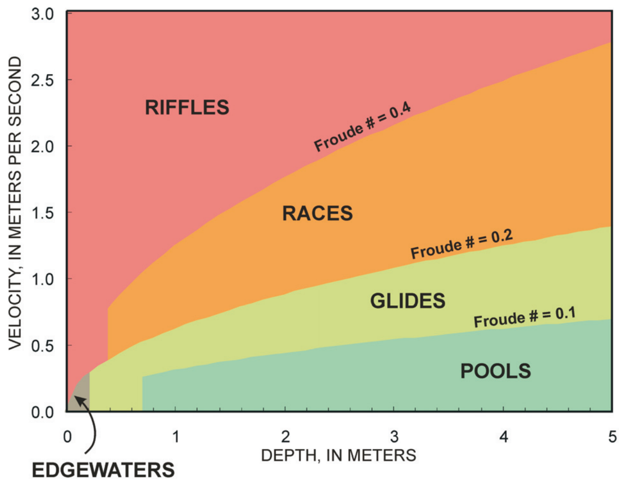


Figure 27. Scheme used for classifying model output into habitat units (Panfil and Jacobson, 1999).

is sensitive to low flows, diminishing to zero below about 0.3 cms. Races were completely absent at Crane Bottom for nearly one half of the modeled time period. Areas of glides, pools, and edgewaters are more consistent over time, and are substantial even during periods of low flow in late summer and fall.

Streambed Mobility

Modeled depths and water-surface elevations can be used to calculate estimates of boundary shear stress on the bed, and to explore how much of the bed is potentially mobilized at various flows. The product of flow frequency and percentage of the bed mobilized by each flow is a measure of geomorphic work accomplished by each flow (following Wolman and Miller, 1960). An understanding of which flows are responsible on average for most of the bed mobilization on Bear Creek will help in evaluating flows necessary for habitat maintenance.

Methods

Bed mobilization can be estimated by comparing boundary shear stress with critical shear stress necessary to entrain bed material. Spatially distributed boundary shear stresses can be calculated using modeled water-surface elevation and depth outputs from the hydraulic models, using the total boundary shear stress equation (Chow, 1959):

$$\tau_b = \rho g d S$$

where, τ_b = boundary shear stress in newtons per square meter (N/m^2), ρ = unit weight of water (kg/m^3, 1000 kg/m^3), g = gravitational acceleration constant (9.8 m/s^2), d = depth in meters, and S is the energy slope, approximated here by the water-surface slope.

A map of water-surface slope was constructed by calculating slope on a cell-by-cell basis from the modeled water-surface elevations. This slope map was then smoothed by calculating a 7 m x 7 m moving average; smoothing helped eliminate extreme slope values resulting from small instabilities in the modeled flow field. The boundary shear stress map was created by multiplying the constants by slope and depth on a cell-by-cell basis.

The shear stress necessary to initiate movement of the bed was estimated by calculating the critical shear stress to mobilize the median of the particle-size distribution (Shields, 1936):

$$\tau_c = \theta(\rho_s - \rho\ )gD_{50}$$

where τ_c = critical shear stress in N/m^2, θ= Shields dimensionless critical shear stress, ρ = unit weight of water (taken as 1000 kg/m^3), ρ_S = unit weight of sediment (taken as 2650 kg/ m^3), g = the gravitational constant, and D_{50} = median particle size, in meters.

The dimensionless critical shear stress varies with flow turbulence and characteristics of the particle-size distribution, including shape and packing of particles. We assumed fully hydraulically rough conditions and used a generally accepted value for gravel-cobble streambeds, 0.04 (Yalin and Karahan, 1979). For D_{50}, we used the median of the entire pebble-count dataset (0.029 m, n = 2,964) for the Crane Bottom reach. By using the lumped, median value, our analysis focuses on the stability of the entire reach, and may therefore under or overestimate stability of areas within the reach.

Incipient motion of the bed occurs when $\tau_b/\tau_c = 1$. As a general approximation, overall bed mobility occurs when the boundary shear stress is twice the critical shear stress, or $\tau_b/\tau_c = 2$ (Wilcock and McArdell, 1993). Subsequent analysis uses both of these conditions.

Results

The hydraulic models predict that boundary shear stresses are at maxima in riffles during flows ranging from about 0.1 – 13.1 cms and begin to relocate to pools by about 25.2 cms (fig. 30A-C). When flows reach 30.9 cms, the shear stress maxima are spread more uniformly in the reach and are no longer concentrated in the low-flow riffles (fig. 30D). At flows of 240 cms and higher, models predict that shear stress maxima are concentrated in the pools (figs. 30D, E), a result that is consistent with the velocity reversal hypothesis (Keller, 1971). The velocity reversal hypothesis states that the locations of maximum velocity in a river shift from riffles to pools when discharge exceeds a threshold, resulting in scour of

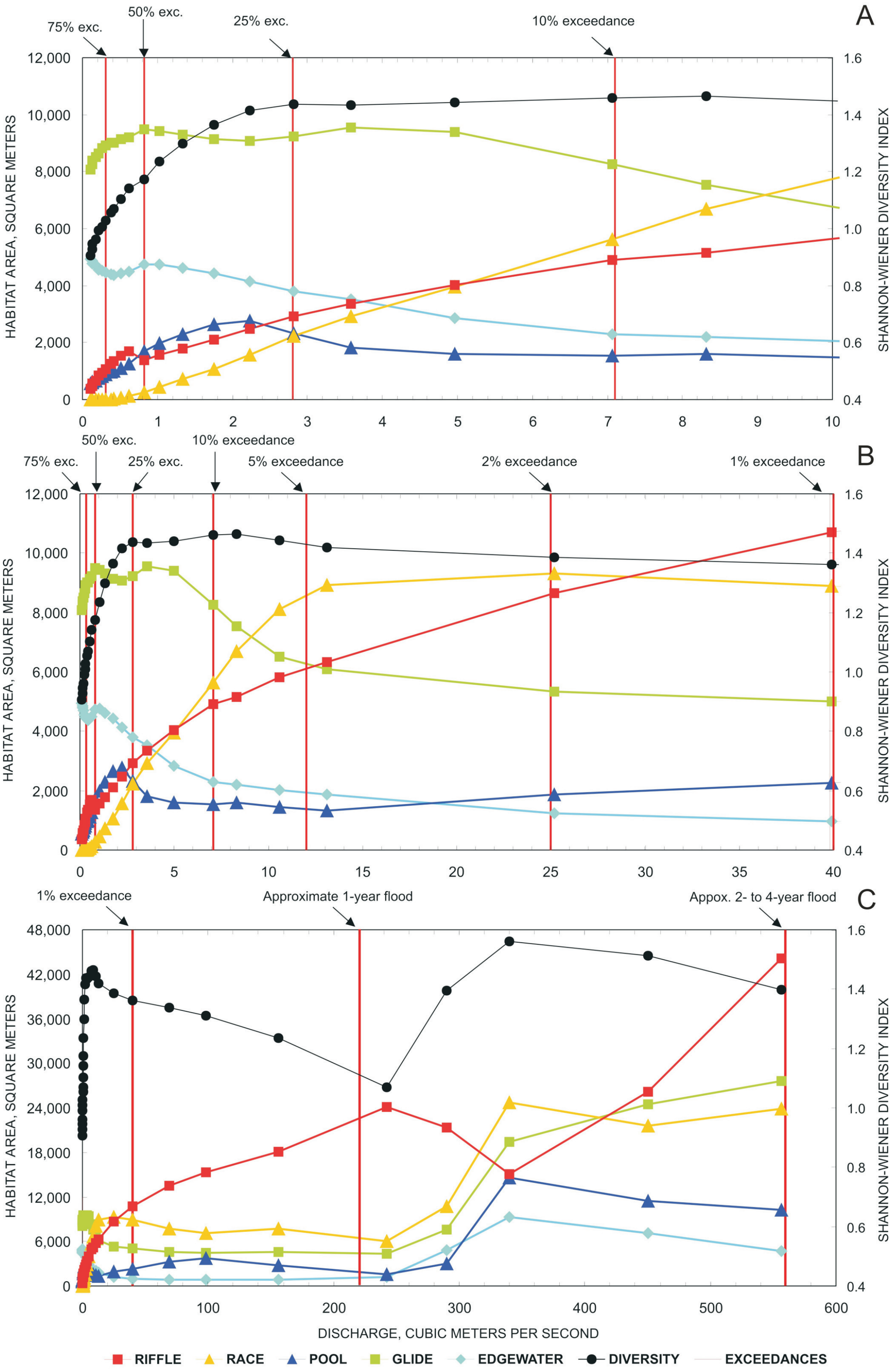


Figure 28. Relations between discharge and area of habitat units, and Shannon-Wiener diversity index. The three graphs are of the same data but over varying ranges of discharge.

pools and deposition in riffles. However, the change from deposition to erosion in pools in Bear Creek, measured as geomorphic change in the cross sections, occurs at flows that are much less frequent than 20 cms: the modeled shear stress reversal occurs at flows that are equaled or exceeded about 7 days per year whereas the survey data indicate that flows that change from pool-filling to pool-scouring occur between once a year to once every 2- to 4-years. It is possible that although shear stress maxima occur in pools at discharges greater than 20 cms, *critical* shear stresses for the total bed material mobilization in the pools are not achieved until discharges are much higher.

Maps of boundary shear stress can be compared to reach-median particle size to calculate the proportion of the bankfull channel bed that can be mobilized by different discharges. The modeling results predict that less than 30% of the bed is fully mobilized until discharges exceed about 40 cms, a flow that is equaled or exceeded only about 1 percent of the time during the year (that is, 3-4 days per year). From 40 to about 100 cms there is a sharp, linear increase in the proportion of the bed mobilized, followed by a gentle rise to an asymptote at about 290 cms. By 450 cms the model predicts that 100% of the bed will be fully mobilized (fig. 31).

The percent of the bed mobilized by a given discharge (magnitude) can be multiplied by the frequency of that discharge to calculate the magnitude x frequency product, a measure of geomorphic work (Wolman and Miller, 1960). According to this theory, when the product of magnitude and frequency is plotted against discharge, the peak of the curve occurs at the discharge that transports most of the sediment, or in this case, is responsible for the most bed mobilization and habitat maintenance. The magnitude frequency product curve for Crane Bottom has a distinct peak at 13-25 cms, flows that attain incipient entrainment for about 20-40% the bed (fig. 31). The magnitude frequency curve for full entrainment peaks at 25 - 40 cms, a flow that is predicted to fully mobilize about 17 - 30% of the bed.

The flows predicted to do the most geomorphic work in terms of mobilizing the bed of Bear Creek at Crane Bottom are relatively frequent, occurring multiple days per year on average. Theory holds that the flows that generally do the most geomorphic work in terms of stream sediment transport – often referred to as dominant discharges —should be around bankfull stage, with recurrence intervals on the order of 1 – 1.5 years on the annual maximum series (Wolman and Miller, 1960; Andrews, 1980). Other authors have pointed out that the peak of the magnitude frequency relation will vary with the shape of the sediment transport curve, the shape of the flow frequency curve, and the caliber of sediment under consideration (Nash, 1994). In this analysis, several factors may be responsible for the relatively high frequency of flows that are dominant in bed mobilization.

- We have used the *area* of the bed mobilized as an indicator of geomorphic work that rejuvenates benthic habitats by flushing sediment. This measure of work is likely to have a discharge-mag nitude relation that rises and reaches an asymptote more quickly with increasing discharge than a bed-load transport curve. Bed load transport curves are unlikely to reach an asymptote as long as sediment is available.
- The frequency distribution of daily mean discharges on Bear Creek is dominated by low flows. This skews the calculation of dominant discharge to low discharge values.
- The relatively high slope (typically 0.2%) and abundant bed material in the coarse gravel size range contribute to high rates of bed mobilization.

The 13 – 40 cms discharge is the best available estimate of the flow that is required to maintain Bear Creek stream habitats by transporting sediment and flushing fine sediment from the substrate. The geomorphic data, however, suggest that flows as much as twice as large (comparable to the January 31, 2002 flood) may be necessary to redistribute substantial quantities of sediment among pools and riffles (table 4, fig. 20).

These calculations illustrate the function of large flows in rejuvenating habitats by entraining and transporting sediment. The specific relations between discharge and percent of the bed entrained (fig. 31) are highly dependent on accuracy of the hydraulic model, choice of the Shield’s parameter value, the assumption that full mobilization occurs when $\tau_b/\tau_c = 2$, and the assumption that bed material particle size is uniform in the reach. Variation in these factors can change the shape of the relation between discharge and bed entrainment. Documented changes in channel morphology during the course of this study support the idea that these calculations are a conservative (minimum) estimate of the mobility of the Bear Creek bed (table 4, fig. 20). The shape of the magnitude frequency product curve, however, is relatively insensitive to the τ_b/τ_c calculation; even if the Shields parameter varies by +/- 40% the peak of the relation remains at a discharge of 25 - 40 cms.

Bed mobilization and habitat alteration may be affected by other factors not taken into account in this

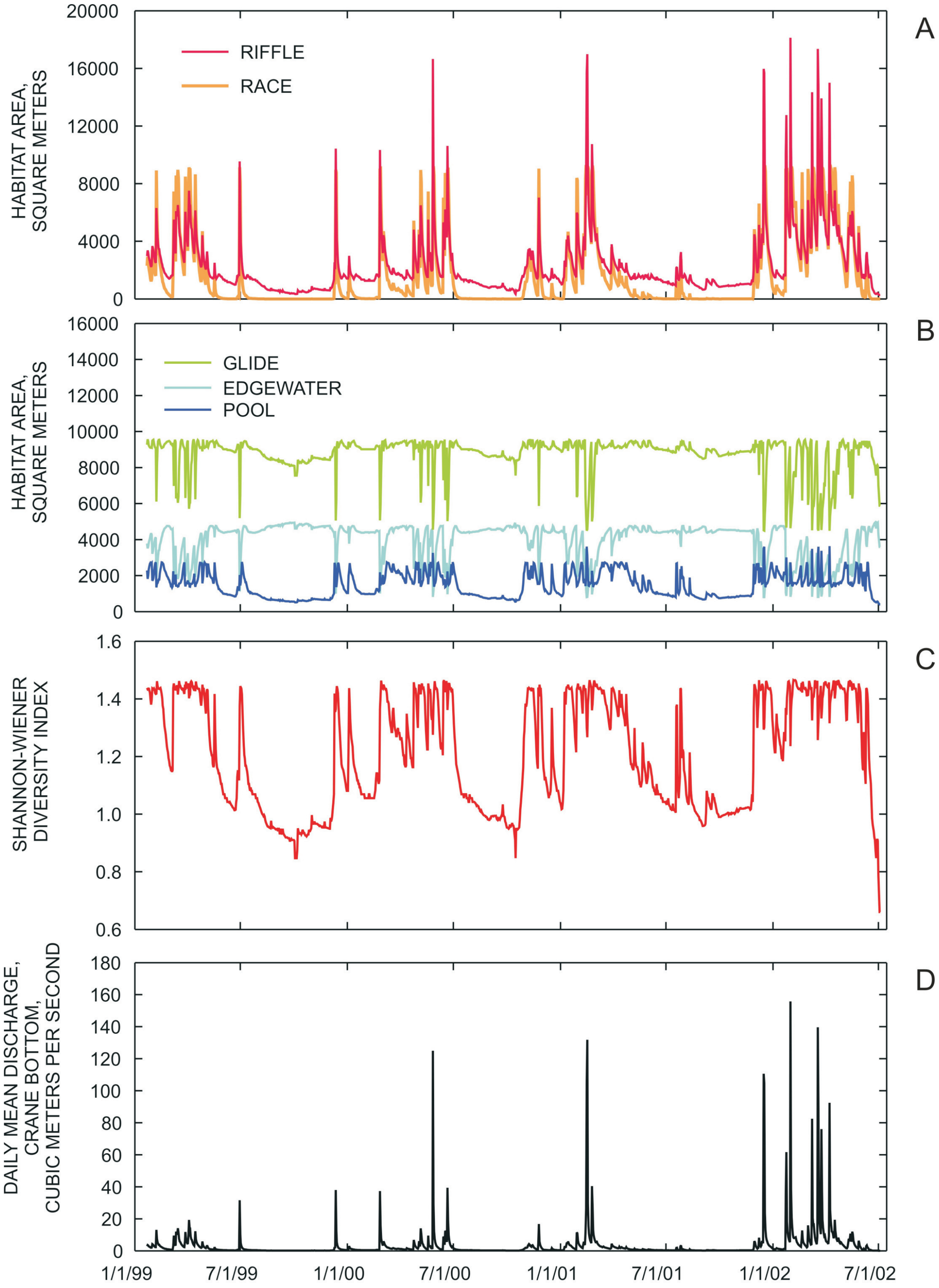
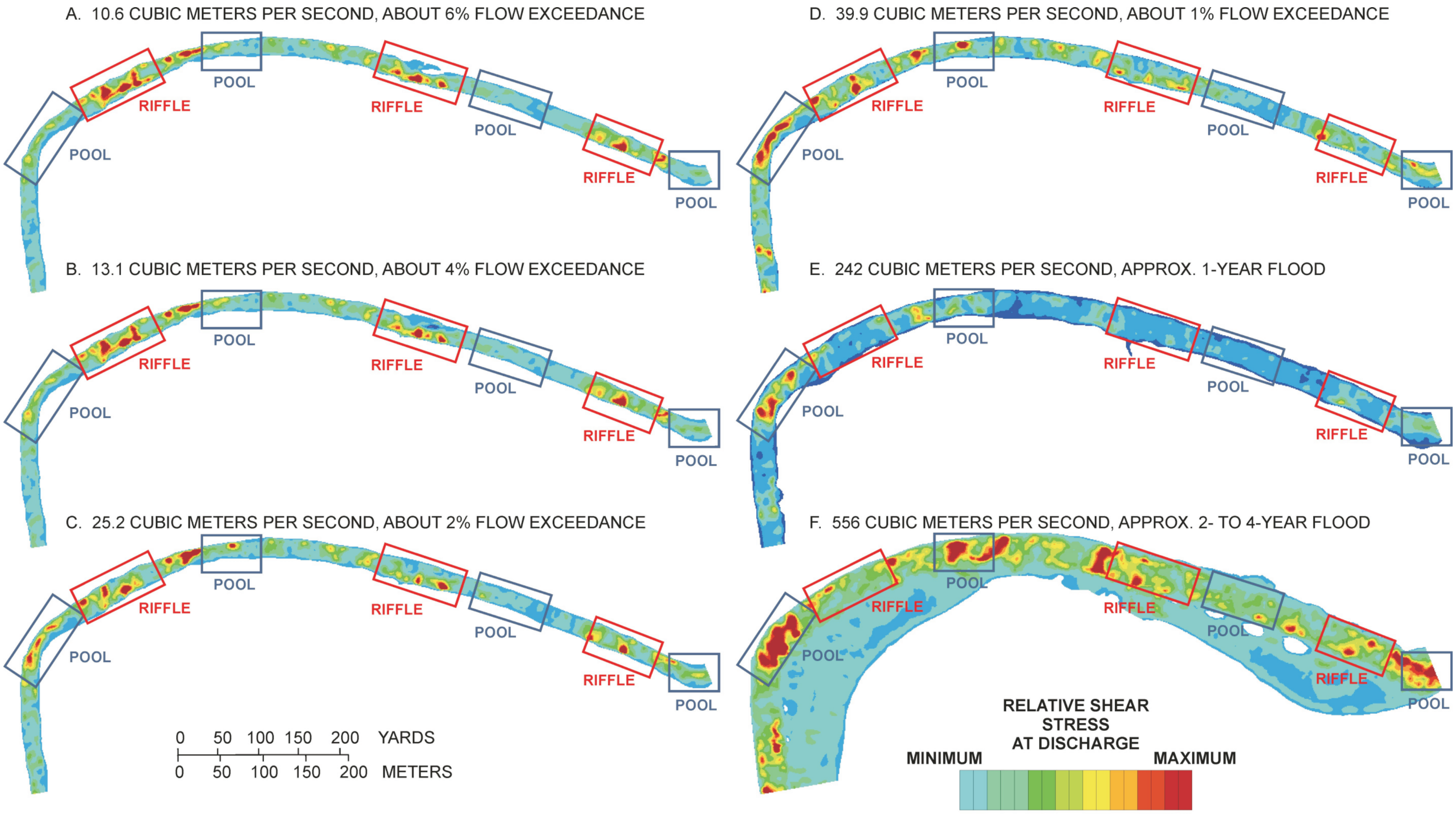


Figure 29. Time series of modeled habitat areas, diversity index, and discharge at Crane Bottom. A. Riffles and races. B. Glides, pools, and edgewaters. C. Shannon-Wiener diversity index. D. Daily mean discharge.


A. 10.6 CUBIC METERS PER SECOND, ABOUT 6% FLOW EXCEEDANCE

B. 13.1 CUBIC METERS PER SECOND, ABOUT 4% FLOW EXCEEDANCE

C. 25.2 CUBIC METERS PER SECOND, ABOUT 2% FLOW EXCEEDANCE

D. 39.9 CUBIC METERS PER SECOND, ABOUT 1% FLOW EXCEEDANCE

E. 242 CUBIC METERS PER SECOND, APPROX. 1-YEAR FLOOD

F. 556 CUBIC METERS PER SECOND, APPROX. 2- TO 4-YEAR FLOOD

Figure 30. Maps of relative ranges of boundary shear stresses showing shift of maximum shear stress from riffles to pools. A. 10.6 cubic meters per second. B. 13.1 cubic meters per second. C. 25.2 cubic meters per second. D. 39.9 cubic meters per second. E. 242 cubic meters per second. F. 556 cubic meters per second. Riffle and pool locations refer to low-flow positions.

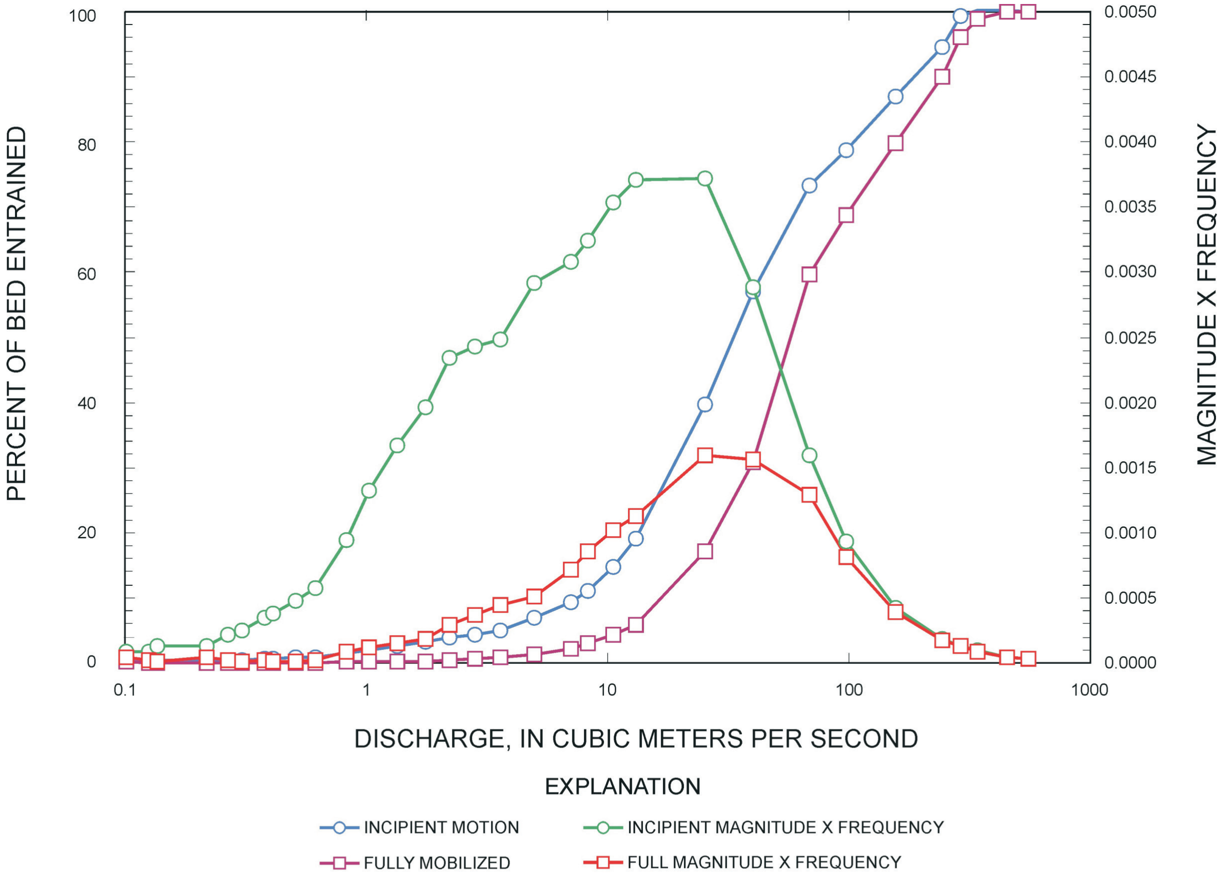


Figure 31. Relations between discharge and calculated percent of bed entrained, and discharge and magnitude x frequency product. Calculations include proportion of bed entrained assuming incipient motion (boundary shear stress is equal to critical shear stress) and assuming full mobilization (boundary shear stress is 2 times critical shear stress).

modeling exercise. In particular, emergent aquatic vegetation – primarily water willow – is clearly a stabilizing influence on these gravel bars, and would impart a substantial transport threshold. The threshold effect could substantially change the calculated relation in fig. 31.

Discussion: Sources of Physical Stream Habitat Variability

Physical stream habitats in Bear Creek vary with discharge (hydrologic dynamics) and with sediment transporting events (geomorphic dynamics). The monitoring period for this study was relatively wet, and high flow events convincingly demonstrated that substantial geomorphic changes in physical habitats are possible on Bear Creek. The hydraulic modeling of habitats served to simulate sensitivity of habitats to hydrologic variation alone.

The broadest aspects of physical habitat at Crane Bottom did not change during the study period: the framework pool-riffle sequence persisted, and the pools and riffles maintained their positions and relative areas. The greatest alteration to the broad-scale framework involved a few 10's of meters of migration of the crest of the downstream riffle (near cross section 7) and some movement of transient, bed-material-wave riffles near cross sections 18 and 20 during the monitoring period.

At the same time, changes in the elevations of some habitats, and evidence of scour, demonstrate that the Bear Creek stream habitats are susceptible to substantial geomorphic change, largely in the vertical dimension. The series of floods monitored during this study were responsible for approximately 2.4 m^3 of net erosion per meter of channel length in the reference channel (table 5). This value is nearly an order of magnitude greater than many other monitored sites in the Ozarks, a fact that might be explained in part by the abnormally high discharges during the monitoring period. Large amounts of geomorphic change might also be associated with passage of waves of sediment that have been liberated by land-use disturbances upstream and are moving slowly through the drainage basin (Jacobson and Gran, 1999).

Like six of seven of the reference monitoring sites in the Ozarks (table 5), Crane Bottom was characterized by net erosion during this monitoring period. This might be a coincidence, or it might be that, as argued by Jacobson (1995), most small drainage basins in the Ozarks are currently exporting sediment to downstream reaches. Without establishing a detailed history of the Bear Creek drainage basin it is impossible to evaluate the extent to which the Crane Bottom reach has been affected by historical land use.

Different floods had substantially different effects on where erosion and deposition occurred. The largest monitored flood (with an estimated 2- to 4-year recurrence interval) scoured pools and deposited gravel and cobbles in riffles whereas floods of an estimated 1-year recurrence interval deposited sediment in pools and eroded riffles. Essentially, the larger flood increased habitat depth diversity whereas the 1-year flood tended to homogenize habitat depths. The specific effects of these habitat changes on biota in Bear Creek are unknown. Certainly, all the floods in excess of 1-year recurrence interval transported sediment over substantial areas of the streambed, processes that could disturb benthic invertebrate populations, and/or rework particle-size characteristics of the bed, and therefore had potential to influence stream communities. Perhaps the most important function of geomorphic dynamics is the deepening of pool habitats by large floods, a process that maintains deep-water areas during subsequent periods of low flows.

Estimates of thresholds of change from shear stress modeling suggest that the bed material of Bear Creek can be mobilized by relatively frequent flows, with as much as 60% of the bed being mobilized by flows that occur, on average, 3 days per year. Over the long term, flows that occur 4-7 days per year are responsible for mobilizing the greatest proportion of the bed area, and are therefore presumably responsible for most rejuvenation of benthic habitats. Vegetation on gravel bars – principally water willow – seems to increase entrainment thresholds and serves to stabilize gravel bars. Decreases in gravel transport due to vegetation are not quantified, but field observations support the idea that emergent aquatic vegetation is an important factor in channel stability in the Ozarks.

Hydraulic modeling provides a basis for evaluating sensitivity of physical habitats to variations in discharge in Bear Creek. Glides and edgewaters are relatively abundant and insensitive to changes in discharge. Pools have residual area of about 4 percent of the total habitat area at the lowest flow modeled, and increase substantially to a peak area at discharges between 50 and 25% exceedance. An even higher peak in pool area occurs at overbank discharge (about 340 cms; fig. 28C) because of large areas of deep, slow water on the flood plain; however, these pool areas exist very infrequently. Riffles and races occupy very small areas at the lowest discharges and increase rapidly with increasing discharge. Races are the most sensitive to discharge because they disappear at discharges below 70% exceedance.

As a general measure of ecological value, the diversity of habitat is very sensitive to discharge from 100 to 50% exceedance, and fairly sensitive up to 25% exceedance, at which point diversity declines slowly with increasing discharge to a minimum when flow goes overbank at about 225 cms (fig. 28). At discharges greater than the top of the bank, diversity increases with increasing discharge as broader areas of the flood plain and terraces are inundated. The sensitivity of the Shannon-Wiener diversity index to discharge variation indicates that alterations to low flows on Bear Creek may be expected to cause substantial changes in ecological structure.

Specific biological effects of varying discharge are more difficult to quantify and were not the subject of this study. However, some information from the literature is available to evaluate potential linkages. Pool area is restricted at the very smallest discharges, which could affect pool-dwelling species such as sunfish and smallmouth bass (Peterson and Rabeni, 2001). Potentially more important, however, is the complete loss of race and riffle habitat that occurs at very low flows (fig. 28A). These habitats are generally used by benthic fish species such as the rainbow darter and the Ozark minnow. Loss of these habitats for extended periods of time could displace or extirpate these species.

Summary and Conclusions

We investigated the physical stream habitat of Bear Creek, northern Arkansas, to document and analyze sensitivity of habitats to geomorphic and hydrologic dynamics. Like most streams in the Ozarks, Bear Creek has had a history of land-use disturbance that has mobilized excess gravel bedload. Continued downstream movement of gravel bedload through the channel network can be expected to cause persistent geomorphic disturbance, which will act as a background to any additional hydrologic alterations.

The study reach selected for monitoring and modeling of Bear Creek is Crane Bottom, about 1 km upstream of the junction of Bear Creek with the Buffalo River. The reach consists of three riffle-pool sequences and has a representative selection of hydraulic habitat units. We installed 31 cross sections for monitoring geomorphic changes; the cross sections were resurveyed three times in a one-year period to document erosion and deposition. Cross-section monitoring was supplemented with particle tracer experiments and re-excavation of scour chains. We used a two-dimensional, finite-element hydraulic model to quantify areas of physical habitat available at a range of discharges from low flows to 2- to 4-year recurrence interval floods. The results of the modeling were used to assess sensitivity of habitat availability to flow alterations, and to evaluate the frequency of flows capable of initiating bed material movement.

The time period selected for this study was relatively wet. Rainfall in the Bear Creek drainage basin was approximately 140% of normal during this time. Seven individual floods of approximate bankfull stage were recorded; the largest was estimated to have a 2- to 4-year recurrence interval.

Monitoring of geomorphic change at Bear Creek during this period documented that relatively frequent floods – those that occur several times per year to those that occur on average once every 2 to 4 years – are instrumental in maintaining diversity of physical habitats through erosion and deposition of gravel. These floods create the geomorphic framework that determines depths and velocities produced by lower discharges. Modeling of the critical shear stresses necessary to initiate sediment movement indicates that most of the bed mobilization that maintains benthic habitat is accomplished by flows that occur 4-7 days per year.

For a range of flows that do not transport appreciable sediment, habitat availability is determined by hydraulic controls on depth and velocity. Habitat availability was modeled using a depth-averaged, finite-element, 2-dimensional hydraulic model, calibrated to measured flows. This class of model can develop inventories of habitat areas, but depends on the assumption that the channel morphology does not change during the range of flows.

Areas of hydraulically defined physical habitats in Bear Creek vary substantially with discharge, especially for flows that are equaled or exceeded 100-50% of the time. An index of diversity of habitat also varies substantially over this range of discharge, indicating that alteration of low flows may be expected to cause changes in the structure of the stream ecosystem. Among hydraulic habitat units, areas of races and riffles are the most sensitive to discharge. These habitats diminish substantially as discharge decreases from 50% to 75% flow exceedance; races disappear completely at about 70% flow exceedance.

This analysis establishes the roles of high and low flows in maintaining and sustaining physical habitat on Bear Creek. Different flows have different roles: high flows determine the geomorphic template by scouring pools, transporting sediment, rejuvenating benthic habitat, and depositing sediment in riffles; low flows that prevail most of the time combine with the geomorphic template to create habitat. How habitat might change in the future, however, is dependent on factors that have not been measured as part of this study. Like most Ozarks streams, Bear Creek is subject to ongoing geomorphic changes as waves of bed-material load migrate downstream through the river basin. These waves could significantly vary sediment supplied to discrete reaches of Bear Creek, and thereby alter sediment transport and the resulting template of channel morphology. In addition, changes in hydrology in the basin could result from land-use change, water resource development, or climate change. Changes in hydrologic budget may change the frequency and magnitude of habitat-maintaining events, and may change the seasonal distribution of low flows and associated habitats. The results of this study document the dependence of physical habitat on the entire spectrum of flows.

Alteration of the availability of physical habitat could be expected to affect ecological communities of Bear Creek. Physical habitats of Ozarks streams are known to be highly associated with specific ecological processes, individual species, or assemblages of species. The high sensitivity of races and riffles in Bear Creek to variability of low flows indicates that benthic, riffle- and race-dwelling species such as the rainbow darter (*Etheostoma caeruleum*) and Ozark minnow (*Notropis nubilus*) could be at risk if low flows were significantly altered. Similarly, pool-dwelling species such as smallmouth bass (*Micropterus dolomieu*) and Ozark bass (*Ambloplites constellatus*) could be at risk if decreases in peak flows favored sedimentation in pools.

References Cited

Andrews, E.D., 1980, Effective and bankfull discharges of streams in the Yampa river basin, Colorado and Wyoming: Journal of Hydrology, v. 46, p. 311-330.

Andrews, E.D., 1984, Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado: Geological Society of America Bulletin, v. 95, p. 371-378.

Barbour, M.T., Gerritsen, J., Snyder, B.D., and Stribling, J.B., 1999, Rapid bioassessment protocols for use in streams and wadeable rivers – Periphyton, benthic macroinvertebrates, and fish (2^{nd} ed.): U.S. Environmental Protection Agency, Office of Water, EPA 841-B—99-002.

Chow, V.T., 1959, Open-channel hydraulics: New York, McGraw-Hill, Inc., 680 p.

DeVries, P. and Goold, D.J., 1999, Leveling rod base required for surveying gravel river bed elevations: Water Resources Research, v. 35, p. 2877-2879.

Doisy, K.E. and Rabeni, C.F., 2001, Flow conditions, benthic food resources, and invertebrate community composition in a low-gradient stream in Missouri: Journal of the North American Benthological Society, v. 20, p. 17-32.

Femmer, S.R., 1997, Water-quality assessment of the Ozark Plateaus study unit, Arkansas, Kansas, Missouri, and Oklahoma — Habitat data and characteristics at selected sites, 1993-95: U.S. Geological Survey, Open-File Report 97-236, 44 p.

Gordon, N. D., McMahon, T. A., and Finlayson, B. L., 1992, Stream Hydrology: An introduction for ecologists: Chichester, England, John Wiley and Sons, 526 p.

Gorman, O.T., and Karr, J.R., 1978, Habitat structure and stream fish communities: Ecology, v. 59, p. 507-515.

Hofer, K.R., Scott, H.D., and Mckimmey, J.M., 1995, Spatial distribution of the surface geology and 1992 land use of the Buffalo River Watershed: Arkansas Water Resources Center Publication, no. 174, pg.43.

Interagency Advisory Committee on Water Data, 1982, Guidelines for determining flood-flow frequency: Bulletin 17B of the Hydrology Subcommittee, Office of Water Data Coordination, U.S. Geological Survey, Reston, Virginia., 183 p.

Jacobson, R.B., 1995, Spatial controls on patterns of land-use induced stream disturbance at the drainage-basin scale—an example from gravel-bed streams of the Ozark Plateaus, Missouri: Costa, J.E., Miller, A.J., Potter, K.W., and Wilcock, P.R., eds., AGU Geophysical Monograph 89, The Wolman Volume, p. 219-239.

Jacobson, R.B., in press, Downstream effects of timber harvest in the Ozarks of Missouri: in, Flader, S., ed., Toward Sustainability for Missouri Forests, U.S. Forest Service NC Research Station General Technical Report.

Jacobson, R.B., Femmer, S.F., and McKenney, R., 2001, Land-Use Changes and the Physical Habitat of Streams: U.S. Geological Survey Circular 1175, 63 p.

Jacobson, R.B. and Gran, K.B., 1999, Gravel routing from widespread, low-intensity landscape disturbance, Current River Basin, Missouri: Earth Surface Processes and Landforms, v. 24, 897-917.

Jacobson, R.B., and Primm, A.T., 1997, Historical land-use changes and potential effects on stream disturbance in the Ozark Plateaus, Missouri: U.S. Geological Survey Water-Supply Paper 2484, (reprint of Open-File Report 94-333). 95 p.

Jacobson, R.B., and Pugh, A.L., 1992, Effects of land use and climate shifts on channel instability, Ozark Plateaus, Missouri, U.S.A.: Proceedings of the workshop on the effects of global climate change on hydrology and water resources at the catchment scale, February 3-6, 1992, Tsukuba, Japan, Japan-U.S. Committee on Hydrology, Water Resources and Global Climate Change, p. 423-444.

Jacobson, R.B., and Pugh, A.L., 1999, Riparian vegetation controls on the spatial pattern of stream-channel instability, Little Piney Creek, Missouri: U.S. Geological Survey Water-Supply Paper 2494. 33 p.

Jeffries, M., and Mills, D., 1990, Freshwater Ecology: Principles and Applications: Belhaven Press, N.Y., 285 p.

Keller, E.A., 1971, Areal sorting of bedload material, the hypothesis of velocity reversal: Geological Society of America Bulletin, v. 82, p. 279-280.

McKenney, R., 1997, Formation and Maintenance of Hydraulic Habitat Units in the Streams of the Ozark Plateaus: unpublished Ph.D. Dissertation, Pennsylvania State University, State College, Pennsylvania, 340 p.

McKenney, R., 2001, Channel changes and habitat diversity in a warm-water, gravel-bed stream, in, Dorava, J., Montgomery, D., Palcsak, B., and Fitzpatrick, F., Geomorphic Processes and Riverine Habitat, American Geophysical

Union, Water Science and Application Series, v. 4. p. 57-72.

McKenney, R., and Jacobson, R.B., 1996, Erosion and deposition at the riffle-pool scale in gravel-bed streams, Ozark Plateaus, Missouri and Arkansas, 1990-95: U.S. Geological Survey Open-File Report 655-A.

McKenney, R., Jacobson, R.B., and Wertheimer, R.C., 1995, Woody vegetation and channel morphogenesis in low-gradient, gravel-bed streams in the Ozarks Region, Missouri and Arkansas: Geomorphology, v. 13, p. 175-198.

Milhous, R.T., 1982, Effect of sediment transport and flow regulation on the ecology of gravel-bed rivers, *in* Hey, R.D., Bathhurst, J.C., and Thorne, C.R., eds., Gravel-bed rivers: Chichester, England, John Wiley and Sons, p. 819-842.

Nash, D.B., 1994, Effective sediment-transporting discharge from magnitude-frequency analysis: Journal of Geology, v. 102, p. 79-95.

National Oceanic and Atmospheric Administration, 2002, Climatography of the United States No. 81, Monthly Station Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1971 – 2000, Arkansas: Asheville, North Carolina, National Environmental Satellite, Data, and Information Service, National Climatic Data Center, 26 p.

Panfil, M.S. and Jacobson R.B., 1999, Hydraulic modeling of in-channel habitats in the Ozark Highlands of Missouri: Assessment of habitat sensitivity to environmental change. View this document online at: <*http:/www.cerc.usgs.gov/rss/rfmodel/*>

Panfil, M.S., and Jacobson, R.B., 2001, Relations among geology, physiography, land use, and stream habitat conditions in the Buffalo and Current river systems, Missouri and Arkansas: U.S. Geological Survey, Biological Sciences Report, BSR-2001-0005, 111 p. online at: <*http://www.cerc.usgs.gov/pubs/center/pdfDocs/BSR2001-0005.pdf*>

Petersen, J.C., Adamski, J.C., Bell, Davis, J.V., Femmer, S.R., Freiwald, D.A., and Joseph, R.L., 1998, U.S. Geological Survey Circular 1158, online at: <*http://water.usgs.gov/pubs/circ1158*>, updated April 3, 1998

Petersen, J.C., Haggard, B.E., and Green, W.R., 2002, Hydrologic characteristics of Bear Creek near Silver Hill and Buffalo River near St. Joe, Arkansas, 1999-2000: U.S. Water-Resources Investigations Report 02-4024, 36 p.

Petersen, J.C., 1998, Water-Quality Assessment of the Ozark Plateaus Study Unit, Arkansas, Kansas, Missouri, and Oklahoma — Fish Communities in Streams and their Relations to Selected Environmental Factors: U.S. Geological Survey, Water-Resources Investigations Report 98-4155, 32 p.

Peterson, J.T., and Rabeni, C.F., 2001, The relation of fish assemblages to channel units in an Ozark stream: Transactions of the American Fisheries Society, v. 130, p. 911-926.

Planking, J.L., Barbour, M.T., Porter, K.D., Gross, S.K., and Hughes, R.M., 1989, Rapid bioassessment protocols for use in streams and rivers: U.S. Environmental Protection Agency, EPA/444/4-89-001, 176 p.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., and Stromberg, J.C., 1997, The natural flow regime: BioScience, v. 47, p. 769-784.

Richter, B.D., Baumgartner, J.V., Wigington, R., and Brau, D.P., 1997, How much water does a river need? Freshwater Biology, v. 37, p. 231-249.

Schlosser, I.J., 1987, A conceptual framework for fish communities in small warmwater streams, in, Matthews, W. J., and Heins, D. C., eds., Community and Evolutionary Ecology of North American Stream Fishes: Norman, University of Oklahoma Press, p. 17-24, 269-299.

Scott, W.B., and E.J. Crossman. 1973. Freshwater fishes of Canada. Bull. Fish. Res. Board Can. 184. 966 pp.

Shannon, C.E., and Weaver, W., 1949, The mathematical theory of communication: Urbana, Ill., The Univ. of Illinois Press, p. 19-27, 82-83, 104-107.

Shields, A., 1936, Application of similarity principles and turbulence research to bedload, in, Anwendung der Aehnlichkeitsmechanik und der Turbulezforschung auf die Geschiebewegung: Mitteilun Preussischen Versuchanstalt fur Wasserbau und Schiffbau, Berlin, No. 26, by Ott., W.P. and van Uchelen, J.C., California Institute of Technology Hydrodynamics, Pasadena, California, Report 167, 43 p.

Steffler, P. and Blackburn, J., 2001, River2D - Two-Dimensional Depth Averaged Model of River Hydrodynamics and Fish Habitat, Introduction to Depth Averaged Modeling and User's Manual: University of Alberta, 89 p.

Thomas, W.O., Jr., Lumb, A.M., Flynn, K.M., and Kirby, W.H., 1998, User's manual for program PEAKFQ, annual flood frequency analysis using Bulletin 17B guidelines, written communication, unpublished ms, 89 p.

U.S. Geological Survey, 2003, Daily streamflow for Missouri: Online digital hydrologic data, URL: http://waterdata.usgs.gov/mo/nwis.

U.S. Geological Survey, 2000a, US GeoData Digital Elevation Models, Fact Sheet 040-00, <*http://mapping.usgs.gov/mac/isb/pubs/factsheets/fs07099.html*>.

U.S. Geological Survey, 2000b, National Land Cover Data, 30-meter resolution, <*http://edcsgs9.cr.usgs.gov/programs/lccp/nationallandcover.html*>.

Whitledge, G.W., and Rabeni, C.F., 2000, Benthic community metabolism in three habitats in an Ozark stream: Hydrobiologia: v. 437, p. 165-170.

Wilcock, P.R., and McArdell, B.W., 1993, Surface-based fractional transport rates – Mobilization thresholds and partial transport of a sand-gravel sediment: Water Resources Research, v. 29, p. 1297-1312.

Wolman, M.G., 1954, A method of sampling coarse river bed material: American Geophysical Union Transactions, v. 35, p. 951-956.

Wolman, M.G., and Miller, J.P., 1960, Magnitude and frequency of forces in geomorphic processes: Journal of Geology, v. 68, p. 54-74.

Yalin, M.S. and Karahan, E., 1979, Inception of sediment transport: Journal Hydraulics Div., American Society of Civil Engineers, v. 105, p. 1433-1443.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave Blank)*	2. REPORT DATE July 2003	3. REPORT TYPE AND DATES COVERED Biological Science Report

4. TITLE AND SUBTITLE
Physical Stream Habitat Dynamics in Lower Bear Creek, Northern Arkansas

5. FUNDING NUMBERS

6.AUTHOR(S)
Joanna M. Reuter, Robert B. Jacobson, and Caroline M. Elliot

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Department of the Interior
U.S. Geological Survey, Biological Resources Division
Columbia Environmental Research Center
4200 New Haven Road
Columbia, MO 65201

8. PERFORMING ORGANIZATION REPORT NUMBER
USGS/BRD/BSR--2003-0002

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Department of the Interior
U.S. Geological Survey
Biological Resources Division
Reston, VA 20192

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Release unlimited. Available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161 (1-800-553-6847 or 703-487-4650). Available to registered users from the Defense Technical Information Center, Attn: Help Desk, 8722 Kingman Road, Suite 0944, Fort Belvoir, VA 22060-2618 (1-800-225-3842 or 703-767-9050).

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*) We evaluated the roles of geomorphic and hydrologic dynamics in determining physical stream habitat in Bear Creek, a 239 km2 watershed in the Ozarks, northern Arkansas. During a relatively wet 12-month period, Bear Creek was altered by a series of floods, including four with discharges exceeding a 1-year recurrence interval and one with an estimated 2- to 4-year recurrence interval. These floods eroded sediment from the study reach at rates in excess of other sites previously studied in the Ozarks. The 2- to 4-year flood scoured gravel from pools and deposited it in riffles. The smaller floods eroded gravel from the riffles and deposited it in pools. A two-dimensional hydraulic model was compiled to assess habitat variation with hydrology. Depths and velocities simulated for discharges of 0.1 to 556 cubic meters per second were classified into habitats using hydraulic criteria. Races disappear completely at the lowest flows; riffles contract substantially. Pools also contract during low flow, but deep scours adjacent to bedrock outcrops sustain some pool area even at the lowest flows. Magnitude and frequency of bed-sediment entrainment show that most habitat maintenance results from flows that occur about 4-7 days a year.

14. SUBJECT TERMS: aquatic habitat, geomorphology, hydrology, Ozarks, Arkansas

15. NUMBER OF PAGES
49 pages +appendices

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited

U.S. Department of the Interior
U.S. Geological Survey

MARCH 3, 1849

USGS
science for a changing world