Land-Use Changes and the Physical Habitat of Streams—A Review with Emphasis on Studies within the U.S. Geological Survey Federal-State Cooperative Program

Circular 1175

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

Stream habitats in the United States are highly variable and have a wide range of potential land-use stressors.

Cover photograph left: The Cascade Mountains of Oregon have high-gradient, coarse-bedded streams.

Cover photograph right: The Chickahominy River in the Coastal Plain of Virginia is a low-gradient, sand-bed stream.

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U.S. DEPARTMENT OF THE INTERIOR

GALE A. NORTON, Secretary

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
Length		
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
Area		
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile
Volume		
cubic meter (m^3)	264.2	gallon
Flow rate		
cubic meter per second (m^3/s)	35.31	cubic foot per second

Temperature in degrees Fahrenheit (˚F) may be converted to degrees Celsius (˚C) as follows:

$$˚C=(˚F-32)/1.8$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Altitude, as used in this report, refers to distance above or below sea level.

Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 ˚C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

NOTE TO USGS USERS: Use of hectare (ha) as an alternative name for square hectometer (hm^2) is restricted to the measurement of small land or water areas. Use of liter (L) as a special name for cubic decimeter (dm^3) is restricted to the measurement of liquids and gases. No prefix other than milli should be used with liter. Metric ton (t) as a name for megagram (Mg) should be restricted to commercial usage, and no prefixes should be used with it.

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ABSTRACT

Understanding the links between land-use changes and physical stream habitat responses is of increasing importance to guide resource management and stream restoration strategies. Transmission of runoff and sediment to streams can involve complex responses of drainage basins, including time lags, thresholds, and cumulative effects. Land-use induced runoff and sediment yield often combine with channel-scale disturbances that decrease flow resistance and erosion resistance, or increase stream energy. The net effects of these interactions on physical stream habitat—depth, velocity, substrate, cover, and temperature—are a challenge to predict. Improved diagnosis and predictive understanding of future change usually require multi-faceted, multi-scale, and multidisciplinary studies based on a firm understanding of the history and processes operating in a drainage basin. The U.S. Geological Survey Federal-State Cooperative Program has been instrumental in fostering studies of the links between land use and stream habitat nationwide.

INTRODUCTION

Land-use changes have occurred to some extent almost everywhere in North America since European settlement. Changes in vegetative cover, disturbance of soils, and the loss of wetlands have created the substantial potential for altered runoff and sediment yield in many regions. Disturbances of streams by activities such as channelization, aggregate mining, livestock grazing, and dams have directly affected channel morphology and streamflow characteristics. Changes in runoff and sediment yield to streams and direct disturbances of channels can severely alter physical stream habi-

Figure 1. Direct disturbances of the stream channel can result in the deposition of fine sediment and channel instability as shown here downstream of an aggregate mine on the North River, Missouri. Some changes in stream habitat are distinct and clearly associated with a particular land-use disturbance.

tat—the template of temperature, turbidity, water depth, current velocity, channel substrate, and cover that supports the stream ecosystem (fig. 1). Cover, such as boulders, root wads, or submerged vegetation, provides concealment and protection to organisms in an aquatic system.

Habitat can be conceptualized as the physical and chemical characteristics of a stream that determine suitability for habitation and reproduction of stream organisms. The characteristics, volume, spatial arrangement, and variation of habitat over time can be fundamental controls that determine which organisms can survive or thrive in a stream and, therefore, may function also as preliminary controls on biotic interactions such as competition or predation.

Physical habitat change has been recognized as a key factor in degradation of many stream ecosystems (Jeffries and Mills, 1990; Waters, 1995). At the same time, the land-use changes that have caused physical-habitat degradation—such as agriculture, mining, forestry, and urbanization—have substantial economic benefits. To evaluate the balance between economic and ecosystem values, there is a need to understand the process links between land-use change and physical habitat change. Improved understanding of these links may lead to more effective resource management and stream restoration strategies.

The links from land-use change to alteration of physical habitat and subsequently to changes in the stream biota can be complex and difficult to trace. Processes and rates of the processes that form the links from land use to habitat vary with time and space. Links can be indirect and cumulative, such as the downstream accumulation of sediment produced by widespread, low-magnitude soil erosion over a drainage basin. In contrast, links can be clear and direct, such as the effect of a dam on discharge flow duration. In many situations, key links between land-use changes and physical-habitat changes have to be identified from a confusing mixture of multiple land-use changes and natural disturbances.

While some habitat-biota links or portions of links have been well established, others are poorly understood. Many aquatic ecologists view availability of particular habitats as a necessary but insufficient condition for biotic responses. Physical and chemical habitat determine *potential* for biotic communities, but realization of the potential is highly dependent on how and when species use habitat, on extrinsic disturbances like floods or droughts, and on biotic interactions that determine population dynamics.

States for two broadly defined applications. The first application is for management of biological resources, principally for sport and commercial fisheries, and more recently for threatened and endangered species. Recognition of the habitat requirements of such species and the processes that generate and maintain those habitats gives managers the knowledge to mitigate adverse effects and promote production. The second broad application is in bioassessment of water quality. Bioassessment recognizes the utility of stream biota to provide an overall index of stream health and to integrate the effects of multiple stressors. Because biota give an integrated response to chemical and physical changes in their environment, physical habitat must also be evaluated to interpret causes for biotic responses. Thus, bioassessment of water quality requires that the effects of physical habitat variations are accounted for. The need for understanding physical habitat was summarized by Rankin (1995) in a discussion of habitat monitoring:

> *"Analyses performed in Ohio suggest that without biosurvey and habitat data there is a high risk of missing non-chemical and chemical impacts to streams.... There is a smaller but still significant risk of 'finding' a water quality impact where one really does not exist when [habitat] monitoring data are insufficient. This could result in a regulatory action that might cost hundreds of thousands of dollars or more to an entity, with costs passed along to consumers."*

THE FEDERAL-STATE COOPERATIVE PROGRAM AND PHYSICAL STREAM HABITAT INVESTIGATIONS

Understanding the links between land-use changes, physical habitat changes, and biotic responses requires a multidisciplinary scientific approach combining hydrology, sediment transport, geomorphology, and ecology. Because the links are sensitive to specific landscape characteristics, disturbance processes, and disturbance histories, improved understanding generally requires a field-oriented approach that is tailored to specific situations. Within the constraints indicated by the field-oriented approach, theoretical and computational models can be used to enhance understanding of the links.

Through the Federal-State Cooperative Program, the U.S. Geological Survey (USGS) has participated in many studies that are intended to develop improved understanding of the processes linking land-use and physical stream-habitat changes. These studies include:

- Historical studies to diagnose how habitats have changed in response to past land-use changes;
- Associative studies of correlations among drainage-basin scale land-use characteristics,
- Process studies of links between land use and habitat, and
- Modeling studies of the links between land use and habitat.

By developing scientific studies in partnership with State and local agencies, the USGS has been able to apply multidisciplinary expertise and a field-oriented scientific approach throughout the United States to help integrate concerns of stream ecosystem management with concerns of land-, mineral-, and water-resources management.

The purpose of this report is to provide a general framework for understanding links between land-use and physical stream-habitat changes. Complete discussion of the wide range of topics that form the framework introduced here is beyond the scope of this report. References are provided to guide the interested reader to more complete treatments in the hydrology, ecology, and geomorphology literature. This framework is supplemented with a discussion of multidisciplinary approaches to investigating links, with illustrative examples from USGS cooperative studies (figure 2).

FACTORS AFFECTING PHYSICAL STREAM HABITAT

Physical stream habitat is studied and defined at multiple scales. The instream microhabitat is within the reach scale, which is a subcategory of the segment scale that exists within the basin scale. The drainage basin scale exists within gross classification units such as physio-

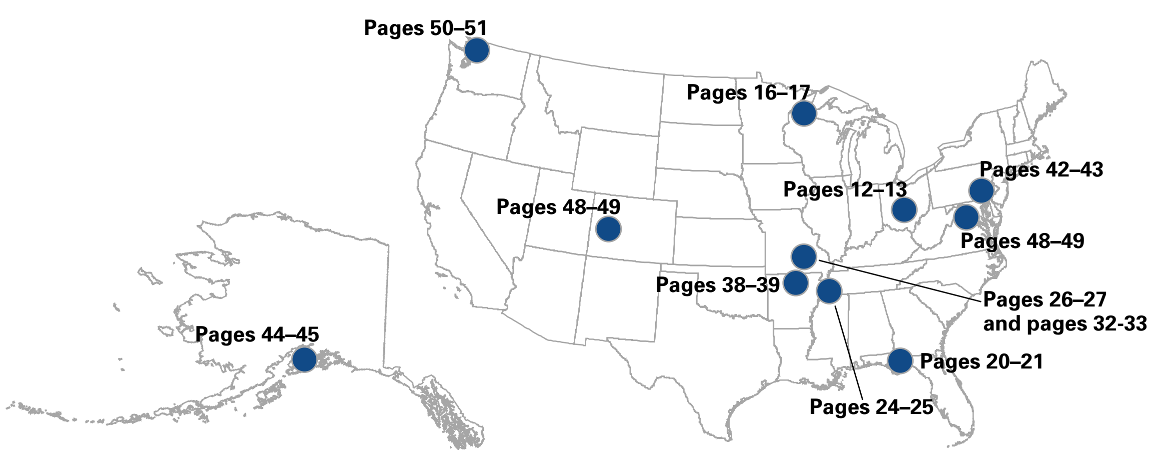


Figure 2. Locations of multidisciplinary USGS cooperative studies, which are discussed in this report, that are investigating the links between land use and physical stream-habitat changes.

graphic settings and ecosystems, although most land-use studies are measured and managed at the drainage basin scale or finer.

This hierarchy forms the basis for river- and stream-habitat classifications. The hierarchy also implies a set of process links: instream habitats are formed by fluxes of water, sediment, and energy; the spatial, temporal, and material characteristics of these fluxes are determined by factors at higher levels of the hierarchy. Sufficient understanding of these process links could allow the prediction of habitat conditions from knowledge of the hierarchical controls on a particular stream reach.

The process links that form habitat are insufficiently known. This results from the inherent complexity of geomorphic systems in which spatial variations in geologic characteristics, physiography, and vegetative covers are combined with temporal variations of climate and tectonics, which are compounded by the "complex response" of drainage basins due to lags, thresholds, and cumulative effects. These factors present real challenges to our understanding of the links between landscape changes and physical stream-habitat changes.

In addition, the link from physical habitat to habitat use by stream organisms presents complications and challenges to our understanding. Stream ecologists recognize that habitat is a necessary foundation for many stream communities, but disturbance regime and biotic interactions also affect community structure and habitat use. This section of the report presents definitions and classifications of rivers and stream habitat, discusses the physical links of habitat formation and disturbance within geomorphic systems, and reviews concepts of the role of physical habitat in structuring stream communities.

Definition and Classification of Physical Stream Habitat

Physical habitat is a general term for the surroundings where organisms live. In streams, physical habitat includes water temperature, turbidity, water depth, current velocity, channel substrate, and cover. Characteristics considered to be part of physical habitat overlap somewhat with water-column chemical characteristics such as pH, dissolved oxygen, nutrients, and other dissolved constituents. For the purposes of this report, however, physical habitat is limited to those characteristics that do not necessarily involve chemical processes.

Physical habitats are classified to inventory the range of physical characteristics between and within stream systems. Classification systems subdivide the continuum of a stream into units with similar characteristics, using consistent criteria to define and separate habitat types. In this manner, habitat availability and quality can be evaluated systematically. Systematic classification aids in statistical sampling design for population estimates, in improving understanding of ecological functioning, and in developing restoration strategies (Hawkins and others, 1993).

Because classification systems are used for planning and management over a range of spatial scales, habitat classification systems exist for a range of spatial scales. The classification scale used depends on the level of information needed. At the broadest levels of classification, ecoregions and physiographic provinces define geologic and climatic constraints on river systems (for example, Pflieger, 1989). Classification of streams at the drainage-basin scale includes classification of areal features of the drainage basin and linear features of the stream network. The areal features of basins typically are classified according to geology, geomorphology, soils, climate, vegetation, and land use. The stream system within a basin can be classified based on the longitudinal profile and channel network characteristics such as stream order.

Within stream systems, a finer scale of classification usually is achieved by subdividing the channel into *segments* that have uniform bedrock and that exist between tributary junctions or point sources of disturbance (Frissell and others, 1986). Uniformity of bedrock and hydrologic characteristics defines a range of channel characteristics for a particular segment. Within segments, *reaches* are defined as lengths of stream that lie between substantial changes in channel morphology, valley width, and riparian vegetation. In streams with mobile beds and banks, reaches generally have multiple occurrences of repeating riffle-pool or step-pool sequences. Hence, reaches usually are defined as lengths of stream that contain representations of all habitat types that exist within a segment. The reach scale commonly is used to investigate stream communities as well as to describe channel morphology (Frissell and others, 1986). The Rosgen classification system (Rosgen, 1996) emphasizes channel planform and cross-sectional channel morphology to classify discrete stream types. This system has been widely used to classify streams at the reach and segment scales.

At the next finer scale, reaches can be subdivided into habitat units or *macrohabitats*. Macrohabitat classifications recognize the existence in streams of "semi-discrete areas of relatively homogeneous depth and flow that are bounded by sharp physical gradients…" (Hawkins and others, 1993, p. 4). These areas are the familiar riffles and pools and subdivisions based on morphology, depth, velocity, turbulence, substrate, and cover (fig. 3). Many macrohabitat classification schemes exist, perhaps because the vast range of channel characteristics and applications precludes any one particular classification scheme. Some effort is being applied to develop overarching, hierarchical classification systems that will resolve useful definitions at a range of scales (for example, Hawkins and others, 1993; Rabeni and Jacobson, 1993a).

Although stream and habitat classifications are useful for many inventory applications, classification is limited in what it can contribute to understanding of stream habitats because it is a static portrayal of a dynamic system (fig. 4). Habitat changes result inevitably from channel dynamics, and most stream channels exhibit changes over time intervals of minutes to decades. The understanding and management of physical habitat requires substantially more than a static classification of streams and associated habitats. The Rosgen system of classification, for example, has been subject to criticism specifically because it does not adequately consider channel dynamics and responses to disturbance (Miller and Ritter, 1996). At the reach scale, the distribution of macrohabitats varies through time with individual flood events and as the channel migrates and adjusts to sequences of channel-forming flows, land-use changes, and random hydrologic occurrences. A process level understanding of factors that control macrohabitat formation, evolution, and stability would be useful extensions to habitat classification systems.

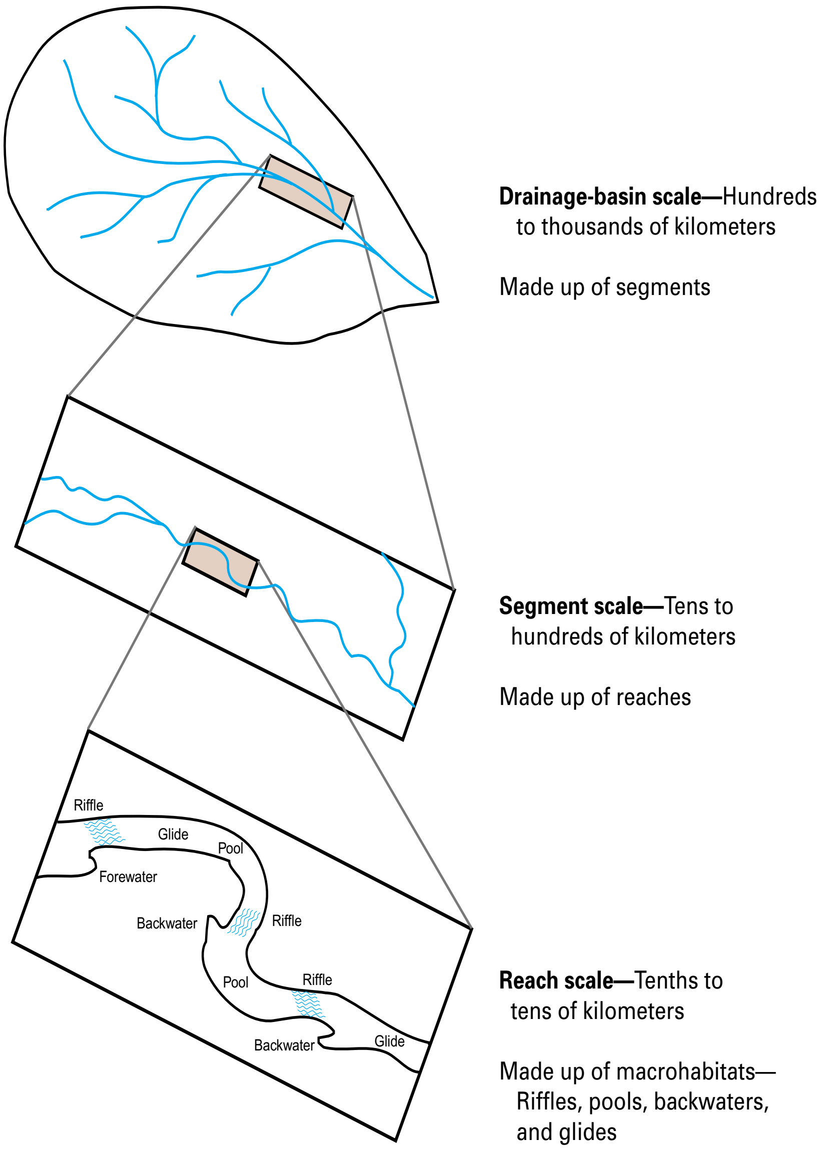


Figure 3. Scales of processes that link land use to stream habitat. Land use at the scale of drainage basins determines runoff and sediment transmitted through the drainage network. Segments are parts of the drainage network between substantial tributaries and are characterized by two or more repeating macrohabitats and relatively uniform channel pattern. Macrohabitats are repeating parts of the stream channel within which depth, velocity, and substrate are uniform. Macrohabitats are bounded by sharp gradients of depth., velocity, and substrate in transition to adjacent macrohabitats. Effects of land-use change on habitat are typically measured at the reach scale in terms of changes to macrohabitats.

Abiotic and Biotic Factors Affecting Habitat Use

Numerous studies have documented that stream community structure relates directly to the quantity and quality of physical habitat in channels. For example, Gordon and others (1992) state:

"Patterns of physical habitats are created along a stream and within the pools, riffles and boulder clusters within particular stream reaches. It is to these patterns that stream biota respond and adapt. An individual species will have a range of tolerance to any given factor, with some factors more critical for some species than others. Thus, if the physical factors are known, predictions can be made about the abundance and/or diversity of organisms."

Ecologists have documented that many stream organisms are highly dependent on stable, spatially heterogeneous habitats, and studies on individual species have demonstrated that many have strong preferences for particular combinations of flow depth, velocity, and bed material. In general, diversity of species in stream communities increases with an increase in the diversity of physical habitat available for use (Gorman and Karr, 1978; Schlosser, 1987; Jeffries and Mills, 1990).

Many organisms show specific preferences for particular physical habitats at different life stages. For example, young fish use macrophyte beds and edgewater habitats for nursery areas, juveniles use channel margins for foraging and avoiding predation, and the adult life-stage use pool, edgewater, and large woody debris habitat (Lobb and Orth, 1991). Hence, physical habitat controls may limit only particular life stages of an organism.

Abiotic conditions are not static, however. Habitat is subject to physical disturbance events of varying magnitudes that may force biota to inhabit nonpreferred areas of their environment or alter food sources or biotic interactions. Extreme events (floods or droughts) can eliminate the biota or the habitat, or both, thereby requiring longer periods of recovery (Power and others, 1988). These stochastic events can enable previously nondominant species to take advantage of and establish dominance in the community. Community organization also experiences cyclic or episodic fluctuations due to temperature, sunlight exposure, and food supply under natural conditions.

In addition to the magnitude, frequency, and persistence of disturbances, the periodicity or lack of periodicity of disturbances can be critical factors in determining community structure and consequent habitat use. Some

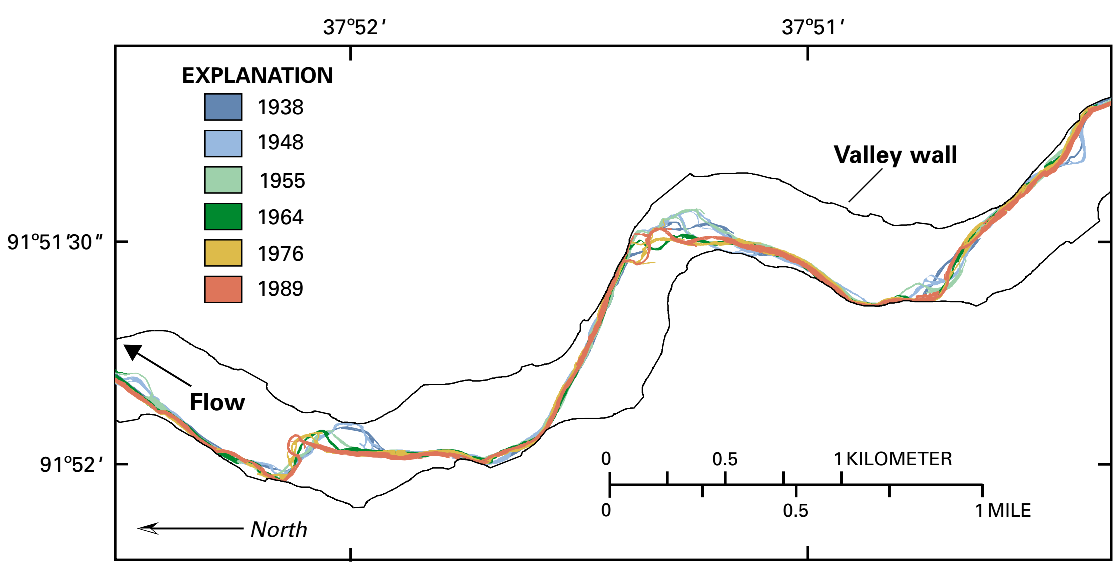


Figure 4. Channel changes in the Little Piney Creek, Missouri, a dynamic stream system, are apparent in this illustration of 50 years of record. Distinct longitudinal differences in inherent channel stability within the river segment are apparent. Stream classification systems for application to habitat evaluations should include measures of stability (Jacobson and Pugh, 1997). The location of Little Piney Creek is shown in the section "Establishing Land-Use History and Habitat Links—Missouri" on p. 32.

communities are structured by frequent flow disturbances that create new and possibly greater numbers of niches available for use, or suppress a normally dominant species (Resh and others, 1988). Disturbances that occur immediately after spawning can lead to longer population recovery times than those that occur during or prior to spawning (Detenbeck and others, 1992). On the other hand, removal of flood disturbances by stream regulation can decrease fish species diversity in some streams (Gehrke and others, 1995). The effects of disturbance and varying community responses complicate the ability to predict community structure based on physical habitat alone.

The effects of physical habitat and disturbance are interrelated with biotic interactions in the determination of the stream community. Behaviors such as colonization processes, species migration, competition (for food and space), and predation can be major determinants in structuring stream communities. Intraspecie and interspecie competition affects the location and density of organisms in streams as they compete for the same space or food source. This competition may determine how many species can occupy the same physical space. Predation affects the community structure in ways similar to competition. Predation can have effects on the individual survival and on community diversity (Jeffries and Mills, 1990). From observation and experimentation, Power and others (1985) determined that grazing, predation, and predator avoidance in conjunction with seasonal and successional events exerted rapid and strong effects on the distribution patterns of the fish and algae in a prairie-margin stream. Power and others (1988) concluded that the distribution of stream organisms in relation to physical habitats is strongly affected by interactions with other organisms.

While species diversity often correlates well with physical habitat diversity, the relation between species abundance (populations) and physical habitat is less clear. Often a linear relation between quantity of habitat available and species abundance is assumed. In fact, evidence in some stream ecosystems is that habitat is a limiting factor in abundance only to a particular population or density. After that point, biotic factors become limiting. For example, Probst and others (1984) concluded that additional habitat elements in a warmwater stream in Missouri could result in increased densities of centrarchid fishes to the point where competition for food would limit population densities.

Reconciliation of abiotic and biotic perspectives on stream community ecology is difficult because exceptions to any generalization will exist. However, the importance of physical habitat in structuring communities is well established. Many stream ecologists consider physical habitat to be the major determinant of stream community *potential* (Schlosser, 1987; Plafkin and others, 1989). The template of physical habitat is a necessary first-order condition that determines the expression of second-order biotic effects such as competition and predation.

Formation and Stability of Physical Stream Habitat

Channel morphology and sediment characteristics—the building blocks of physical habitat—result from adjustments of the channel to the water discharge and sediment load imposed on the channel from upstream and from changes in bank strength and flow resistance. Literature is abundant, in fluvial geomorphology, on the factors that determine channel characteristics, on concepts of equilibrium channel forms, and on how channels adjust when these factors are altered. However, stream ecologists recognize that the conventional geomorphic view of a river does not resolve characteristics of importance to fish and invertebrates (Bisson and others, 1982; Hawkins and others, 1993). That is, there are spatial features smaller than riffles and pools and temporal fluctuations more frequent than annual floods that determine the structure and function of stream ecosystems. Disturbance and adjustment of channel morphology almost always involve changes in habitat quantity, quality, or stability and, thereby, affect stream biotic communities. The concepts of equilibrium channel form, disturbance, and adjustment underlie understanding of how land-use changes are linked to physical stream habitat.

Channel Morphology and Stream Habitat

Channel morphology results from interdependent adjustment of channel characteristics to the discharge of water and sediment load supplied to the channel, tempered by effects of bank strength and hydraulic flow resistance. In some channels, morphology is determined almost completely by external effects such as landslides, bedrock walls, or engineering structures. As external constraints are removed from a channel, adjustment of depth, width, and slope takes place to the extent that the river can erode its bed and banks or deposit sediment supplied to it from upstream. Channels formed in erodible, relatively homogeneous sediments (for example, alluvial channels) are considered self-formed and attain familiar characteristic forms, such as braided, meandering, or straight. Empirical studies of river systems have defined broadly the gradient, discharge, and sediment load that determine channel patterns and the associated physical stream habitats (Leopold and Wolman, 1957).

Channel adjustments in cross-sectional-morphology, planform, and longitudinal profiles are thought to occur by depth, width, and slope adjustments constrained to minimize work and variation in the distribution of work (Leopold, 1994). The adjustments result in remarkably consistent relations between channel cross-sectional measures such as bankfull depth, bankfull width, and discharge. These statistical models of hydraulic geometry form another broad level of understanding of how physical stream habitats are formed.

Many of the features and characteristics of channels that relate to habitat, however, are finer than the riffle-pool scale and comprise the outliers of statistical hydraulic geometry models. These features are formed by nonideal processes such as hydraulic interactions with vegetation, large woody debris, bedrock outcrops, cohesive bank sediments, debris introduced by slope processes, and bars and bedforms relict from extreme floods. Understanding the formation and stability of macrohabitat features requires more detailed understanding of vegetation dynamics, hydraulics of flow around vegetation and obstructions, processes of bank erosion of heterogeneous materials, and the effects of magnitude, frequency, and sequence of sediment-transporting events. Computational hydraulic and sediment-transport models promise to provide insight into the processes of how channel morphology adjusts to discharge and sediment load in idealized channels (Smith and McLean, 1984; Wiele and others, 1996). Research into understanding hydraulics at the macrohabitat scale is a fairly new and growing discipline of fluvial geomorphology.

Channel Equilibrium and Stream Habitat

The concept of equilibrium in a stream system is valuable because it is a shorthand description of the state of the system and expected change in morphology. The concept of *dynamic equilibrium* (Hack, 1960) acknowledges the fact that no stream system is static, but exhibits fluctuations of morphological characteristics in response to climatic, land-use, and random disturbances. A stream in dynamic equilibrium is expected to show fluctuations about a mean condition. Conversely, a stream described as *disturbed* is expected to show directional change in some of its characteristics as it readjusts.

The concept of equilibrium helps in evaluation of when and where ongoing adjustments of the fluvial system should be a concern to stream biota. Every stream, over time, tends toward a state in which it accommodates discharge and sediment load by adjusting its interdependent hydraulic variables (gradient, width, depth, velocity, and hydraulic roughness). This tendency toward adjustment has been called *quasiequilibrium* (Leopold and Maddock, 1953). The remarkably consistent patterns of variation of stream channel morphology with discharge is evidence that such adjustments occur as a result of fundamental physical processes (Leopold, 1994). However, the adjustment is not instantaneous, and, therefore, channels can exist in nonequilibrium states for substantial periods of time.

The physical characteristics of a stream (for example, discharge, depth, velocity, and channel cross-sectional shape) affect stream organisms by defining habitat volume, habitat quality, and disturbance magnitude and frequency. Hence, the question of whether a stream is in physical equilibrium is essential to understanding the quantity, quality, and stability of habitat available to stream communities. An evaluation of the physical equilibrium of a stream can indicate whether trends in biotic communities result from physical adjustments of the river, rather than from independent biological or chemical processes.

Practical consideration of equilibrium in fluvial systems requires that some limits are set on time scale, spatial scale, and magnitude of events that are considered to depart significantly from equilibrium values. As discussed by Schumm and Lichty (1965), detection of trends and magnitude of variation depend on the spatial and temporal frames of interest. In a decadal time frame, a 100-year flood is likely to cause significant variation in channel characteristics; however, if the time frame of interest is millennial, this same flood probably would create insignificant background variation. If the spatial frame of interest is a particular pool-riffle pair, aggradation of that pool would be considered a significant event; however, if the spatial frame is that of a stream segment of several tens of kilometers, the fate of one pool may be insignificant, or aggradation of one pool may be offset by scour of another for zero net effect.

The spatial and temporal frames of interest in stream habitat evaluation can be narrowed by considering spatial and temporal characteristics of typical stream communities. For organisms with limited distribution and limited capacity to colonize new sites, habitat changes at the scale of individual macrohabitats or cross sections can be extremely important. For anadromous fishes that migrate between the oceans and far inland, the effects of disturbance accumulated over the scale of the entire range of movement may need to be assessed. For many purposes, the reach scale will be the most practical. With the reach as the spatial scale, offsetting variations in habitat within the reach would be considered background variation of a system in equilibrium.

In Resh and others (1988), the discussion of the background theory of disturbance in stream ecosystems provides some insight into temporal frames for assessing habitat equilibrium. They note that the disturbance (departure from an equilibrium condition) is a relatively discrete event in time that disrupts ecosystem, community, or population structure and that changes resources, availability of substratum, or the physical environment. They further state that the frequency and intensity of the disturbance event should be beyond a predictable range. For example, seasonal changes in habitat availability can be quite large in some environments. However, because seasonal variation is a predictable cycle of repeatable magnitude, stream organisms can adapt to it, and seasonality can be considered background variation of an equilibrium system. Because of the wide range of life histories existing in typical stream ecosystems, the time frame for assessing habitat equilibrium probably needs to be defined by the life histories of individual organisms of concern.

Channel Disturbance and Adjustment

Physical disturbances such as land-use changes, instream engineering, and large floods often cause changes in channel pattern, cross sectional morphology, and bed material (Baker, 1977; Eschner and others, 1981; Graf and others, 1995; Friedman and others, 1996), thereby potentially altering habitat characteristics and availability. These changes can occur because of changes in the magnitude of physical processes or rates of processes, or because a threshold within a fluvial system was exceeded.

Fluvial systems can exhibit lagged, threshold, and cumulative responses to imposed disturbances (Schumm, 1977). Lagged responses exist because erosion, deposition, and transport of sediment are not instantaneous and because sediment tends to travel finite distances before being retained temporarily in storage. Thresholds exist because of critical shear stresses that must be exceeded to transport sediment or because of other barriers to geomorphic change that, once overcome, produce a nonlinear geomorphic response. Disturbances to one part of the fluvial system can translate upstream or downstream through the network and diminish or grow in the process, yielding complex cumulative responses. At a given site along the channel network, therefore, the stream channel can be disturbed from activities that occurred at various times in the past and at various places elsewhere in the fluvial system. This behavior generally is known as “complex response” (Schumm, 1977). It may be necessary to understand the history of adjustments everywhere within the fluvial system to understand fully the effects at one particular point within the system.

Fluvial systems can respond to disturbance according to several conceptual models (fig. 5). In dynamic equilibrium, channel morphology and stream processes fluctuate around some condition or value (Bull, 1991). The acceptable variability in magnitude and frequency of the fluctuations depends on factors such as the time frame or species of interest. External forcing events, such as extremely large floods or land-use changes, may cause a stream to transform into a nonequilibrium or disturbed state. A change to a nonequilibrium state occurs when the event causes erosion and deposition processes or rates of processes to change dramatically.

For a special article about channel disturbance and adjustment, please see "Hydrologic disturbance in an agricultural-urban basin—Big Darby Creek, Ohio," on pages 12–13.

The general case of disturbance and response consists of a forcing event, a response lag, a response, and a relaxation period (fig. 5*B*,*C*). After the forcing event, during the response-lag period, little change occurs in either channel form or stream processes. During the response period, channel form and stream processes react to the external forcing. After the response, the channel may relax (recover) to a predisturbance condition at varying rates (fig. 5*B*), or it may maintain a new state (fig. 5*C*).

The type and extent of land-use disturbances and the characteristics of the drainage basin and channel control the magnitude, frequency, spatial extent, and persistence of disturbances affecting stream habitats. When a basin is temporarily disturbed by forest harvest activities, channels may react and eventually relax to predisturbance conditions (fig. 5*B*). On the other hand, a persistent change in land use—such as row-crop agriculture or a dam—will have a persistent effect on channel forming processes and result in an alternative equilibrium state (fig. 5*C*). Where the fluvial system response is governed by thresholds, even a minor, transient disturbance might have persistent effects on channel morphology and habitat. An example would be the oversteepening of streambanks with the resultant loss of root strength to resist erosion (fig. 6). Once such an irreversible threshold is passed, the system may remain in the alternative state for substantial periods of time (Jacobson and Pugh, 1997).

Habitat Disturbance

Common types of physical disturbances of stream habitat can be categorized as those that change the habitat volume (for example, by filling pools or widening riffles), those that change habitat quality (for example, changing the particle-size distribution of substrate or altering vegetative cover), and those that destabilize substrate but leave no net change in either habitat volume or quality (for example, reaches where floods transport bedload but leave the reach with the same morphology and substrate after the flood). These will be referred to as volume, quality, and stability disturbances.

The effects of these different types of disturbances vary depending on the life history of individual organisms and how they use particular habitats. For example, some stream insects may have short life cycles of days to months. These organisms will be insensitive to stability disturbances if the disturbances are infrequent relative to their short life cycles. Conversely, they might be quite sensitive to quality disturbances that change the particle-size distribution of substrate. A quality disturbance—for example, deposition of fine sediment into substrate interstices—could last many macroinvertebrate lifetimes and prevent recolonization.

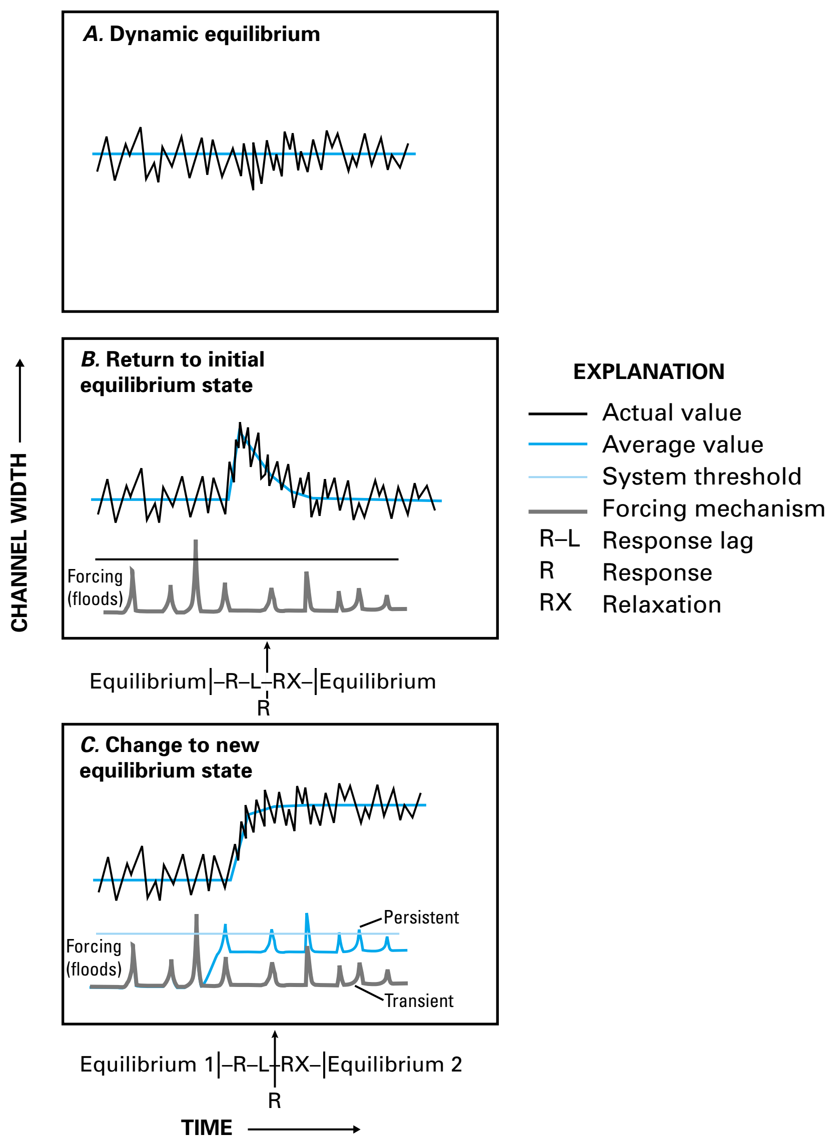


Figure 5. Types of equilibria, disturbance, and response patterns for streams (modified from Bull, 1991).

Other species may require long periods of stable substrate as well as habitat volume and quality. Mussels, for example, are long-lived and relatively immobile; they depend on stability of the substrate on which they live, as well as the habitat quality (Cummings and Mayer, 1992; Di Maio and Corkum, 1995). Their immobility in adult life stage also limits their ability to seek refuge from disturbance or recolonize sites once disturbed. Stream fishes, in contrast, may be relatively insensitive to stability disturbances because they are mobile. If habitat quality or volume is degraded in one reach of the stream, they can move and exploit similar habitats in other reaches.

Biotic responses to physical disturbance would be expected to vary with the persistence, magnitude, and frequency of the disturbance. For example, bed scour during an individual flood may constitute stability disturbance, but if sediment is redeposited to the original channel form during streamflow recession, habitat volume may not be disturbed for a meaningful period of time. In contrast, gravel deposited in a riffle during an extreme flood may be of sufficient volume to create an island with associated persistent changes in benthic habitat in the adjacent channels. Because this effect is likely to exist until intermediate-sized floods can remove the excess gravel, the effect of this habitat-quality disturbance should be measured in part by its persistence through time. Similarly, Wolman and Gerson (1978) proposed that *the geomorphic effectiveness* of a flood should be measured in part by the rate of recovery of the channel to preflood conditions. A flood that produces persistent morphological changes is considered to be more geomorphologically effective and, in many cases, would also be more ecologically effective.

Finally, disturbance in either the geomorphic context or the ecologic context is not necessarily detrimental. In the geomorphic realm, the concept of a reach or fluvial system in dynamic equilibrium implies orderly movement of sediment through the system. A disturbed system may be characterized by increased rates of erosion or deposition at sites within the system. Usually, accelerated rates of erosion or deposition degrade a valued resource. For example, erosion can undermine bridge piers or send productive agricultural land downstream; excessive deposition can fill a flood-control reservoir. However, when geomorphic effects are extended to the subject of stream habitat, the value judgment is not as clear. For example, accelerated bank erosion may result in delivery of large woody debris to the stream ecosystem, thereby creating scour pools, cover, and substrate usable by some organisms. Increased disturbance in a stream ecosystem may favor a different mix of species rather than unequivocal degradation of the biological resource. For example, according to the intermediate disturbance hypothesis (Resh and others, 1988), increased environmental disturbance in some ecosystems can actually increase species richness by displacing some of the habitat-specific species with habitat-general, colonizing species. Conversely, too much disturbance can result in subsequent decreases in species

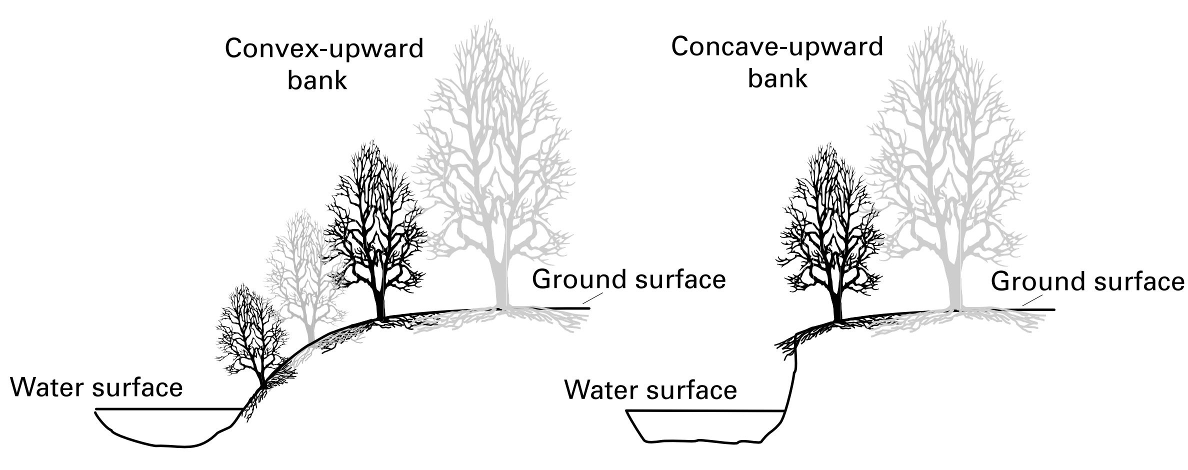
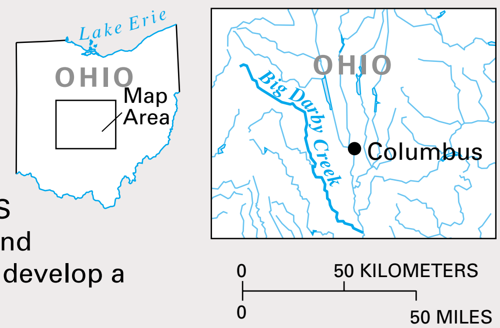


Figure 6. Effect of oversteepening streambanks. Loss of erosion resistance from roots on convex-upward banks results in a threshold effect as the bank is steepened to vertical or concave-upward. On steep banks, roots no longer provide substantive strength to resist bank erosion, resulting in accelerated bank erosion (Jacobson and Pugh, 1997).

Hydrologic Disturbance in an Agricultural-Urban Basin—Big Darby Creek, Ohio

Like most streams in the Midwestern United States, Big Darby Creek in Ohio has been affected by widespread, intensive row-crop agriculture. In addition, the eastern margin of Big Darby Creek Basin is being affected by urban expansion of the Columbus, Ohio, metropolitan area. These sources of potential land-use disturbance have motivated studies of Big Darby Creek by the USGS in cooperation with the city of Columbus, Ohio, and Franklin, Madison, and Pickaway Counties. The USGS study has been coordinated with a unique partnership of public agencies and private landowners—The Darby Partners—that has recognized the need to develop a rigorous scientific basis for management of aquatic resources.



Despite the history of intensive agricultural land use, Big Darby Creek supports diverse and abundant fauna, including 86 species of fish and 40 species of freshwater mussels. Because of these qualities, Big Darby has been designated a “State Scenic River” by the Ohio Department of Natural Resources, a “National Scenic River” by the U.S. Department of the Interior, and a “Last Great Place” by The Nature Conservancy. The threat of increased urbanization with potential for increased peak flows and associated increases in loads of nonpoint-source contaminants prompted a detailed field study to evaluate present-day effects of disturbance on the habitat and benthic communities.

The Big Darby Creek Drainage Basin is dominated by intense agricultural land use, and it is bordered on one side by expanding suburbs of Columbus, Ohio. Despite this destabilizing potential, Big Darby Creek has maintained extremely high biological diversity. Photograph courtesy of J.A. Hambrook, U.S. Geological Survey.

The study objectives were to (1) document suspended-sediment and water-quality characteristics of the drainage basin; (2) quantify benthic habitat disturbance; (3) measure the washout of streambed substrate and recolonization by macroinvertebrates and algae; and (4) relate physical disturbance factors to washout and recolonization rates. The understanding of disturbance and recovery processes gained from this study provide a foundation for predicting future changes to benthic communities as hydrology and sediment supply are altered.

The study design was based on pre- and postflood characterization of bed material, macroinvertebrates, and algal communities. The results of two monitored floods demonstrated that the floods substantially changed bed-material particle-size distributions and decreased macroinvertebrate and algal-cell densities. However, the magnitudes of the floods and the biological responses were poorly correlated. The investigators indicated that the temporal adjustment of the macroinvertebrate community was affected by time lags and biotic factors such as life-stage history. For example, a decrease in Diptera (true flies) densities in July probably was related to emergence from larval to adult life stage, not to disturbance by a preceding flood. The investigators also—

determined that the sensitivity of macroinvertebrates to disturbance varied with season and flow-exposure group (that is, groups of macroinvertebrates characterized by the way in which body shape is adapted to specific flow conditions). Algal responses to disturbance similarly were complicated by form. Mat-forming blue-green algae appeared to be less sensitive to disturbance than stalked species. Moreover, recolonization of algal communities appeared to be a complex function of disturbance magnitude, water temperature, canopy conditions, initial density of algal cells, and grazing by fish and invertebrates. Because the study characterized both physical and biological components of flood disturbance in detail, it provides understanding necessary to link habitat changes with biological responses. For the moderate floods monitored, changes in physical habitat were documented by changes in bed-material particle size. The biological response to this moderate disturbance was measurable but complex. The implication of these complexities is that expected increases in magnitude and frequency of disturbances will have substantial but relatively unpredictable effects on the benthic community of Big Darby Creek.

For more information, refer to Allan (1991), Hambrook and others (1997), Mihaly (1994), and Palcsak (1995).

The U.S. Geological Survey and the Darby Creek Partners have been studying the effects of hydrologic disturbance and sediment yield on algal population and benthic invertebrates in Big Darby Creek Here, U.S. Geological Survey hydrologists employ a freeze-core sampling device to obtain undisturbed samples of bed material for analysis. Photograph courtesy of J.A. Hambrook, U.S. Geological Survey.

richness if communities become dominated by colonizers. The maximum richness occurs at intermediate levels of disturbance that can accommodate some of both habitat-specific and colonizing species. In another example of the potential value of disturbance, unstable reaches of streams in the Ozarks (southern Missouri and northern Arkansas) have some of the most productive marginal habitats for primary productivity, organic matter cycling, and rearing of young fish (C.F. Rabeni, U.S. Geological Survey, oral commun., 1997).

Land-Use Induced Disturbances of Physical Stream Habitat

Both upland and riparian land-use changes can cause habitat disturbances by altering the amount and timing of runoff and sediment yield in streams (table 1). Runoff is that portion of rainfall that falls to earth and runs off the ground surface rather than infiltrating into the soil or evaporating. Sediment yield is the quantity of eroded material that is discharged from above a point in a drainage basin. Upland land-use changes are considered to be those that occur on slopes and ridges at elevations above the flood plain. Riparian land-use changes generally refer to changes occurring from the margin of the low-water channel up to and including the flood plain.

Upland and riparian land-use changes can occur over a short period, or they can be persistent. They may be restricted to a small area or occur throughout a drainage basin. For example, effects of agricultural land clearing generally persist for decades or more, causing a persistent, widespread disturbance. In contrast, instream gravel mining to build a local road may cause a short-term point disturbance directly in the channel. The location, type, persistence, and propagation of a disturbance determine the severity of the effect on the physical habitat of the stream.

Upland Land-Use Changes

Upland land-use changes, such as deforestation, reforestation, and urbanization, often alter rainfall-runoff relations, thereby changing the hydrologic budget of a stream. Many land-use changes increase runoff by decreasing infiltration rates, evapotranspiration, or permeable area. Increases of impermeable area in urbanized basins typically result in substantial and well-documented increases in peak discharges (Haan and others, 1994). Generally, channel area increases (fig. 7) to accommodate the increased discharge, leading to channel deepening or widening, or both (Booth, 1990).

Increased runoff from land-use practices in rural areas can be more subtle and difficult to document, especially for drainage basins greater than about 5 square kilometers in area (Potter, 1991; Jones and Grant, 1996). In addition, hydrologic effects of land clearing and forestry (fig. 8) can be subject to rapid recovery if vegeta-

Figure 7. Hydrologic changes due to urbanization in a drainage basin can have severe effects on stream habitat. Increased impermeable area in urbanized drainage basins typically yields greater storm runoff, higher peak flows, and diminished base flows. In this example from St. Louis County, Missouri, increased peak flows have resulted in substantial widening, incision, and instability of stream channels. Loss of habitat is complete because of loss of base flow; before urbanization, this stream supported perennial flow and diverse aquatic habitat.

For a special article about land-use induced disturbances of physical stream habitat, please see "Geomorphic instability and sediment loads—Wisconsin," on pages 16–17.

tion is allowed to regrow (for example, Hornbeck, 1975). An illustration of the subtle effect of rural land use on storm runoff is shown in figure 9. Here, the percentage of rainfall that runs off the landscape is shown as calculated from a curve-number method (Soil Conservation Service, 1972) for two storm durations, two soil groups, and a range of land-use practices. For a 1-inch, 24-hour rainfall, the percentage of rainfall becoming runoff ranges from 69 to 95 percent, and for a 4-inch, 24-hour rainfall, the percentage ranges only from 91 to 98 percent. Land use has a relatively minor effect on runoff for the more intense storm events that would be expected to create flows capable of rearranging channel habitat.

The effects of rural land-use change on channel morphology and habitat can be more difficult to discern than the effects of urban land use. For example, Costa (1975) noted that streams on the Maryland Piedmont that had been affected by agricultural runoff had greater

Figure 8. Upland land-use processes in rural areas can decrease infiltration, increase runoff, and increase soil erosion. Typical land-clearing practices in the Ozarks of Arkansas have the potential to increase peak flows moderately until grasses are reestablished. The effect of increased sediment yield from such clearing can be severe. In this case, sediment yield is minimized by storage of organic debris in the axis of the unchanneled valley. However, sediment accumulations in the organic debris may be delivered to streams years in the future as the organic debris decomposes.

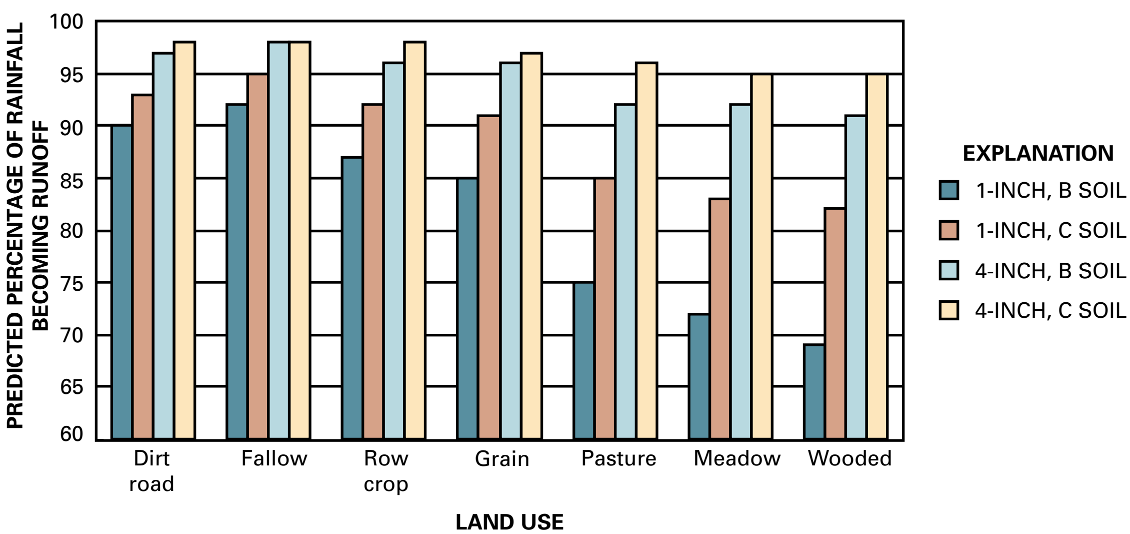
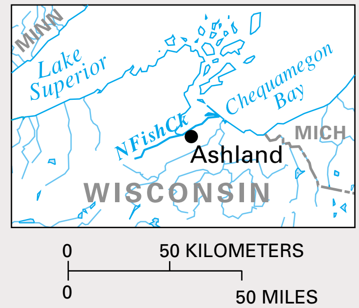


Figure 9. Predicted percentage of rainfall becoming runoff estimated from the Soil Conservation Service (1972) curve number method for typical rural land uses. If all other factors are constant, changes in land use create variations in runoff. The B and C soil hydrologic groups are for soils with moderate infiltration and storage characteristics. For low-intensity rainfall (1 inch in 24 hours), the most severe land-use practice will produce as much as 25 percent greater runoff than the least intrusive land-use practice. For more intense rainfall (4 inches in 24 hours), comparable to the intensity necessary to generate a channel-forming flow, runoff is relatively insensitive to land use.

Geomorphic Instability and Sediment Loads—Wisconsin



Historical information was used to investigate links between land-use changes and channel changes in a small basin on the shore of Lake Superior, northern Wisconsin (Fitzpatrick and others, 1999). Excessive degradation and aggradation of stream channels has been thought to contribute to degradation of spawning habitat for steelhead, coho salmon, and trout, and also may be affecting coastal wetlands. A study by the USGS in cooperation with the Wisconsin Department of Natural Resources evaluated long-term changes in sediment loads, changes in channel morphology, and links to land-use practices. North Fish Creek was selected for the study because it has one of the largest anadromous fish populations in the State and because information gathered on North Fish Creek should apply to many other tributary basins to Lake Superior.

North Fish Creek is a small creek (drainage area 122 square kilometers) that drains into the Chequamegon Bay of Lake Superior. Despite its small size, the physiography of North Fish Creek varies considerably from upstream to downstream. The upper reach (river kilometer 19 to 27) has a steep channel gradient, narrow flood plain, and valley walls with large, highly erosive bluffs. The channel bed substrate is composed of boulder, cobble, gravel, and sand. The middle reach (river kilometer 13 to 19) has a transitional channel gradient and widening flood plain. The channel bed substrate is gravel to mostly sand with occasional gravel. This reach is characterized by mass wasting of the stream banks and an unstable channel. The lower reach (river kilometer 0 to 13) has a flat channel gradient and a wide flood plain. The channel bed substrate is sand with minor gravel. Few eroding bluffs are in this reach because the flood plain is wide enough to accommodate the meandering pattern of the stream. Banks are stable and vegetated, but subject to accelerated sedimentation from floods.

The drainage for North Fish Creek is geologically young, having been formed by incision into glacial deposits during the last 9,000 years. Ongoing geomorphic responses to incision and isostatic adjustments create complications for separating natural geomorphic changes from human-induced changes. For example, excessive sedimentation in the downstream reaches may be controlled in part by relative downward isostatic adjustment of the land surface and in part by land-use induced increases in sediment supply. Moreover, like most landscapes, North Fish Creek is affected by highly variable hydroclimatic events that obscure direct links to land-use changes.

Channel incision in the upper reaches of Fish Creek apparently has resulted in accelerated streambank erosion and delivery of sediment directly to the channel. Photographs courtesy of F.A. Fitzpatrick, U.S. Geological Survey.

North Fish Creek near Ashland, Wisconsin, 1994.

North Fish Creek near Ashland, Wisconsin, 1996.

The excessive sedimentation in the lower reaches of North Fish Creek is thought to have started with land-use changes beginning in the late 1870's. During European settlement approximately 125 years ago, the forest lands were cleared by logging and burning and converted to farm lands. Currently (2000), the land use is a mixture of pasture, hay fields, and immature forest that commonly is harvested for pulp wood.

A stratigraphic approach was used to characterize presettlement variability in sedimentation rates and processes and to evaluate the magnitude of change associated with post-European land-use changes. Sediment cores from relict channels were used to identify the original size, shape, and sediment texture of these channels. Also, 25 stream banks and bluff exposures were examined to assess presettlement and historical sedimentation rates and to assist with the interpretation of long-term changes in the drainage system. The sedimentation rate in the lower reach has been episodic during both pre- and postsettlement time, although large sedimentation events have become more common in postsettlement time. A single large flood in 1946 caused the most sedimentation and channel change since European settlement. Both the amount and texture of sediment deposits have changed after European settlement and have continued to change during the last 100 years. The postsettlement sediment deposits are coarser than those of presettlement, and most of the recent sediment load appears to have originated from 17 large eroding bluffs located in the middle and upper reaches.

Vibracoring of sediments of Fish Creek provides evidence for changes in stream energy and sediment yield over hundreds to thousands of years. These data help determine the natural background of channel changes for comparison to channel changes suspected to have resulted from land-use changes. Photograph courtesy of F.A. Fitzpatrick, U.S. Geological Survey.

Modern and historical stream channels were compared where land-survey section lines cross North Fish Creek from the mouth to river kilometer 27. Historical channel dimensions and substrate characteristics were obtained from a Government Land Office survey of the area done during 1855. The resurveys indicate that in the upper and middle reaches the channel eroded vertically 1 to 3 meters during the last 125 years. The stream channel has narrowed and incised, resulting in a channel that can accommodate larger flows than the channel that existed in 1855. Confinement of the flow to the narrow channel is thought to result in increased potential to erode stream banks and the channel bed. This type of channel is efficient at rapidly transporting sediment and water downstream. Pre- and postsettlement channel bed substrates were similar. Surveys at 6 of 17 large bluffs in the upper and middle reaches have shown retreat magnitudes of 0 to 28 meters, with an average retreat of 16 meters, during 52 years.

In contrast to the incision and erosion documented in the upper and middle reaches, the stream channel of the lower reach has aggraded by as much as 2 meters and has widened during the last 140 years. Lower stream banks enable sediment-laden flows to spill easily into the wide flood plain and deposit the sediment load. The sediment load is estimated to be almost 10 times greater today than in presettlement times. Both the channel and flood plain have aggraded 1 to 2 meters in this reach during the last 140 years.

Historical analyses of the links between land-use and habitat changes on North Fish Creek provide information that may be important for future resource-management decisions. The historical data show the spatial link between erosion at discrete points in upstream reaches and sedimentation in downstream reaches, thus showing resource managers where restoration efforts would be most effective. These data also document the presettlement reference condition and show how instream and riparian habitats are likely to change in response to extreme hydroclimatic events.

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recurrence intervals for bankfull flows for drainage basins smaller than 26 square kilometers than for drainage basins greater than 26 square kilometers. Costa (l975) and Jacobson and Coleman (1986) interpreted these data to indicate that smaller streams had entrenched, in part due to increased runoff from agricultural land use. Channels also may narrow as a result of basinwide recovery from land-use changes. For example, Buttle (1995) documented channel narrowing and decreased width-to-depth ratios following reforestation and consequent reduction of peak flows in the headwaters of the Ganaraska River in Canada.

The net result of upland land-use practices on channels and stream habitat also is greatly affected by sediment yield, and in many cases runoff and sediment yield both change with land-use changes (fig. 10). Increases in the sediment yield from the basin to the stream often result from loss or change of vegetative cover, increases in roads, or increases in gullies (Trimble, 1974; Reid and Dunne, 1984; Waters, 1995). Generally, for a given upland land-use change, the relative increase in soil erosion on slopes is many times greater than the increase in storm runoff. This is illustrated with a comparison of cover factors from the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). If all other factors on a slope are held constant except for land-use change as depicted by the cover factor variable, soil erosion will be proportional to the cover factor. For the range of land-use types shown in figure 11, soil erosion is predicted to be as much as 1,000 times greater than the natural background rate (that is, compared to natural woodland or natural grassland). By comparison with figure 9, it can be seen that the potential relative effect of land-use change on sediment yield typically is much greater than that of runoff.

Realization of the soil-erosion potential requires that eroded soil is delivered from slopes to stream channels. However, sediment can move slowly from slopes to the channel and downstream as it is episodically deposited, stored, and remobilized. Therefore, sediment yield is can be substantially less than predicted by soil erosion models and yield is expected to lag behind the disturbance.

Increased sediment yield to streams generally results in channel aggradation or changes in bed material grain sizes, or both (Schumm, 1977). A common result of increased upland sediment yields is increased deposition of fine sediment (silt and clay) with potential decreases in pool volume, increases in substrate embeddedness, and decreases in interparticle pore space in gravel used for spawning (for example, Lisle and Hilton, 1992; Madej, 1995). In some cases, aggradation also can be expected to lead to increased channel instability and habitat disturbance. A comprehensive review of the effects of sedimentation on stream habitats is presented by Waters (1995).

Some types of land-use change—or recovery from previous disturbance—can result in decreased sediment yield. Decreases in sediment yield may result from increased vegetative cover or artificial barriers to erosion, such as retaining walls and asphalt cover (Arnold and others, 1982; Buttle, 1995). Decreased sediment

Figure 10. Landslides develop on intensely grazed slopes such as those in the Appalachian Mountains of West Virginia. Increased frequency of shallow landslides like these has been associated with conversion of woodland to grassland (Jacobson, 1993). These landslides deliver sediment directly to the stream channel.

yield can cause channel degradation or widening (Jacobson and Coleman, 1986) and coarsening of bed material (Dietrich and others, 1989).

Because water and sediment move downstream in a branched network, the effects may be cumulative downstream. A key question is whether sediment from disturbances travels downstream as coherent waves or spreads out longitudinally along the stream channel (for example, studies by Meade, 1985; James, 1993; Madej, 1995). In the former case, waves that meet and grow in the channel network would be expected to create substantial downstream cumulative effects. In the latter case, sediment effects would be expected to diminish downstream.

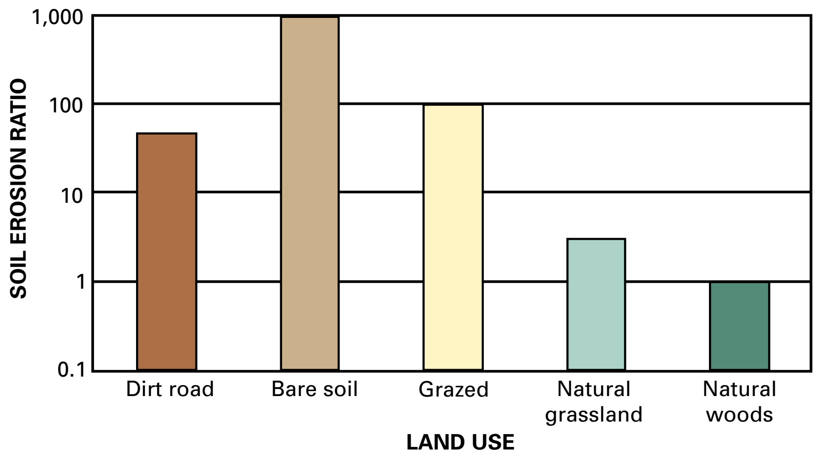


Figure 11. Predicted ratio of soil erosion from specified land-use classes to soil erosion from natural woodland. These ratios are calculated from Universal Soil Loss Equation (Wischmeier and Smith, 1978) cover factors for typical rural land-use types. If all other factors—slope, rainfall intensity, soil properties—are constant, soil erosion increases with the cover factor. Hence, inherent soil erosion potential can be quantified as a ratio to the least severe land-use class. Note that the ratios are on a logarithmic scale.

The timing and sequence of hydrologic and sediment yield changes can result in extreme changes in channel morphology and habitat availability. An example is the typical model of channel responses to a cycle of urbanization (Arnold and others, 1982). In the Sawmill Brook Basin, Connecticut, runoff and sediment yield initially increased in response to urbanization. Then, as construction waned and land surfaces were stabilized, sediment yield decreased while storm runoff remained substantially elevated relative to nonurban conditions. Decreased sediment yield coupled with increased runoff led to loss of coarse bed material in the downstream portion of the basin and consequent channel incision (Arnold and others, 1982). In a contrasting example, Odemerho (1992) noted that extreme urbanization in a tropical landscape in Nigeria resulted in channel narrowing and aggradation because the increases in sediment yield were much greater than simultaneous increases in runoff and sediment transport capacity.

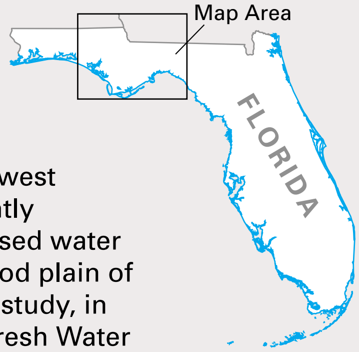
Riparian Land-Use Changes

Similar to upland land-use changes, some riparian land-use changes (for example, impoundments and outfalls) also can alter water discharges and sediment yield (fig. 12). Other riparian land uses can alter hydraulic resistance, erosion resistance, or energy of a channel without changes in hydrologic and sediment budgets being imposed (fig. 13). Because riparian land-use changes affect the channel directly or nearly directly, the effects on channel morphology and stream habitat often are directly manifest and clearly discerned.

Figure 12. Dams and reservoirs directly affect stream habitat by controlling quantity and timing of water discharge and by decreasing sediment yield to downstream channel segments—Gavins Point Dam, Missouri River, near Yankton, South Dakota.

For a special article about water withdrawals and their effects on habitat, please see "Water withdrawals and maintenance of flood-plain ecosystems—Florida," on pages 20–21.

Water Withdrawals and Maintenance of Flood-Plain Ecosystems—Florida



Surface- and ground-water withdrawals in a drainage basin may have substantial effects on river flood-plain ecosystems, even in the humid coastal plain of the southeastern United States. The USGS, in cooperation with the Northwest Florida Water Management District, recently completed a study of the effects of increased water withdrawals on aquatic habitats in the flood plain of the Apalachicola River. A previous USGS study, in cooperation with the Florida Game and Fresh Water Fish Commission, investigated the use of flood-plain habitats by fish in the Ochlockonee River. These studies have been designed to develop a more complete understanding of how flood-plain ecosystems function on low-gradient, coastal-plain streams; define ecological reference conditions to assess the affects of changing hydrology; and quantify the volumes and durations of aquatic flood-plain habitat under natural and regulated conditions.

North Florida coastal-plain rivers wind slowly through densely-forested floodplains. Although some parts of the flood plain are as much as 4.6 meters above low water in the adjacent river channel, the entire flood plain generally is inundated with flowing water each year during the annual flood. Some parts of the flood plain are submerged for only a few weeks, whereas others are submerged for nearly one-half of the year because of differences in flood-plain elevations. Flood-plain depressions are vegetated with tupelo and cypress trees and often contain water that is isolated from the main channel. Many streams and lakes in the flood plain are alternately connected to and disconnected from the main channel as river levels fluctuate. Increased withdrawals or flow regulation can decrease the amount of flood-plain habitat accessible to main-channel fishes. Decreases in flood-plain flooding duration can also alter the flood-plain vegetation community.

Approximately three-fourths of known main-channel fish species were collected in the flood plain of the Ochlockonee River during floods. The diversity of fish species in the flood plain indicates that flood-plain habitats probably play a crucial role in the life cycle of many main-channel fish. Fishes in inundated forested flood plains have access to abundant supplies of food, spawning sites (many species have eggs that adhere to wood), and refuges for young and nesting fish. Altering the season or magnitude of the annual flood could substantially restrict the use of flood-plain habitats by these fish species. In ponded habitats on the flood plain, the diversity of fish species tends to decrease dramatically as pond area decreases. Dwindling habitat size, caused by droughts or water withdrawals, could decrease the diversity of fish species, with the greatest effect on those species that are restricted to the flood plain.

For more information refer to Leitman and others (1991) and Light and others (1998).

North Florida coastal-plain rivers wind slowly through densely forested flood plains. The diversity of fish species in the flooded plain indicates that these habitats probably are crucial in the life cycle of many main-channel fish. Studies have quantified the link between channel hydrology and availability of flood-plain aquatic habitats. The link is essential for evaluating the ecological effects of alternative water-withdrawal decisions.

Studies that link forest habitat and fish habitat availability to river levels are an important tool that water managers can use to assess the effects of water use on flood-plain ecosystems. Areas of higher elevation support bottomland forests of spruce pine, sweet gum, live and water oak, and the lower elevations support a cypress/tupelo forest community.

Water impoundments and diversions can alter the timing and amount of water in a stream, as well as changing channel morphology. Reviews of the geomorphic and ecologic effects of reservoirs can be found in Williams and Wolman (1984), Ligon and others (1995), and Collier and others (1997). Direct effects of regulation by reservoirs often are transmitted as changes in streamflow, water temperature, and sediment-related turbidity. Regulation for multiple purposes such as flood control, power generation, and navigation usually changes flow characteristics, which in turn change the seasonal distribution of depths, velocities, temperatures, and turbidity that are available to organisms. In particular, regulation that disrupts an annual flood pulse (Junk and others, 1989; Bayley, 1995) has been implicated in the decline of native species. Seasonal temperature changes can directly affect fish energetics and disrupt temperature-related spawning cues (Hesse and Sheets, 1993). On the other hand, consistent, low-temperature discharge from reservoirs also can support substantial coldwater fisheries. Decreases in turbidity due to sediment trapping by dams also can result in a competitive advantage for sight-feeding nonnative fishes relative to species that have evolved to compete in high-turbidity environments.

Geomorphic changes as a result of regulation can include channel simplification, incision, disconnection of side-channel and flood-plain water bodies, and bed-material coarsening. Investigations of morphological and sedimentological changes due to river regulation have shown that effects can extend tens to hundreds of kilometers downstream (Williams and Wolman, 1984). Regulation typically involves decreases in peak flows, resulting in decreases in flows that transport sediment and maintain in-channel habitats. Decreases in peak flows and sediment-transporting events often lead to encroachment of vegetation, which increases the stability of sediment and, thereby, causes channel narrowing and island growth and attachment to the flood plain (Graf, 1978; Freidman and others, 1996; Scott and others, 1996). Increased stability of the channel under regulated conditions may result in the disappearance of habitats formerly maintained by disturbance—for example, unvegetated sandbars. In addition, loss of sediment load due to trapping of sediment in the reservoir

Figure 13. Aggregate mining in stream channels or in riparian zones can affect stream habitats directly.

A, Flood-plain aggregate mining pits, Little Piney Creek Missouri. Although this process is not directly in the stream channel, the stream habitat has been degraded by straightening the channel and removing all riparian canopy, thereby reducing hydraulic diversity, shading, cover, and organic input. Moreover, the buffers between the channel and the pits cannot be expected to remain intact as natural stream migration takes place (compare with map of channel migration for this same stream, fig. 3).

B, Dense riparian vegetation and nearly closed canopy about 3 kilometers downstream of area shown in ***A***. The location of Little Piney Creek is shown in the section "Establishing Land-Use History and Habitat Links—Missouri" on p. 32.

can result in channel incision disconnecting the channel from the flood plain and side channels. Loss of fine sediment typically results in coarsening of the streambed sediment in tailwater (downstream) segments of the river, potentially resulting in changes in spawning habitat and decreasing the ability of some benthic organisms to burrow into the bed (Donnelly, 1993).

In contrast to the case of sediment starvation below dams, mining effluent can introduce large quantities of sediment directly to the channel or riparian zone (Gilbert, 1917; Lewin and others, 1983; Marron, 1992; James, 1994; Waters, 1995). Large volumes of mining-related sediment can aggrade channels, fill pools, and choke channel substrates with fine sediment. Excessive sediment also can cause channels to steepen, with consequent increases in braiding, sinuosity, migration rates, and disturbance.

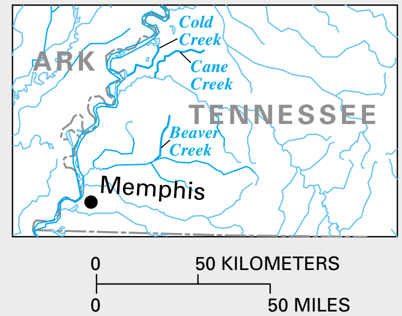
Channel engineering directly alters physical stream habitat (fig. 14). Generally, instream engineering such as channelization, levees, and navigation structures substantially decreases the surface area of the channel, thereby decreasing shallow-water habitat area (Gore and Shields, 1995). In addition, these types of engineering projects generally decrease habitat diversity by decreasing the range of available depths and velocities. Channelization can have particularly severe and persistent effects on channel morphology by increasing channel slopes while decreasing hydraulic roughness. The net result in many areas is channel incision and widening, with increases in solar radiation and decreases in organic contributions from riparian vegetation. The processes of disturbance by channelization and subsequent channel recovery have been described by Hupp and Simon (1991), Simon and Hupp (1992), and Simon (1994).

Levees constrict flows at high discharges, thereby increasing channel energy and isolating the channel from its flood plain. Constricted flows from levees and navigation structures have been implicated in exacerbating channel incision and in increasing flood stages (Belt, 1975). Disconnecting channels from flood plains decreases water and sediment storage on flood plains, preventing exchanges of organic material and nutrients between the channel and the flood plain, and decreasing spawning and rearing habitat for many fishes. Levees often contribute to the disruption of the flood pulse on regulated rivers (Junk and others, 1989; Bayley, 1995). Bank revetments and wing dams or spurs intended to stabilize and maintain navigation channels can have complex functions in altering habitat. Revetments that close off side channels and off-channel habitats from the main flow decrease the diversity of habitat available to stream organisms. Wing dams (fig. 15) focus the flow to maintain depth and scour in a navigation channel, but have the added effect of adding a diverse mixture of depth and velocity on the landward side. The habitats created by such navigation structures are not natural to most navigable rivers, but they may be useful for many organisms. Structures can be designed to optimize engi-

Figure 14. Channelization has resulted in a deeply incised stream channel on Cane Creek, western Tennessee. This is a typical Mississippi Lowland physiographic region stream that has been subject to channelization to improve land drainage. In response to the increased gradient, the channel incises, which subsequently destabilizes the stream banks, beginning a process of recovery that may take 50 years to complete (Simon and Hupp, 1992). The location of Cane Creek is shown in the section "Habitat in Channelized Streams—Tennessee" on p. 24. *Photograph courtesy of C.R. Hupp, U.S. Geological Survey.*

For a special article about how channel engineering can alter stream habitat, please see "Habitat in channelized streams—Tennessee," on pages 24–25.

Habitat in Channelized Streams—Tennessee



Streams of the low, wet ground of the Mississippi Embayment have been subjected to extensive straightening and channelization to drain land for cultivation. The geomorphic and botanical effects of this direct land-use change in west Tennessee stream channels have been the subject of extensive study by the USGS in cooperation with the Tennessee Department of Transportation. Recently, study of channelized west Tennessee streams has expanded to include consideration of how riparian vegetation functions in the addition, transport, and processing of organic materials in these highly disturbed streams. This recent work was part of a cooperative interagency effort among the USGS, the U.S. Department of Agriculture–Natural Resources Conservation Service, the Shelby County (Tennessee) Soil and Water Conservation District, and the University of Memphis Geography Department.

Historical analysis of stream responses to channelization identified a six-stage process (Simon and Hupp, 1992). In this sequence, construction is followed by degradation, bank instability, and channel widening. After several decades, the channel recovers through flattening and revegetation of the banks and deposition of point and lateral bars on the channel margins. Physical channel and bank recovery is accompanied by systematic vegetative recovery in the riparian zone. Vegetation on the banks also increases bank stability. Although studies of channel instability in west Tennessee focused on channel adjustments and riparian vegetation, changes to instream habitat can be inferred. Immediately following the construction phase, channels would be expected to be wide and shallow with no woody debris and little hydraulic diversity or canopy cover. With increased gradient, bed scour and habitat disturbance would be frequent; at this stage, bank failures can reintroduce large, woody debris into the channel and there by enhance scour habitat. As banks stabilize and the channel begins to meander between lateral bars within the constructed banks, the low-flow channel would be expected to narrow and form riffle-pool sequences. Finally, as woody vegetation recovers on the banks, shading, cover, and organic matter would increase. Studies on stream habitat in channelized streams in northwest Mississippi confirm these associations (Shields and others, 1994).

The effects of riparian vegetation on biological structure and organic processing functions of channelized streams were studied in detail on a first-order segment of Beaver Creek in southwestern Tennessee. Beaver Creek is a channelized stream that is located in a basin dominated by agricultural land use. The creek is 4.02 kilometer in length and primarily is a pool/riffle stream type during base-flow conditions. The creek drains a 2.02-square kilometer area that predominately is in row-crop cultivation.

The study was designed to evaluate biological functions of the creek as an indicator of stream health and water quality. The ability of a stream to process organic material for use as an energy source is one indicator of stream health. Modification of streams may disrupt additions, transportation, and processing of organic matter, either by directly changing organic matter additions from riparian vegetation or by changing the instream habitat in which processing organisms live. Particulate organic matter is the base of the food chain, feeding stream invertebrates which, in turn, feed higher trophic levels.

herbaceous riparian vegetation and a 1-kilometer downstream reach of woody riparian vegetation. The reach with herbaceous riparian vegetation was shallower and wider than the woody reach, and the banks were actively eroding by mass wasting processes. The banks of the reach with woody riparian cover appeared to be more stable; however, the streambed of the woody reach was observed to be mobile during 17 weeks of observation. Five pools were sampled in each reach and one pool was sampled in the transitional zone between the two reaches.

The biological structure was assessed by collecting macroinvertebrate samples by grab and leaf-pack methods in each pool. Both types of samples were collected 36, 66, and 116 days after the leaf packs were deployed. The leaf packs were weighed before and after deployment. The net change in dry weight was recorded and used as a measure of decomposition or processing function. Invertebrates in the leaf packs were identified and counted to determine population characteristics. Temperature, specific conductance, pH, dissolved oxygen, alkalinity, and turbidity were measured weekly at the sites.

The herbaceous reach generally had greater variability and range in the chemical measurements than the woody reach. The number of macroinvertebrates were greater in the herbaceous reach than in the woody reach, but the population of invertebrates (measured in terms of abundance and diversity) in the woody reach was more stable. Leaf weight loss indicated that the material was decomposed (processed) in the herbaceous reach at a rate 45 percent greater than that in the woody reach. The higher rate of decomposition could be because the herbaceous reach, which had less shading, had higher water temperatures, which stimulates faster rates of processing and a greater number of macroinvertebrates.

The study results demonstrate the substantial effect that riparian vegetation can have on organic processing and invertebrate populations in these disturbed streams. Increased rates of organic processing in herbaceous reaches may affect downstream reaches by decreasing export of energy sources. Increased fluctuations of invertebrate populations in herbaceous reaches also might be expected to affect population fluctuations among fish that feed on invertebrates. Byl and others (1996) indicated that differences in bank and bed stability between the herbaceous and woody reaches probably were an additional interdependent factor determining biological functions of the stream.

For more information refer to Byl and Carney (1996), Byl and Hutson (1996), Diehl (1994), Diehl (1997), Doily and Baker (1995), Petersen and Petersen (1991), Shields and others (1994), and Simon and Hupp (1992).

Channelized streams in the Mississippi Embayment of western Tennessee typically undergo a multiple-stage process of channel evolution from disturbance to recovery (Simon and Hupp, 1992). This evolution creates dynamic habitat changes, with substantial changes to depth, width, and canopy closure (photos A–D). Photographs courtesy of T.D. Byl, U.S. Geological Survey.

A, *Beaver Creek, an unchannelized reach with stable banks, meandering channel, and a closed canopy.*

B, *Beaver Creek, a channelized reach with open canopy and a straight channel.*

C, *Cane Creek, a channelized, incised reach with unstable, slumping banks, high sediment yield to streams, and no canopy.*

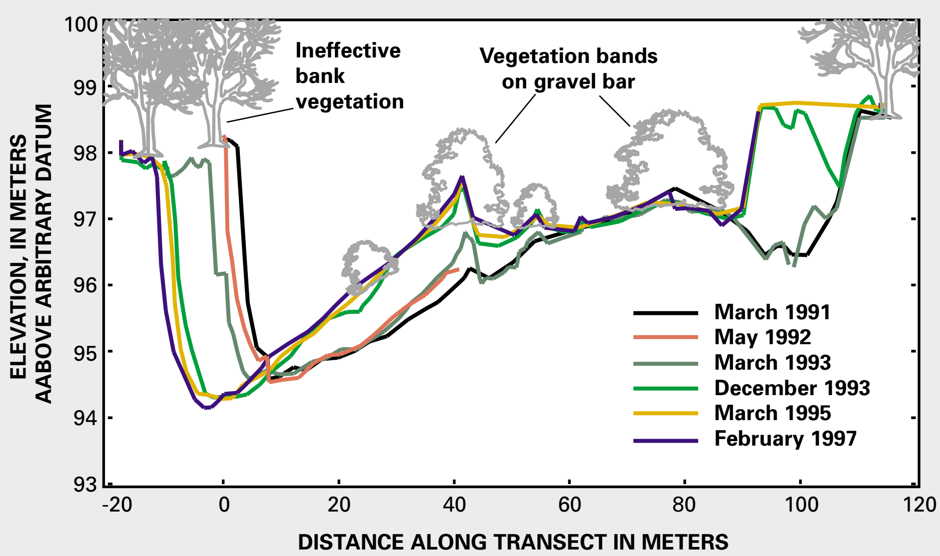
D, *Cold Creek, in the recovery stage in which the formerly incised channel is aggraded by sediment from upstream. In this reach riparian, woody vegetation is becoming established, but excessive sand deposition has clogged the channel.*

Riparian Vegetation and Maintenance of Physical Habitats—Missouri

Riparian vegetation often is cleared for flood-control or agricultural purposes. Because vegetation increases flow resistance by as much as an order of magnitude, vegetation removal can substantially affect channel shape and stream habitats. In cooperation with the Missouri Department of Conservation, the USGS has been studying the effects of woody riparian vegetation on stream habitats in the Ozarks (Missouri and Arkansas). These studies show vegetation substantially affects the type and diversity of habitats in many stream reaches.

An abundance of aquatic species live in the clear, spring-fed streams of the Ozarks. More than 100 fish species live in Ozarks streams—56 fish species and subspecies are restricted to the Ozarks. This rich natural heritage may be threatened because erosion and deposition, which can result from removal of riparian vegetation, continually alter stream habitats.

Study results indicate that flow resistance contributed by vegetation is most effective in areas where gravel deposition is occurring. Willows and sycamores often sprout on gravel bars in bands parallel to the stream. Dense vegetation bands on gravel bars increase flow resistance and trap sand and gravel during floods. The sand and gravel trapped in the vegetation band confines the stream, resulting in local deepening of the channel and maintenance of a steep bank across the channel from the bar. Channel deepening in these areas provides pool



Surveyed cross section on the Jacks Fork, Missouri, showing accretion of sediment in vegetation bands on a gravel bar. Sediment deposition occurs where hydraulic roughness is greater than surrounding areas due to dense growth of willows and sycamores. On the nearly vertical cut bank opposite the gravel bar, woody riparian vegetation provides minimal hydraulic resistance or erosional resistance.

habitat in stream reaches that are otherwise uniform and shallow. In riffles, erosion around dense vegetation creates complex channels with diverse, closely spaced habitats.

The studies also determined that riparian vegetation was not effective in stabilizing banks in many Ozarks streams where bank height exceeds rooting depth. In these cases, the roots do not strengthen the bank near the stream surface. Because the lower part of the bank is not strengthened, it erodes easily during floods. The unstable, undercut banks that result from this process slump into the stream, supplying readily transportable sediment.

For more information refer to Jacobson and Pugh (1997), McKenney and others (1995), and Pflieger (1989).

Growth of woody vegetation in bands increases hydraulic flow resistance on the gravel bar, resulting in deposition of ridges of gravel and sand within the vegetation bands. As gravel is deposited in the vegetation bands, the channel flow is constricted, resulting in a narrower channel and deeper, swifter flows along the opposite side of the channel.

Riparian vegetation provides hydraulic flow resistance and erosional resistance, both of which can contribute to channel stability. In gravel-bed streams of the Ozarks, willows and sycamores colonize unstable gravel bars in distinctive bands.

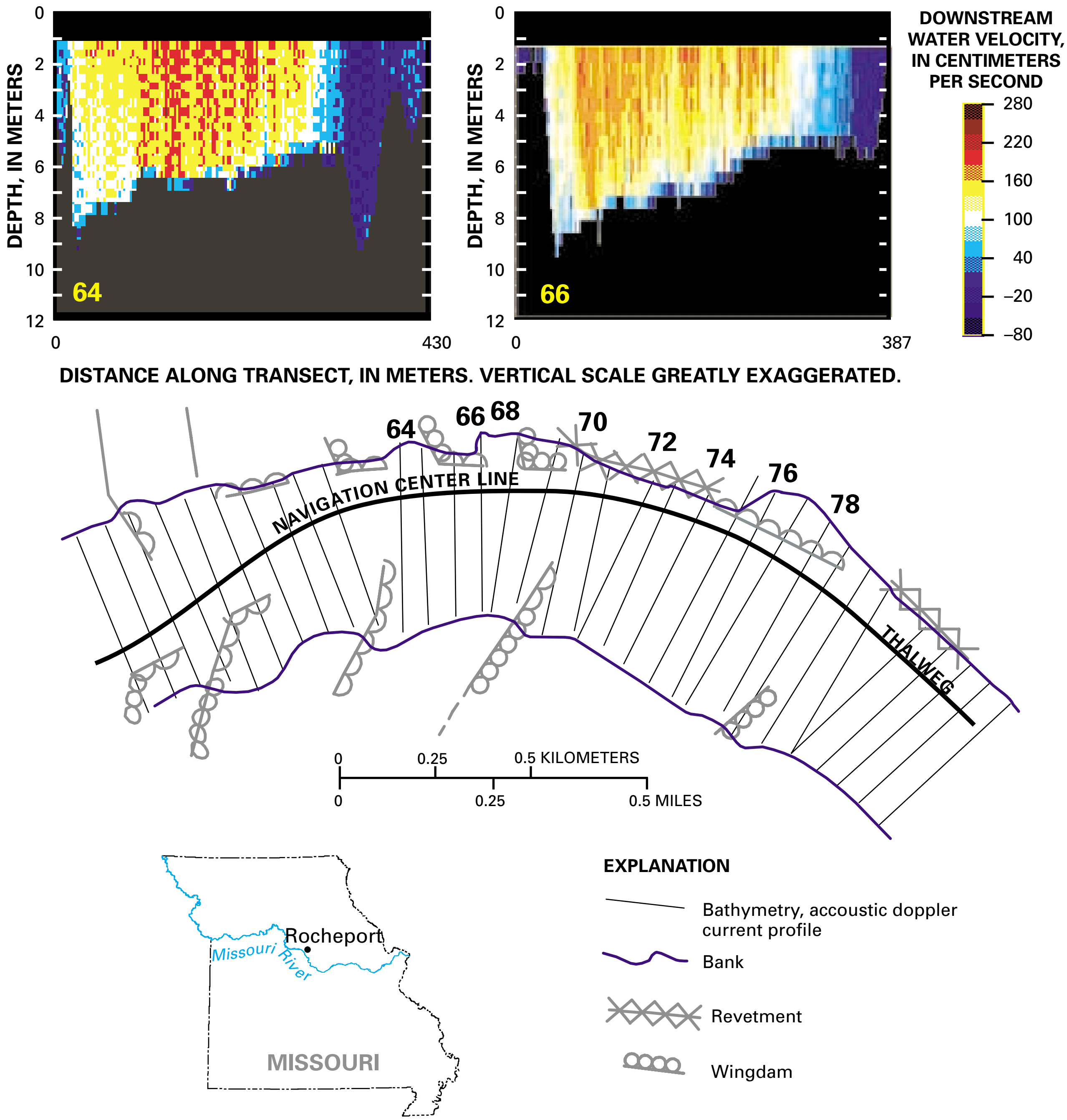


Figure 15. Bathymetry and velocity data from a navigational reach of the Missouri River near Rocheport, Missouri. All transects are viewed looking downstream with the current velocity projected into the line of the transect. The velocity data obtained by an acoustic Doppler current profiler show complex flow fields around wing dams. Dark blue colors in the velocity profiles indicate negative velocities—that is, current velocity in the upstream direction. These areas occur in large eddies downstream of wing dams. The main thread of current is shown as hot colors, with velocities as much as 250 centimeters per second. Also, the bottom topography of the river shows a complex of deep and shallow areas related to the navigation structures. Although quite unlike the shallow, braided stream channel morphology that existed prior to emplacement of navigation structures, the structured channel still has substantial habitat diversity. (Continued on page 29.)

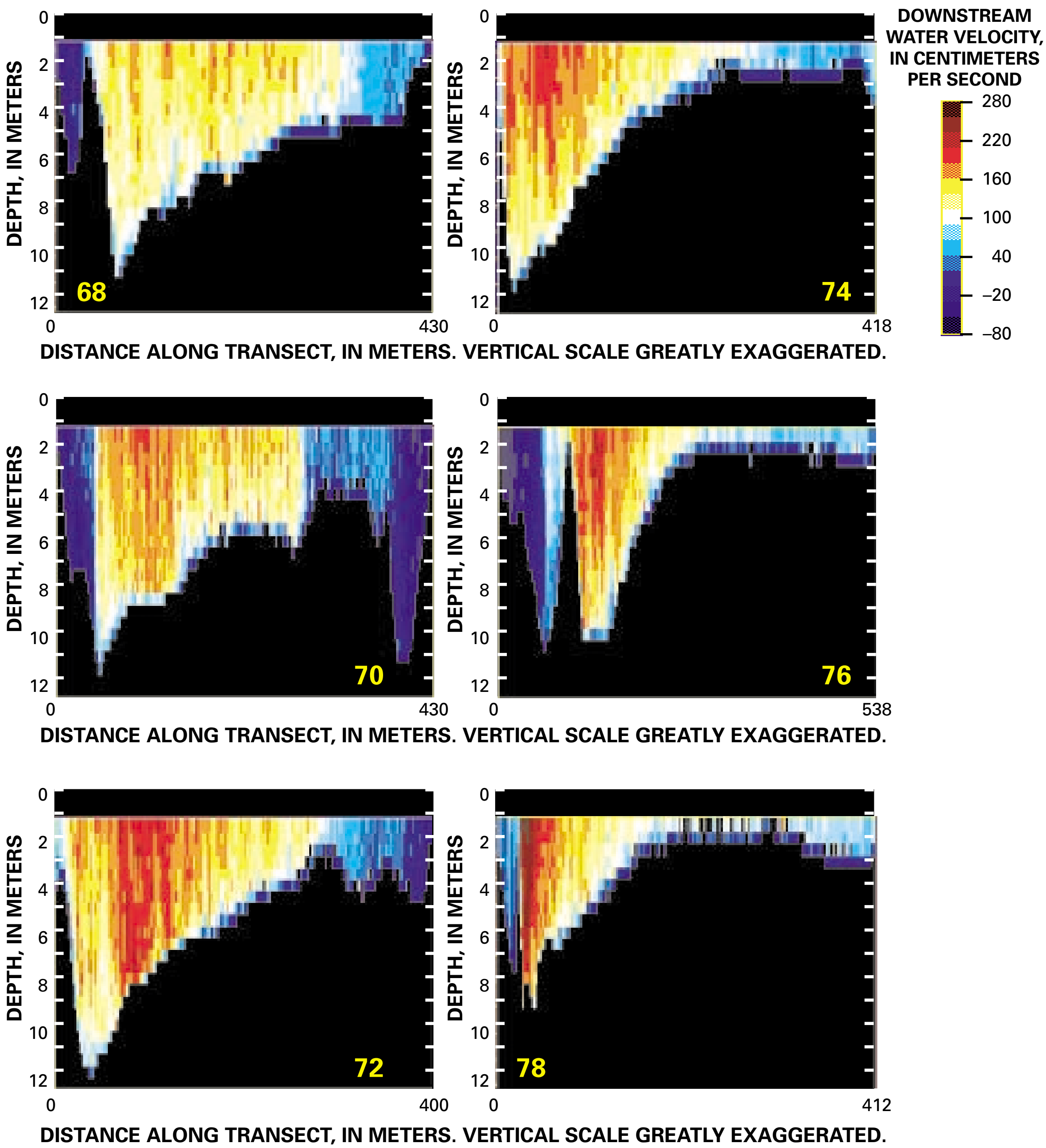


Figure 15—Continued. Bathymetry and velocity data from a navigational reach of the Missouri River near Rocheport, Missouri.

neering functions as well as providing cover, substrate, and hydraulic refugia (Gore and Shields, 1995).

Land-use changes that alter vegetation conditions in the riparian zone can substantially affect hydraulic resistance and erosion resistance with consequent effects on stream habitat. Removal of large woody debris from the channel (snagging), agriculture, forestry, and grazing practices that decrease hydraulic and erosion resistance are widespread on many landscapes. Lowered flow resistance increases velocity, thereby decreasing stage for a given discharge. Because of this effect on stage, vegetation and wood debris have been removed through the process of snagging in many areas as a flood-control

For a special article about how removal of vegetation can affect stream habitat, please see "Riparian vegetation and maintenance of physical habitats—Missouri," on pages 26–27.

measure (Shields and Nunnally, 1984). Decreases in vegetation also commonly decrease erosion resistance of banks because of decreases in cohesive strength provided by roots. As a result, the rate of bank erosion and channel migration may increase, with resultant habitat disturbance and changes in sediment yield. Recently, Waters (1995) has argued that sediment yield from unstable, eroding riparian zones has been vastly underestimated as a source of nonpoint source pollution.

Livestock grazing in riparian zones has been implicated in many studies as a direct cause of habitat degradation (Platts, 1990; Meyers and Swanson, 1992; Trimble and Mendel, 1995). Livestock decrease vegetation densities, which in turn decrease hydraulic resistance and erosional resistance. In a controlled exclosure experiment of the effects of cattle on streambank erosion, Trimble (1994) determined that the effects of riparian vegetation were of secondary importance in controlling bank erosion compared to the direct trampling effect of cattle. Trimble identified cow ramps—areas where cattle consistently entered and exited the stream channel—as focal points for bank erosion and sediment yield in areas of high grazing density.

Although decreases in woody riparian vegetation commonly have been associated with channel instability and habitat degradation in humid parts of North America, regrowth of riparian vegetation does not necessarily have an immediate or beneficial effect on streams. In small streams in Wisconsin, Trimble (1997) determined that stream reaches with woody riparian vegetation were wider and shallower than comparison reaches with grassy vegetation. Trimble attributed this trend to the increased complexity of secondary currents around tree trunks and large woody debris that tended to widen the channel. The net effect on stream habitats in these Wisconsin streams is unknown, but the increased width-to-depth ratio noted in wooded stream reaches could be an indicator of relative loss of pool habitats. In the Missouri Ozarks, Jacobson and Pugh (1997) showed that woody riparian vegetation had a negligible effect on bank erosion rates; they attributed this lack of stabilization in part to the oversteepening of banks that diminished the erosion resistance function of tree roots (fig. 6).

Riparian vegetation not only contributes to hydraulic resistance and erosion resistance, but also provides organic material, shading, cover, and delivery of large woody debris. Organic material provides the basis of the food chain. Delivery of organic material is enhanced when woody vegetation borders the stream channel. Retention of organic material within a stream reach is determined by physical factors such as hydraulic complexity and connection of the channel with off-channel water bodies. Shading is largely a function of canopy closure over a stream. Riparian land-use changes that decrease shading can increase temperatures and temperature fluctuations and increase primary productivity. Hence, the net effect of decreased shading should be evaluated in the context of trophic levels, food, and energy dynamics within a basin (Hicks and others, 1991).

Cover and habitat complexity are positively associated with large woody debris delivered to stream channels (fig. 16). Comprehensive literature is available on the benefits of large woody debris in providing physical habitat and the relations between riparian land use and large woody debris dynamics (for example, Swanson and others, 1976; Gippel, 1995; Keller and others, 1995; Wood-Smith and Buffington, 1996). In general, large woody debris provides cover, hydraulic diversity, and pool habitats. Large woody debris also provides substrate for some types of invertebrates. The net effect of large woody debris on stream habitat is a function of the size of the channel (individual large woody debris pieces have less effect on channel morphology in larger channels than in smaller ones), the rate at which large woody debris is delivered to streams (usually through bank erosion), the rate at which it moves through stream reaches, the rate at which it rots or otherwise breaks down, and the potential for large woody debris to be buried by sediment. The role of large woody debris also increases in complexity as individual pieces interact to form multi-piece obstructions to flow (Abbe and Montgomery, 1996).

INVESTIGATING THE LINKS BETWEEN LAND-USE AND PHYSICAL STREAM-HABITAT CHANGES

Some of the links between land-use changes and stream habitat changes are direct and clearly defined, whereas others are difficult or impossible to establish with confidence. Generally, cause and effect are more easily linked the closer they are to each other in time and space. For example, causal links can be identified with considerable confidence when considering channel degradation and loss of spawning habitat directly downstream from a dam. The strength of the link and ability to quantify the effect diminishes as downstream tributaries add water and sediment, as energy is expended, and as opportunities increase for sediment in transport to be deposited on bars and flood plains. Similarly, the cause of stream siltation directly downstream from an instream aggregate mine may be inferred with confidence, but the cumulative downstream effects of timber management that has varied spatially and temporally in a drainage basin over several decades may be quite difficult to separate from other natural- and anthropogenic-induced sources of disturbance.

Studies designed to establish links and evaluate the sensitivity of physical stream habitat to land-use changes vary considerably in their design and ability to discern links. Studies have been classified into four main approaches: historical, associative, process, and modeling. Some investigations use more than one approach to develop greater understanding over suitable scales of space and time. Historical approaches evaluate the sequence of land-use changes and effects over long time periods and take advantage of existing data. A historical approach often is needed to evaluate a reference state for a stream habitat and whether or not a stream is in the process of adjusting to previous disturbances. An associative study could be used to explore multivariate correlations of habitat conditions with different land uses. This approach can establish effects of spatially varying factors and can, in some cases, be used to identify factors that control habitat sensitivity to land-use change. Process-based approaches can be used to provide complimentary information that quantifies short-term links and responses in a more controlled setting where processes can be measured in an experimental or monitoring framework. A modeling approach can be used to provide a predictive understanding for extrapolating results to other sites and conditions.

Historical Approaches

Historical data provide an important long-term framework for evaluation of land-use and habitat links. Historical data can define a reference condition for assessment of the magnitude of habitat change, can be used to assess variability and trends for a specific time period, and can be used to correlate historical land-use changes with documented ecosystem responses. Historical approaches to understanding the links between land-use changes and stream habitat are especially important when dealing with land-use changes at the

Figure 16. Accumulation of large woody debris on Little Piney Creek, Missouri. Large woody debris accumulations were removed or burned by early settlers to decrease flood hazards and improve conditions for floating railroad ties down the river. In the past 50 years, increased riparian woodland area has caused more large woody debris to enter the stream channel, and in some places along the channel, large woody debris concentrations are sufficiently high that log jams are beginning to reform. Although studies have shown that woody riparian vegetation does not act to stabilize channel migration on this river (Jacobson and Pugh, 1997), bank erosion and consequent delivery of large woody debris to the channel provides essential stream habitat. The location of Little Piney Creek is shown in the section “Establishing Land-Use History and Habitat Links—Missouri” on p. 32.

For a special article about how historical information can aid the documentation of land-use and stream-habitat changes, please see "Establishing land-use history and habitat links—Missouri," on pages 32–33.

Establishing Land-Use History and Habitat Links—Missouri

Many common land uses disturb the landscape at low to moderate intensities over broad areas and long time intervals. Agriculture and forestry are two prominent examples. Their effects on streams are persistent and cumulative rather than acute and direct. In addition, many landscapes have multiple land uses and natural disturbances that could affect physical stream habitat. In these situations, the links between land-use changes and stream habitat changes can be difficult to establish.

In cooperation with the Missouri Department of Conservation and the National Park Service, the USGS has been evaluating links between land-use history and habitat changes in streams in the Ozarks of Missouri. Timber-cutting practices in the late 1800's to early 1900's were thought to be responsible for extensive stream instability and gravel aggradation in the Ozarks. However, a systematic evaluation of the potential for land-use changes to disturb streams produced different conclusions. Among many interacting land-use and climatic disturbances, livestock grazing in riparian areas probably was the most direct and damaging land-use link to stream instability.

To understand the key links between land-use changes and stream changes requires the development of historical information. In the Missouri Ozarks, the USGS documented land-use changes using a considerable range of data sources, including primary historical documents such as land deeds and explorers' diaries, Government Land Office records, U.S. Census data, old landscape photographs, oral histories, archival aerial photography, maps, and satellite imagery. Among these sources, oral historical information proved especially helpful in establishing specific agricultural and timber-cutting practices and how these practices might have disturbed streams.

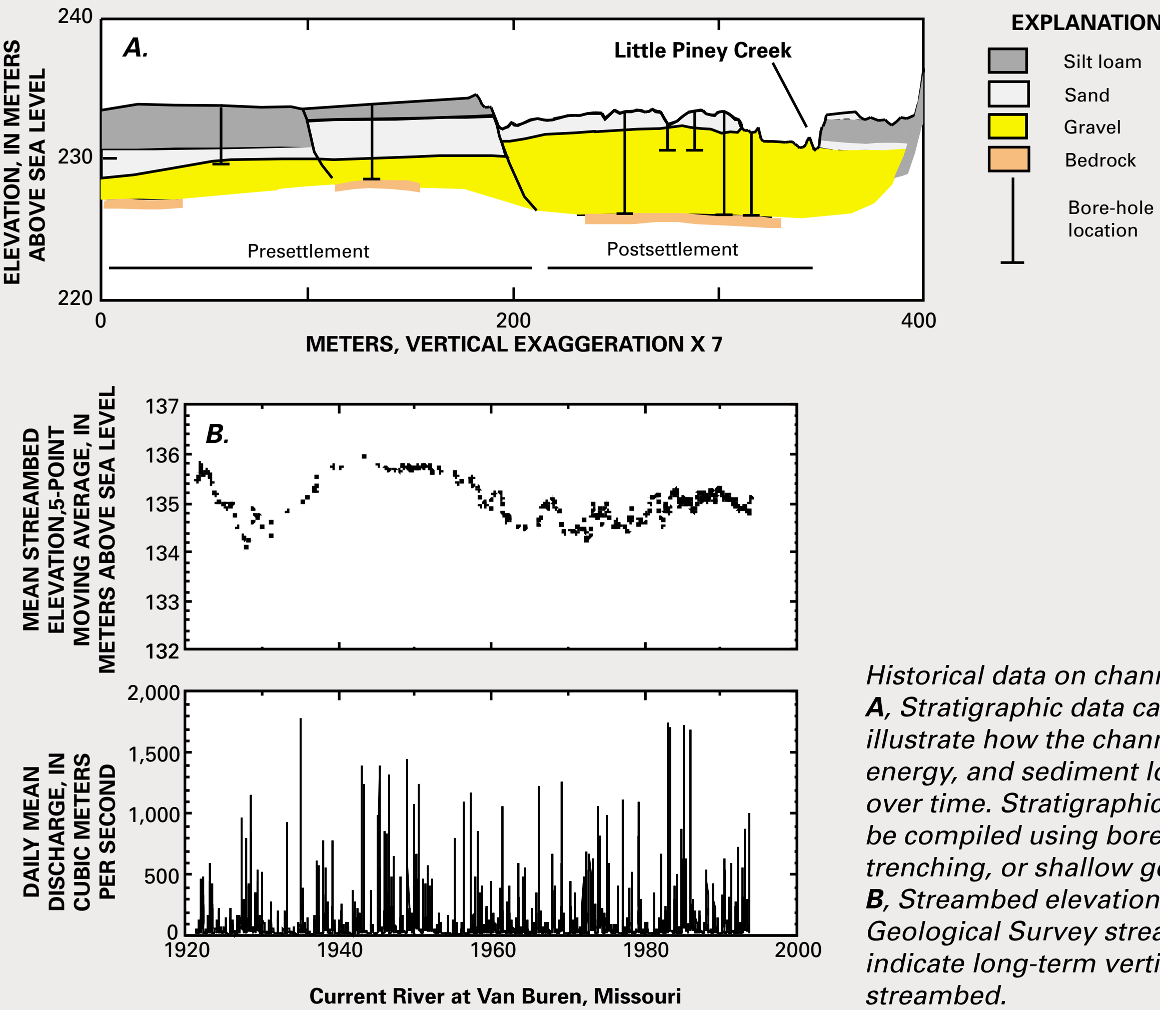
Historical data from old photographs, census records, and oral history can provide essential insight into land-use changes and the effects on stream habitats. Photograph courtesy of D. Ulmer.

Tie drives during the early 1900's in the Ozarks often carried 500,000 board feet of loose logs spread over 25 kilometers of river—usually during high flows (Jacobson and Primm, 1997). Photograph courtesy of the Ozark National Scenic Riverways collection; photographer unknown.

Historical records of stream responses were compiled from stratigraphic studies of flood-plain sediments, USGS stream-gage data (which can indicate large changes in streambed elevation), and historical aerial photography. The stratigraphic data were considered essential for evaluating a reference state for Ozarks rivers—what did streams look like and what was habitat availability under natural conditions before postsettlement land-use changes? These data indicated that streams had accumulated substantial quantities of gravel in the postsettlement period at the expense of fine (silt and clay) sediment. From these observations it was inferred that presettlement streams generally were narrower and deeper. In many parts of North America, intensive row-crop agriculture or grazing has resulted in accelerated upland soil erosion and aggradation of fine sediment in channels and flood plains. In contrast, Ozarks streams responded to postsettlement land-use changes by eroding fine sediment from flood plains and depositing substantial quantities of gravel. Streambed-elevation changes from the 1920's to the 1990's showed that postsettlement aggradation had ended in small basins, but waves of gravel continued to move downstream to accumulate in midsized basins. Hence, the land-use practices over the last century continue to cause channel instability and accelerated aquatic-ecosystem disturbance.

In the Ozarks, improved understanding of the historical links between land-use changes and stream-habitat changes has been useful in land, water, and fisheries management decisions. This understanding has allowed resource managers to focus concerns on riparian land-use changes that have had the most effect on streams. In addition, an understanding of the historical trends in disturbance has helped prioritize stream-habitat restoration efforts. With this understanding, restoration can be applied to streams that are at a stage of recovery rather than streams that are continuing to respond to historical disturbances.

For further information refer to Jacobson (1995), Jacobson and Primm (1997), Jacobson and Gran (1999), and Jacobson and Pugh (1992).



Historical data on channel changes.
***A**, Stratigraphic data can be interpreted to illustrate how the channel morphology, energy, and sediment load has changed over time. Stratigraphic cross-sections can be compiled using bore-hole transects, trenching, or shallow geophysical methods.*
***B**, Streambed elevation data from U.S. Geological Survey stream-gage sites indicate long-term vertical changes in the streambed.*

scale of drainage basins (for example, Wissmar and others, 1994). Within drainage basins, the effects of land-use changes may not affect a stream reach for many years because sediment or channel adjustments are transmitted slowly within the channel network. As basin size increases, the opportunities for more sources of variability increase. In turn, increases in variability increase the need to separate background variation from climatic events and natural complex responses of the drainage basin from the effects of land use (Ryan and Grant, 1991).

Historical data can help in defining a reference state, a prerequisite to environmental assessment. A reference state may define an acceptable condition—for example, a percent channel area occupied by pool habitat at a particular discharge. Definition of acceptable reference states frequently requires application of some judgment of optimal ecosystem functioning. Because this optimality often implies subjective judgment of the worth of some species or functions over others, the reference state commonly is defined instead as the natural condition of the river or reach and to assume that the natural condition optimized ecosystem characteristics such as diversity and abundance.

Historical analysis of a river system can provide a description (ranging from qualitative to quantitative) of the natural condition of a river for a period preceding land-use disturbance (fig. 17). Historical analysis also can contribute to defining variability of a river system before, during, and after some historical disturbance. This type of understanding is necessary for many restoration and mitigation efforts in which it is desirable to know if a river system presently is in a degraded or unstable state. Where historical data are exceptionally good, correlations with historical disturbance events can provide a complete history of disturbance, reaction, and recovery of the river system. Past responses of physical habitat to known disturbances probably are the best indicators of future responses.

Historical data can come from many sources (Jacobson and Primm, 1997; Kondolf and Larson, 1995). These sources vary widely in scale, resolution, and reliability. Some historical data were collected originally for purposes completely unrelated to an evaluation of links between land-use changes and habitat responses; as the only data available for historical time frames, these data are extremely valuable, but often they require careful interpretation and professional judgment.

Observations of sediment characteristics, stratigraphic relations, and soil formation characteristics of flood-plain sediments allow interpretation of how rivers have responded to historical and prehistorical changes in hydrology and sediment yield (for example, Trimble, 1974; Knox, 1977; Magilligan, 1985; Jacobson and Coleman, 1986). Even with extremely detailed stratigraphic data and reliable dating of deposits, stratigraphic analysis may provide only a qualitative or semi-quantitative description of a river-system changes. In cases where land-use changes have been substantial, this level of analysis can provide useful information. For example, Jacobson and Coleman (1986) documented aggradation of flood plains in the Maryland Piedmont and attributed the aggradation to increases in sediment load coincident with farming practices during 1730–1930. However, within the accuracy of stratigraphic methods and without direct historical data, these authors could only infer the relative contributions of hydrologic and sediment-yield changes. In cases where the effect of land use has been small compared to climatic background variation, stratigraphic analysis may not resolve the effects of land-use change.

As the time interval of interest nears the present, the number, detail, and reliability of historical data sources generally increase. U.S. Census records, aerial photography, satellite imagery, climatic records, and economic records can document potential land-use stressors. Hydrologic records, aerial photography, surveys of river sections at bridge crossings, historical maps, sediment and water-quality data, and reservoir resurveys can supply the information needed to document and evaluate effects on physical habitat (for example, Wolman, 1967; Costa, 1975; James, 1991).

In some cases the spatial and temporal relations between land-use and habitat effects will be clearly defined. For example, channel straightening may cause nearly immediate channel incision that would cause an abrupt change in the stage-discharge relation (“rating shift”) of a nearby stream gage (for example, Simon and Robbins, 1987). In this case, the causal link between stream straightening and channel incision is quite clear. In many other cases, the data may be sufficient only to constrain possible interpretations. For example, McIntosh and others (1994) were able to document changes in fish habitat in eastern Oregon and Washington by comparing survey data from 1934 to 1942 with resurveys between 1990 to 1992. These historical snapshots provided a strong assessment of change, but the causal links to land-use history had to be inferred because detailed measurements of conditions were not available for the broad study area for the time interval studied.

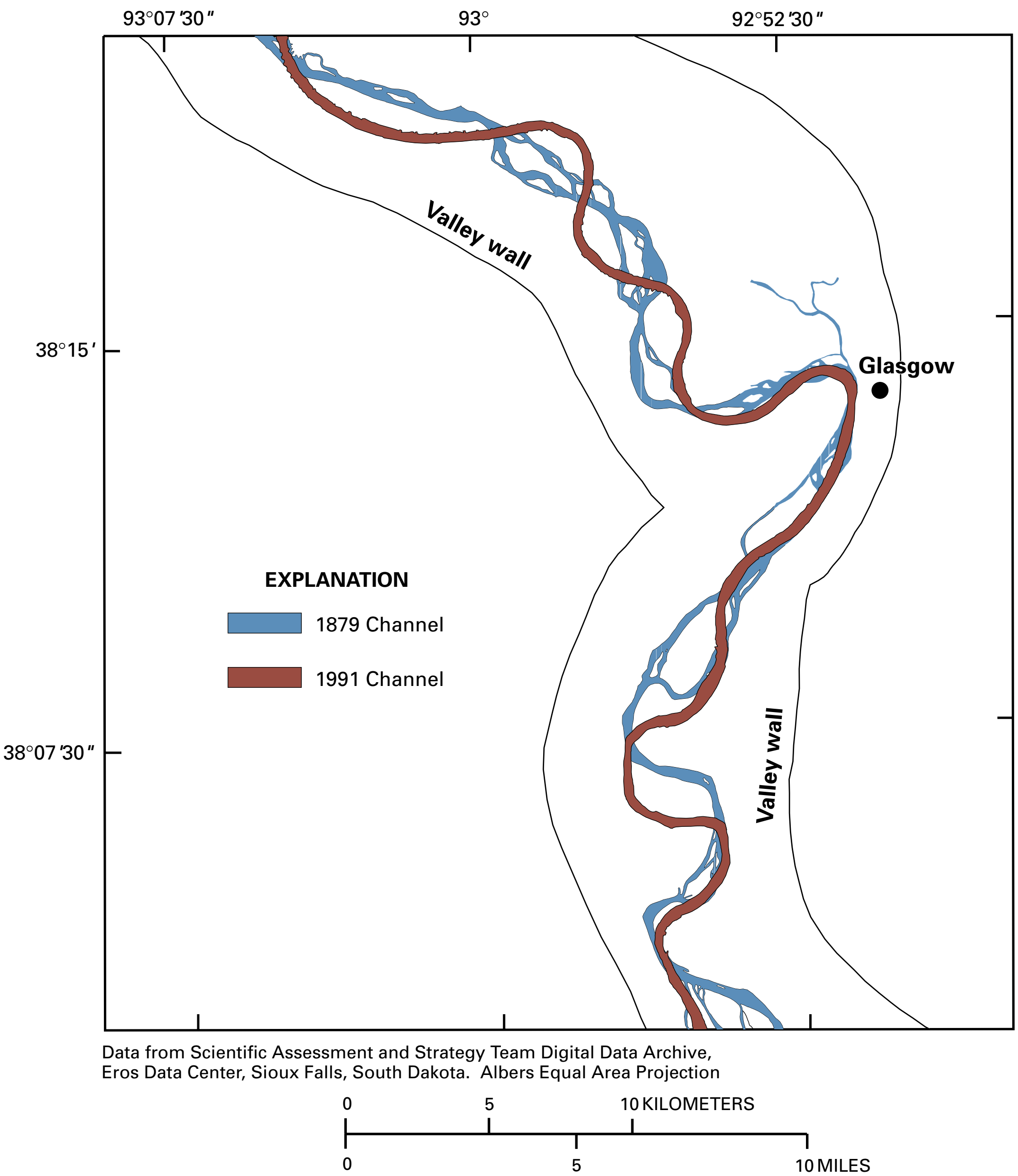


Figure 17. Channel positions of the Missouri River near Glasgow, Missouri, 1879 and 1991. Historical analysis of channel changes is important for evaluating the magnitude of land-use effects and determining reference conditions for restoration activities. In the case of the Missouri River, flow regulation and navigation structures have changed the river from a braided system with transient sand islands and multiple shifting, shallow channels to a meandering stream with stable banks, greater average depths, higher average velocities, and many fewer connections between the channel and flood-plain habitats.

Associative Approaches to Land Use—Habitat Links

Links between land use and stream habitat can be assessed through studies that associate or correlate basin-scale or riparian land use with measured habitat variables. Broad-scale associations are of interest for developing general understanding of regional controls on habitat availability and for developing regional water-quality evaluations. Associative studies can be used as coarse filters of potential links between land use and stream habitats before efforts are spent on other, more time-intensive approaches.

Extensive associative studies and assessments typically make use of integrated indices to evaluate health of rivers and streams. Most of these indices incorporate some measure of habitat quality along with biological characteristics. The U.S. Environmental Protection Agency's (USEPA) Rapid Bioassessment Protocol (RBP) is an example of a method used to conduct cost-effective biological assessments of streams and rivers. The RBP method attempts to provide an integrated assessment of habitat and stream community measures in comparison to a defined reference situation. The RBP method has been used to characterize the existence and severity of stream impairment through associations with land-use practices, to identify sources and causes of impairment, to evaluate the effectiveness of control actions, or to characterize regional biotic characteristics. Other indices also are used to characterize habitat in associative studies. The Ohio Environmental Protection Agency's Qualitative Habitat Evaluation Index (QHEI), for example, is widely used in midwestern assessments (Rankin, 1995).

Associations for Assessing Habitat Availability

Associative studies can determine broad relations between land use and habitat availability. These types of studies often are useful for regional management of biological resources and sport fisheries. The value of associative studies for resource management depends on identifying reliable correlations between measured land-use characteristics and habitat availability. Because of the complex geomorphic and hydrologic response of drainage basins to land-use changes and the confounding effects of interacting land-use changes and natural disturbances, such studies frequently encounter difficulties in determining cause and effect. Nevertheless, associative studies can serve as useful indicators of landscape-scale effects of land use on stream habitats (Richards and others, 1996).

Many studies have attempted to document associations between land use and instream habitat availability and use. Based on these studies, channel substrate seems to relate most readily to land-use changes. Substrate characteristics are considered one of the most important factors in distributions of macroinvertebrates and some fish guilds (Berkman and Rabeni, 1987). For example, channel substrate embeddedness and invertebrate community composition have been shown to vary systematically with basin-scale variables such as amount of urbanization and agricultural land use (Richards and Host, 1994).

Links between basin-scale land use and channel geometry have been harder to document except in cases of extreme land-use change such as urbanization (Leopold, 1994). Even in cases of urbanization, complex responses of channels to the balance of hydrologic and sediment response can cause unexpected results (Odemerho, 1992). The difficulty in relating basin-scale land use to channel geometry results from the many geologic, riparian, and hydrologic factors that can additionally affect channel geometry. For example, Ryan and Grant (1991) documented that suspected associations between timber-harvesting activity in southwest Oregon and active channel width were obscured by several factors including the spatial complexity of slope-channel interactions and large historical floods. Similarly, in central Michigan, channel width was associated more with bedrock geology and structure than with land use (Richards and others, 1996). A better statistical relation was obtained discriminating channel conditions between drainage basins with and without timber harvesting in southern Alaska (Wood-Smith and Buffington, 1996). The strength of this relation apparently was because of the direct links between timber harvest practices and pools that were associated with large woody debris.

The numerous studies that document association do not necessarily identify causality that could lead to a better understanding of the link between land use and habitat. Because of the complex, lagged responses that are possible in landscapes, instream habitats may be affected by land uses that existed at some time in the past, or

For a special article about an integrated study of the surface- and ground-water resources of a river basin, please see "Land-use characteristics and aquatic community structure—Ozark Plateaus NAWQA study unit," on pages 38–39.

habitat conditions at one point in time may be relict from a single large flood or drought in the past. Moreover, it can be difficult to establish which of many land-use practices in a drainage basin is responsible for observed habitat characteristics. For example, channel substrate and cross-sectional morphology may be affected by basin-scale effects on runoff and sediment yield (Richards and others, 1996) by local land-use in the riparian zone (Rabeni and Smale, 1995), or by both. Associative studies may not be able to measure processes with sufficient resolution to determine the source of channel disturbance, but such studies provide valuable data constraining possible sources.

Associations for Water-Quality and Environmental Assessments

Broad-scale water-quality and environmental assessment programs typically seek to evaluate associations between land use and habitat to provide comparable assessments using bioindicators. In such programs, stream biota are the primary interest because they are robust and integrative indicators of water quality and overall biological integrity (Plafkin and others, 1989). However, stream biota also are affected by physical habitat, so the physical differences must be considered in comparing sites:

"Habitat, as affected by instream and surrounding topographic features, is a major determinant of aquatic community potential. Both the quality and quantity of available habitat affect the structure and composition of resident biological communities. Effects of such features can be minimized by sampling similar habitats at all stations being compared. However, when all stations are not physically comparable, habitat characterization is particularly important for proper interpretation of biosurvey results." (Plafkin and others, 1989, p. 2–4)

The need for physical habitat characterization in water-quality studies also is stated by Rankin (1995, p. 181):

"A key concept of the Clean Water Act is the protection of biological integrity of the streams and rivers of the United States. Basic to maintaining diverse, functional aquatic communities in surface waters is the preservation of the natural physical habitat of these ecosystems."

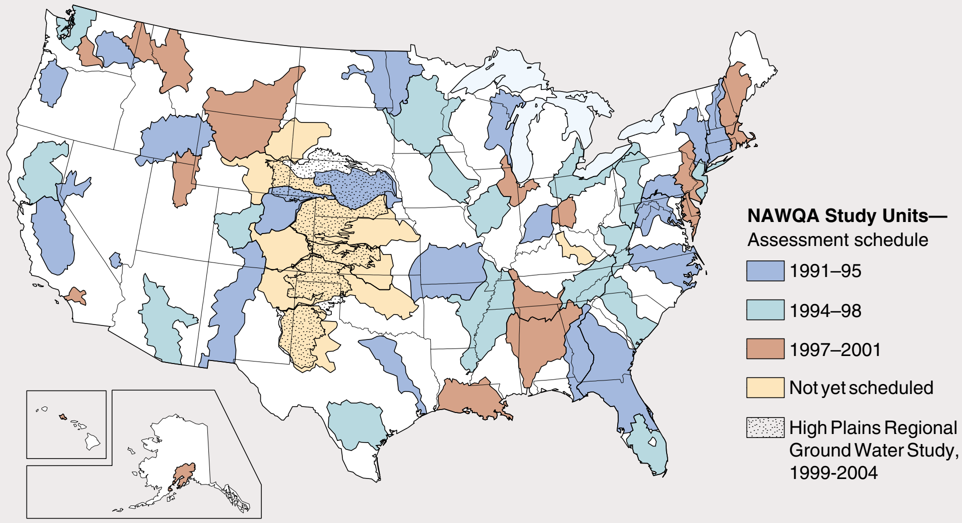
Several national programs seek to address associations between land use and the aquatic community as part of water-quality or environmental assessment.

The USGS National Water Quality Assessment (NAWQA) Program, which started in 1991, is intended to provide a nationally consistent description of the water-quality conditions for a large part of the Nation's water resources. The NAWQA Program has structured its sampling efforts toward establishing multiple lines of evidence of stream health, water-column chemistry, bed sediment and tissue contaminant surveys, and ecological surveys (fish, invertebrates, algae, and multiple-scale physical habitat). These investigations are being conducted on a rotational basis in more than 50 study units throughout the Nation, which incorporate about 60 to 70 percent of the water used and population served by public water supplies. Biological, habitat, and water-quality data are compared to basin-wide and local land use to identify associations between land use and stream health. The NAWQA Program sample sites have been selected specifically to compare contrasting land-use effects on water quality, and physical habitat assessment is used for necessary baseline information on environmental settings. Associations noted in the NAWQA Program study units (for example, Goldstein and others, 1996; Maret and others, 1997) provide useful inter-site comparisons of habitat effects on biota and generate hypotheses for more detailed investigations of links between land use and stream communities.

The USGS also is conducting a national-scale study, the Biomonitoring of Environmental Status and Trends (BEST) Program, designed to identify and understand the effects of environmental contaminants on biological resources, particularly those resources located on U.S. Department of the Interior lands, at the national, regional, and local levels. The BEST Program is focused on the use of bioassessment for evaluation of contaminants in the environment and includes terrestrial as well as aquatic species. The role of contaminants is evaluated by comparison with the roles of habitat limitations and biotic interactions in determining species health. A summary of the BEST program is found in Schmitt and Dethloff (2000).

The USEPA's Environmental Monitoring and Assessment Program (EMAP) is a long-term program intended to document and assess the condition of the Nation's environmental quality change (U.S. Environmental Protection Agency, 1990). The EMAP focuses mainly on national and regional scales for extended periods of time—years to decades. The EMAP collects

Land-Use Characteristics and Aquatic Community Structure—Ozark Plateaus NAWQA Study Unit



The U.S. Geological Survey (USGS) began implementation of the National Water-Quality Assessment (NAWQA) Program in 1991 to provide a nationally consistent description of current water-quality conditions, define long-term trends, and to identify, describe, and explain the major factors that affect water quality for a large part of the Nation's surface- and ground-water resources. When fully implemented, the NAWQA program will include 51 study units, which incorporate parts of most major river basins and aquifer systems in the United States. This nationwide database will provide abundant information for associative-level studies to correlate stream habitat, stream biota, and water quality with drainage-basin level descriptors of land use.

The 51 study units will be rotated through a cycle of intensive field data collection and a low intensity phase. The first 20 study units began in 1991 and continued through 1996. The second 16 study units began in 1994, and the third set of 15 study units began their investigations in 1997. Intensive water-quality and biological investigations are conducted for 3 years, followed by 5 to 6 years of low-level monitoring, with the cycle perpetually repeated. The first set of 20 study units will restart their intensive phase in 2001. Many cooperative projects have been generated from these NAWQA studies due to the information gained.

The initial phase of the Ozark Plateaus NAWQA study unit began in 1991. The study unit is approximately 122,900 square kilometers (48,000 square miles), and includes parts of Missouri, Arkansas, Oklahoma, and Kansas and is drained by seven major river basins. Land use is primarily forest and agriculture (includes pasture and cropland).

Longitudinal and transverse surveys and permanent vegetation plots were established at 13 sites in the Ozark Plateaus study unit. Resurveys of these sites will give information on the movement of the stream channel and changes in the riparian vegetation over time.

The 1990 population within the study unit was approximately 2.3 million people. Data analyses from 41 sites in the Ozark Plateaus study have shown multiple lines of evidence of elevated concentrations of trace elements in the water column, bed sediments, and tissue samples collected in basins with mining land use. Data collected from sites with predominately agricultural land use have shown elevated concentrations of nutrients, bacteria, and agrichemicals in the surface and ground water and have characteristic fish community structures (Davis and Bell, 1998; Petersen, 1998).

Associations between land use and physical habitat have been more subtle than those between land use and chemical habitat. Sites in basins with predominantly agricultural land use tended to have more open canopies, steeper segment gradients, and more sinuous stream channels than the forested sites. Sites in predominantly forested basins tended to have deeper and swifter flow, smaller channel widths, and more dense woody riparian vegetation (at small basin size) than the agricultural sites (Femmer, 1997). Of the land use-habitat associations studied, canopy opening, channel width, and channel sinuosity were thought to result, at least in part, from agricultural practices. Associations between land use and water velocity, sideslope gradients, and flood-plain widths were not thought to reflect cause/effect linkages (Petersen and others, 1998). Also, the most dramatic association between land use and fish communities in this dataset was an increase in relative abundance of stoneroller minnows at agricultural sites. The greater relative abundance was thought to result in part from chemical habitat—increased nutrients—and, in part, from physical habitat—open canopies and wider channels that encourage algae growth (Petersen and others, 1998).

Information such as bank height, bank angle, channel width, canopy angles, and stream-bed substrate was collected at each site. This reach scale data is combined with segment and basin scale data to characterize the basin upstream of the site.

Ecological surveys of fish, invertebrate, and algal communities were conducted at a subset of 41 sites in the Ozark Plateau s study unit. Ecological surveys were conducted for 3 consecutive years and at three sites at multiple reaches to reduce year-to-year and reach-to-reach variation.

data on the ecological condition of randomly selected sites from multiple ecosystems with the intent of integrating these data to assess environmental change (U.S. Environmental Protection Agency, 1990). Within the EMAP framework, land use is considered a stressor indicator and habitat conditions are considered exposure indicators; ultimately, correlations among indicators within the EMAP data base will be investigated (U.S. Environmental Protection Agency, 1990).

Process Studies of Land Use—Habitat Links

Cause-and-effect links between land-use changes and stream habitat can be more firmly established by focusing on detailed process measurements or developing well-controlled field experiments (fig. 18). Because of cost constraints, such approaches usually are more limited in scope than historical or associative approaches. Process studies typically focus on either drainage-basin scale measures (changes in runoff, peak flows, or sediment yield) or channel-scale measures (changes in habitat volume, substrate characteristics, or channel morphology). In some cases, multiscale and multidisciplinary studies have been designed to synthesize detailed process measurements at the drainage-basin and channel scales. Examples of these include studies associated with the Long Term Ecological Research Sites, sponsored by various universities, USDA-USFS, and the National Science Foundation, at the H.J. Andrews Experimental Forest, Blue River, Oregon, and the Coweeta Hydrologic Laboratory, Otto, North Carolina, and interagency multidisciplinary work centered on Redwood Creek Basin, northern California (Nolan and others, 1995).

Study designs for process-level approaches generally involve comparisons of habitat responses between treatment and control sites or monitoring of a single site before, during, and after a land-use disturbance. Paired drainage-basin experiments have long been used to evaluate hydrologic and sediment-yield changes due to agricultural or forestry practices (for example, Hornbeck, 1975). More powerful, however, are paired basin designs that also measure processes before, during, and after land-use change (for example, Jones and Grant, 1996).

At the channel scale, experiments may involve intentional changes to the channel or may rely on monitoring a natural sequence of events. Manipulative experiments create conditions with considerable control for testing specific hypotheses. For example, Smith and others (1993) removed all large woody debris from a small, gravel bed stream in Alaska and evaluated the effects on channel morphology over 4 years using a high density of periodically resurveyed channel cross sections. The detailed control over the disturbance (large woody debris removal) and high resolution measurement of the response allowed the investigators to evaluate quantitatively the link between large woody debris and channel morphology and habitats.

For a special article about a paired-basin experiment, please see "Mill Creek cattle enclosure study—Pennsylvania," on pages 42–43.

Figure 18. Detailed measurements are made to study land-use effects on stream geomorphology and habitat in the Ozark region of Arkansas. Unlike manipulative field experiments in which experimental treatments are imposed by scientists with considerable control, monitoring experiments rely on an opportunistic time series of changes to provide insights into processes and rates of processes of habitat changes. Such monitoring studies may record the effects of land-use or climatic disturbances, but even if substantial changes do not occur during the monitoring period, these studies provide important documentation of background rates of change.

An example of a controlled field experiment was the spring 1995 controlled flood on the Colorado River in the Grand Canyon. This experiment utilized a design discharge from Glen Canyon Dam to determine how the channel and associated habitats responded to a flow substantially larger than was normal under dam regulation. The main hypothesis tested was whether the design flood would be capable of redistributing sand to replenish sand bar and backwater habitats that had been lost due to flow regulation (fig. 19). Under tightly controlled experimental conditions, a multidisciplinary team was able to collect detailed and systematic data on the processes of habitat change (Collier and others, 1997).

Direct manipulations of the stream systems are not always possible or cost effective. In many cases, detailed process measurements can be made in a monitoring environment in which experiments are run opportunistically as land-use change or other disturbances take place. For example, McKenney and Jacobson (1996) describe monitoring habitat change in Ozarks streams during a period of recovery from past land-use practices. During the monitoring period, the investigators also were able to document disturbance and recovery of stream habitats from a 50-year flood.

For a related special article, please see "Effect of boat wakes on bank erosion and salmon habitat—Alaska," on pages 44–45.

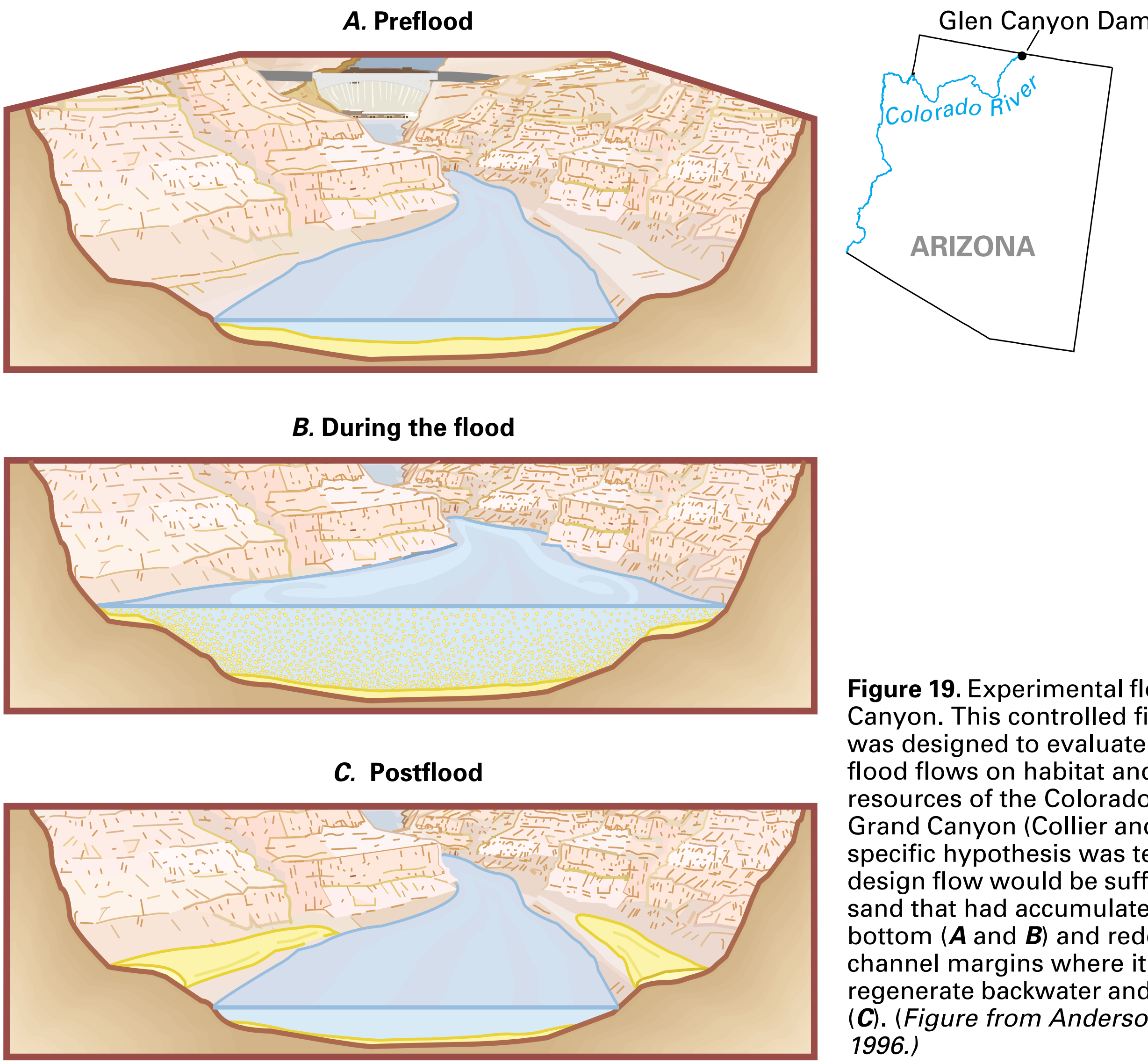
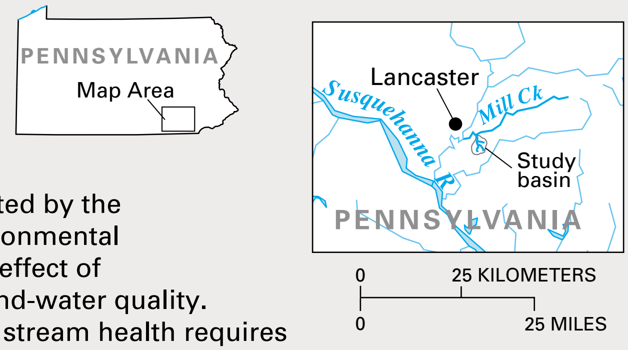


Figure 19. Experimental flood on the Grand Canyon. This controlled field experiment was designed to evaluate the effects of flood flows on habitat and biological resources of the Colorado River in the Grand Canyon (Collier and others, 1997). A specific hypothesis was tested that the design flow would be sufficient to suspend sand that had accumulated in the channel bottom (***A*** and ***B***) and redeposit it on channel margins where it would regenerate backwater and sand bar habitat (***C***). (*Figure from Anderson and others, 1996.*)

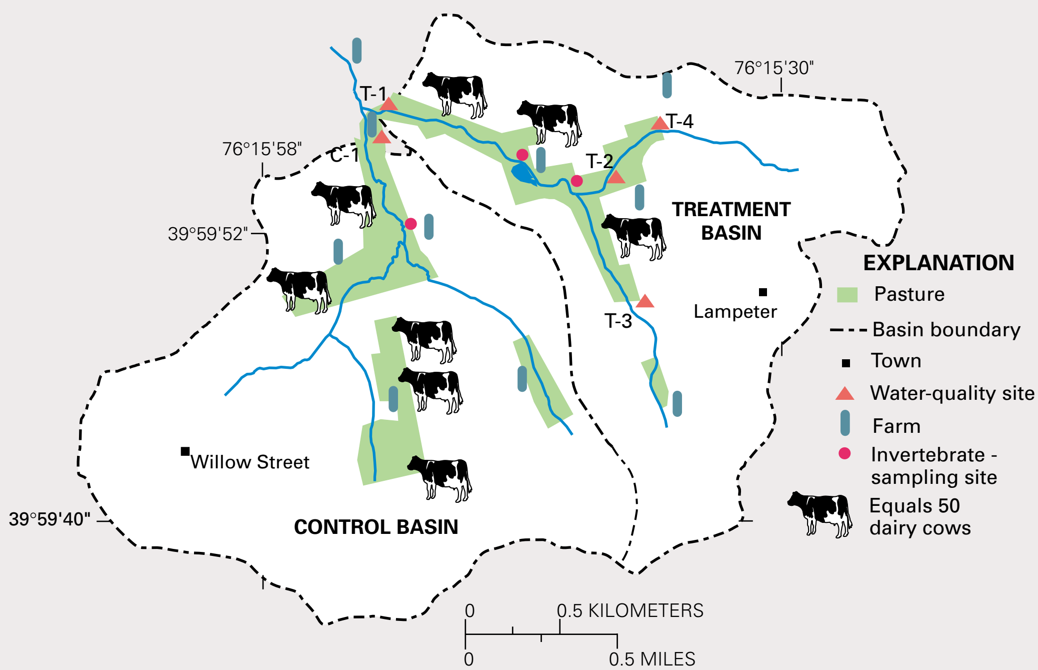
Mill Creek Cattle Enclosure Study—Pennsylvania



Manipulative experiments are designed to explore how alluvial systems behave under relatively well-controlled conditions. By controlling specific variables, some of the inherent variability of the natural system can be accounted for. Such an experiment is underway in a subbasin of Mill Creek in southeast Pennsylvania to attempt to isolate the effect of livestock grazing on stream health. The study is being conducted by the USGS in cooperation with the Pennsylvania Department of Environmental Protection. The primary objective of this study is to evaluate the effect of exclusion of livestock from stream reaches on surface- and ground-water quality. The use of benthic macroinvertebrate community data to assess stream health requires evaluation of physical habitat changes accompanying exclusion.

The study uses a paired basin design with additional pre- and postexclusion and upstream and downstream analyses. Two adjacent subbasins of Mill Creek with similar agricultural land use, climate, topography, geology, and size (about 5 square kilometers) were selected. Both subbasins have substantial numbers of dairy cattle that had unlimited access to the stream channel in the pre-exclusion period. After a period of pre-exclusion data collection, streambanks in four treatment reaches were fenced. The prefencing period was 1993 to 1997, and the study will continue to November 2001.

A comprehensive suite of chemical, physical, and biological data are being collected in treatment and control sites. The data collection is designed to detect significant variations in measured constituents under base-flow and runoff conditions. Biological indices are being used to indicate the overall health of the streams using the assumption that the biological community structure is sensitive to physical and chemical habitat. Benthic macroinvertebrates were chosen as an index of stream health and as an appropriate metric for comparing to designated uses of the stream. Absence of pollution sensitive taxa such as Ephermeroptera (Mayflies), Plecoptera



The Mill Creek Basin, Southeastern Pennsylvania. Treatment stream segments have cattle excluded from them by fencing, whereas control stream segments have open access of dairy cattle to the stream.

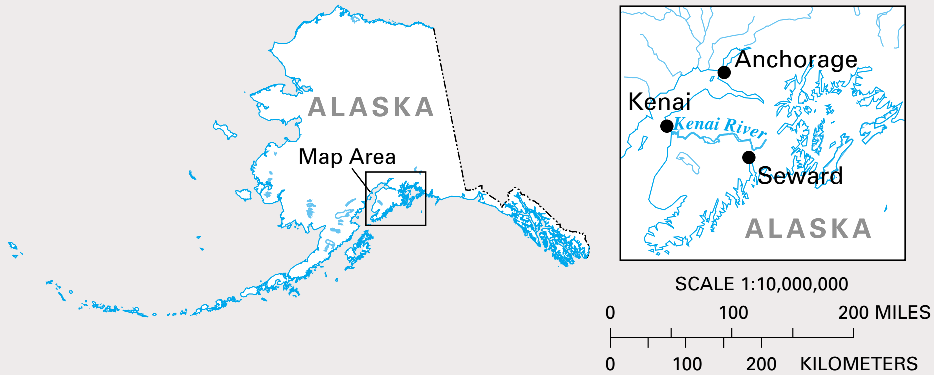
(Stoneflies), and Trichoptera (Caddisflies) generally is considered to be indicative of poor water quality, if other abiotic and biotic factors are not limiting. Dominance by a single taxa, low taxa richness, or differences in community structure compared with reference sites also are considered to be useful indicators of stream health (Plafkin and others, 1989). The Mill Creek study design incorporates community, population, and functional scores into a biological evaluation. Channel width, depth, and velocity are surveyed at each site during invertebrate sampling to record physical changes in stream channel habitats and to account for habitat effects on the biotic communities.

For further information refer to Galeone and Koerkle (1996), Galeone (1999), and Plafkin and others (1989).

Kick-net sampling of stream benthic invertebrates in the Mill Creek Basin, Pennsylvania, cattle enclosure experiment. Changes in benthic invertebrates will be compared between streams with and without cattle access, and before and after cattle are excluded. The direct control of disturbance and detailed measurements of physical, chemical, and biological responses will provide information on processes linking livestock grazing and stream biota. Photograph courtesy of D.G. Galeone, U.S. Geological Survey.

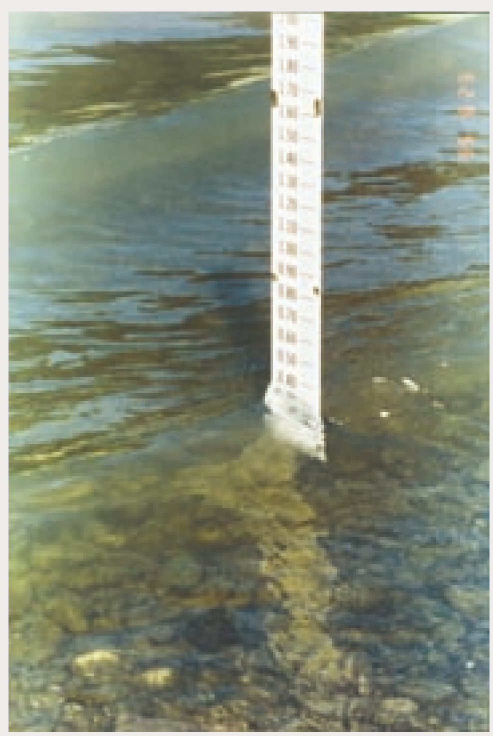
Effect of Boat Wakes on Bank Erosion and Salmon Habitat—Alaska

Rapid bank erosion on the Kenai River, Alaska, is caused by boat wakes from private and guided fishing boats. Increased sediment from bank erosion can adversely affect juvenile chinook salmon habitat, which is already in short supply. Because the recreational salmon fishery on the Kenai River contributes as much as $40 million per year to the local economy, bank erosion is a subject of regional concern. The USGS, in cooperation with the Alaska Department of Fish and Game, developed a streambank erosion monitoring program and performed a controlled boat-wake experiment to determine the effect of boat wakes on bank erosion.



Bank erosion was measured using erosion pins and sedimentation pans, and boat wake size was measured using specially designed boat wake gages. Erosion pins were installed in stream banks in two areas: areas that allowed the use of motorboats, and areas that were restricted to unmotorized boat use. This

Rapid bank erosion is occurring in several areas on the Kenai River, Alaska. Boat wakes from private and guided fishing boats have been associated with rapid bank erosion. Increased sediment from bank erosion can adversely affect juvenile chinook salmon habitat, which is already in short supply. Photograph courtesy of J.M. Dorava, U.S. Geological Survey.



This controlled U.S. Geological Survey experiment determined that in sections of the Kenai River that allow motorboats, 19 percent to 97 percent of the energy directed at the banks during the study period resulted from boat wakes. Photograph courtesy of J.M. Dorava, U.S. Geological Survey.

experimental design allowed the scientists to determine whether the erosion was caused by natural river processes or boat wakes. Erosion pins also were installed after the 1995 fishing season, measured before the 1996 fishing season started, and measured after the 1996 fishing season ended, so that the timing of erosion could be compared to times of intense recreational use. Erosion pins also were installed in areas with bank-erosion control structures to evaluate the efficacy of mitigation measures such as coconut fiber logs, willow sprouts, spruce-tree revetments, rock riprap, and log revetments. Wake gages measure boat wake height and frequency, which can then be used to calculate the amount of energy directed at the bank by boat wakes. Erosion measurements collected during the off season and in areas where motorboats were restricted provide natural erosion rates for comparison. Streamgage data were used to calculate the erosive energy directed at the bank by the river currents without contributions by boat wakes.

As an additional analysis of the effects of boat wakes, controlled boat-pass experiments were performed with three different hull designs and variations in distance from the bank and passenger loading; each boat was driven at its maximum speed. During this experiment, wake heights were measured and sediment eroded from the banks was collected and measured in sedimentation pans attached to the banks.

This study determined that in sections of the Kenai River that allow motorboats, 19 to 97 percent of the energy directed at the banks during the study period resulted from boat wakes. Variations in boat wake energy are caused by different use levels, variations in fishing patterns, stream morphologies that concentrate or disperse natural and boat wake energy, and different boat travel patterns. The greatest bank erosion occurred when high streamflow coincided with high recreational boat use. Erosion in areas where the use of motorized boats is restricted was approximately 25 percent of erosion in the most popular, unrestricted boating areas. Among the bank-protection measures investigated, all were equally effective at reducing boat wake heights and slowing erosion. A spruce-tree revetment provided the most habitat for juvenile salmon.

For more information refer to Dorava and Liepitz (1996), Dorava and Moore (1997), and Dorava (1999).

Experimental boat passes used boats with three different hull designs, varied distances from the bank, and different passenger loads to determine effects of the different combinations on boat wake size and bank erosion. Photograph courtesy of J.M. Dorava, U.S. Geological Survey.

Modeling Links between Land Use and Physical Stream Habitat

Links between land-use changes and habitat responses can be portrayed with physically based models. Currently (2000), models exist at two spatial scales, with little overlap. Basin-scale models are designed to predict or analyze how changes in land use affect basin hydrology and sediment yield. Channel-scale models are designed to predict or analyze how channel morphology and habitat availability vary with discharge, sediment transport, and bank erosion. Some research is being pursued to integrate the two scales of models (Colorado climate study special section on p. 48, for example); however, much work still remains to develop rigorous models linking basin- and channel-scale processes to stream habitat.

Basin-Scale Models

The link between land-use changes and hydrologic responses is addressed by many rainfall-runoff models. The models range in complexity from statistical representations—like regional flood frequency models—to spatially distributed, physically based models that account for rainfall, evapotranspiration, infiltration rates, soil moisture storage, variable-source area runoff production, and channel routing.

Effects of land-use changes can be explored and quantified in basin-scale models by changing factors such as evapotranspiration (as a function of land cover) or infiltration and storage (as functions of factors such as impermeable area, soil compaction, and impoundments). Two examples of this type of hydrologic model are the Precipitation-Runoff Modeling System (Leavesly and others, 1983) and the Hydrologic Simulation Program-FORTRAN (Bicknell and others, 1993). In most cases, the ability of a model to predict changes in runoff and hydrograph timing is dependent on the calibration of some model parameters with measured data sets. Because models commonly cannot be calibrated under the conditions that are of interest—for example, future land-use changes—considerable uncertainty in the model predictions exist. Confidence in model predictions increases with the degree to which the model can represent realistic physical processes and the range of conditions over which it has been calibrated.

Sediment transport models traditionally have been more difficult to formulate and less reliable than hydrologic models. Statistical approaches to soil erosion models dominated the field for many years in the form of the USLE and variants (Wischmeier and Smith, 1978). The statistical approach of the USLE provided useful predictions of soil erosion from field-size plots without requiring rigorous modeling of the hydrologic, erosion, and sediment transport processes that contribute to soil erosion. More recently, physically based models have begun to compete with the USLE approach. The dominant model is the Water Energy Prediction Project (WEPP) model (Lane and Nearing, 1989). The WEPP model is based more on the physical representation of the hydrologic, soil erosion, and sediment transport processes than the USLE. Consequently, the WEPP model is considerably more complex and requires more data. In either type of model, the effects of land-use changes on soil erosion in a drainage basin can be simulated by changing parameters related to soil erodibility and vegetation characteristics.

Once runoff or sediment is simulated at the hill-slope scale in a model, it needs to be routed to a channel before its effects on instream habitat can be evaluated. Hydrograph routing through impoundments, structures, and channels typically is included in distributed hydrologic models; hydrograph routing requires additional data for channel characteristics, but the theory and application are well established.

In contrast, sediment routing is not as well understood in theory or in practice. In fact, sediment routing is considered one of the most complex and challenging problems in geomorphology (Wolman, 1977). At the hill-slope scale, the mass of soil delivered to adjacent channels can be related to the mass of soil eroded by empirical sediment delivery ratios. Sediment delivery ratios are known to vary with drainage area and basin characteristics, but the mechanical basis for determination of sediment delivery ratios is poorly understood (review in Walling, 1983). Once delivered to the stream channel, sediment typically does not move conservatively with water through fluvial systems. Instead, sediment can be deposited on the channel beds, banks, and bars and remain in storage for highly variable intervals before being remobilized and continuing its downstream travel (Meade and others, 1990). Recent advances in computational models of sediment routing have focused on delivery of sediment from slopes to the channel and routing of fine, dominantly suspended-load sediment in relatively small drainage basins (Walling, 1983; Arnold and others, 1995). These models emphasize delivery of sediment to a basin outlet as a measure of offsite effects rather than evaluating the effects of sediment delivery and storage along the channel within the basin. Little emphasis has been placed in these computational models on sediment movement and routing within drainage basins or at scales where the sediment can affect stream habitats.

Channel-Scale Models

Links between water discharge variations and physical habitat availability in a channel reach are often estimated using hydraulic flow modeling. Physical habitat simulation was developed as a component of the Instream Flow Incremental Methodology (IFIM) (Bovee, 1982). The IFIM predicts the effects of incremental changes in streamflow on channel structure, water quality, temperature, and habitat availability by using a series of models. The physical habitat component (PHABSIM) of IFIM is a one-dimensional flow model that predicts usable habitat areas based on water discharge and fish habitat preferences (Bovee, 1982). This type of modeling approach is used to predict the effects of water diversions, dams, engineering structures, and changes in water release schedules on habitat availability for a selected species or habitat-use guild.

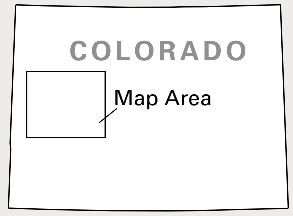
Modeling approaches, such as PHABSIM, require a variety of data to set up, calibrate, verify, and analyze the model prior to its use as a management or planning tool. Data required to use the model include reach topography and channel roughness characteristics, and calibration data consisting of water-surface elevations, velocities, and depths at multiple cross sections in a reach for one or more discharges. In addition, habitat-use data are needed to build habitat suitability curves for the species of interest. From these data, PHABSIM calculates a weighted usable habitat area at given discharges for a selected fish species or group of species. Habitat predictions can then be analyzed in terms of the time domain by considering the percentage of time habitat conditions exist during an average year or the probability that critical habitat conditions will exist during a specific time of the year, such as a spawning season.

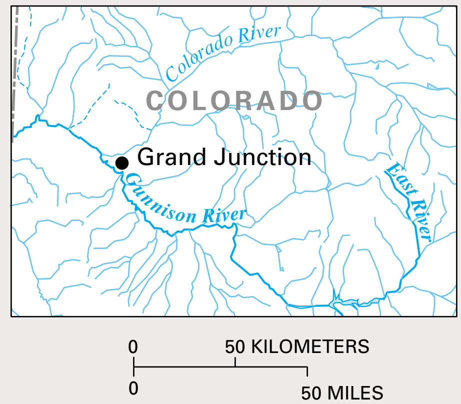
Predictions from PHABSIM, and the PHABSIM procedure, have been questioned because of weak relations between predicted weighted usable habitat area and fish population size. Researchers have questioned whether fish sampling can define useful statistical models relating habitat to populations, and whether it should be expected that stream biota will use habitat in proportion to its availability (Orth, 1987; Zorn and Seebach, 1995). Biologic responses to changes in instream flows may include the effects of changes in food availability and distribution, water quality, temperature, and biotic interactions as well as physical habitat. Generally these biotic and chemical effects are not included in hydraulic simulations of habitat availability (Orth, 1987). In addition, weak relations between predicted and actual conditions have been attributed in part to low quality of the underlying hydraulic models. Hydraulic models in habitat simulation have been criticized because of the low spatial resolution of one-dimensional model formulations (Leclerc and others, 1995); because of dynamic channel instability that alters channel morphology during a flood hydrograph (Kondolf and Sale, 1985); and because variation in cross-section characteristics is not captured realistically in the models (Williams, 1996).

Because of these concerns with conventional hydraulic habitat analyses, other approaches to instream flow modeling are being studied (fig. 20). Two-dimensional hydraulic models, which have higher spatial resolution, have been proposed to improve predictions of depth and velocity responses to instream flow changes (Leclerc and others, 1995). Two additional analytical approaches have been proposed for the linkage of channel hydraulics with biologic responses. Latka and others (1993) avoid the issue of biological responses by comparing the distributions of channel depths and velocities with discharge scenarios to a historically defined hydraulic reference state. The underlying assumption in this approach is that the historical reference state had an optimal spatial and temporal distribution of habitats for native stream species. Another variation on the traditional instream flow approach is to assign discrete ranges of depth and velocity to particular macrohabitat types. The biological value of these habitat types would be determined from independent knowledge of critical habitat use by particular species. For example, behavioral studies of spawning might independently define a preferred depth and velocity range for a species of concern. The modeling analysis, then, would focus on the

For a special article about how PHABSIM is being used in Virginia and Washington States, please see "Minimum instream flow modeling—Virginia and Washington," on pages 50–51.

Climate Change Effects on Sediment and Streamflow—Colorado





Previous studies have indicated that changes in climate may affect the timing and supply of water to riverine systems, but few studies have attempted to assess the effect of these changes on streamflow dependent processes. The USGS, in cooperation with the Colorado Water Conservation District, the Upper Gunnison River Water Conservancy District, Bureau of Reclamation, Bureau of Land Management, and National Park Service, used a series of process models to predict channel response to climate change in the East River, a tributary of the Gunnison River, in west-central Colorado. The effects of changes in climate on bed-sediment flux were simulated by linking a watershed model (Leavesly and others, 1983), a one-dimensional hydraulic model, and a sediment-transport relation (Parker and others, 1982). Using these models, hydrologic changes at the drainage-basin scale have been linked to channel hydraulics, which, in turn, are linked to sediment transporting events—the events that alter physical habitat.

The East River (drainage area 748 square kilometers) is a major contributor of streamflow to the Gunnison River in western Colorado. The basin elevations range from 2,440 to 4,359 meters and the mean monthly air temperatures range from less than -10° Celsius in January to almost 13° Celsius in July. Precipitation ranges from 25 to almost 60 millimeters per month with the highest levels in November through March (mainly snowfall). Streamflow starts to increase in April with peak discharges in late May to early June due to snowmelt. The streambed substrate is cobble with a mean diameter of 112 millimeters for the surficial material and has a channel slope of 0.0048. The bankfull discharge at the gaging station at Almont, Colorado, is 89.2 cubic meters per second with a channel width of 25.9 meters and a mean depth of 1.58 meters.

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The East River is a major contributor of streamflow to the Gunnison River in western Colorado. Using data collected by the U.S. Geological Survey and climatological data, the effects of three air temperature values were modeled for a reach of the East River. Photograph courtesy of R.S. Parker, U.S. Geological Survey.

Using data from October 1993 through September 1994, the effects of three mean annual air temperature values (2, 4, and 6° Celsius) were modeled for a reach of the East River. These increases in air temperature altered the timing of the streamflow hydrograph and reduced the annual streamflow volume by only 2, 5, and 7 percent. The changes in the timing of the streamflow hydrograph had a substantial effect on the bed-sediment discharge for the reach, however. The sediment flux was reduced by 86 percent for a 6° Celsius increase in air temperature.

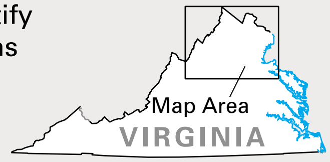
Using linked models to simulate the effect of drainage-basin scale events on reach hydraulics and habitat maintenance provides a valuable tool to predict habitat responses to climate changes or other hydrologic disturbances. Although extension of such models to uncalibrated and unverifiable conditions can yield unreliable results, the models can provide essential insights into the operations of complex fluvial systems. In particular, such models can be used to explore tradeoffs and sensitivities among variables that govern runoff, sediment yield, and sediment transport.

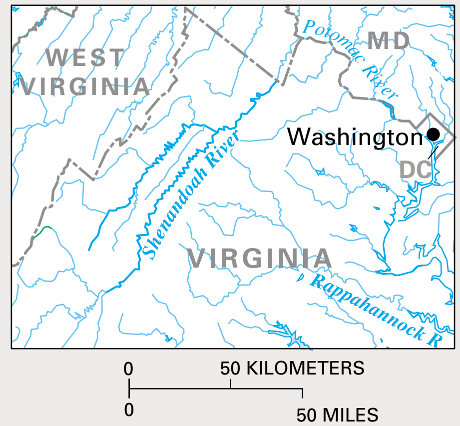
For more information refer to Leavesly and others (1983) and Parker and others (1997).

Most studies use streamflow volumes to evaluate the effects of climate change on water resources and often overlook streamflow-dependent issues such as channel maintenance, habitat, and sediment transport. In this study, a pebble size count technique was used to determine size distribution of the bed material. Photograph courtesy of R.S. Parker, U.S. Geological Survey.

Minimum Instream Flow Modeling—Virginia and Washington

Instream flow methodologies are useful to quantify habitat as a function of water discharge. Concerns have been raised that flow diversions from the Shenandoah River, Virginia, for public-water supply may decrease habitat volumes available for fish. The USGS is working cooperatively with the Lord Fairfax Planning District Commission, Virginia Polytechnic University, Virginia Department of Game and Inland Fisheries, and the U.S. Army Corps of Engineers to evaluate minimum streamflows necessary to maintain fish habitat in the Shenandoah River. The study is using the PHABSIM model to quantify the areal extent of depth and velocity in the stream channel for a range of discharges.



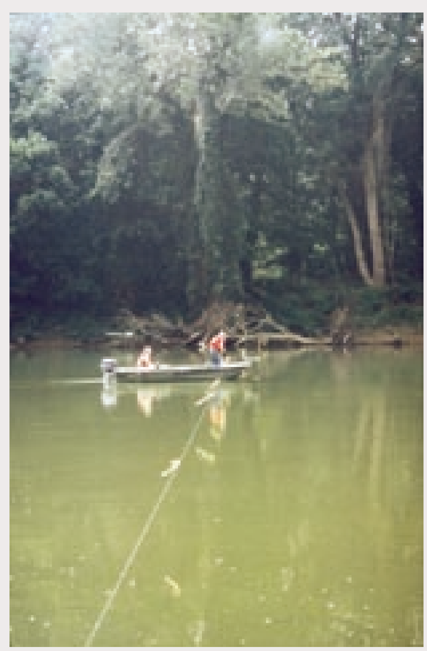


Representative reaches for instream flow modeling were selected based on a basinwide overview of hydrologic, geologic, and soils data. The mainstem of the Shenandoah River has three distinct segments: the upper segment of mostly long pools and short riffles, the middle segment similar to the upper segment with the additional features of islands and bends, and the lower segment, which has longer and wider riffles than the other segments.

A reach in the middle segment was selected for modeling in a demonstration project (Zappia and Hayes, 1998). Twenty-one cross sections were laid out to determine the variability in macrohabitats and to define hydraulic controls. Stage, velocity, and depth data were collected at three different discharges for use in calibration and verification of the hydraulic model. Bed-material particle-size data were collected to help estimate hydraulic roughness coefficients.

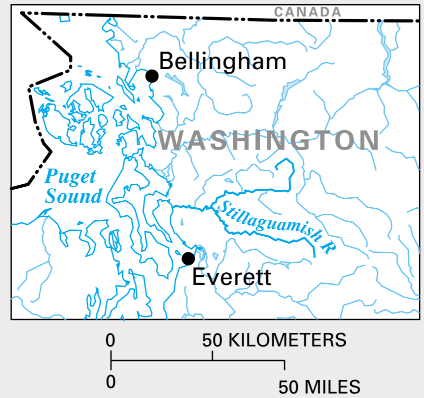
Once calibrated and verified, the hydraulic model results were merged in the PHABSIM model with fish distribution information selected from previously published reports. Fish species were classified into habitat preference guilds to minimize variations due to nonphysical causes. Habitat suitability curves were compared with the hydraulically based model to illustrate habitat availability at various discharges and to estimate the biological effect of low flows.

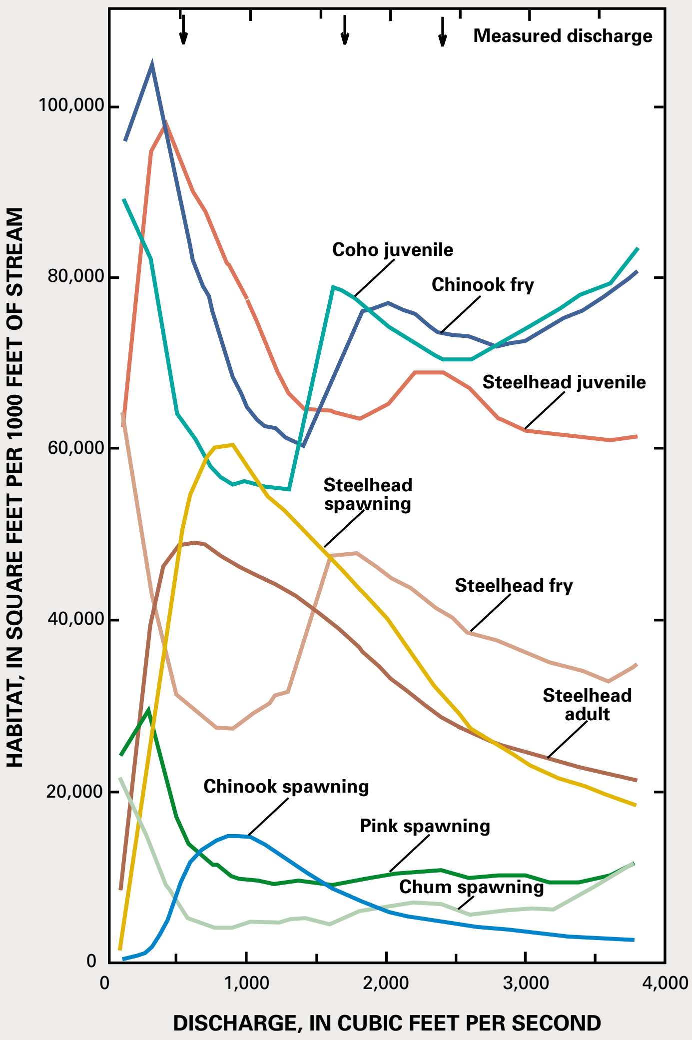
The Shenandoah River, Virginia, is dominated by riffle and run habitats. Studies are intended to evaluate how fish populations in these habitats would be affected by decreases in streamflow.



Depth, velocity, and bed-material data are collected along transects on the Shenandoah River to calibrate the hydraulic part of the Physical HABitat SIMulation (PHABSIM) model. Photographs courtesy of D.C. Hayes, U.S. Geological Survey.

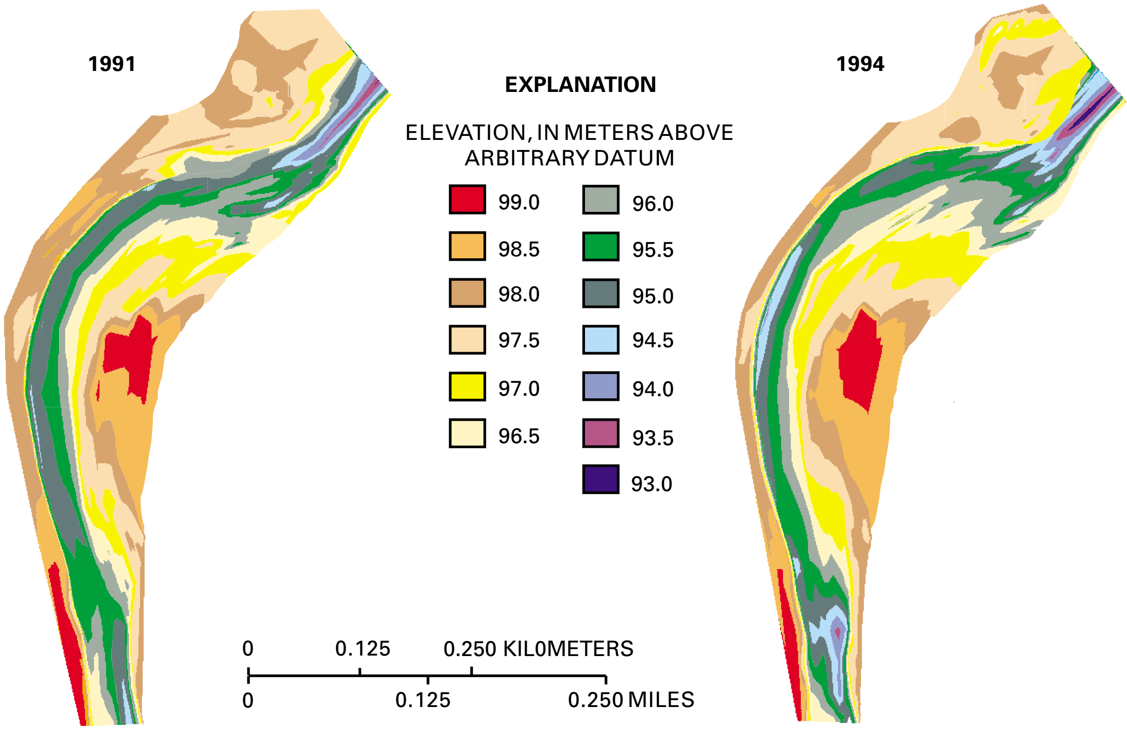
Similar studies have been carried out by the USGS in cooperation with the Stillaquamish Indian Tribe, Pierre County Department of Public Works, and the State of Washington Department of Ecology in the Pacific Northwest, where maintaining flows for salmonid habitats is of great concern (Embrey, 1987; 1991). These studies underscore the point that different flows are necessary at different times of the year to optimize habitat for particular species and life stages. For example, on the South Fork Stillaguamish River, Washington, optimization of discharge for spawning of Steelhead would require discharges that would minimize available habitat for Steelhead fry.





For more information refer to Bovee (1982), Embrey (1987, 1991), Leclerc and others (1995), Zappia and Hayes (1998), and Williams (1996) or contact District Chief, U.S. Geological Survey, 3600 West Broad Street, Richmond, VA 23230.

Results from instream flow modeling in Washington State show the availability of habitat for a variety of fish species and life stages as a function of discharge. On the South Fork Stillaguamish River, flows that optimize habitat for some life stages and species provide minimal habitat for other life stages and species. On regulated rivers, managers can use this type of information to design complex seasonal release patterns to optimize benefits to all species.



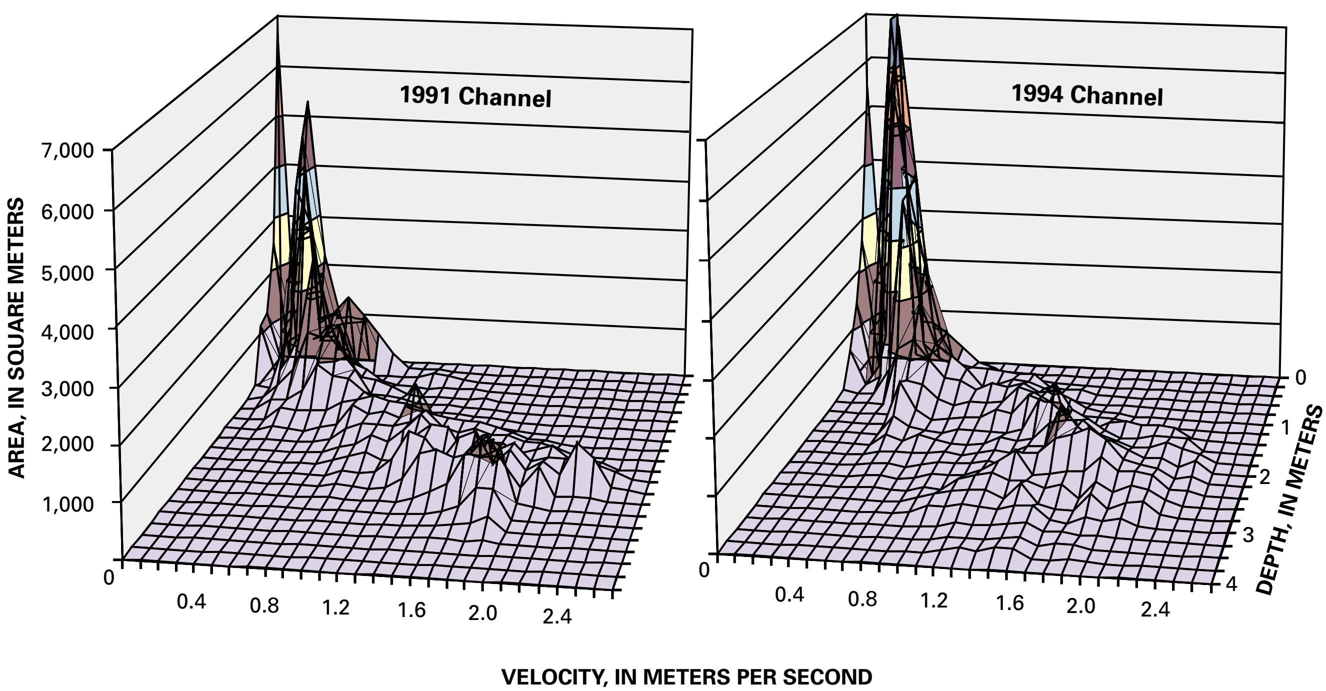


Figure 20. Example of using a two-dimensional hydraulic model to determine areal distributions of velocity and depth pairs for an entire reach, same bankfull discharge, for two different channel configurations. This example is from a small stream (about 700 square-kilometers drainage area) in the Missouri Ozarks. Between the 1993 topographic survey and the 1994 topographic survey, the channel was subjected to about a 50-year recurrence-interval flood. The maps show the topographic mesh and the graphs (bottom) show modeled areal distributions of depth and velocity for the two cases. The 1994 channel shows greater hydraulic diversity as indicated by the spread of depth and velocity distribution.

spatial and temporal distribution of the spawning macrohabitat patch rather than on predictions of fish populations (Bovee and others, 1997). This approach avoids difficult considerations of biotic responses while adding the ability to explicitly analyze the spatial organization of macrohabitat patches within a reach.

Hydraulic habitat simulation models commonly assume that the channel bed and banks are stable during the time interval of interest. This assumption frequently is violated in channels with sand-size and smaller bed material in which bedload transport can change channel morphology substantially during an individual flood. Recent developments of models that incorporate sediment erosion and transport and bank erosion promise to increase understanding of habitat stability and change in dynamic channels. Wiele and others (1996) presented such a model to investigate changes in channel morphology resulting from the design flood on the Colorado River. This model included sediment transport and deposition and demonstrated that computational models could predict channel changes at a scale applicable to fish habitat.

LAND-USE CHANGES AND THE PHYSICAL HABITAT OF STREAMS

Physical stream habitat is defined by the water temperature, turbidity, depth, velocity, bed material, and cover in which stream organisms live. Stream habitat is thought to be a first-order determinant of stream ecosystem structure and functioning because it defines the physical spaces within which organisms use stream resources. Resource partitioning theories and empirical studies of distributions of stream organisms among habitats support the importance of physical habitat in determining ecosystem structure. Water-column chemical characteristics can have an equal or greater effect on stream ecosystems by defining a chemical habitat, depending on chemical concentrations and constituents. Physical habitat changes can affect ecosystems either independent of water-column effects or in concert with them. Hence, physical stream habitat should be evaluated to determine the cause-and-effect links between suspected environmental stressors and biological characteristics. In general, physical-habitat changes are more persistent and more pervasive than chemical-habitat changes. Together, physical and chemical habitats define the template of which within potential biotic interactions—such as predation and competition—act to determine details of ecosystem structure.

Many land-use changes have the potential to alter stream channels and physical stream habitat by changing rates and mechanisms of channel-forming processes. The realization of potential depends on the magnitude and characteristics of the land-use change, where it occurs on the landscape, and, in many cases, the history and subsequent sequence of climatic and land-use events. Determination of whether a change has occurred or is occurring can itself be problematic because of the spatial and temporal variability within fluvial systems. To identify habitat disturbance due to land-use changes requires quantifying the natural variability of streams in dynamic equilibrium so conditions of nonequilibrium (disturbance) can be identified.

The fluvial systems within which land-use changes are transmitted to stream habitats can respond to disturbances with lags, thresholds, and cumulative responses. As a result, disturbances may affect sites far removed from where they originated and, at times, long after they occurred. Discerning the links between land-use changes and stream habitats is easier for direct disturbances in the riparian zone than for diffuse land-use changes throughout a drainage basin. The "complex response" of fluvial systems presents a challenge to predictive models.

Within the spatial and temporal variability of these factors, valid generalizations of how land-use changes will affect stream habitats can be difficult to make. As stated by Leopold (1994): "The river responds to physics, but there remains much latitude in the morphology that a channel may assume." There is even greater latitude when considering channel characteristics at the macrohabitat scale. In many cases, unique combinations of land-use change, climate, geology, or biological interactions will result in unique metamorphosis of the channel and associated habitats.

Land-use changes generally can be placed into two categories: those that affect uplands and those that affect the channel or riparian zone directly (table 1). Upland land-use practices can be further categorized into those that affect runoff characteristics (quantity and timing) and those that affect sediment yield. Runoff and sediment yield are not independent, yet they often change at different rates depending on the type of land-use change. It is, therefore, useful to consider the effects separately.

The response of channel reaches to land-use changes in the uplands can be conditioned by lags, thresholds, and cumulative effects. The slow and episodic routing of sediment from upland disturbances can cause channel and habitat changes in a downstream reach at a time far after the initial disturbance. Internal thresholds can result in nonlinear responses when the threshold is overcome. Wave-like movement of sediment in drainage networks can result in downstream increases in channel and habitat instability.

Unlike the complexities inherent with routing runoff and sediment from upland disturbances, those disturbances that occur in or adjacent to the channel are more easily associated with physical habitat responses. In many cases, however, land-use changes in the riparian zone occur at the same time as changes in the uplands. In these cases, a primary consideration may be to determine the relative magnitude of the effects so monitoring or policy can be most effectively applied.

Changes in the riparian zone that affect physical stream habitat can be classified into four general types (table 1): those that alter discharge and sediment yield at points in the stream network (usually dams, diversions, or outfalls); those that alter channel slope or cross-sectional morphology directly; those that alter hydraulic flow resistance; and those that alter erosional resistance of the bed or banks.

For any particular riparian land-use change, one or more of these types might apply. For example, common stream channelization practices involve simultaneous decreases in flow resistance provided by riparian vegetation, decreases in bank erosional resistance, and direct changes in channel slope and cross-sectional morphology. Responses from one riparian land-use change may also progress from one type to another. For example, an instream gravel-mining operation may only take gravel from the bed of a stream, thereby increasing local slope and initiating channel degradation. Channel degradation, however, may oversteepen banks, resulting in bank instability and decreased flow and erosional resistance.

Diagnosis of the links between land use and habitat change can require multifaceted, multiscale, and multidisciplinary approaches. In some cases, simple hydrologic and nonpoint-source sediment models can provide insight sufficient to determine if particular land-use changes have the potential to substantially alter runoff and sediment yield. However, computational models do not typically include time frames and realistic representations of sediment routing or channel-scale processes necessary to determine the effects on stream habitats. Improved understanding of the links between land-use changes and stream habitats likely will require a combination of historical, associative, process-scale, and modeling approaches.

Table 1. Typical channel habitat responses to changes in land use in upland and riparian areas

[LWD, large woody debris. Channel and habitat responses are typical and assume that only one factor has changed. In reality, most fluvial systems will be characterized by simultaneous changes of two or more factors, thereby complicating prediction of responses. Riparian areas encompass the land in and adjacent to the stream channel. Land uses in the riparian areas include direct effects on the channel (such as impoundments and channelization) and on the adjacent bars, banks, and flood plain. Embeddedness is a measure of the extent to which the interstices of bed material are filled with finer sediment.]

<table>
<tr><th>Location</th><th>Factor</th><th>Typical land-use examples</th><th>Typical effects on channel and habitat</th><th>Complications and interactions</th></tr>
<tr><td rowspan="4">Upland areas</td><td>Runoff increase</td><td>Urbanization, agriculture, or forestry practices can increase annual runoff volume and/or peak discharge.</td><td>Increase in channel cross sectional area, flood disturbance, LWD recruitment, and connections with flood plain; decrease in drought disturbance, embeddedness, cover, and LWD retention; width-to-depth ratio changes dependent on particle sizes of bedload, bed, and banks.</td><td rowspan="2">Interactions with sediment load are critical to morphology changes. Cumulative effects downstream affected as well by contributions of other land uses, channel network effects on flow routing, and riparian effects on flow routing.</td></tr>
<tr><td>Runoff decrease</td><td>Fire suppression, exotic vegetation encroachment, and detention ponds can decrease annual runoff by increasing evapotranspiration and infiltration, perhaps decreasing peak discharge.</td><td>Decrease in channel cross sectional area, flood disturbance, LWD recruitment, and connections with flood plain; increase in drought disturbance, embeddedness, cover, and LWD retention; width-to-depth ratio changes dependent on particle sizes of bedload, bed, and banks.</td></tr>
<tr><td>Sediment yield increase</td><td>Urbanization, agriculture, forestry, or mining can increase soil erosion and sediment yield above natural levels.</td><td>Decrease in channel cross sectional area; increase in sedimentation disturbance, embeddedness, cover, LWD retention, and connections with flood plain; width-to-depth ratio changes dependent on particle sizes of sediment load, bed, and banks.</td><td rowspan="2">Sediment does not route immediately to streams. Storage and lagged remobilization may complicate channel and habitat response. Sediment routed through channel networks may increase in volume or diminish downstream. Sediment yield changes may interact with changes in runoff to determine channel and habitat responses. Increased sediment yield may trigger channel instability.</td></tr>
<tr><td>Sediment yield decrease</td><td>Fire suppression, exotic vegetation, or small impoundments that trap sediment can result in sediment yield that is less than that of natural landscape.</td><td>Increase in channel cross sectional area; decrease in sedimentation disturbance, embeddedness, cover, LWD retention, and connections with flood plain; width-to-depth ratio changes dependent on particle sizes of sediment load, bed, and banks.</td></tr>
</table>

Table 1 continues on the next page.

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Location	Factor	Typical land-use examples	Typical effects on channel and habitat	Complications and interactions
Riparian areas	Discharge increase	Augmentation from diverted flow from other basins or irrigation return flow can increase mean annual runoff; seasonal timing is likely to differ from natural condition; discharge timing changed.	Increase in channel cross-sectional area, flood disturbance, LWD recruitment, connections with flood plain. Decrease in drought disturbance, embeddedness, cover, LWD retention. Width-to-depth ratio changes dependent on particle size of bedload, bed, and banks.	Sediment loads downstream of dams are typically diminished, and those contributed by augmented discharge are likely to be low; therefore, sediment deficits will tend to me more sever than case of increased runoff alone. Interactions with sediment load are critical to morphology changes. Cumulative downstream effects influenced as well by contributions of other land uses, channel network effects on flow routing, and riparian effects on flow routing.
	Discharge decrease	Diversions, irrigation, reservoirs, and encroachment of phreatophyte vegetation can decrease mean annual discharge; seasonal timing is likely to differ from that of natural condition, see discharge timing change below.	Decrease in channel cross sectional area, flood disturbance, LWD recruitment, and connections with flood plain; increase in drought disturbance, embeddedness, cover, LWD retention; width-to-depth ratio changes dependent on particle sizes of bedload, bed, and bank.	
	Discharge timing change	Diversion, irrigation, and reservoirs typically change seasonal patterns of discharge, increase base flow, and decrease peak flow.	Same as above, plus alterations of seasonal availability of habitats.	Effects of prolonged base flows below bed-sediment-transport thresholds on channel morphology are uncertain. Effects of peaking releases on channel habitats are poorly quantified.
	Sediment yield increase	Instream aggregate mining, urbanization, agriculture, or forestry practices in the riparian zone can increase sediment yields directly to stream reaches.	Decrease in channel cross sectional area; increase in sedimentation disturbance, embeddedness, cover, LWD retention, and connections with flood plain; width-to-depth ratio changes dependent on particle sizes of sediment load, bed, and banks.	Sediment routes immediately to adjacent, downstream segments. Additional downstream routing must account for storage and lags. Sediment routed through channel networks may increase in volume or diminish downstream. Sediment increases may interact with changes in runoff to determine channel and habitat responses. Fine sediment additions during low flow have greater effect on substrate conditions than the same sediment yield during natural floods.
	Sediment yield decrease	Reservoirs, dredging, and instream aggregate mining (coarse sediment) can reduce sediment load of the river.	Increase in channel cross sectional area; decrease in sedimentation disturbance, embeddedness, cover, LWD retention, connections with flood plain. Width-to-depth ratio changes dependent on particle sizes of sediment load, bed, and banks.	Decrease in sediment load is transmitted directly to the channel. Bed degradation due to decreased sediment load may extend both upstream and downstream from the site of disturbance. Decreases in sediment load often are associated with decreases in peak flows due to reservoir regulation leading to complex channel and habitat responses.

Table 1 continues on the next page.

Table 1. Typical channel habitat responses to changes in land use in upland and riparian areas

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Location	Factor	Typical land-use examples	Typical effects on channel and habitat	Complications and interactions
Riparian areas	Slope increase	Channelization and instream aggregate mining can increase local channel slopes.	Channel incision leads to bank and bed instability; straightened reaches recover by increasing sinuosity. Increase in channel cross sectional area; decrease in sedimentation disturbance, embeddedness, cover, LWD retention, connections with flood plain; initial decrease in width-to-depth ratio, but ultimate changes dependent on particle sizes of sediment load, bed, and banks.	Response to channelization and instream mining can extend up and downstream. Bank erosion processes are instrumental in determining rates and processes of recovery.
	Cross-sectional area increase	Channelization and instream aggregate mining can increase channel cross-sectional areas by direct excavation.	Initial disturbance determines channel morphology, decreases LWD retention, and can have variable effects on bed material.	Responses to direct channel change and recovery may be rapid and interrelated with slope and hydraulic resistance.
	Cross-sectional area decrease	Levees and navigation structures can decrease floodway and channel cross-sectional area.	Decrease in channel cross section area, width-to-depth ratio, LWD retention, connection to flood plain, cover, embeddedness, and sedimentation disturbance; generally decrease in hydraulic diversity.	Decreased channel migration tends to decrease lateral disturbance, whereas greater depths increase basal shear stresses and bed disturbance. Decreased diversity of main channel may be compensated by new, but different, habitats associated with structures.
	Flow resistance increase	Vegetation encroachment on the channel can increase flow resistance.	Decrease in channel cross sectional area, embeddedness, width-to-depth ratio. Increase in depth, sedimentation disturbance on margins, cover, LWD retention, connections with flood plain.	Vegetation interactions with flow depend on stem density, cross-sectional area presented to flow, where vegetation is in flow field, and extent to which it bends. Vegetation effects also vary with community age and structure. May decrease disturbance associated with channel migration.
	Flow resistance decrease	Bank revetments, channelized streams, and clearing of riparian areas for agriculture or forestry can decrease hydraulic flow resistance in channel and flood plain.	Increase in channel cross sectional area, width-to-depth ratio, embeddedness, disturbance; decrease in cover, LWD retention.	Decrease in flow resistance can be permanent (for example, concrete channel bed and banks) or temporary (from clearing LWD). Temporary changes will involve transient responses as channel and riparian vegetation adjust.
	Erosion resistance increase	Revetments and vegetation encroachment can increase the strength of banks and bed to resist erosion.	If banks are strengthened, but bed is not, then depth will increase in and width-to-depth ratio will decrease; if bed is strengthened but banks are not (for example, grade-control structures), then opposite is likely; decrease in disturbance from channel migration, embeddedness, and LWD loading. Increase in bed-scour disturbance, and cover.	Erosional resistance interacts with flow resistance and channel morphology. Bank stabilization measures to increase erosion resistance in one reach can result in lowered flow resistance and consequent transmission of energy downstream.
	Erosion resistance decrease	Urbanization, agriculture, and forestry can decrease erosional resistance of bed and banks.	Increase in width, width-to-depth ratio, disturbance, and LWD loading. Decrease in cover.	Decreases in bank erosion resistance are subject to thresholds as banks go from convex to concave upward. Steep and high banks have minimal strength contributed by vegetation.

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