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A Multiscale Conceptual Framework for Integrated Ecogeomorphological Research to Support Stream Naturalization in the Agricultural Midwest

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ABSTRACT / The complexity of fluvial systems necessitates interdisciplinary research in fluvial geomorphology and aquatic ecology to develop a fundamental understanding of interconnections among biotic and abiotic aspects of these systems. Integrated knowledge of this type is vital for environmental management of streams in human-dominated environments. A conceptual framework is presented for integrating geomorphological and ecological research on streams in East Central Illinois, USA, a glaciated low-relief agricultural landscape. The framework embodies a multiscale perspective in which a geomorphological conception of the fluvial system is used to define a hierarchy of characteristic spatial scales for exploring important linkages between stream geomorphology and aquatic ecology. The focus ecologically is on fish, because a rich body of historical information exists on fisheries in East Central Illinois and because past work has suggested that availability of physical habitat is a major factor influencing the community characteristics of fish in this human-altered environment. The hierarchy embodied in the framework includes the network, link, planform, bar unit, bar element, and bedform/grain scales. Background knowledge from past research is drawn upon to identify potential linkages between geomorphological and ecological conditions at each of these scales.

The conceptual framework is useful for guiding integrated ecogeomorphological research at specific scales and across different scales. It also is helpful for illustrating how widespread human modification of streams has catastrophically altered the scalar structure of fluvial systems in East Central Illinois. Knowledge emerging from the integrated research provides a basis for environmental-management schemes directed toward stream naturalization.

An emerging trend in environmental science and management is to link theory and methods in fluvial geomorphology and stream ecology to gain a holistic understanding of rivers as integrated ecological and geomorphological (ecogeomorphological) systems (Statzner and others 1988, Heede and Rinne 1990, Fisher 1997). A primary aim of this approach is to define linkages between geomorphological conditions and aquatic ecosystems via the influence of fluvial processes and forms on physical habitat. Although habitat can be defined by physical, chemical and biological characteristics (Odum 1971), an ecogeomorphological perspective emphasizes physical factors that produce habitat or constrain habitat quality.

Ecologists recognize that stream geomorphology is an important factor governing habitat and species diversity in streams (Schlosser 1982, Frissell and others 1986, Osborne and Wiley 1992, Fisher 1997, Kemp and others 1999). Spatial variation in channel form produces variability in mean velocity, flow depth and substrate characteristics, which, in turn, influence the spatial structure of physical habitat and the composition of aquatic communities (Southwood 1977, Frissell and others 1986, Gelwick 1990, Osborne and Wiley 1992, Aadland 1993, Fisher 1997). In fluvial systems modified and controlled by humans, the lack of spatial diversity in geomorphological conditions may be *the* most critical habitat attribute constraining biological diversity (TerHaar and Herricks 1989, Angermeier and Schlosser 1989, Illinois Department of Energy and Natural Resources 1994, Herricks 1996).

Geomorphologists view streams as dynamic systems in which causal interrelations among fluvial forms and processes vary according to the scale of analysis (e.g., Schumm and Lichty 1965). The geomorphological per-

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spective on fluvial dynamics spans an enormous continuum of spatial and temporal scales, ranging from the evolution of regional landscapes over millions of years (e.g., Young and McDougall 1993) to the shaping of microscale streambed topography by hydraulic processes over a few seconds (e.g., Robert 1993). Views informed by the multiscale geomorphological perspective are emerging in stream ecology (Minshall 1988) and finding application in watershed-based approaches to stream management (Kondolf and Downs 1996). However, integration of ecological and geomorphological perspectives within a conceptual framework that acknowledges the multiscale abiotic and biotic structure of stream systems and the relevance of this structure for management is an intellectual challenge that has yet to be adequately met.

Previous conceptual schemes have adopted a hierarchical perspective on spatial scale to define functional and structural relationships in aquatic ecosystems (Bisson and others 1982, Frissell and others 1986, Hawkins and others 1993, Fisher 1997), but these conceptualizations have incorporated mainly ecological, rather than geomorphological characterizations of the physical environment of streams. Ecological characterizations of physical habitat tend to neglect stream dynamics (Jowett 1988, Poole and others 1997), which are an essential element of the geomorphic perspective (Knighton 1998). Stream dynamics depend not only on general physical principles, but also on contingent geological, topographical, and hydrological attributes of particular landscapes (e.g., Rhoads and Thorn 1996). Thus, attempts to reduce the complexity of stream adjustments to a simple universal conceptual scheme (e.g., Rosgen 1994) are fraught with difficulties (Miller and Ritter 1996). A real danger of such schemes is that they may be completely inappropriate for certain fluvial environments, especially those that differ greatly from the environments that serve as the empirical foundation for the scheme. Application of a "universal" scheme in an inappropriate environmental management context may have ruinous practical consequences in terms of cost, damage, and risk of project failure.

This paper presents a conceptual framework that links stream ecology and fluvial geomorphology over a hierarchy of scales for watersheds in East Central Illinois—a low-relief landscape in the agricultural Midwest in the United States. In contrast to past schemes, the framework developed here starts with a geomorphological perspective on the hierarchical structure of a stream system and then identifies critical linkages with an ecological perspective over the scale hierarchy. The ecological focus of the scheme is on fish, because most environmental management initiatives in this region are directed toward fish resources (Rhoads and Herricks 1996) and over 100 years of comparable, spatially distributed data are available on the composition of the fish community (Forbes and Richardson 1908, Thompson and Hunt 1930, Larimore and Smith 1963, Osborne and others 1991, TerHaar and Herricks 1989, Illinois Department of Energy and Natural Resources 1994, Hauser 1999). Moreover, the availability of physical habitat, especially in human-modified streams, is a fundamental factor influencing fish diversity in aquatic ecosystems of East Central Illinois (Schlosser 1982, TerHaar and Herricks 1989). Through specification of critical linkages among geomorphological conditions, physical habitat and fish-community structure and dynamics, the framework serves as a guide for multiscale ecogeomorphological analysis to support emerging efforts to "naturalize" streams in East Central Illinois (Rhoads and Herricks 1996, Rhoads and Monahan 1997, Rhoads and others 1999). It also provides insight into how agricultural development has destroyed certain linkages, thereby catastrophically altering the ecogeomorphological structure of stream systems in this part of the United States.

Regional Context for the Conceptual Framework

The low-relief landscape of East Central Illinois (Figure 1) is predominantly a product of late Pleistocene glaciation (Hansel and Johnson 1992). Maximum relief in the region is only 15–30 m over distances of 1–5 km. The surficial geology consists of unconsolidated glacial or fluvioglacial deposits (Willman and Frye 1970) overlain by 0.5–2 m of loess (Fehrenbacher and others 1986). Thus, spatial variation in resistance to fluvial erosion is minor compared to that which exists in mountainous uplands with complex spatial patterns of rock type and structure. East Central Illinois is drained mainly by seven low-energy river systems (Figure 1). Channel gradients of the steepest streams are on the order of 0.001–0.0001 m/m.

Initial European settlement of the region started in about 1820, and by the end of the 19th century the landscape had been radically transformed by agriculture (Urban 2000). Recent estimates suggest that the extent of prairie in East Central Illinois prior to European settlement probably exceeded 2.2 million ha. Today, less than 0.005% of that prairie remains and expansive tracts of farmland dominate the landscape (Illinois Department of Energy and Natural Resources 1994).

After removing the prairie, farmers soon discovered that the low-relief landscape was too poorly drained to

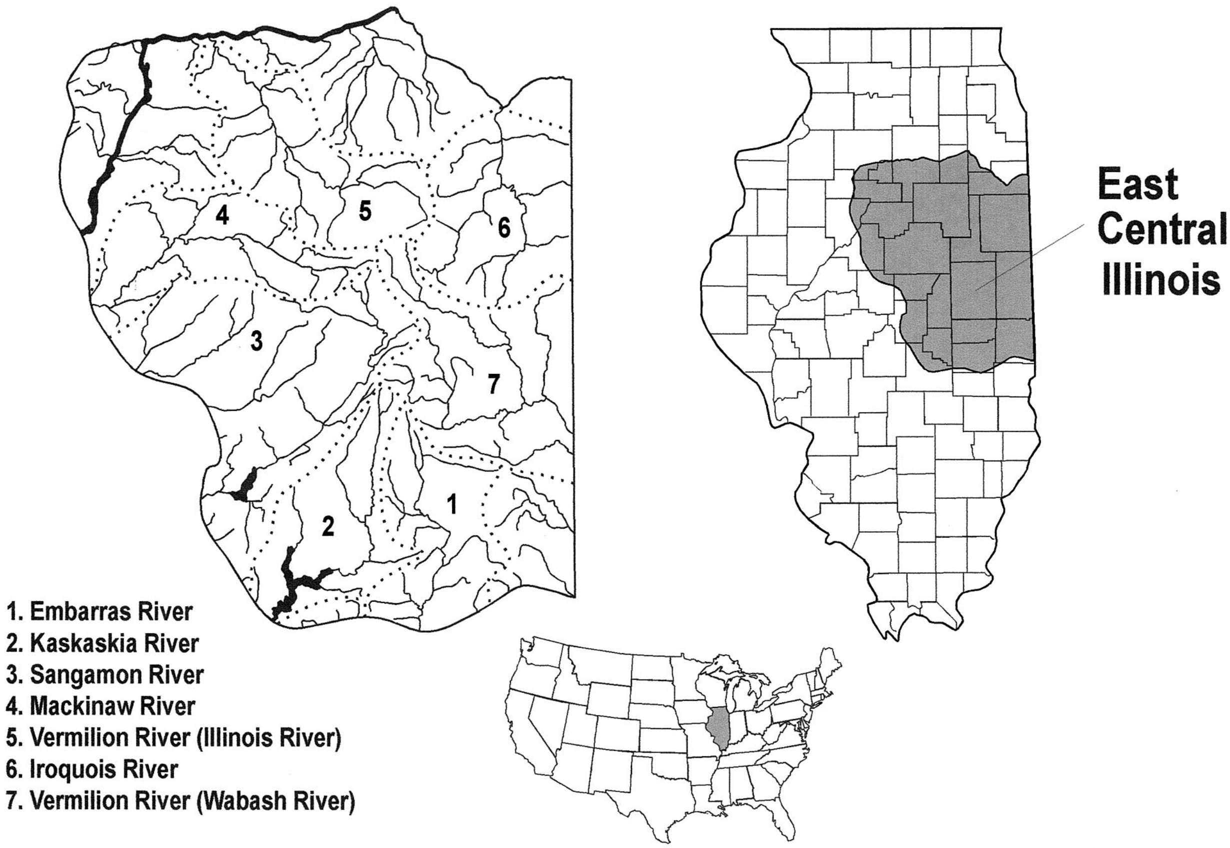

Figure 1. East Central Illinois and major drainage basins in this region (dashed lines indicate boundaries of drainage basins).

consistently grow crops. To overcome this problem, widespread land drainage took place in East Central Illinois during the late 1800s and early 1900s (Rhoads and Herricks 1996). Part of this land drainage involved channelization or "ditching" of streams to provide enhanced capacity for field drainage in headwater areas of the watersheds. Most headwater streams now exist in a channelized state, either as additions to the preexisting network or as highly modified remnants of prairie streams.

Conceptual Framework

At the most basic level, a fluvial system can be viewed from a geomorphological perspective as the product of the dynamic interaction between inertial forces associated with flowing water and the resisting forces associated with earth materials. Over time, this dynamic interaction continuously shapes the three-dimensional properties of watersheds, stream networks, and stream channels. The geomorphological structure of the system at any particular time can be associated with characteristic spatial scales, which in turn have definable linkages with ecological properties (Table 1). As the focus of analysis shifts upward through the spatial hierarchy, the time scale of dynamic change in relevant geomorphological and ecological properties generally increases (Table 1).

Network Scale

The most characteristic property of fluvial systems at the scale of an entire watershed is the arrangement of streams in networks. The structure of drainage networks is hierarchical (Abrahams 1984), consisting of links, which can be defined by order (Strahler 1952) or magnitude (Shreve 1966), and nodes, which are confluences of conjoining links. Over the long-term, interactions among hillslope processes, the channel network, basin hydrology, and sediment yield can lead to changes in network structure (Kirkby 1993), but for most fluvial systems, such changes occur over time spans of centuries, millennia, or longer (Schumm and Lichty 1965). Over the time scale of watershed management, the structure of the drainage network is relatively

Table 1. Scale-based classification of relations between geomorphological and ecological structure of a stream system

Scale	Geomorphological view	Ecological view
Network	Links and nodes	Species composition of network/watershed
	Influence of network structure on hydrological response	
	Hydraulic geometry relations	River Continuum Concept
	Downstream trends in sediment characteristics	
	Downstream trends in stream power along discrete sediment-transport pathways	Influence of network structure on spatial variation in community composition
Link	Uniform hydrology, sedimentology, and average channel size, but planform may vary	Functional and structural uniformity of internodal physical habitat or assemblage of planform habitat patches
Planform	Reaches with uniform planform characteristics	Planform habitat patches
Bar unit	Discrete bedform that scales with channel width; fundamental bed unit of planform development	Characteristic mosaic of bar element habitat patches; pool–riffle sequences, stream confluences
Bar element	Discrete sedimentological elements of bar units, e.g., pools, riffles, point bars	Bar element habitat patches or mosaic of microhabitat patches
Grain	Individual large grains, grain clusters, or bedforms	Microhabitat patches

constant and provides the physical framework within which directed flows of water and sediment operate to shape the geomorphological characteristics of stream channels (Rodriguez-Iturbe and Rinaldo 1997) and to define physical habitat (Vannote and others 1980, Imhof and others 1996, Poff and others 1997) while integrating effects from the watershed (Naiman and others 1988, Ward 1989).

The down-network movement of water and sediment in response to gradients of gravitational energy leads to absolute increases in mass flux that, in turn, produce systematic changes in stream-channel geometry (Leopold and Maddock 1953, Rhoads 1992) and bed-material characteristics (Knighton 1980, 1987). Changes in channel geometry are especially pronounced at stream confluences where discharge increases abruptly, compared to the relatively constant average hydrologic and geometric conditions between confluences (i.e., within links) (Richards 1980). Recognition of such discontinuities has emphasized the importance of spatial variations in stream power and channel geometry along alternative stream pathways through drainage nets on sediment storage within watersheds (Lecce 1997).

The most prominent conceptualization of network-scale ecological processes in streams is the River Continuum Concept (RCC) (Vannote and others 1980). The RCC identifies systematic downstream trends in organic matter loading, transport, utilization, and storage; organism functional groupings and physical habitat change along a river continuum (Minshall and others 1983, 1985). Early work on the RCC emphasized a longitudinal continuum of channel morphology with narrow, high-gradient headwater streams flanked by well-developed riparian forests grading continuously into wide, low-gradient rivers flowing through open riparian environments (Vannote and others 1980, Minshall and others 1985). Factors such as climate, geology, stream geomorphology, and long-term human impacts on a network complicate this model of the continuum (Minshall and others 1985, Naiman and others 1988, Wiley and others 1989, Allen and Johnson 1997), but at the network scale the continuum scheme continues to influence stream ecology.

An important ecological issue at the network scale in East Central Illinois is the inversion of continuum elements (Wiley and others 1989). Prior to European settlement, wet prairie and scattered trees flanked headwater streams. Riparian forests did not occur until large-order channels provided moisture conditions that protected trees from prairie fires. In the present setting, the prairie has been eradicated by agriculture, croplands now extend to the margins of streams throughout the headwaters, and woody vegetation is regularly removed as a drainage management practice. Riparian forests now, as in the past, exist only along medium- and large-size rivers. The result is an aquatic ecosystem in which primary production is high in the headwaters and the ratio of respiration to production progressively increases downstream.

Of importance for fish communities is the recognition that channel morphology and resource availability are better predictors of species diversity and richness when used in conjunction with a measure of spatial position of a tributary within a network (Schlosser 1982, Osborne and Wiley 1992). Small channels in close proximity to the main channel generally have greater fish species richness than small channels that flow into streams of similar size in headwater portions of the drainage network (Osborne and Wiley 1992).

Community structure and function at the network scale will be associated with both transient and resident species in these networks. A wide range of habitats is needed to accommodate the time-specific requirements of these two types of species. Further, fish communities will be structured by upstream and downstream influences (Osborne and Wiley 1992). Finally, because fish are mobile, issues such as interannual flow variability, seasonal patterns of movement, refuge habitat, and other filters that affect the fish community are important at the network scale (Poff and others 1997).

Link Scale

The link scale is defined geomorphologically as a section of stream between two stream confluences (network nodes). Changes in discharge and channel characteristics within links usually are insignificant compared to changes in stream hydrology and channel characteristics at confluences (Richards 1980, Roy and Woldenberg 1986). If geologic conditions throughout the watershed are relatively uniform, as is the case in East Central Illinois, discharge, bed-material texture, and channel dimensions should fluctuate around stationary mean values within a link (Richards 1980, Rhoads 1987, Pizzuto 1995, Rice and Church 1998). Channel planform may or may not be constant within a link, depending on the sensitivity of the stream system to factors influencing planform development and on the environmental history of the link.

Ecological studies have not focused specifically on the link scale. Stream links, however, have the potential to act as filters for mobile stream organisms (Poff and others 1997) and provide a basis for evaluating ecological conditions within reaches of stream bounded at either end by abrupt changes in hydrologic and channel conditions (Jayjack 1993). A link that contains reaches with distinctly different planform characteristics can be considered an assemblage of planform habitat patches (Table 1). Alternatively, a link that has uniform planform characteristics may still have substantial variability in bed morphology and physical habitat (e.g., pool-riffle sequences within a uniformly meandering reach), producing bar-unit or bar-element scale habitat patches (Townsend 1989).

The hydrologic and sedimentological uniformity of some links suggests that ecological research at this scale may be valuable for isolating specific influences on fish community structure and dynamics. Two links with the same magnitude and watershed conditions, but with different geomorphological conditions (e.g., channelized versus unchannelized links) may have fundamentally different fish communities because of important differences in their assemblages of physical habitat. Alternatively, two links with comparable magnitudes and similar channel morphologies, but different watershed conditions also may have different population characteristics. A related effect is that link boundaries, specifically confluences, pose migration choices for fish, which can lead to spatial differences in link-scale community structure. For example, sampling of adjacent tributaries in East Central Illinois shows that the largest carp (*Cyprinus carpio*) populations are found in the tributary with the greatest turbidity (Jayjack 1993). In this case, differences in water-quality conditions for two links with similar channel morphologies influence the path of fish migration to local habitat.

Planform Scale

The planform scale is defined by channel segments in the stream system that have uniform planform characteristics (e.g., meandering versus braided or high sinuosity versus low sinuosity). The spatial extent of this scale category varies. The lower limit is the minimum length of channel required to distinguish distinct planform properties for a reach of stream. For meandering streams, such as those that develop in the absence of human intervention in East Central Illinois (Rhoads and Herricks 1996), this minimum length is generally about 10–14 channel widths, which corresponds roughly to the average wavelength of a complete meander (Leopold and Wolman 1957). Single-thread channels with little or no sinuosity over this minimum length can be classified as straight. The upper limit coincides with the length of stream over which channel planform characteristics remain consistent. In the extreme case where channel pattern is self-similar over the entire extent of the drainage network, the planform scale can converge on the network scale. If channel pattern is uniform over lengths greater than the average spacing of tributaries, the planform scale will exceed the link scale. In most cases, planform varies within links because of local heterogeneity in valley slope or channel materials (Ferguson and Ashworth 1991). The sensitivity of the stream system to local heterogeneity in environmental conditions will depend on its proximity to a threshold of planform change (Leopold and Wolman 1957, Knighton and Nanson 1993, Nanson and Knighton 1996) and on the overall capacity of the system to overwhelm the influence of local variability via internal hydrodynamic processes. Low-energy meandering stream systems, such as those in East Central Illinois, are especially susceptible to the

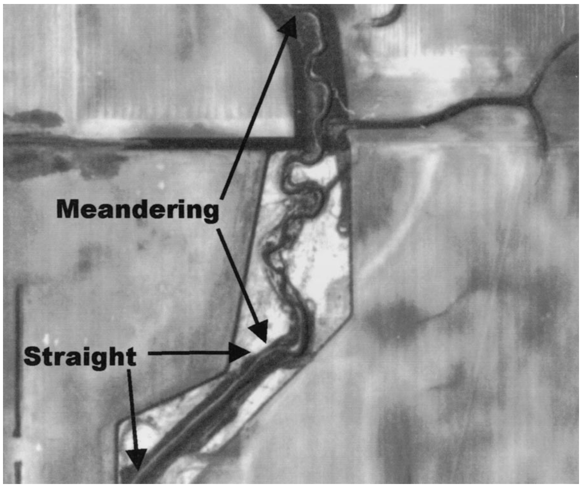

Figure 2. Aerial photograph illustrating change in channel planform from meandering to straight in the downstream direction along the Embarras River, Illinois. The straight section was channelized between 1975 and 1982, whereas the meandering section has not been channelized since 1936, the date of the earliest aerial photography of the river. The scene shows an area approximately 88 m × 970 m and north is toward the top of the photograph. From Illinois Department of Transportation photography IL-14-513, April 1998.

influence of local environmental heterogeneity, which induces irregular spatial patterns of channel sinuosity (Ferguson 1975).

Differences in the environmental history of various segments of a fluvial system also can produce substantial spatial variation in channel planform characteristics. This factor is especially prominent in East Central Illinois, where stream morphology has been strongly influenced by human modification. Prior to land drainage in the late 1800s, streams in this region had meandering planforms (Rhoads and Herricks 1996). Since that time river planform has been altered greatly by human action. This alteration has occurred in a piecemeal fashion over time but has affected virtually the entire length of every headwater stream in the region. Differences in planform properties, therefore, are defined mainly by abrupt changes in sinuosity that reflect differences in the timing of human intervention in specific reaches and variations in rates of postintervention recovery associated with local environmental heterogeneity (Rhoads and Herricks 1996, Rhoads and Urban 1997, Urban 2000) (Figure 2).

Ecologically, the planform scale segregates stream reaches into general habitat types, or patches, on the basis of discrete differences in channel pattern (Rosenfield 1997). In ecological and management research, differences in general habitat conditions and fish communities within different types of planform-scale habitats are often of considerable interest. For example, the effects that straightening a channel has on habitat diversity have been evaluated by comparing fish communities in modified straight channels versus unmodified meandering channels (Gorman and Karr 1978, Swales 1982, 1988, Cowx and others 1986, Frothingham and others 2001). In these studies, the physical unit of analysis is defined based on homogenous planform characteristics in each reach where ecological conditions are evaluated.

Bar Unit Scale

Most past work linking aquatic ecology and stream geomorphology has focused on pools and riffles, distinctive morphological elements of meandering streams. Recent empirical and theoretical studies in fluvial geomorphology define an emerging view of pools, riffles, and point bars that differs from classical notions about these features. This emerging view maintains that pools, riffles, and point bars are elements of a morphological structure known as a bar unit (Thompson 1986, Dietrich 1987). According to this perspective, the bar unit is the fundamental bed-morphological structure in a meandering stream, and particular bar elements (e.g., pools, riffles) change by necessity as the bar unit evolves.

The initial development of bar units is an important process in the initiation of river meandering in channels that have been artificially straightened (Rhoads and Welford 1991). A bar unit in a straight channel has a fish-scale shape with a scour hole (pool) at the upstream end, an elevated portion (alternate or point bar) at the downstream end, and an intermediate-elevation middle (riffle) where flow moves laterally across the bar unit into the upstream end of the adjacent bar unit on the opposite side of the channel (Dietrich 1987) (Figure 3). These features, which migrate downstream, are believed to emanate from inherent dynamic instability of flow over a mobile bed (Parker 1976). Nonlinear interactions between the flow and the developing bar unit produce the characteristic three-dimensional shape (Columbini and others 1987).

As meanders develop, interaction among channel curvature, bed topography, and flow structure yields steady bar units that wrap around the bends in a systematic fashion (Seminara and Tubino 1989, Rhoads and Welford 1991, Garcia and Nino 1993) (Figure 3). The result is the characteristic bed morphology associated with meandering streams: pools along the outer banks of bends, point bars along the inner banks, and riffles near the inflexion points of curvature (Dietrich 1987). Bar units are hypothesized to play a critical role

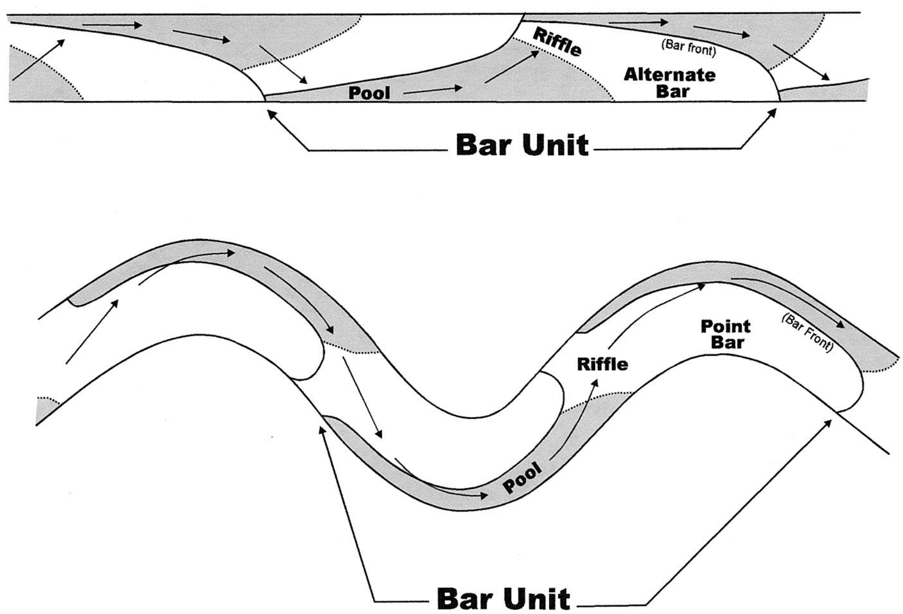

Figure 3. Plan view of bar units in straight (top) and meandering (bottom) channels. Shaded areas correspond to portions of the bed below the mean bed elevation. The highest elevation occurs at the portion of the bar unit corresponding to the alternate bar or point bar. Path of thalweg (thread of highest velocity) is indicated by arrows (after Dietrich 1987).

in meander dynamics with bed morphology and channel curvature interacting over time to produce complex nonlinear patterns of meander train evolution and adjustment (Furbish 1991, Howard 1992, Stolum 1998).

The emergence of the bar unit concept has greatly refined attempts to explain the origin of pools, riffles, and point bars in meandering streams—these bar elements now being viewed as essential components of the bar unit. Not all pool–riffle sequences, however, are highly three-dimensional in shape and the bar unit concept may not provide a universal explanation for the origin of systematic variations in bed morphology in natural streams. More research is needed to determine whether all pool–riffle sequences in straight or meandering rivers are associated with bar unit forms or whether these sequences can develop via other mechanisms. Some pools, such as those associated with woody debris (Montgomery and others 1995), are clearly shaped by processes other than the dynamic instability mechanism.

Although the bar unit concept has not been explicitly related to stream confluences, it provides a convenient analog for characterizing the geomorphology of confluences. At the bar unit scale, a stream confluence can be viewed as a dynamically integrated fluvial feature with a characteristic physical habitat and important connections to link- and network-scale ecology. The spatial boundaries of a confluence correspond to the confluence hydrodynamic zone (CHZ) (Kenworthy and Rhoads 1995), or region of flow in the tributaries and downstream channel affected by the complex patterns fluid motion and energy loss induced by turbulent mixing of two convergent streams. The structure of the CHZ varies over time within a confluence with changes in total discharge and momentum ratio of the conjoining flows and from confluence to confluence with variations in junction angle and planform symmetry (Mosley 1976, Best 1987, 1988). Distinctive mosaics of bar elements typify symmetrical and asymmetrical confluences (Figure 4). Each bar element corresponds to a specific hydrodynamic region within the confluence. These regions, and the associated bar elements, change dynamically in position and dimensions as the momentum ratio of the confluent flows varies over time (Rhoads 1996, Rhoads and Kenworthy 1995, 1998).

Few, if any, ecological studies have been conducted at the bar unit scale as defined in this paper. Because the focus has been on riffles and pools, most field investigations include two or more bar units and recognize only bar elements. A benefit of working at the bar unit scale ecologically is that a continuum of bar element habitat patches can be identified and related to species life-history requirements. Two concepts, habitat complementation and habitat supplementation, are particularly relevant for fish-community analysis at this scale (Schlosser 1995). Habitat complementation refers to the spatial juxtaposition of suitable habitat areas (e.g., feeding habitat, spawning habitat, refuge habitat) required by a certain species (Schlosser 1995). The closer different habitat elements are to one another, the more accessible they are to an organism that requires these different elements. Thus, distance between habitat elements is an important indicator of habitat quality. Habitat supplementation occurs when the suit-

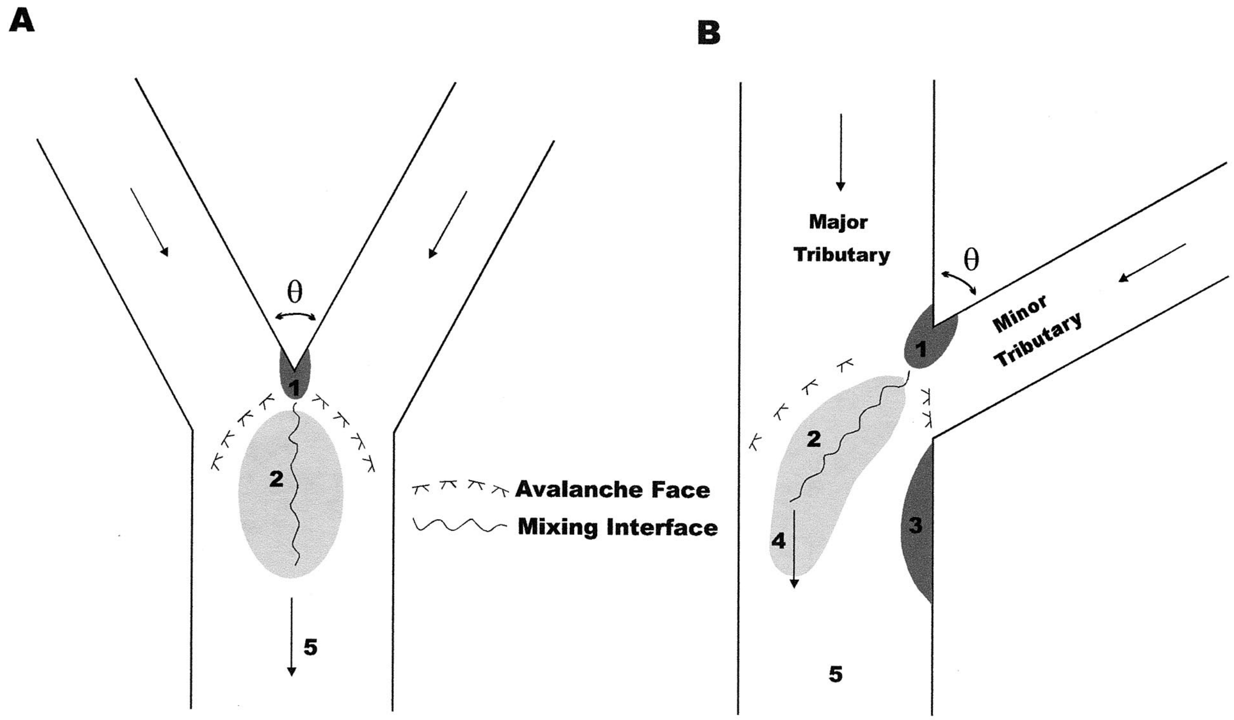

Figure 4. Characteristic assemblage of hydrodynamic/bar elements at symmetrical (A) and asymmetrical (B) confluences. Major elements include: (1) flow stagnation and stagnation-zone bar, (2) flow deflection and scour hole, (3) lateral flow separation and separation-zone bar, (4) maximum velocity and scour extension, and (5) zone of flow recovery and transverse bar (after Best 1987).

ability of a habitat element is increased because it fulfills multiple habitat requirements (Schlosser 1995); for example, a pool may serve as suitable habitat for a particular fish species both for feeding and for refuge.

Investigating habitat complementation and supplementation at the bar unit scale should prove interesting because this scale includes habitat elements, such as pools, riffles and point bars, that are suitable for different aquatic species at the same time as well as for particular species at different times. The bar unit scale also provides a framework for exploring habitat use by aquatic organisms within dynamically coherent geomorphological units of the stream system. Field studies of fish distributions within an asymmetrical stream confluence in East Central Illinois have shown how pronounced spatial segregation of different fish species over distances of only a few meters corresponds to the characteristic spatial mosaic of bar element habitats at this site (Hoglund 1991). Dynamic changes in the spatial structure of the habitat mosaic produce corresponding changes in the spatial distribution of fish species within the confluence (Jayjack 1993). Similar results have been obtained within a meandering section of the Embarras River, where spatially defined fish sampling within bar units has shown that species composition differs among habitat elements (pools and riffles) of the unit (Frothingham 2001, Schwartz and others 2001).

Bar Element Scale

Bar element research in geomorphology has focused on the dynamics of pools, riffles, and point bars. Geomorphological analysis has quantified the morphology, spacing, and sedimentology of pools and riffles (Leopold and others 1964, p. 203, Richards 1976, Keller and Melhorn 1978, Hirsch and Abrahams 1981, Bhowmik and Demissie 1982, Knighton 1982, 1983; Wohl and others 1993, Thompson and others 1996); investigated the influence of pools and riffles on energy dissipation (Yang 1971, Cherauer 1973) and patterns of sediment movement (Sear 1996); evaluated how pools and riffles develop and are maintained (Clifford and Richards 1992, Clifford 1993); and assessed the role of pools and riffles in meander development (Bhowmik and Demissie 1982, Clifford 1993, Sear 1996). Point bars, another important type of bar element, can have

Figure 5. Fine gravel armor layer at the head of a point bar in the Kaskaskia River, East Central Illinois. Numbers on tape are tenths of a meter.

a major influence on patterns of flow and sediment transport in meandering streams (Dietrich and Smith 1983, 1984). Changes in point-bar dynamics with changes in flow stage also may play an important role in meander dynamics by influencing the local pattern of meander migration and the evolution of the corresponding pool–riffle sequence (e.g., Anthony and Harvey 1991, Bartholdy and Kisling-Moller 1996).

The local hydrodynamic conditions that generate bar elements influence the size and degree of sorting of particles within and on the surface of these features. Armoring, or the development of a segregated layer of coarse grains at the bed surface (Gomez 1984), can occur over long stretches of gravel-bed rivers, but in the sandy streams of East Central Illinois fluvial armor is restricted spatially to bar elements or to portions of bar elements. These armor layers generally develop in zones of high shear stress either at low flow (e.g., riffles) or at high flow (e.g., the heads of point bars or the downstream end of pools) (Figure 5).

The bar element scale has been a primary focus for assessment and sampling in ecological research. Pools, riffles, and runs/glides typically are viewed as discretely occurring habitat types that fish utilize differently as life-history habitat requirements change. Most studies have failed to recognize that pools, riffles, and point bars can constitute bar-element habitat patches that are genetically connected to the bar unit and meet habitat needs as requirements for habitat change over time scales ranging from seconds or minutes (predatory pressures) to months or years (life-history requirements).

Research at the bar element scale has mainly compared pool versus riffle habitat patches (Bisson and others 1982, Angermeier and Schlosser 1989, Gelwick 1990, Lobb and Orth 1991, Aadland 1993, Gregory and others 1994, Freeman and others 1997, Poole and others 1997). Physical habitat at this scale typically is defined by geomorphological characteristics (mean depth, velocity, and substrate conditions) of bar element habitat units (e.g., Angermeier and Schlosser 1989, Gelwick 1990), but lacks a multidimensional context that adequately relates bar elements to dynamic habitat descriptions. Flow variability is an important factor in habitat dynamics at the bar element scale. Physical conditions in pools and riffles change with flow stage, and these changes can influence fish assemblages or benthic-community characteristics (Delucchi 1988, Aadland 1993, Rabeni and Jacobson 1993, Poff and Allan 1995, Poff and others 1997, Kemp and others 1999). Shallow pool and riffle habitat generally diminishes during high flow, while deep pools separated by shallow riffles are present at low flow. Thus, flow variability constrains habitat availability (Aadland 1993). This constraint, along with the variable habitat needs of the fish community, implies that habitat conditions are highly dynamic at the bar element scale.

The bar unit model indicates that many pool–riffle sequences have strongly three-dimensional shapes. The importance of this three-dimensionality is supported by measures of habitat volume in pools and riffles, which is generally a better predictor of species richness than area alone (Angermeier and Schlosser 1989). An increase in the complexity of the physical structure of a stream (i.e., habitat diversity) also typically results in an increase in species diversity, abundance, and biomass (Gorman and Karr 1978, Schlosser 1982, Gelwick 1990, Lobb and Orth 1991). The three-dimensionality of bar elements also has important management implications; currently, most artificial habitat structures designed to emulate pools and riffles are two-dimensional rather than three-dimensional (Carline and Klosiewski 1985, Shields and others 1995, Van Zyll De Jong and others 1997).

Bedform/Grain Scale

The bedform/grain scale corresponds to individual particles or particle assemblages that are the constituents of bar elements. The general character of material on the bed of a stream is a function both of the type of sediment supplied to it and the capacity of the stream to sort this material. Most streams in East Central Illinois have beds consisting of abundant sand and fine gravel. In streams of this type, individual particles tend to arrange themselves into coherent bedforms, such as ripples, dunes, plane beds, and antidunes, that vary with changes in mean velocity or stream power (Simons and Richardson 1966, Vanoni 1974). Sorting of the

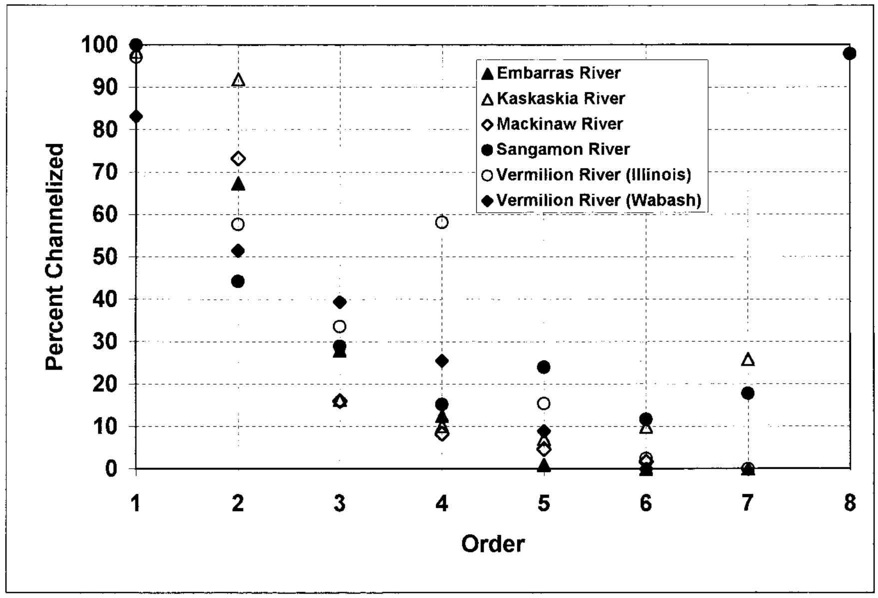

Figure 6. Percent of total stream length that has been channelized by stream order in major drainage basins of East Central Illinois (data from Mattingly and others 1993).

gravel fraction into armor layers occurs locally in zones of high bed shear stress at the scale of bar elements.

Ecological research at the bedform/grain scale has focused mainly on the extent to which particular substrate conditions provide habitat for benthic macroinvertebrates and spawning sites for fish. It also has examined how individual bedforms in sand-bed streams or large particles in gravel-bed streams create microhabitat patches. For the most part, fish are mobile and can easily move beyond the spatial scale of a single grain or small cluster of grains to seek alternative habitat at larger scales for feeding or refuge. The size of an individual fish commonly equals or exceeds the dimensions of individual grains or bedforms, but if individual particles are large relative to the size of fishes, these particles may serve as refugia from fast currents or predators. This concept underpins the management practice of introducing boulder clusters into streams with fine bed material to enhance fish habitat (Federal Interagency Stream Restoration Working Group 1998). Fluvial processes that sort substrate, such as armoring, produce bed material characteristics that are important for fish spawning. Spawning is a temporary use of habitat; nonetheless this habitat is critical for meeting life-history needs and sustaining viable fish populations.

Practical Utility of the Conceptual Framework

The conceptual framework provides an overarching construct to guide integrated ecogeomorphological analysis in human-impacted agricultural streams of East Central Illinois. The goal of the integrated analysis is to generate foundational knowledge for management schemes that sustain utilitarian goals of local people, but that also enhance environmental quality by working with, rather than against, the characteristic geomorphological and ecological processes of the stream system. The framework also is valuable for defining how human modification of stream systems in East Central Illinois has affected the scalar structure and function of these systems, including the effects of human action on geomorphological and biological diversity.

Human Impact on Scalar Properties of Fluvial Systems in East Central Illinois

Channelization of fluvial systems in East Central Illinois has affected the geomorphological and ecological characteristics of these systems over a hierarchy of scales. The greatest impact of channelization has been in the headwaters; virtually all first-order streams are straight trapezoidal ditches, and in most watersheds over 50% of the total length of second-order streams is channelized. In general, the extent of channelization decreases with stream order (Figure 6).

Channelization has simplified the cross-sectional geometry and planform of streams in East Central Illinois, resulting in decreased spatial variation in channel form and dynamics (Rhoads and Welford 1991, Rhoads and Urban 1997). It has destroyed bar units, producing smooth bed topography and uniform velocity and substrate conditions. The reduction in hydraulic friction associated with the removal of bar units, channel straightening, and the obliteration of other channel irregularities increases flow velocities and stream power, especially during large floods (Brookes 1988). During channelization, the channel cross section often is enlarged, enhancing the increase in stream power. In many stream systems throughout the United States, such increases in stream power result in a postchannelization response characterized by incision, widening, and eventual stabilization of a new stream within an incised, widened channel (Schumm and others 1984, Harvey and Watson 1986, Simon 1989, 1992, Hupp and Simon 1991, Hupp 1992). However, streams in East Central Illinois generally have low values of bankfull stream power (<15 W/m^2), even in the channelized state (Rhoads and Herricks 1996). Moreover, these streams have been artificially deepened to the extent that their beds lie in densely compacted glacial till that limits the vertical response of the streams to channelization. Under these conditions, postchannelization response is characterized by lateral processes, such as recovery of sinuosity via lateral migration of a straightened channel (e.g., Barnard and Melhorn 1982) or deposition within the modified channel and the development of a sinuous channel through the deposited material (e.g., Brookes 1988, Rhoads and Herricks 1996). Complete recovery of predisturbance sinuosity following straightening of channels in this region may take as long as several centuries (Barnard and Melhorn 1982). A recent study of stream planform change along the Embarras River demonstrated that none of the channelized reaches recovered the prechannelization planform over a 57-year period and that many channelized reaches exhibited no detectable change in planform following channel straightening (Rhoads and Urban 1997).

The effect of channelization has been most pronounced at the planform scale. Although Rhoads and Herricks (1996) identified nine different types of channels in East Central Illinois, ranging from straight trapezoidal streams that recently have been channelized to freely meandering streams that have regained sinuosity several decades after initial channelization, meandering streams can be considered a rare and endangered geomorphological species in this region. The prevailing attitude is to straighten, if possible, these "troublesome" meandering segments. Most existing geomorphological diversity consists of structure at the bar unit scale and lower that has developed within straight channels subsequent to channelization (Rhoads and Herricks 1996). Even in systems that recover geomorphologically to this extent, repeated maintenance for land drainage periodically eliminates the bar structures, thereby contributing to overall spatial homogenization of stream geomorphology.

From a geomorphological perspective, channelization of streams in East Central Illinois can be viewed as catastrophic in the sense that the spatial extent of channelization has been widespread and the amount and rate of change in channel form produced by channelization greatly exceeds the capacity of the system to reconfigure itself via natural erosional and depositional processes (e.g., Wolman and Gerson 1978, Urban 2000). Extensive channelization has decreased morphological and hydraulic diversity over vast portions of stream networks, thereby causing convergence of these fluvial systems toward a simple, uniform spatial structure. The majority of the streams have straight channels with flat uniform beds and homogenous sand and/or fine gravel substrates. Spatial variation in channel properties largely has been eliminated and these properties are uniform at a scale approaching the network level.

From a fisheries perspective, the effects of channelization and other changes in the stream network have been mixed. Channelization typically decreases spatial variation in channel morphology and sediment properties, resulting in decreased habitat diversity for macroinvertebrates and fish (Naiman and others 1988, Swales 1988, Poff and others 1997, Kemp and others 1999). The removal of streamside vegetation that accompanies channelization reduces shading, thereby increasing diurnal temperature variations, eliminating cover for fish, and decreasing organic inputs. Long-term fish sampling in East Central Illinois indicates that a number of species have been extirpated by channelization and other human impacts (e.g., reservoir construction) (Illinois Department of Energy and Natural Resources 1994). It is also clear that fish species diversity and abundance have increased in headwater reaches after channelization. This finding may seem contradictory, but historical records suggest that ditching for land drainage has extended channel networks into previously unchanneled portions of the landscape, thereby producing new habitat (Rhoads and Herricks 1996). The construction of reservoirs also has increased fisheries potential. Major movements of fish during suitable flow conditions (Jayjack 1994, Schwartz and others 2001) has led to an overall increase in the species richness of fish communities in highly modified headwater stream channels (Chambers 1994, Hauser 1999). Although diversity has increased, habitat is still limiting to fish communities in these channelized streams (Tompkins 1998). Where high-quality habitat is available (e.g., the juxtaposition of supplementation and complementation habitats), fish communities are the most diverse and stable (Hauser 1999, Frothingham and others 2001, Schwartz and others 2001).

Integrated Ecogeomorphological Research and Stream Naturalization

In East Central Illinois, an emerging grass-roots interest in the environmental quality of watersheds is taking hold after decades of land drainage and stream channelization (Rhoads and others 1999). Despite this interest, local people recognize that intensive use of the land for agricultural production proscribes complete restoration, i.e., a return to predisturbance conditions (National Research Council 1992). Instead, communities are seeking to "naturalize" channelized streams by preserving or enhancing hydraulic, morphological, and ecological diversity (Rhoads and Herricks 1996). Stream naturalization uses the modified state of the system (straight, trapezoidal channels with flat, uniform beds) as the reference state for management and attempts to devise innovative management strategies that move the system away from this homogenous condition toward alternative configurations with greater geomorphological heterogeneity (Rhoads and others 1999). It also recognizes that in human-dominated landscapes, human intervention has become a "natural" process that must be accounted for in environmental management. Thus, innovative management schemes may embrace human intervention as a necessary ingredient in attempts to produce sustainable, diverse and dynamically stable ecogeomorphological systems. The conceptual framework developed in this paper serves as an organizing construct for integrated ecogeomorphological analysis that will yield new knowledge to support stream naturalization in East Central Illinois.

Most grass-roots naturalization initiatives are severely constrained by limited financial resources and decentralized political authority (Rhoads and Herricks 1996). Although watershed planning may occur via collective action among a wide range of concerned parties, individual naturalization projects are likely to be implemented progressively over time at spatial scales corresponding to the planform scale or lower, rather than being implemented at one time over an entire watershed. A crucial element of this incremental approach is to assess accurately the myriad ways that a mosaic of integrated naturalization elements can be incorporated into the system to enhance environmental quality, yet maintain geomorphological and ecological stability. This type of assessment should be based on a thorough understanding of the relative importance of various external controls on the internal dynamics of channel change at specific scales of analysis (Rhoads and Monahan 1997) and on possible corresponding responses in fish communities. In particular, a critical need exists for information on the process-based connectivity among geomorphological conditions, physical habitat and fish-community composition at the planform, bar unit, and bar element scales. The history of piecemeal channelization and maintenance of streams in East Central Illinois has produced an ideal testing ground for evaluating the connectivity issue. A variety of juxtaposed planform and bar element scale reaches, with different fisheries quality, already exist in this region. By studying differences between and connections among these juxtaposed reaches, integrated ecogeomorphological analysis will generate information to help guide the formulation of naturalization schemes that preserve the stability of individual spatial elements over the entire stream system.

The limited spatial scale of individual naturalization projects and the potential for recurring human intervention in streams of East Central Illinois suggests that management approaches based on an understanding of patch dynamics, habitat segmentation and intermediate disturbance effects will be important for enhancing ecological diversity in naturalized streams. Patch dynamics in lotic ecology (Pringle and others 1988, Townsend 1989) complements the River Continuum Concept by focusing attention on spatial and temporal variations in local mechanisms that constitute not only the building blocks of network-scale trends, but also local departures from these trends (e.g., Schlosser 1982, 1995). Thus, a patch-dynamics approach provides justification for basing stream ecological research on discrete geomorphological features over the scale hierarchy. Studies of fish communities at the planform scale emphasize interactions among specific patch types in the habitat mosaic (e.g., Gorman and Karr 1978, Angermeier and Schlosser 1989). From a naturalization perspective, the critical issue at the network scale is the number, size, and distance between habitat islands in a stream network (Sedell and others 1990). At the planform, bar unit, and bar element scales, the critical management issue is not only the establishment and maintenance of these habitat islands, but also the accommodation of geomorphological and ecological dynamics in naturalization design (Herricks 2000). The consideration of dynamics suggests that the intermediate disturbance hypothesis, which relates species richness to dynamic variability in habitat, may be relevant for evaluating how rates and magnitudes of biotic and abiotic processes affect fish communities (Ward and Stanford 1983). The evaluation of responses to disturbance, pathways of recovery, measurement of progress to new equilibria, and identification of conditions under which systems shift to new equilibrium states are a few of the dynamics that must be considered (e.g., Statzner and others 1988; Bain 1985).

Conclusions

The interrelations among geomorphological and ecological aspects of fluvial systems are complex and incompletely understood. In part, this lack of understanding can be attributed to compartmentalized research constrained by traditional disciplinary boundaries. Investigations in aquatic ecology have been based on rather rudimentary conceptions of fluvial geomorphology, whereas fluvial geomorphologists have largely ignored the biotic aspects of fluvial systems. The great breadth and depth of knowledge in geomorphology and ecology necessitate interdisciplinary approaches if attempts to advance knowledge of the interrelations among ecological and geomorphological processes are to be effective. A holistic understanding of streams is most likely to emerge from integrative approaches that meaningfully synthesize state-of-the-art concepts from related disciplines.

The conceptual framework presented in this paper provides a foundation for integrated ecogeomorphological analysis to support scientifically based stream management at multiple scales in human-dominated agricultural landscapes of East Central Illinois. Ideally, stream management should be coordinated throughout the watershed; however, many projects will continue to be undertaken on a piecemeal basis by local communities, even when these communities participate in watershed-scale planning programs (Rhoads and Herricks 1996). Thus, scientific information underpinning stream management must be developed for a variety of spatial scales (Sear and others 1994).

A multiscale focus is important not only for management, but also for enhanced scientific understanding. Research in fluvial geomorphology and aquatic ecology has emphasized the importance of scale issues to the understanding of biotic and abiotic stream processes (Frissell and others 1986; Schumm and Lichty 1965). Several integrated research activities currently are being conducted at different scales within the context of the conceptual framework, including work at the network (Urban 2000), planform (Ladewig 1999, Hauser 1999, Frothingham and others 2001), bar unit (Frothingham 2001), and bar element scales (Schwartz and others 2001). These activities are part of an overall research program aimed at developing a sound scientific framework for stream naturalization (Rhoads and others 1999, Wade and others submitted). The consideration of scale also provides a context for conceptualizing the impact of widespread stream channelization on scalar diversity of geomorphological and ecological conditions throughout the drainage network.

Although the framework has been developed specifically to guide integrated ecogeomorphological research and management in East Central Illinois, it is based on general principles from geomorphology and ecology and *may* be adaptable to other environments in the Midwest and elsewhere. Adaptability is not meant to imply universality, however, and in some geographic settings, especially those with radically different environmental conditions, fundamental reconceptualization of ecogeomorphological relationships may be needed.

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